ISSN 0096-4522

SOIL and CROP SCIENCE
SOCIETY of FLORIDA

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PROCEEDINGS
VOLUME 63
2004

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SIXTY-THIRD ANNUAL MEETING
DAYTONA BEACH HILTON OCEANFRONT RESORT
DAYTONA BEACH, FLORIDA
21-23 MAY 2003

Mission Statement for Soil and Crop Science Society of Florida

The objectives of the Soil and Crop Science Society of Florida shall be those of an educational and scientific corporation qualified for exemption under Section 501(c)3 of the Internal Revenue Code of 1954 as amended, or a comparable section of subsequent legislation. The mission of the Society is: 1) To advance the discipline and profession of soil and crop science in Florida a) by fostering excellence in the acquisition of new knowledge and in the training of scientists who work with crops and soils, b) through the education of Florida citizens, and c) by applying knowledge to challenges facing the State, and 2) to contribute to the long-term sustainability of agriculture, soils, the environment, and society by using scientifically-based principles of soil and crop science to promote informed and wise stewardship of Florida's land and water resources.

The Soil and Crop Science Society of Florida provides a non-regulatory and non-political forum to foster scientific ideas and exchange of information for those interested in agricultural production and the sustenance of the agro-ecosystem in Florida. The mechanisms by which this society fosters exchange and displays of objective information include: 1) The presentation, at annual meetings, of papers by those who have completed scientifically-designed and analyzed data on subject matter that is pertinent to agriculture and environmental quality. 2) The publication of scientifically-designed treatments and analyzed experiments in papers on specific subject matters that are peer reviewed and published in a longstanding series of the Proceedings (Soil and Crop Science Society of Florida Proceedings). 3) The publication of position papers in the Proceedings that are needed by those who design laws and statutes on contemporary and applied subject matters related to agriculture and the environment in Florida that require objective viewpoints based on scientifically-attained information. 4) The fostering and training of students to participate in scientific dialogue by providing them with a competitive forum at the annual meeting of the Society where they can present their scientifically-attained data on agriculture and the environment and by providing them with opportunities to interact with professional people from universities, commercial companies, agribusiness, and growers. 5) The establishment of educational credits (e.g. C.E.U.s) which allow professionals to maintain their competency and certified status.

Drs. G. H. Snyder and T. A. Kucharek, January 2000.

Logo of the Soil and Crop Science Society of Florida. At the 40th Annual Business Meeting at 1120 h, 8 Oct. 1980 at the Holiday Inn, Longboat Key, Sarasota, FL, a report was presented by the *ad hoc* Logo Committee composed of J. J. Street, Chair, R. S. Kalmbacher, and K. H. Quesenberry. All Society members were eligible to participate in the contest which would result in the selection of a logo design for the SCSSF. The presentation of the winning entry would be made at the 1981 Annual Meeting. David H. Hubbell was announced as the winner of the contest and was awarded a free 10-yr membership in the Society. The design, shown above, depicted the chief interests of the Society: Florida Soils, and Crops. Soils and Crops were given equal weight with Florida. Soils was depicted as the soil texture triangle which shows the percentage of sand, silt, and clay in each of the textural classes, but simplified so as to permit clarity in reduction when printed. Crops was shown as a stylized broadleaf plant, including the roots. Florida was shown, minus its keys, with only one physical feature in its interior, Lake Okeechobee. Enclosed within nine rays such as might be envisioned as being made by the sun emitting light (sunburst) behind the symbols are two concentric circles containing the words "SOIL AND CROP SCIENCE SOCIETY" in the top semicircle and "FLORIDA" at the bottom of the lower semicircle. A schematic likeness of the State of Florida occupies 0.5 of the area within the smaller circle, while the symbol for Soils and the symbol for Crops occupy 0.25 of the area each, with the sum of the three parts totalling unity.

The first printing of Society stationery following the award on 28 Oct. 1981, and the printed program of the Society since the 1982 meetings, have featured the logo.

V. E. Green, Jr., Editor, Volume 45

SOIL AND CROP SCIENCE SOCIETY OF FLORIDA

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Published annually by the Soil and Crop Science Society of Florida. Membership dues, including subscription to the annual Proceedings, are $30.00 per year for domestic members and $35.00 per year for foreign members. At least one author of a paper submitted for publication in the Proceedings must be an active or honorary member of the Society except for invitational papers. Ordinarily, contributions shall have been presented at annual meetings; exceptions must have approval of the Executive Committee and the Editorial Board. Contributions may be (1) papers on original research or (2) invitational papers of a philosophical or review nature presented before general assemblies or in symposia. A charge of $45.00 per printed page in the Proceedings will be billed to the agency the author represents to help defray printing costs. Members are limited to senior authorship of one volunteered paper per annual meetings; there is no limit for junior authorship.

CROPS SECTION

SOIL AND WATER SECTION

ENTOMOLOGY & NEMATOLOGY

†At the author's request, these refereed papers have been externally reviewed.
‡Paper presented before 2003 (Daytona Beach). This manuscript is a carry-over.

GRADUATE STUDENT FORUM

ABSTRACTS

Crops and Pest Management

(Continued on next page)

Soils and Environmental Quality

†Manuscripts were prepared from these abstracts, and they appear in this volume.

SOCIETY AFFAIRS

DEDICATION OF THE SIXTY-THIRD PROCEEDINGS SOIL AND CROP SCIENCE SOCIETY OF FLORIDA

Grover C. Smart, Jr.

GROVER C. SMART, JR.

Grover C. Smart, Jr. was born on 6 Nov. 1929 on a flue-cured tobacco farm in Stuart (Patrick Co.), VA. He earned the B.A. degree, in Biology in 1952 from the Univ. of Virginia. He entered the military where he served in the Army Security Agency from March 1953 until January 1956. After his discharge from the Army, he entered the Graduate School at the Univ. of Virginia and earned the M.S. degree in 1957. He earned the Ph.D. degree in Nematology (Department of Plant Pathology) from the Univ. of Wisconsin, Madison, in 1960.

From 1960 to1964, he was employed as Assistant Professor by the Virginia Polytechnic Institute at its Tidewater Research Station in Holland, VA. His research there was on the soybean cyst nematode, and among other things, he was the first to demonstrate that the Peking variety of soybean thought to be resistant to the nematode, was not. Thus began the recognition of strains of the nematode. In 1964 he was employed as Assistant Professor in the Entomology and Nematology Department, Univ. of Florida. Dr. Smart was promoted to Associate Professor in 1967 and to Full Professor in 1973. He served as Assistant Chair of the Entomology and Nematology Department from 1976-1979, as Acting Chair from 1979-1980, and Graduate Coordinator from January 1997 until his retirement in June 2003.

For the first part of his career, his research was on plant-parasitic nematodes. In 1985, with the outbreak of the mole cricket problem in Florida, especially in pastures and golf courses, he switched his research to insect-parasitic nematodes. He co-authored the description of a nematode pathogen of mole crickets found in South America, and has obtained three patents to use the nematode to control mole crickets and other insects in the order Orthoptera. The nematode is now commercially available for use as a biological control agent. He has over 160 research publications.

Dr. Smart has taught numerous students in one undergraduate course, two graduate courses, and a graduate seminar, all in nematology. He also directed the research of several M.S. and Ph.D. students.

He has served the Society of Nematologists as a member of its Executive Committee, as Chair of its Honors and Awards Committee and its Archives Committee, as Co-Editor of its newsletter, and as Editor and Editor-in-Chief of its Journal of Nematology. He has served on committees and as President of the Florida Nematology Forum, and as President of the Florida Chapters of Gamma Sigma Delta, and Sigma Xi. He has served The Soil and Crop Science Society of Florida as an Associate Editor of its Proceedings, as a member of the Board of Directors, as Vice-President, and as President.

Dr. Smart was elected a Fellow of the Society of Nematologists. He received the Distinguished Service Unit Award from the USDA for helping develop a nationwide educational program on Agricultural Law, Pesticides, and the Environment. He received the Florida Entomological Society Team Award for his work on the biological control of mole crickets.

HONORARY LIFE-TIME MEMBER
Paul L. Pfahler

PAUL L. PFAHLER

Dr. Paul L. Pfahler received a Bachelor of Science degree from the Univ. of Michigan, a Master of Science degree from Michigan State Univ., and a Doctor of Philosophy degree from Purdue Univ. He joined the Agronomy Dep. at the Univ. of Florida in 1958 working in the Plant Breeding and Genetics area. A major portion of his research activities at the Univ. of Florida, involved active participation in the small grains breeding and genetic improvement programs conducted at the main campus and the North Florida Research and Education Center at Quincy. Many outstanding, widely-adapted cultivars, unique germplasm releases, and refereed publications resulted from his cooperative efforts with Drs. Wallace, Chapman, Sechler, Barnett, Blount and Luke. Dr. Pfahler also devoted a part of his research efforts to studying plant reproductive biology in corn and sesame and was a active participant in developing the International Plant Reproductive Biology Society which organizes annual meetings and is associated with the publication of the International Journal Sexual Plant Reproduction. In the teaching area, he developed and taught the course Population Genetics and has served on numerous graduate committees over the years both as major professor and committee member. Dr. Pfahler served on many Soil and Crop Science Society of Florida committees and was an editor for the Soil and Crop Science Society of Florida Proceedings from 1991-1993. He was also editor of the International Journal Theoretical and Applied Genetics for 25 years.

CROPS SECTION

Remotely Sensed Temperatures and Evapotranspiration of Heterogeneous Grass and Citrus Tree-Canopy Surfaces

L. H. Allen, Jr.,* K. F. Heimburg, R. G. Bill, Jr., J. F. Bartholic, and K. J. Boote

ABSTRACT

Methods for regional assessment of evapotranspiration are needed to predict surface and meteorological effects on water supplies. This study was conducted to evaluate the potential of airborne thermal scanning of surface temperatures and several methods for determining surface-to-air transport resistance of sensible heat for measuring evapotranspiration by a resistance-energy balance technique. Aircraft overflights provided thermal images of a pasture and a citrus grove, which included other short and tall vegetation. Remotely-sensed surface temperatures covered a range of ~20°C, with bare soil and close-cropped inactive pasture vegetation being the warmest, and water and tall vegetation being the coolest. Evapotranspiration rates (latent energy flux densities), depending on method, ranged from ~30 W m^{-2} in the warmest areas with limited water availability to ~500 W m^{-2} in the coolest areas where water was not limiting. The area-weighted evapotranspiration rates of the various methods were 87 to 104% of rates measured by a Bowen ratio apparatus. Three methods for computing surface-to-air heat transport resistance gave similar values. A major finding was that the surface-to-canopy air space resistance for short grass was much larger than the canopy air space-to-boundary layer reference height resistance. Furthermore, this surface resistance to heat transport was much larger than reported elsewhere for soybean [*Glycine max* L. (Merr.)] and sorghum [*Sorghum bicolor* L. (Moench.)]. These remote sensing methods clearly show differences based on surface vegetation conditions. They certainly can be applied to show the wide range of variation of surface temperatures and flux densities of sensible heat and latent heat across landscapes, and they can be used to compute evapotranspiration accurately, provided that reliable surface-to-air heat transport resistances can be obtained.

Evapotranspiration (ET) can be regarded as a coupled mass-flow and energy-flow process. As mass flow, ET depends upon the gradient of water vapor concentration (Δe) and the resistance (r) to vapor flow between two points in the vapor flow continuum, i.e., Flux = $\Delta e/r$. As energy flow, ET is expressed as latent heat flux density. We will use ET and latent heat flux density interchangeably. The energy balance flux density equation for net radiation (Rn), latent heat (ℓE), sensible heat (H), soil heat (S), photochemical energy (λP), and plant heat (B) over a terrestrial surface is:

$$Rn = \ell E + H + S + \lambda P + B \qquad [1]$$

The λP and B components are usually small and can be ignored. Thus:

$$Rn = \ell E + H + S \qquad [2]$$

Since the pioneering ET work of Penman (1948), the description of water vapor transport in plant canopies has been refined (Monteith, 1965; Tanner and Fuchs, 1968; Lemon et al., 1971; Shuttleworth, 1976; and Deardorff, 1978). Use of theoretical methods for predicting ET has lagged due to measurement difficulties. One approach for estimating ET from large areas is based on remotely sensed surface temperatures for input with other data from a sparse ground network. Such methods rely on the energy balance, and, if possible, avoid aerodynamic techniques that require periodic wind profile measurements over various surfaces.

To develop a remote sensing technique for determining ET over a large area, methods are needed for partitioning Rn into components of ℓE, H, and S, where the amount and partitioning of Rn may vary with time and space. The objective of this study was to develop a method for computing large-area ET from surface temperatures obtained with an airborne thermal scanner, using micrometeorological measurements and theory to obtain Rn and transport factors; and to compare these techniques of computing ET with both micrometeorological and portable chamber measurements of ET.

MATERIALS AND METHODS

Theory

The most important parameter affecting ET is Rn, which is difficult to obtain over large areas with conventional ground measurements. Remote sensing data, however, can assist in determining Rn.

Estimating Rn by remote sensing

At the earth's surface Rn is made up of the following flux densities: downward solar radiation (Qs) minus upward reflected solar radiation (Qsr) plus downward thermal radiation from the atmosphere (Qa) minus upward thermal radiation leaving the surface (Qbs), i.e., Rn = Qs - Qsr + Qa - Qbs.

L. H. Allen, Jr., USDA-ARS, Agronomy Dep. and Dep. of Horticultural Sciences, Univ. of Florida, Gainesville, FL 32611-0965; K. F. Heimburg, formerly graduate student, Environmental Engineering Sciences Dep., Univ. of Florida; R. G. Bill, Jr. and J. F. Bartholic, Horticultural Sciences Dep., Univ. of Florida; and K. J. Boote, Agronomy, Dep., Univ. of Florida, Gainesville, FL 32611-0500. This research was supported by the Florida Agric. Exp. Stn. and is approved for publication as Journal Series No. R-10455.

*Corresponding author (LHAJR@ifas.ufl.edu).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:1-20 (2004).

Incoming solar radiation (Qs). Techniques for correlating Qs and cloud brightness determined by hourly GOES visible data have been developed (Tarpley et al., 1978; Tarpley, 1979). Cloud amount and cloud thickness control the fraction of extraterrestrial solar radiation reflected to space. Cloud amount can be computed from the number of remote sensing pixels in clear, partly cloudy, and cloudy classes (Shenk and Salomonson, 1972).

Reflected solar radiation (Qsr). Reflectivity of solar radiation at the earth's surface is governed by ground cover. Combining reflected energy in visible and near infrared bands of remote sensing data under clear sky conditions will provide Qsr values, which range from 5% for organic soil, 10 to 25% for vegetation, and up to 50% for white sandy surfaces.

Thermal radiation (Qa, Qbs). From knowledge of water vapor and air temperature profiles, Qa can be calculated based upon methods by Greenfield and Kellogg (1960), where the atmosphere is divided into a set of parallel slabs. The thermal radiation coming from each slab and being attenuated by the intervening atmosphere must be aggregated and then integrated over the hemispheric solid angle.

Atmospheric transmissivities for thermal radiation were tabulated by Elsasser and Culbertson (1960) and Davis and Viezee (1964). Radiatively active gases such as carbon dioxide, methane, nitrous oxide, and ozone contribute to downwelling thermal radiation, but their concentration profiles remain fairly constant unlike those of water vapor, the primary radiatively active gas. Research on methods for extracting these various profiles from the satellite data has been conducted (Weinreb, 1977).

If the sky is clear, Qbs can be obtained by thermal radiation flux density to the satellite through the 8 to 14 µm wavelength atmospheric window. If the sky is not clear, estimates of the value of Qbs can be obtained from methods of Koberg (1958). Qbs can be obtained from surface temperatures and has a value of 450 W m^{-2} (0.64 cal cm^{-2} min^{-1}) at 25°C. With just two clear satellite passes during a 24-h period and knowledge of soil water content, crop conditions, and air temperature, surface temperatures for the entire day can be estimated (Carlson et al., 1981). With adequate soil water, surface temperatures are not greatly different from air temperature. A 5°C surface temperature error gives a Qbs error of ±28 W m^{-2} (±0.04 cal cm^{-2} min^{-1}).

Energy balance partition and ET measurements

Models of ET. Two physical models of ET are the resistance-energy balance model (Heilman and Kanemasu, 1976; Verma et al. 1976; Verma and Barfield, 1979) and the Penman type combination model (Monteith, 1965; Tanner and Fuchs, 1968). Common inputs to these models are Rn, surface temperature (Ts), air temperature at a reference height (Ta), wind speed (U), and S. One form of the resistance-energy balance model to compute ET (ℓE) of sorghum, soybean, and millet (*Panicum meliaceum* L.) as the residual, ℓE = Rn - H - S, was successfully tested by Verma et al. (1976) and Heilman and Kanemasu (1976). This method is also known as the residual energy balance concept since RE is computed as the residual of Rn, H, and S (Magliulo et al., 2003). The combination model (Tanner and Fuchs, 1968) calculates ET by eliminating temperature and temperature gradients as explicit parameters. There appears to be no advantage in using the combination model rather than the resistance-energy balance model for remote sensing applications; both models are mathematically interchangeable, and the combination model requires bulk stomatal resistance (difficult to obtain), air vapor pressure, and saturation vapor pressure. A third simplified model (Priestley and Taylor, 1972) calculates ET as an adjustment, α, to the ET that would occur under vapor saturation conditions. Kanemasu et al. (1979) and Barton (1979) showed applications of the Priestley-Taylor model. The only remotely sensed parameter needed would be Rn. This would be a simple model if α were known for each vegetation and climate condition.

The resistance-energy balance model. The Eq. [2] form of the energy balance equation is used. The atmosphere gradient expressions near the earth's surface for H and ℓE are:

$$\begin{aligned} H &= -\rho C_p K_H (dT/dZ) = \\ &-\rho C_p K_H (T_2 - T_1)/(Z_2 - Z_1) \text{ and} \end{aligned} \qquad [3]$$

$$\begin{aligned} \ell E &= [\rho \ell (M_w/M_a)/P] K_w (de/dz) = \\ &-(\rho \ell \epsilon /P) K_w (e_2 - e_1)/(Z_2 - Z_1), \end{aligned} \qquad [4]$$

where the subscripts "2" and "1" refer to the heights, Z, above the ground, T is temperature, e is vapor pressure, K_H and K_W are turbulent eddy diffusivities for heat and water vapor, respectively, ρ is atmospheric density, C_p is atmospheric heat capacity, P is atmospheric pressure, ℓ is latent heat of vaporization of water, and $M_w/M_a = \epsilon$ is the ratio of molecular weights of water vapor and dry air.

Assuming turbulent diffusivities for heat and water vapor are the same, the ratio of $H/\ell E$, the Bowen ratio, β, can be expressed as:

$$\beta = H/\ell E = (C_p P/\ell \epsilon) [(T_2 - T_1)/(e_2 - e_1)]. \qquad [5]$$

Latent heat flux density can be expressed in terms of β as:

$$\ell E = (Rn - S)/(1 + \beta). \qquad [6]$$

It would be desirable to use this Bowen ratio-energy balance approach of Eq. [6] directly, but there is no way to measure e and T gradients near the earth's surface with remote sensing. We can, however, measure surface foliage temperature, T_s, with remote sensing and compute the saturation vapor pressure, $e_s(T_s)$, of the surface.

It would be desirable to use a Bowen ratio approach indirectly with

$$\beta = (C_p P/\ell \epsilon) (T_s - T_a)/[e_s(T_s) - e_a], \qquad [7]$$

where e_a and T_a are measured at weather shelter height, T_s measured from remote sensing, and $e_s(T_s)$, the saturation vapor pressure at the canopy surface, computed from T_s. However, leaves introduce a stomatal diffusion resistance not found for bodies of water or wet soil surfaces. The energy balance for a leaf can be given by:

$$Rn = \rho C_p (T_s - T_a)/r_a + (\rho \ell \epsilon /P) [e_s(T_s) - e_a]/(r_a + r_s), \qquad [8]$$

where the first and second terms on the right represent H and ℓE, respectively, and where r_a is the aerial diffusion resistance and r_s is the stomatal diffusion resistance. Applied to a canopy of leaves:

$$(Rn - S) = \rho C_p(T_s - T_a)/r_a + (\rho \ell \in /P)\ [e_s(T_s) - e_a]/(r_a + r_s). \qquad [9]$$

The resistance-energy balance method could use air temperature from standard weather shelters along with Rn and surface temperature from satellite observations. The resistance-energy balance is a direct physical model of ET derived from substitution into the energy balance equation:

$$ET = \ell E = Rn - S - \rho C_p(T_s - T_a)/r_a. \qquad [10]$$

The sensible heat flux density equation for transport from a surface to a reference height is:

$$H = \rho C_p(T_s - T_a)/r_a. \qquad [11]$$

The aerial diffusion total resistance, r_a, consists of two parts in series: The resistance across the surface of individual elements (aerodynamic boundary layer resistance), r_b, and the resistance from the boundary layer to the reference measurement height, r_t, defined by:

$$H = \rho C_p(T_o - T_a)/r_t, \qquad [12]$$

where T_o is the temperature at the roughness height, Z_o. Thus, $r_a = r_b + r_t$. Integrating the reciprocal of the eddy diffusivity for heat ($1/K_H$) from Z_o to a reference height, Z, can provide r_t.

$$r_t = \int dZ/K_H. \qquad [13]$$

Eddy diffusivity for momentum increases linearly with height as $K_m = kU^*Z$, where k = von Karman's constant and U^* = friction velocity. If $K_H = K_m$, and integrating from Z_o to a reference height, Z, then:

$$r_t = \int dz/(kU^*Z), \qquad [14]$$

$$r_t = (1/kU^*)\ \ell n_e(Z/Z_o). \qquad [15]$$

From the logarithmic wind speed (U_Z) profile law for neutral conditions:

$$U_Z = (U^*/k)\ \ell n_e(Z/Z_o) \qquad [16]$$

Therefore,

$$r_t = U_Z/U^{*2}. \qquad [17]$$

The other resistance term is the resistance across the aerodynamic boundary layer defined by:

$$H = \rho C_p(T_s - T_o)/r_b. \qquad [18]$$

The values of r_b can be calculated for a single leaf surface as:

$$r_b = 1.3\ (L/U)^{1/2}, \qquad [19]$$

where L is the width of the leaf in m and U is the wind speed near the leaf in m s^{-1} (Monteith, 1965). For two leaf surfaces in parallel, the coefficient is 0.65. The leaf-to-air transport of leaves interfere with each other, so the effective resistance is not as low as in Eq. [19]. A shelter factor, SF, must be introduced (Thom, 1971; 1972). For a canopy of leaves of leaf area index, LAI, acting in parallel:

$$r_b = (SF/LAI)\ 0.65\ (L/U)^{1/2}. \qquad [20]$$

Heilman and Kanemasu (1976) computed an aerodynamic resistance based on $T_c - T_a$ where T_c was the canopy temperature determined from copper-constantan thermocouples attached to the underside of leaves. Their resistance term, r_H, was based on a turbulent analog which used T_c as the mean surface property. This analog was used to predict a heat transport roughness length, Z_H, which was smaller than the aerodynamic roughness length, Z_o. The turbulent component of aerial resistance to r_t and the "individual element" component to aerial resistance r_b can be approximated by plotting air temperature as a function of height (on a log scale) and extrapolating to Z_o, the roughness length parameter, the height at which wind speed extrapolates to zero. This would yield a temperature, T_o. From H, the defining expression for r_t from Eq. [12] is:

$$r_t = \rho C_p(T_o - T_a)/H. \qquad [21]$$

The bulk boundary layer resistance would be defined by:

$$r_B = \rho C_p(T_s - T_o)/H. \qquad [22]$$

Here r_B is used instead of r_b to imply that this resistance would be determined for an ensemble of surfaces rather than for an individual leaf.

Values of r_B, r_t, and r_a could be investigated under a range of conditions of wind speed, surface roughness, atmospheric instability, temperature, soil moisture, and radiation regimes, and vegetative surface conditions, to determine relevant controlling factors. For a given vegetation type, r_a could be used to compute H and hence ℓE and ET from Eq. [10] for other similar surfaces where ground truth H cannot be measured.

Another method of computing r_a depends on atmospheric stability, surface roughness, Z_o, wind speed U at height Z, and temperature, T. Atmospheric stability may be characterized through the Richardson number, *Ri*, a dimensionless parameter:

$$Ri = g(dT/dZ)/[\Theta(dU/dZ)^2] = gZ(T_a - T_o)/(\Theta U^2), \qquad [23]$$

where g is the acceleration of gravity (9.8 m s^{-2}) and Θ is the absolute air temperature (°K). Similarity theory along with empirical data for profiles of temperature and velocity in the turbulent planetary boundary-layer are summarized by Paulson (1970) and Businger (1973) as:

$$(T_a - T_o)/T^* = (1/k)\ [\ell n(Z/Z_o) - \Psi_1] \text{ and} \qquad [24]$$

$$U_* = kU/[\ell n(Z/Z_o) - \Psi_2], \qquad [25]$$

where Ψ_1 and Ψ_2 are known functions of *Ri*, and $T^* = H/(\rho C_p U^*)$. From these relationships and Eq. [12], r_a may be calculated as:

$$r_a = (1/kU^*)\ [\ell n(Z/Z_o) - \Psi_2] \qquad [26]$$

Thus, if T_o and Rn are known through remote sensing and T_a and U are known from ground stations, r_a and H may be calculated. Estimation of S will be discussed below. For tall canopies Z is replaced by Z - D where D is the displacement height (Rosenberg et al., 1975).

Bulk stomatal resistance. From Eq. [9] the ℓE component is:

$$\ell E = (\rho \ell \in /P)\ [e_s(T_s) - e_a]/(r_a + r_s). \qquad [27]$$

Once ℓE is determined from any model, the bulk stomatal resistance can be estimated, assuming r_a for vapor flux density is the same as r_a for H. The r_t component should definitely be the same for both sensible heat and latent heat transfer. The r_B component may be slightly different.

$$r_s = (\rho \ell \in /P)\ [e_s(T_s) - e_a]/\ell E - r_a. \qquad [28]$$

Measurements

Aircraft instrumentation and measurements

Personnel at the NASA Kennedy Space Center, Cape Canaveral, FL provided the instrumented aircraft and conducted the airborne system measurements. A NASA modified twin-engine Beechcraft C45H, fitted with a Daedalus DS-1250 (Daedalus Enterprises, Inc., Ann Arbor, MI) multiple spectral sensor/thermal infrared scanner, was used to obtain thermal images along three to six east-west flight lines across the upper part of the Taylor Creek—Nubbin Slough Watershed, Okeechobee Co. The scanner had two thermal wavelength channels (3-5 µm and 8-14 µm). Flights were made on 26 and 28 Apr. 1978 and 17 Oct. 1978. Surface temperature data from the 8 to 14 µm channel were printed on 70-mm color-coded film strips. The actual scenes selected for further data analysis were obtained from a General Electric Image 100 analyzer at the Kennedy Space Center. Only remote sensing data obtained on 26 and 28 April will be reported herein.

Ground truth instrumentation and measurements

A site was chosen in a large pangolagrass (*Digitaria eriantha* Steud.) pasture in the Taylor Creek—Nubbin Slough Watershed, Okeechobee Co. An 11-m tall instrumentation tower was located ~80°49'13"W. and ~27°27'29"N, ~500 m west of U.S. 441 and ~100 m north of a private road to a dairy site. Air temperature profiles were measured at heights of 0.3, 0.6, 1, 2, 5, and 10 m with naturally-ventilated, copper-constantan thermocouples between unaspirated, radiation-shielded discs. Incoming global and reflected solar radiation flux density was measured with upright and inverted pyranometers (model No. B-48, The Eppley Laboratory, Newport, RI), respectively. Net radiation flux density was measured with a net radiometer (model No. S-1, Swissteco Instruments, Oberriet, Switzerland). Another Swissteco net radiometer was mounted with a bottom cover to shield upward radiation. All radiation instruments were mounted at a height of 2 m. The net radiometers were slowly flushed with dry air from a container of "Drierite" (magnesium perchlorate). Wind speed and direction were measured at a height of 10 m with a cup anemometer and wind vane system (model No. 6405, R.M. Young Co., Traverse City, MI). Dewpoint temperature was recorded at this height with a dew cell (model No. 26432-09, Atkins Instrument Co., Gainesville, FL).

At 40 m west from the main tower, another 6-m tall tower was erected with a precision radiation thermometer (model No. PRT-5, Barnes Engineering Co., Stamford, CT) at the top. The precision radiation thermometer was aimed eastward at a point on the ground about 20 m away near the location of soil thermocouples. Copper-constantan thermocouples were used to measure soil temperatures at 0, 0.025, 0.05, 0.10, 0.25, and 0.50-m depths at six locations about 2 m apart. These soil temperature data were used later to calculate S since heat plate measurements failed.

Profile Bowen ratio inputs (profiles of air temperature and humidity) were measured with a vertical traversing sensor system (Allen et al., 1974). The sensors consisted of a fine wire (0.51 mm) copper-constantan thermocouple for air temperature and a Brady Array sensor (model No. BR 101B, Thunder Scientific Corp., Albuquerque, NM) for humidity (Bill et al., 1978). This apparatus consisted of naturally-ventilated sensors mounted between two, flat-plate radiation shields, 0.15-m diam. The sensor and shield assembly was mounted on a swivel that was attached to a V-belt driven by an electric motor. Each cycle of sampling of signals was triggered during each up and down traverse of the sensors by a 1.5-v pulse through a microswitch attached to the bottom of the support assembly. The signal sampling-times were controlled by a data acquisition system. Data were sampled at the bottom of the vertical traverse, and at 1/3 height, 2/3 height, and at the top of the traverse. Additional samples were collected at the 2/3 height and 1/3 height as the sensor system descended. The slope of the temperature vs. the slope of the vapor pressure profiles (reduces to $\Delta T/\Delta e$) were aggregated over each half hour used to compute β by the Profile Bowen ratio (Allen et al., 1974) through Eq. [5]. Then ℓE was computed from Eq. [6] and H was computed from the β definition of Eq. [5].

Micrometeorological data were recorded by a controller/data acquisition system (model 2100, Hewlett-Packard Co., Palo Alto, CA). A master program scheduled several other programs, e.g., for executing the Bowen ratio system to compute H, ℓE, and S on a 30-min cycle, and for both 10-min and 30-min micrometeorological data summaries. Later, these energy balance components were recomputed because S had to be recomputed from soil temperature profile data.

Other ground measurements

On 27 and 28 Apr. 1978, measurements of ET from bermudagrass (*Cynadon dactylon* L.) and pangolagrass surfaces were obtained near the meteorological tower by using a portable pop-on chamber technique similar to that of Reicosky and Peters (1977). A Mylar film chamber covering 1 m^2 and ~1 m^3 in volume was used following the techniques of Boote et al. (1985). Data were collected at frequent intervals throughout each day over two areas of both grass types. Rates of ET were interpolated and averaged on an hourly basis to compare these rates with Bowen ratio-energy balance ET rates.

Soil water content measurements were made at 0-2.5, 2.5-5.0, 5.0-10.0, and 10.0-25.0 cm depth intervals daily from 1700 h EST 27 April to 1700 h EST 1 May, a period of 5 d. Daily water use was calculated in cm d^{-1}. Since the data were scattered, mean daily water use across the 5 d was converted to latent heat flux density and compared with mean daily ℓE across the same 5 d by the profile Bowen ratio method.

On 22 and 23 May 1978, a vegetation survey was made of the area around the meteorological test site after thermal images and infrared photography prints were available for comparison with ground level features. A vegetation survey was also made in another area containing a citrus grove.

Data Analyses

Ground truth micrometeorology

Ground truth meteorological measurements (solar radiation, net radiation, soil heat flux, soil temperature profile, surface temperature from the radiation thermometer, wind speed and direction at 10 m, and air temperature at 2 m) and the Bowen ratio were made in April and October 1978 and analyzed at 30-min intervals during daylight hours for computing ET. Corrected soil heat flux densities were computed for 30-min intervals based on Eq. [3.4-3] of Kimball and Jackson (1979), namely $\Delta S/\Delta z = C_{sv}\,\Delta T/\Delta t$, where C_{sv} is the soil volumetric heat capacity and t is time. This equation was applied across the five soil-depth intervals using the trapezoid rule for integration of heat flux density through the five layers to provide the resultant mean soil heat flux density across the 0 to 0.50-m depth of each daytime 30-min interval. The value of C_{sv} was estimated to be a conservatively low value of 1.3 MJ m^{-3} °C^{-1} for a 0.0 v/v water content based on Table 1 of Kimball and Jackson (1979).

Aircraft thermal infrared scenes

We selected two scenes from Image 100 photographs that were obtained on 28 April (a pasture scene including the ground truth site) and 26 April (a scene including a citrus grove, scattered areas of trees with dense and sparse stands, and pastures). The 28 April pasture scene (Fig. 1) was obtained ~1222 to 1225 h EST, and the 26 April citrus grove scene (Fig. 2) was obtained ~1415 to 1422 h EST. The scenes were color-coded by the Image 100 to cover cold-to-hot scales of orange, blue, yellow, pink, aqua, and black, with tan being the out-of range color code for the warm side. The temperature increment codes of the figures are shown in Table 1. For 26 April, at a height of 10 m, the mean wind speed was 12.1 m s^{-1}, the air temperature was 24.4°C, and the relative humidity was 59% (dewpoint temperature, 10.6°C). For 28 April, the mean wind speed was 4.4 m s^{-1}, the air temperature was 26.1°C, and the relative humidity was 59% (dewpoint temperature, 11.1°C).

Tracings were made of the areas represented by each color code, and areas of each color code image were determined using a digitizer system (model No. 9864A, Hewlett-Packard Co., Palo Alto, CA) with programmable calculator (model No. 9830A, Hewlett-Packard Co., Palo Alto, CA). The actual ground area covered by each scene was determined by locating landmarks on U.S.G.S. 7.5-min topographic maps, and determining the area within the borders. The area was 13.5 km^2 for the 26 April citrus grove scene (flown at ~2.44 km) and 3.82 km^2 for the 28 April scene (flown at ~1.37 km). Table 1 shows the actual and relative areas under each temperature range of each scene. Because of actual north-south distortions in the image due to scanner optics and potential east-west distortions due to potential variations in aircraft ground speed, a scale bar was not drawn on Figs. 1 and 2.

Applications of Remote Sensed Data to ET

Temperature profile—Method 1

The 28 Apr. 1978 data were used to compute the turbulent resistance component (r_t) and the bulk boundary layer resistance component (r_B) and the total aerial resistance to heat transfer according to Eq. [21] and Eq. [22]. Sensible heat flux density was obtained from half-hourly Bowen ratio-energy balance measurements from 0830 to 1530 h EST. Temperature profiles were plotted against the logarithm of height on semilog graph paper. The r_t values were calculated from a height of 1.5 m (T_a) to a height of 0.02 m (T_o) using Eq. [15] and [21]. The 1.5 m height was chosen as representative of weather shelter height and the 0.02 m height was chosen as Z_o for this short grass surface. We assumed Z_H, the roughness length for heat transfer, to be equal to Z_o. The r_B values were calculated from Eq. [22], using radiation thermometer data for the surface temperature, T_s.

The average values for r_B, r_t, and r_a were 77, 36, and 113 s m^{-1}, respectively. These values were also representative of the 1200 to 1230 h EST values at the time of the aircraft overflights. The r_t values were smaller in the afternoon than in the morning, but the r_B values showed less difference. The r_a values were more consistent throughout the day than either r_B or r_t. The r_t values tended to decrease as a function of wind speed for the afternoon hours only.

Since the overall r_a values were more stable than r_B or r_t, then it is possible that the level of the effective T_o changed throughout the day. Also, the temperature gradient (T_s - T_o) was about twice as large as (T_o - T_a). It is possible that the height for T_o is overestimated by using an estimated value of $Z_o - Z_H = 0.02$ m for the height of T_o. However, the T_s to T_o temperature differences were large enough to cause the height of T_o to be reduced by three orders of magnitude (0.00002 m). The precision radiation thermometer measurements at 1230 h EST agreed with the airborne scanner surface temperature, and were substantiated by soil surface temperature measurements of the soil profile temperature system. It may be possible that the surface temperature is higher because of low ground cover, and that much of the heat and latent heat exchange involves the soil directly. However, the precision radiation thermometer was mounted at an angle that would view mainly the surface cover rather than the soil surface. We chose to view the trans-

Table 1. Color code and percentage land area for surface temperature ranges from Fig. 1 and 2. Air temperature at 1.5 m was 25.6°C on 28 Apr. and 24.3°C on 26 Apr. 1978.

	28 Apr. 1978. 1222-1225 h EST Pasture scene, 3.82 km^2		26 Apr. 1978. 1432-1435 h EST Citrus grove scene, 13.5 km^2		
				Area	
Color	Temp.	Area	Temp.	Tall†	Pasture
	°C	%	°C	%	
Tan	>42.2	23.3	>41.1	0.0	0.0
Black	38.9-42.2	24.2	37.8-41.1	0.0	0.3
Aqua	35.6-38.9	25.1	34.4-37.8	0.0	10.8
Pink	32.2-35.6	16.5	31.1-34.4	0.0	13.9
Yellow	28.9-32.2	6.6	27.8-31.1	12.9	19.8
Dark blue	25.6-28.9	2.2	24.4-27.8	14.6	3.2
Orange	22.2-25.6	2.1	21.1-24.4	11.8	1.1
PK‡	—	0.0	31.1-34.4	4.7	0.0
Y/P§	—	0.0	31.1	0.0	6.9
Percentage land area totals		100.0		44.0	56.0

†Tall includes all tall vegetation, i.e., citrus trees and native trees and shrubs growing in moist soil.

‡PK is an unresolved mixture of small areas of aqua, pink and yellow that average within the pink code temperature interval.

§Y/P is an unresolved mixture of borders along the yellow-pink temperature intervals that average near the cut-off temperature (31.1°C for the 26 April scene).

fer processes in two steps; a transfer from surface to T_o (an effective bulk boundary layer transfer) and transfer from T_o to T_a (a turbulent field boundary layer transfer).

Heilman and Kanemasu (1976) computed only one aerial resistance, over soybean and over sorghum, by extrapolating the above-canopy temperature profile down to a canopy temperature, T_c, obtained either by leaf thermocouples or by infrared radiation thermometer. Their data would indicate that the ratio of Z_o to Z_H would range from 1 to 3 for the sorghum and soybean crops. If we extrapolated temperature profiles to 0.00002 m, then we would have obtained $Z_o/Z_H = 1000$, a much larger ratio for this close-cropped grassland than the soybean and sorghum canopy data of Heilman and Kanemasu (1976). This bulk aerial resistance approach assumes that Rn, S, and bulk aerial resistance are uniform over the pasture area.

The method used to compute ET from the 28 April pasture scene was as follows. Sensible heat flux density for each surface temperature class of Table 1 was computed and weighted by the fractional area (FA_i) in each surface temperature class.

$$H_i = \rho C_p \, \Delta T_i \, FA_i / r_B, \qquad [29]$$

where the subscript "i" refers to the values of a particular color-coded surface temperature scene (Table 1, Figs. 1 and 2) and ΔT is the surface-to-air temperature difference. Latent heat flux density was computed by difference.

$$\ell E_i = Rn - S - H_i. \qquad [30]$$

The sensible heat flux density from the whole scene is:

$$H = \Sigma H_i = (\rho C_p / r_B) \, \Sigma \Delta T_i FA_i. \qquad [31]$$

Total latent heat flux density (ET) over a scene can be also computed by summation.

This method of computation does not allow for or explain any variations in effects of atmospheric stability, boundary layer and turbulent resistance, wind, leaf area index, plant height and surface parameters (D and Z_o) or stomatal resistance, on sensible heat and latent heat transport processes. The next section describes one approach to evaluating some of these effects on heat transport processes, and ultimately, on ET.

Stability corrected heat flux density—Method 2

The overall approach was to calculate H from the vegetated surface, estimate S, and calculate ET as the residual using a directly measured Rn. The bulk of this effort lay in developing means to obtain H from a remotely sensed surface temperature, an air temperature, and a wind speed. Key problems were how to deal with various stability regimes and how to use surface temperatures.

The first problem was approached via diabatic influence functions, which are empirical corrections to the neutral atmospheric stability transport theory based on the windspeed log profile law. These corrections are based on *Ri*, Eq. [23]. These correction functions exist in the literature in integrated forms of Eq. [24] to [26] (Businger, 1973) and differential forms (Morgan et al., 1971; Pruitt et al., 1973); due to much greater ease of calculation, the latter form was adopted.

The log law wind profile, valid when air temperature profiles are neutral, can be described by:

$$\partial U / \partial Z = U^* / kZ, \qquad [32]$$

where the friction velocity is:

$$U^* = kU / \{\ell n_e [(Z - D - Z_o) / Z_o]\}. \qquad [33]$$

When the air layer is stable or unstable (not neutral), a correction for momentum transfer ϕ_m is applied:

$$\partial U / \partial Z = (U^* / kZ) \, \phi_m \qquad [34]$$

analogously, a correction for heat transfer ϕ_H is applied:

$$\partial T/\partial Z = [H/(\rho C_p\ kU^*\ Z)]\ \phi_H. \qquad [35]$$

The correction functions are interrelated by the eddy diffusivity for momentum, K_m, and for heat, K_H:

$$\phi_H = \phi_m\ (K_m/K_H). \qquad [36]$$

The stability corrections used in the study were those developed during a long-term research program by a group at the Univ. of California at Davis (Morgan et al., 1971; Pruitt et al., 1973) and are listed below. [Many other stability correction methods have been developed and used such as earlier ones discussed by Kanemasu et al. (1979) and Monteith and Unsworth (1990) or a later method (Mahrt and Ek, 1984) used by Jackson et al. (1987).]

$$\phi_m = (1 + 16\ Ri)^{1/3}\ \text{STABLE} \qquad [37]$$

$$\phi_m = (1 - 16\ Ri)^{-1/3}\ \text{UNSTABLE} \qquad [38]$$

$$K_H/K_m \approx K_w/K_m = 1.13\ (1 + 95\ Ri)^{-0.11}\ \text{STABLE} \qquad [39]$$

$$K_H/K_m \approx K_w/K_m = 1.13\ (1 - 60\ Ri)^{0.074}\ \text{UNSTABLE} \qquad [40]$$

The approximation in the second set of relationships is based on the near equality of K_H and K_w documented by Dyer (1967). The Richardson number is the ratio of buoyant and turbulent momentum transport influences, shown here in derivative form:

$$Ri = (g/\Theta)\ (\partial T/\partial Z)/(\partial U/\partial Z)^2. \qquad [41]$$

The equation used to calculate H was developed from the basic turbulent transport equations:

$$H = \rho C_p\ K_H\ (\partial T/\partial Z)\ \text{and} \qquad [42]$$

$$\tau = \rho K_m\ (\partial U/\partial Z) = \rho U^{*2} \qquad [43]$$

to make use of the empirical relationships for ϕ_m and K_H/K_m. Eq. [42] may be rewritten:

$$H = \rho C_p\ (K_H/K_m)\ K_m(\partial T/\partial Z). \qquad [44]$$

Solving Eq. [43] for K_m, the eddy diffusivity of momentum, then:

$$K_m = U^{*2}/(\partial U/\partial Z). \qquad [45]$$

Solving $\partial U/\partial Z = U^*\ \phi_m/(kZ)$ for U^* and substituting

$$K_m = (k^2\ Z^2/\phi_m^{\ 2})\ (\partial U/\partial Z)\ \text{and} \qquad [46]$$

$$H = \rho C_p\ k^2\ Z^2\ (K_H/K_m)\ (1/\phi_m^{\ 2})\ (\partial U/\partial Z)\ (\partial T/\partial Z). \qquad [47]$$

In difference form:

$$H = \rho C_p\ k^2\ (Z_{gm}/\Delta Z)^2\ (K_H/K_m)\ (1/\phi_m^{\ 2})\ \Delta U\ \Delta T, \qquad [48]$$

where $\Delta Z = Z_2 - Z_1$ and Z_{gm} is the geometric mean of Z_1 and Z_2. The corresponding Ri is

$$Ri = (g/\Theta)\ \Delta Z\ \Delta T/(\Delta U)^2. \qquad [49]$$

The behavior of H vs. $Ri = f(\Delta T, \Delta U, Z_o)$ based on Eq. [47] was investigated in unstable conditions by varying ΔT, ΔU, and Z_o one factor at a time and plotting (graph not shown). The magnitude of H increased with increasing ΔT as expected. However, the changes in H with respect to increasing ΔU was not so obvious; apparently, at moderately low wind speeds air movement may actually suppress natural convection (the buoyant rising of warm air). At larger values of ΔT, H increased both with increasing ΔU (which occurred in the region where $Ri > -0.1$) and with decreasing ΔU (which occurred in the region where $Ri < -0.1$) with a small minimum tendency near the point where $-0.1 < Ri < -0.1$. Increasing Z_o tended to increase H for given ΔT and ΔU values.

Transport relationships like Eq. [47] may also be cast in terms of r_t, the resistance to heat transport in the turbulent boundary layer. This behavior or H vs. $Ri = f(\Delta T, \Delta U)$ was calculated and plotted (graph not shown). Values of r_t, increased with decreasing ΔU and tended to increase with decreasing ΔT, especially at low values of ΔU.

The usefulness of these equations was tested in two stages. First, in order to establish the applicability of the empirical results, H was calculated between the various levels at which temperatures had been measured. Since the site was uniformly vegetated, met fetch requirements, and could be considered near steady state during a given 30-min period, the calculated sensible heat flux densities should have been equal (indicating the same H at all levels). Second, to determine the absolute accuracy of the calculated sensible heat flux densities, they were compared to values of H obtained via the ground truth Bowen ratio method.

All quantities in the equations were physical constants or measured directly except ΔU, since no wind profile was measured. A stability-corrected ΔU was calculated iteratively. First, a friction velocity was calculated from the 10-m wind speed measurement according to Eq. [33]. The displacement height D and the roughness parameter Z_o were obtained graphically from temperature profiles, assuming $Z_H = Z_o$ and $D_H = D_m = D$. Heilman and Kanemasu (1976) assumed the latter equality, but obtained Z_H by extrapolation. Then, assuming U^* constant over the profile, ΔU was approximated by the difference form of Eq [34]:

$$\Delta U = (U^*/k)\ \phi_m\ \Delta Z/(Z - D)_{gm}. \qquad [50]$$

First an estimate for ΔU was used to compute Ri, which in turn was used to calculate ϕ_m and then a new ΔU was used as a new estimate, and the procedure repeated. Generally, this procedure converged on a ΔU of three significant digits in four to five iterations.

The constancy test for sensible heat flux density (Table 2) showed several problems in the stability corrected calculation method. These were: 1) relatively high values of H calculated for surface and near surface air layers, 2) relatively low values of H calculated for layers extending from very low to very high levels, and 3) relatively high values of H for air layers high in the profile. In general, reasons for these departures from constant sensible flux density can be traced back to wind and temperature profiles at levels outside the 0.35- to 2.0-m layer studied at Davis, CA (for which stability corrections were determined by Morgan et al., 1971; Pruitt et al., 1973).

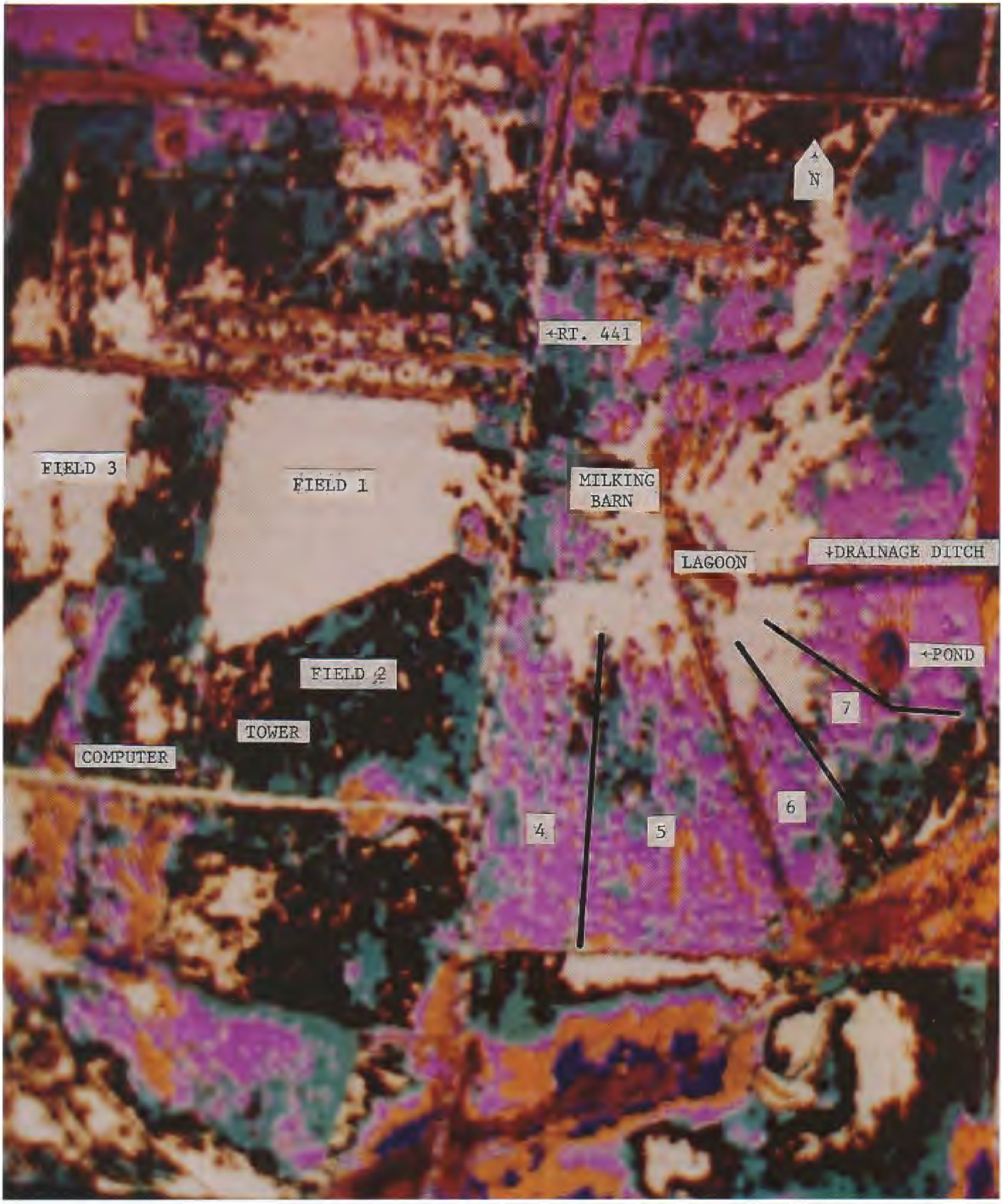

Fig. 1. Infrared image of pasture in Taylor Creek Watershed, 28 Apr. 1978 at 1222-1225 h EST. Temperature codes are given in Table 1. Photographed from General Electric Image 100.

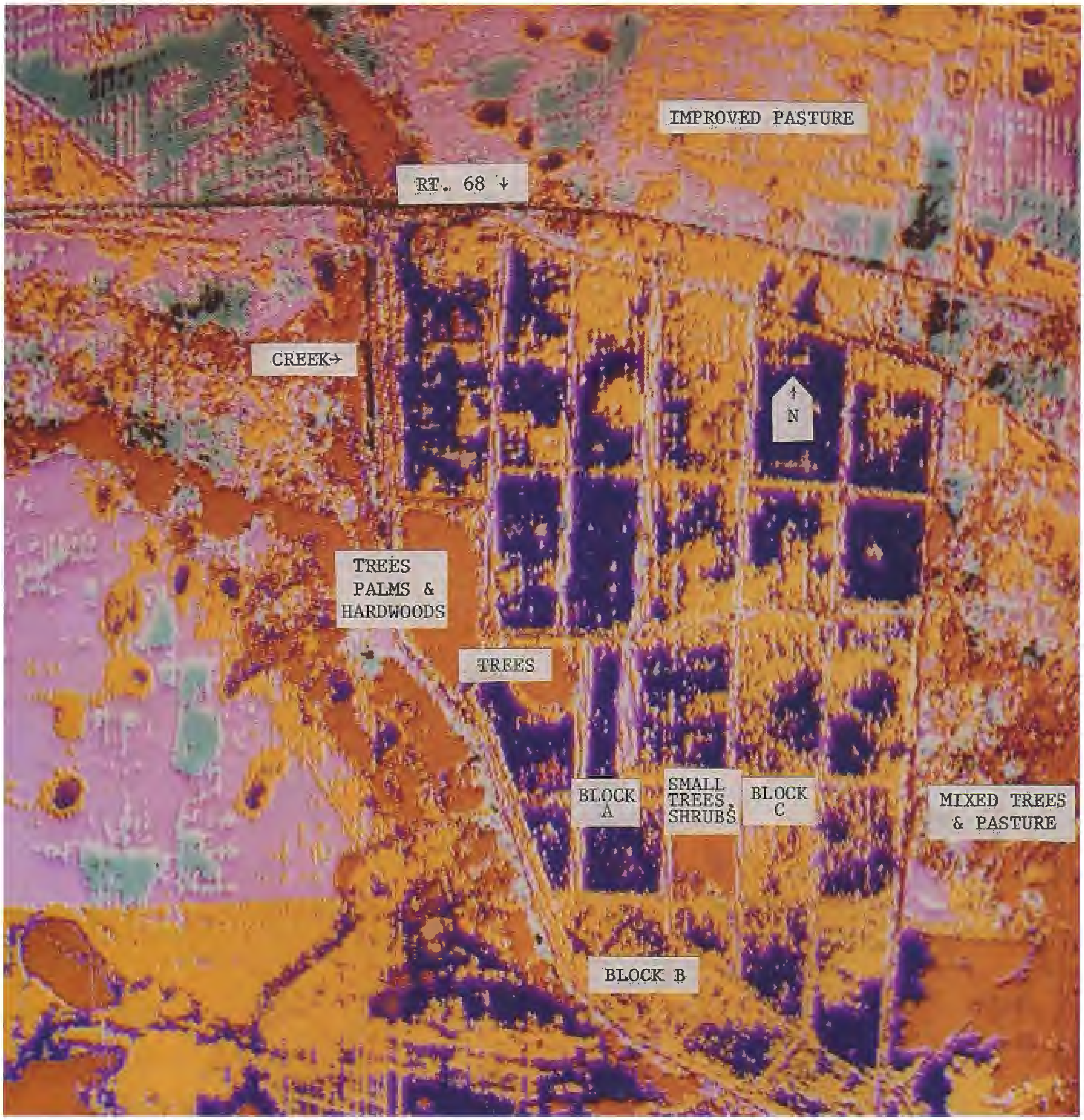

Fig. 2. Infrared image of a citrus grove in Taylor Creek Watershed, 26 Apr. 1978 at 1432-1435 h EST. Temperature codes are given in Table 1. Photographed from General Electric Image 100.

Calculated values of H are high in air layers bounded on the bottom by the vegetation surface because of the extremely high temperature gradients near the surface. As well as increasing ΔT directly, high temperature gradients force up the iteratively calculated ΔU, sometimes to physically unrealistic levels. The dominance of ΔT in the sensible heat flux density of Eq. [48] continues from the surface to the 2.0-m level. At this point the second problem area begins: sensible heat flux densities become relatively lower because of the increasing importance of Z_{gm} in the equation. The geometric mean of Z_1 and Z_2 is intended to be the point on the profile at which $\Delta U/\Delta Z$ or $\Delta T/\Delta Z$ is the slope of the wind or temperature profile; this holds only approximately when the profiles are not truly logarithmic. Since the stability corrected wind profile is calculated as a correction to a log profile, the geometric mean height will effectively underestimate the point at which a gradient calculated by differences holds in the unstable case, and overestimate in the stable case. These effects are most

Table 2. Test for sensible heat flux density constancy with stability corrections.†

	Z_2, cm					
Z_1, cm	0.3	0.6	1.0	2.0	5.0	10.0
0.0	761	319	259	160	112	83
0.3		154	132	108	82	67
0.6			144	138	120	100
1.0				156	144	107
2.0					179	168
5.0						220

†Sensible heat flux densities, in W m^{-2}, are calculated for an average temperature profile and 10-m wind speed measured between 1500 and 1530 h EST on 27 Oct. 1978. Z_2 and Z_1 are the upper and lower bounds of the air layer for which the sensible heat flux density was calculated.

noticeable when geometric mean heights are calculated over heights more than an order of magnitude apart. The final problem area is calculations made between upper levels. Here ΔT's are small, leading to unreasonably small ΔU's, which in turn lead to very high *Ri* values and corresponding very high stability correction factors.

Thus, to stay on the safe side, it was decided to restrict our calculations to the Davis study layer of 0.35 to 2.0 m (Morgan et al., 1971; Pruitt et al., 1973).

Since many temperature profile data were available for pasture surfaces, regressions relating the difference in surface and air temperatures to the difference in air temperature over the air layer in which the empirical relationships hold were developed.

$\Delta T_T = T_S - T_{1.5}$ temperature difference between surface and 1.5 m

$\Delta T_{BL} = T_S - T_{0.3}$ difference between surface and 0.3 m

$\Delta T_t = T_{0.3} - T_{1.5}$ difference between 0.3 and 1.5 m

First temperatures at Z - D = 0.3 and 1.5 m were tabulated from graphs of the temperature profiles. Then ΔT_T was graphed vs. ΔT_{BL} for all profiles (figure not shown), a line with zero intercepts was fit to the data by eye, and slope of the line computed.

$$\Delta T_{BL} = C\Delta T_T \qquad [51]$$

The 44 values of ΔT_{BL} vs. ΔT_T plotted from the fall 1978 data gave a slope of 0.819. All points clustered close to the linear relationship over the ΔT_T range of ~2 to 8°C.

The equation used to calculate T_t was

$$\Delta T_t = \Delta T_T - \Delta T_{BL} \text{ and} \qquad [52]$$

$$\Delta T_t = (1 - C)\ \Delta T_T. \qquad [53]$$

These ΔT_{BL} vs. ΔT_T plots for spring and fall data (short grass and tall grass pastures, respectively) suggest that generalized relationships involving parameters such as vegetation height may be developed so that these relationships need not be measured for all surfaces that may be encountered.

For taller vegetation (forest trees, citrus trees, shrubs, and saw palmetto [*Serenoa repens* (W. Bartram) Small]), the transport processes and aerial resistances would be much different than for short grasses. Since no ground truth measurements were made over this type of vegetation, we had no way of calculating or estimating the bulk aerial resistance directly. A leaf-to-air heat transport resistance equation developed by Thorpe and Butler (1977) and Landsberg and Powell (1973) was adapted. This type of equation was developed for leaves in an apple (*Malus domestica* Borkh.) orchard where shelter or interference effects among leaves were evident. The generalized equation was:

$$r_a = 2.7\ (L/U)^{1/2}. \qquad [54]$$

For an assumed leaf dimension (L) of 0.06 m (where U is in m s^{-1}) The above equation reduces to:

$$r_a = 6.6\ U^{-1/2}. \qquad [55]$$

The wind speed at the top of the tall vegetation was estimated to be one-half of the measured wind speed (over pasture) at 10 m. Many examples in the literature show that this is a reasonable approximation (Allen, 1968).

Converting thermal scenes into regional ET. To summarize the technique developed and show its application to thermal scenes, the entire calculation procedure is outlined below. It is assumed that roughness length and displacement height are known, air temperature and wind speed are known from auxiliary ground measurements, and surface temperature is available from remotely sensed data.

First, the range of vegetation roughness lengths (Z_o) and surface temperature (T_s) were divided into suitable increments. The area of each Z_o, T_s combination was determined and the percentage of total area in each combination as $P(Z_o, T_s) = A(Z_o, T_s)/A(\text{total})$ was computed (in the most complex scene on 26 April, two roughness conditions, corresponding to short and tall vegetation, in seven temperature increments were considered).

For short vegetation (where Z_o - 0.01 m and D = 0.0 m), regressions of ΔT_T vs. ΔT_{BL} were used to calculate ΔT_t (EC) for each T_s. Next, friction velocity U* (m s^{-1}) was calculated as:

$$U^* = k\ U_{10}/\{\ell n_e\ [(Z - D - Z_o)/Z_o]\} = 0.0579\ U_{10}. \qquad [56]$$

Then, $\Delta Z = Z_2 - Z_1$, $(Z - D)_{gm}$, and $(Z - D)_{gm}{}^2/(\Delta Z)^2$ were calculated where:

$$(Z - D)_{gm} = \exp\{[\ell n_e\ (Z_1 - D) + \ell n_e\ (Z_2 - D)]/2\} \qquad [57]$$

An iterative technique was used to calculate ΔU. First, a value of ΔU was estimated. Then, based on Eq. [23], calculate $Ri = (g/\Theta)\ (\Delta T/\Delta Z)/(\Delta U/\Delta Z)^2$ where Θ is absolute temperature (°K). Then, from Eq. [50], calculate a new ΔU as $\Delta U_{new} = U^*\ \Delta Z\ \phi_m/[k(Z - D)_{gm}]$, where $\phi_m = (1 + 16\ Ri)^{1/3}$ STABLE {Eq. [37]}, or $(1 - 16\ Ri)^{-1/3}$ UNSTABLE {Eq. [38]}. Using the ΔU_{new} calculate a new value of *Ri*. Repeat the process until ΔU converges to a stable value (within 0.01 m s^{-1}). Finally, calculate H in (W m^{-2}) for each ΔT_t for each surface temperature condition as:

$$H = \rho C_p\ k^2\ (K_H/K_m)\ (1/\phi_m{}^2)\ [(Z - D)_{gm}/(\Delta Z)]^2\ \Delta U\ \Delta T. \qquad [58]$$

For tall vegetation, the leaf-to-air resistance technique was used to calculate H for each T_s using Eq. [55], where $H = \rho C_p (T_s - T_a)/r_a$, the same as Eq. [11].

For each Z_o, T_s combination, ET was calculated. First soil heat flux density was estimated. For short vegetation measured S at the micrometeorological site was used, and under tall vegetation S was considered negligible. Then, $ET(Z_o, T_s) = Rn$ (measured or remote) $- H(Z_o, T_s) - S$. Regional ET was calculated by summation over the Z_o and T_s combinations as:

$$ET = \sum \sum P(Z_o, T_s)\, ET(Z_o, T_s) \qquad [59]$$

Stability-corrected integral profile—Method 3

Mean meteorological data acquired from the micrometeorological tower were obtained at 1245 h EST on 28 April. These data were: $T_a = 23.9$°C, dewpoint temperature = 11.0°C, Rn = 596 W m^{-2}, S = 95 W m^{-2}, U = 5.07 m s^{-1}, and $\beta = 0.47$. These data were input into the models shown in Eq. [24] to [26] with the surface temperature shown in Table 1 (38.9-42.2°C) and Fig. 1 (black color code). Stability parameters Ψ_1 (momentum) and Ψ_2 (heat) were computed according to the integration of Paulson (1970). Aerial resistance can be computed from Eq. [26] for use in the resistance-energy balance model of Eq. [10] or the combination model (Equation not given). The roughness length parameter, Z_o, is required to compute r_a. Webb (1965) indicated that Z_o for open grassland is ~0.02 to 0.04 m. According to Szeicz et al. (1969), this would correspond to grass heights of about 0.05 to 0.10 m. Some of our pasture vegetation was estimated to be 0.04 m, so < 0.01 m may be a more representative Z_o.

RESULTS AND DISCUSSION

Vegetative Cover Analysis

Two different areas were chosen for study of plant cover. One area (primarily in Section 22, T. 35S., R. 35E. or about 27°25'N, 80°49'W), the area in which the meteorological towers and instrumentation were located, was primarily improved grass pastures used by grazing dairy cattle or improved grass utilized as a hay crop (Fig. 1). The other area (primarily in Section 36, T. 35S., R. 34E. or about 27°23'N, 80°53'W) in which some detailed observations of plant life were made was mostly in a citrus grove (Fig. 2).

Pasture scene

Irregularly-shaped areas, near dairy barns where heavy cattle traffic had eliminated plants, were the warmest (right center of Fig. 1). A mixture of sandy soil and partially decomposed manure made up the surface which was warmer than 42.2°C in the thermal scene, although reference air temperature at the time of the overflight was only 26.1°C.

In areas with vegetation cover, the physical condition of a given species could be differentiated in the thermal imagery. For example, Field 2 (Fig. 1) contained primarily pangolagrass except for the west end which was primarily bermudagrass. This field had surface temperatures mainly in the 38.9 to 42.2°C range. Field 1 also contained primarily pangolagrass but this field was warmer (>42.2°C) because it had been cut for hay the previous fall and then grazed heavily prior to 28 Apr. 1978. Field 2 had also been cut for hay, but it had not been grazed. Although this field had a lot of non-transpiring stubble and matted residue from hay making operations, the grasses were in a healthy growing condition, and thus Field 2 appeared cooler than Field 1 on the thermal image.

The bermudagrass in the southwest end of Field 2 was cooler than the adjacent pangolagrass in the same field. On 27 and 28 April, when portable chamber ET measurements were made, we observed that bermudagrass had more spring regrowth than pangolagrass, which should result in greater evaporative cooling.

Field 2 also contained a depression with Placid fine sand (sandy, siliceous, hyperthermic Typic Humaquepts) on the southern edge along old SR 68 (Fig. 1). Vaseygrass (*Paspalum urvillei* Stued.) was the predominant species around this wet area. Sedges (*Cyperus* spp.) were dominant on the southern side of the road around the depression. The cooler (35.6-38.9°C) eastern edge of this field (along U.S. 441) contained vaseygrass and unidentified woody shrubs in a north-south strip parallel to the highway.

Field 3 was a heavily grazed mixture of white clover (*Trifolium repens* L.), pangolagrass, carpetgrass (*Axonopus affinis* Chase), and bermudagrass with a few other widely scattered species. Some of the variability in the thermal representation of this field was likely caused by higher soil moisture in a slightly lower-lying strip to the south and by heavily grazed areas to the west. About 17 mm of rain fell on this part of the watershed on 24 Apr. 1978.

Fields 4, 5, 6, and parts of 7 were pastures separated by fences radiating away from the barn area. They contained heterogeneous patches of grass (mainly bermudagrass) interspersed with broadleaved weeds (largely rough pigweed, *Amaranthus* spp.) and some sedges, with surface temperatures typically 32.2 to 35.6°C. Southeast of these fields was a cooler (22.2-25.6°C) wet area with woody shrubs as the primary ground cover. Field 5 showed irregular warmer (35.6-38.9°C) dry areas which had some residual dead plant material on the surface. The eastern boundary of this field showed a cool (22.2-28.9°C) abandoned drainage ditch that was covered with woody shrubs.

In the midst of the irregular shaped warm (>42.2°C) barn area near the middle of Fig. 1, a cool (22.2-25.6°C) lagoon shows up as a small, orange, elongated rectangle running northwest to southeast. Wastewater from the lagoon passes through a culvert to a drainage ditch which appears as a cool (22.2-28.9°C) east-west linear feature. A shallow pond south of this ditch also shows up in Fig. 1 as an ellipse with a temperature from 22.2 to 28.9°C. The cool orange, blue, and yellow area near the bottom of the thermal image was caused by a cloud shadow.

Citrus grove scene

Thermal imagery of complex vegetation associated with a citrus grove and rangeland is shown in Fig. 2. Taylor Creek forms the western and southern boundary of the grove. Areas containing dense native trees (palms and hardwoods) and woody shrubs were coolest (21.1-24.4°C). These areas were slightly below reference air temperature at the micrometeorological site (24.4°C). Temperatures of improved pastures in the surrounding fields were predominantly 31.1 to 34.4°C with some cooler (27.8-31.1°C) and some warmer (34.4-37.8°C) areas.

In the citrus grove itself, Block A (Fig. 2) contained mature, healthy grapefruit (*Citrus* × *paradisi* Macfad.) with a surface temperature of 24.4 to 27.8°C. Vaseygrass grew in the low centers between the bedded rows of trees. Block B contained a stand of somewhat smaller, but healthy grapefruit trees with slightly higher temperatures (27.8-31.1°C). Beds were oriented northeast to southwest. All other beds in the grove were aligned east to west. The warmer temperature of this block may be due in part to bed alignment, but the smaller trees also contributed by providing less ground cover.

Block C had a poor stand of orange trees [*Citrus sinensis* (L.) Osbeck]. Some trees appeared to be affected by blight, and many trees were missing. Vaseygrass covered much of the ground area. Thermal imagery for this block showed a warmer surface temperature (27.8-31.1°C) than Block A.

There are two possible reasons why the citrus trees were warmer than other trees and shrubs. First, the citrus stomatal resistance could have been higher. Second, the leaf boundary layer resistance in the citrus groves could have been greater due to either individual leaf properties or to dense crowns with greater shelter factor effects.

Saw palmetto was pervasive in the unimproved rangeland areas. Some grasses were broomsedge bluestem (*Andropogon virginicus* L.), wiregrass (*Aristida beyrichiana* Trin. & Rupr.), and vaseygrass, with many others being present. Temperatures of large areas dominated by palmetto in the lower left part of Fig. 2 ranged from 24.4 to 31.1°C.

Within the ecosystems observed and under the environmental conditions at the time of the study, the following generalizations may be postulated: 1) Physical conditions within a grass species affected remotely sensed surface temperatures markedly; 2) Physical conditions of grasslands were primarily related to management (e.g., grazing, haying); 3) Physical condition of the grasses greatly contributed to the percentage ground cover; 4) Differences of surface temperatures among various grass species could be observed (i.e., cooler vegetated surfaces of bermudagrass than pangolagrass may be the result of earlier spring regrowth of the former species); but condition of the species of grass was typically more important; 5) Trees and woody shrubs tended to be cooler than grasses. This may be a biased observation because these plant types were generally located in wetter soil environments. However, at the same site, citrus trees on bedded soils appeared cooler than vaseygrass growing in lower-elevation middles. Windy conditions on 26 April may have enhanced convective cooling of trees and woody shrubs to a greater extent than the short grasses which were sheltered in part by the trees of the grove.

Evapotranspiration by the Profile Bowen Ratio Method

The daytime cycle of ET determined by the Bowen ratio was computed and graphed as latent heat flux density (ℓE) for the following days: 26, 27, 28, 29, and 30 April; 1 and 2 May; 17, 18, 20, 26, and 27 October; 2 and 3 November. The energy balance data summed for the daytime periods are summarized in Table 3. Hourly time-course data are shown only for 26 April (Fig. 3), 27 April (Fig. 4), 28 April (Fig. 5), and 20 Oct. (Fig. 6).

Table 3. Spring and fall 1978 daytime surface energy budget components of solar radiation (Qa), net radiation (Rn), and soil heat (S) over pastureland in Okeechobee Co., Florida, with latent heat (ℓE) and sensible heat (H) calculated by the Profile Bowen Ratio (β) method.

Date 1978	Time interval h EST	Qa	Rn	S	ℓE	H	β
		MJ m^{-2}					
26 Apr	0700-1800	23.22	12.49	0.45	7.28	4.76	0.65
27 Apr	0700-1800	27.07	13.92	0.92	7.98†	5.02	0.63
28 Apr	0700-1800	27.68	14.03	1.42	9.05†	3.56	0.39
29 Apr	0700-1800	26.96	13.64	1.23	9.41	3.00	0.32
30 Apr	0700-1800	22.56	11.25	1.40	7.16	2.30	0.37
1 May	0700-1800	17.24	9.24	1.23	4.54	3.46	0.76
2 May	0700-1830	18.86	10.00	1.25	5.78	2.98	0.52
17 Oct	0700-1800	18.49	9.97	0.27	6.33	3.37	0.53
18 Oct	0700-1800	16.23	9.09	0.37	5.87	2.38	0.48
20 Oct	0730-1700	17.98	10.08	0.62	6.73	2.73	0.41
26 Oct	0730-1700	17.65	10.02	0.67	7.02	2.33	0.33
27 Oct	0730-1700	17.10	9.68	0.65	6.95	2.08	0.30
2 Nov	0730-1700	17.81	9.51	0.53	6.48	2.50	0.39
3 Nov	0730-1700	16.34	8.84	0.54	6.12	2.17	0.35

†Chamber ℓE (0700-1900 EST) for bermudagrass and pangolagrass on 27 April was 8.51 and 5.39 MJ m^{-2}, respectively, and on 28 April was 10.11 and 6.83 MJ m^{-2}, respectively. The mean daily 27 April to 1 May ℓE was 7.72 MJ m^{-2} by soil water balance and 7.63 MJ m^{-2} by the Bowen ratio.

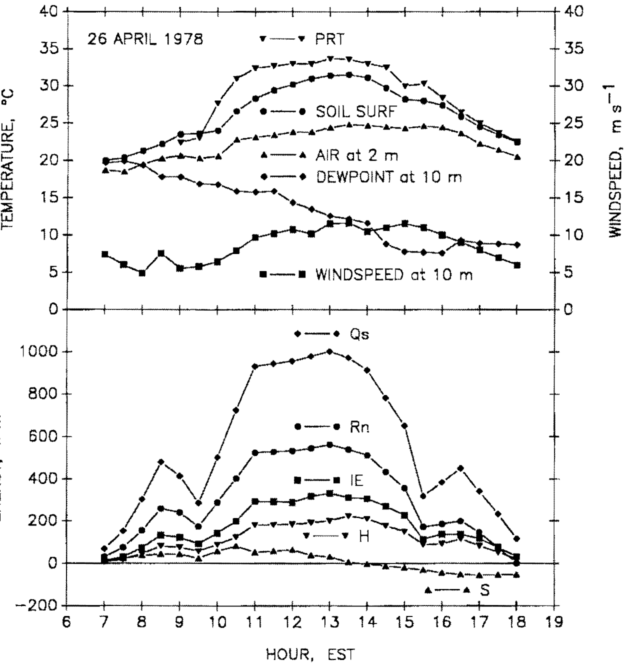

Fig. 3. Daytime course of flux densities of global solar radiation (Qs), net radiation (Rn), soil heat (S), and latent (ℓE) and sensible heat (H) by the profile Bowen ratio-energy balance technique, and precision radiation thermometer surface temperature (PRT), soil surface temperature (Sfc T), air temperature at 2 m (Air T), dewpoint at 10 m, and wind speed at a height of 10 m over primarily pangolagrass pasture at the beginning of spring regrowth, 26 Apr. 1978.

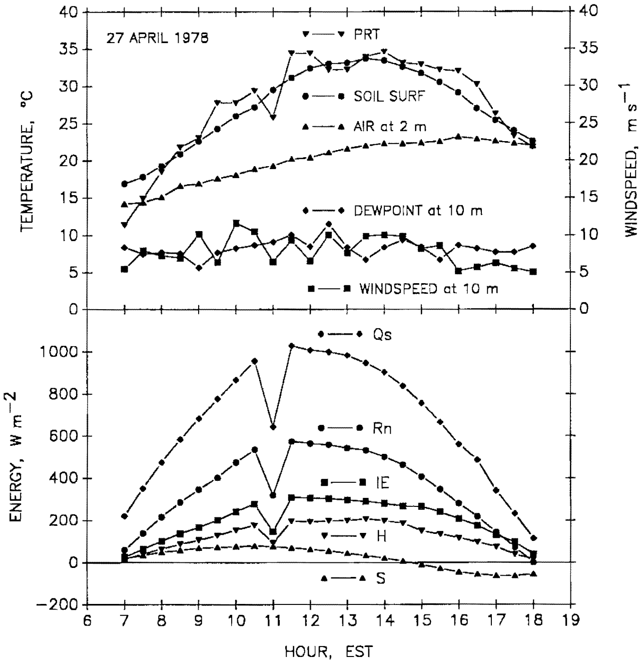

Fig. 4. Daytime course of flux densities of global solar radiation (Qs), net radiation (Rn), soil heat (S), and latent (ℓE) and sensible heat (H) by the profile Bowen ratio-energy balance technique, and precision radiation thermometer surface temperature (PRT), soil surface temperature (Sfc T), air temperature at 2 m (Air T), dewpoint at 10 m, and wind speed at a height of 10 m over primarily pangolagrass pasture at the beginning of spring regrowth, 27 Apr. 1978.

These four figures also show the daytime patterns of flux densities of global solar radiation (Qs), net radiation (Rn), soil heat (S), and sensible heat (H), and precision radiation thermometer surface temperature (PRT), thermocouple-measured soil surface temperature (Soil Surf), and air temperature at 2 m (Air at 2 m).

The daytime energy budget components (from early morning to late afternoon) given in Allen et al. (1980) were summarized. Mean and standard deviations for Qs, Rn, S, H, and ℓE were 23.4 ± 4.2, 12.1 ± 2.0, 1.1 ± 0.3, 3.6 ± 0.9 and 7.3 ± 1.7 MJ m^{-2}, respectively, for 7 d of the spring dataset. The whole-day β ranged from 0.32 to 0.76, with mean and SD of 0.52 ± 0.17. Days with higher β also were days with higher wind speeds. Wind direction also was primarily from the north on these days, and upwind air flow included fields with lower vegetated ground cover and higher surface temperatures.

The PRT temperatures tended to be slightly greater than the Soil Surf temperatures most of the time on 26, 27, and 28 April. Dewpoint temperature dropped from a high of 20°C at 0700 h EST throughout the day of 26 April to a low of <10°C by 1500 h EST. Dewpoint temperature was <10°C on 27 April, but increased slightly to ~11°C on 28 April. Wind speed at the 10-m height increased to >10 m s^{-1} on 26 April when the dry air mass was moving into the area. Wind speed and was generally <10 m s^{-1} and more variable on 27 April and conditions were calm on 28 April with wind speeds generally well <5 m s^{-1}. Soil surface-to-air temperature gradients tended to be larger on days with high solar radiation and low wind speed. The soil had little green vegetative cover in the spring. Therefore, the soil and litter surface received a large part of the solar radiation, rather than green vegetation, and thus gave high surface temperatures during the day.

Prior rainfall may have influenced S, β, and soil surface-to-air temperature gradients to some extent. About 17 mm of rain fell on 24 April. We had no micrometeorological data on 25 April, but the soil surface-to-air temperature gradient was somewhat smaller on 26 April than on 27 April. As the soil surface dried from 26 to 28 April, S increased (0.45, 0.92, and 1.42 MJ m^{-2}, respectively).

Means and standard deviations for Qs, Rn, S, H, and RE were 17.4 ± 0.8, 9.6 ± 0.5, 0.5 ± 0.1, 2.6 ± 0.4, and 6.5 ± 0.4 MJ m^{-2}, respectively, for the 7 d of data from 17 October to 3 November. Bowen ratios (0.40 ± 0.08, with a range of 0.30-0.53) were generally lower than for the spring data. Based on rainfall, the soil water contents were higher during this fall period than in the spring. Rainfall totaled 155 mm in September and 52 mm in October but only 30 mm from 10 March through 24 April. On 20 October, dewpoint temperatures at 0730 h EST were slightly above 20°C were very close to the soil surface temperature and to the air temperature at 2 m. Dewpoint temperature decreased throughout the day beginning at 0900 h EST. Wind speeds were generally steady at about 5 m s^{-1}. The soil surface temperatures during the day were generally slightly lower than air temperatures at 2 m, and the PRT temperatures were generally lowest of all on this date (Fig. 6). During the

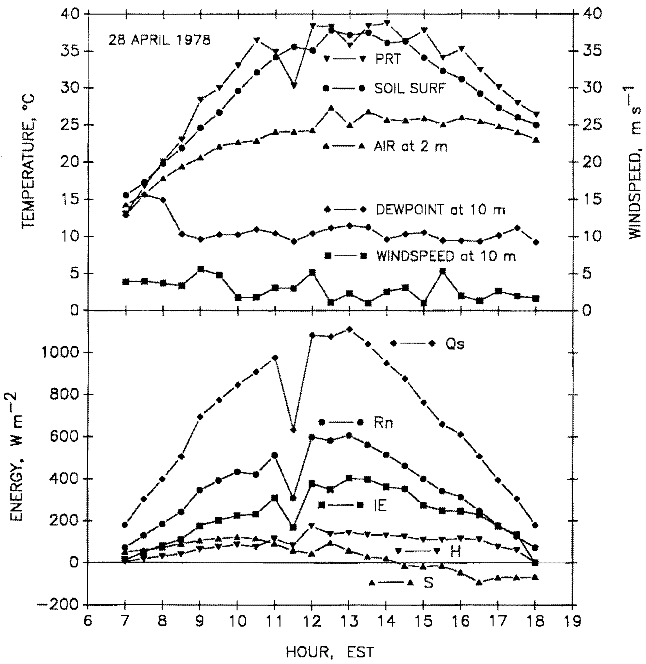

Fig. 5. Daytime course of flux densities of global solar radiation (Qs), net radiation (Rn), soil heat (S), and latent (ℓE) and sensible heat (H) by the profile Bowen ratio-energy balance technique, and precision radiation thermometer surface temperature (PRT), soil surface temperature (Sfc T), air temperature at 2 m (Air T), dewpoint at 10 m, and wind speed at a height of 10 m over primarily pangolagrass pasture at the beginning of spring regrowth, 28 Apr. 1978.

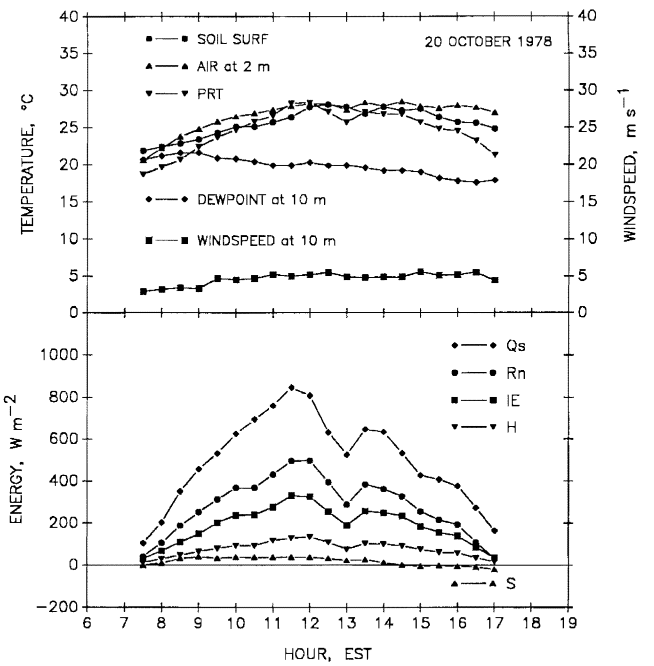

Fig. 6. Daytime course of flux densities of global solar radiation (Qs), net radiation (Rn), soil heat (S), and latent (ℓE) and sensible heat (H) by the profile Bowen ratio technique, and precision radiation thermometer surface temperature (PRT), soil surface temperature (Sfc T), air temperature at 2 m (Air T), dewpoint at 10 m, and wind speed at a height of 10 m over primarily pangolagrass pasture at the beginning of fall senescence, 20 Oct. 1978.

fall, pangolagrass had a dense vegetative cover of both senescent and active plant material. The nocturnal air temperature was always cooler than the vegetative surface temperature. This effect could be explained by the dense vegetative cover that would cause the vegetation, rather than the soil surface, to be the "surface radiator" to space. Therefore, the air in convective contact with the vegetation should be cooler than the soil surface.

The 27 April to 1 May mean daily ET by the soil water balance was 7.72 MJ m^{-2}, which compares closely with the mean daily ET by the Bowen ratio, 7.63 ± 1.94 MJ m^{-2}.

Evapotranspiration by the Portable Chamber Method

Daytime ET measured by the portable chambers on 27 and 28 April agreed closely with the profile Bowen ratio-energy balance. In general, portable chamber ET rates from the bermudagrass exceeded the values obtained by the Bowen ratio-energy balance, whereas portable chamber ET rates from the pangolagrass were less (Fig. 7). On 27 April, the daily ET expressed as latent heat exchange was 8.51, 5.39, and 7.98 MJ m^{-2} for the bermudagrass chambers, the pangolagrass chambers, and the Bowen ratio-energy balance, respectively. On 28 April, the ET values were 10.11, 6.83, and 9.05 MJ m^{-2}, respectively. The weighted values of daily ET for bermudagrass and pangolagrass were 9% greater and 28% smaller, respectively, than the Bowen ratio-energy balance measurements.

The ET rates obtained by the profile Bowen ratio-energy balance were mainly from pangolagrass ground cover; therefore we would have expected the rates to be closer to the portable chamber values for pangolagrass than for bermudagrass. Nevertheless, the daily portable chamber values did bracket the Bowen ratio-energy balance values. Overall, the results of the two methods support each other for ground truth observations.

Applications of Remote Sensed Data to ET

Temperature profile—Method 1

On 28 April, the average r_a for the day (30-min data, 0800-1530 h EST) was 113 ± 25 s m^{-1}. The values for the periods ending at 1200, 1230, and 1300 h EST were 109, 119, and 99 s m^{-1}, respectively. Table 4 shows the weighted H and weighted ℓE for 28 April (1200-1230 h EST) for the pasture. The values for the whole scene were 122 and 365 W m^{-2}, respectively. These values compare with the Bowen ratio-energy balance ground truth measurements of 137 and 350 W m^{-2} for H and ℓE, respectively, for this time period. The value of 137 W m^{-2} for H lies between the Black and Aqua color codes of Table 4. Figure 1 shows that the meteorological tower was located in a surface temperature area characterized by Black, with Aqua (cooler) and Tan (warmer) areas nearby.

This method demonstrates that if H is known or measured, then bulk aerial resistance can be calculated

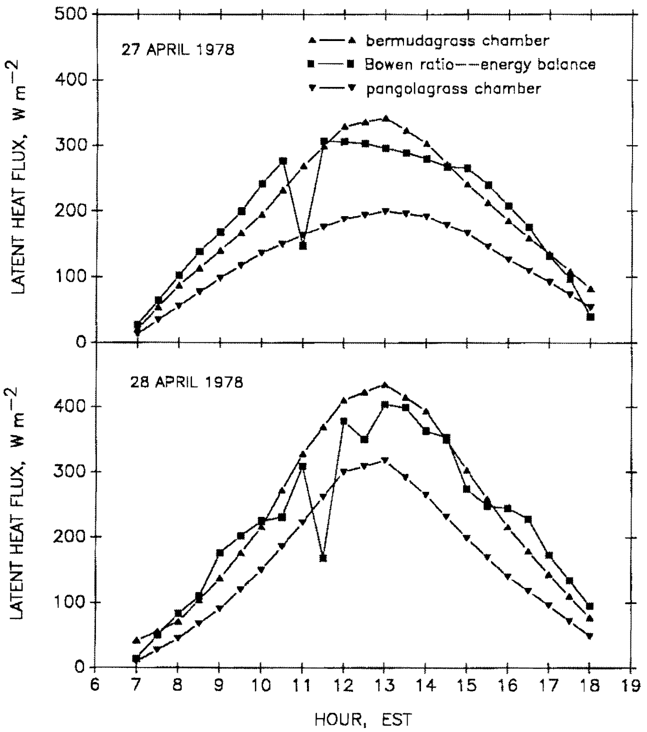

Fig. 7. Daytime course of latent heat flux density (ℓE) from portable chamber measurements over bermudagrass and pangolagrass compared with profile Bowen ratio-energy balance ℓE data for 27 and 28 Apr. 1978.

for similar surfaces. If remotely sensed temperature patterns of similar evaporating surfaces are known, then the regional ET rates can be determined. If the surface conditions are different, then a different aerial resistance would have to be determined for each surface.

Dependence of r_a on wind speed. Wind speed would be expected to have a large effect on bulk aerial resistances under similar surface conditions. Data from the fall on a high wind day (18 October), a moderate wind day (20 October), and a low wind day (27 October) were compared to determine wind speed effects.

Temperature profiles were plotted on semilog graph paper. Pangolagrass in the fall was ~0.3-m tall. Inspection of the temperature data plot from the six heights showed that a D of 0.25 m gave the best straight line fits on semilog plots. We estimated Z_0 at 0.03 m. When air temperature profiles were extrapolated to this small height, there was still a very large difference between the extrapolated temperature at this height, and the surface temperature measured by a precision radiation thermometer. Therefore, we calculated both a turbulent resistance component (from Z - D = 0.03 m to Z - D = 1.5 m) and a bulk boundary-layer resistance (from the surface temperature to the temperature at Z - D = 0.03 m). In most cases, the surface-to-Z_0 temperature difference was larger than the Z_0-to-1.5 m temperature difference, implying that bulk boundary layer resistance was larger than turbulent transport resistance.

The turbulent resistance and the bulk boundary layer resistance were calculated from Eq. [21] and Eq. [22] for each half hour of data on 18, 20, and 27 October. Wind speed was found to be steady for 5 to 7 h periods during those days. The turbulent resistance, r_t, and the bulk boundary layer resistance, r_B, as well as wind speeds were averaged over the steady wind periods, and standard deviations computed. These average resistance values were plotted against wind speed.

Bulk aerial resistance and the two components, r_B and r_t, showed a decrease with increasing U at the 10-m height. Values of r_B, r_t, r_a, and U_{10} were 28 ± 3, 20 ± 4, 48 ± 5 s m^{-1}, and 9.33 ± 0.48 m s^{-1}, respectively, on 18 October; 42 ± 8, 28 ± 4, 70 ± 6 s m^{-1}, and 5.80 ± 0.35 m s^{-1}, respectively, on 20 October; and 52 ± 13, 32 ± 4, 84 ± 13 s m^{-1}, and 3.55 ± 0.38 m s^{-1}, respectively, on 27 October. Values of r_B were always larger than r_t. Over the range 3.55 to 9.33 m s^{-1} mean wind speeds, mean resistances (s m^{-1}) increased linearly with decreasing wind speed ($r_B = 66.4 - 4.14\ U_{10}$, $r_t = 39.7 - 2.09\ U_{10}$, $r_a = 106.1 - 6.23\ U_{10}$; $r^2 = 0.99$ for each). However, at lower wind speeds they would likely increase nonlinearly with decreasing wind speed until natural convection conditions prevailed.

The r_B values were large for the short grass surface. This shows that boundary layer resistance and resistance in low turbulence flows of short vegetation are important in overall transport processes.

These relationships of resistances to wind speed were not used further in this paper, but show that linear or near-linear functions could be developed to express resistance as a function of wind speed in future remote sensing ET studies.

Stability corrected heat flux density—Method 2

Tables 5 and 6 summarize regional ET rates arrived at using the preceding procedure on two thermal scenes. The results are reasonable judging from a comparison to the Bowen ratio-energy balance ground truth measurement, and demonstrate that this approach is workable.

A better insight into the effect of the diabatic influence function stability treatment could be obtained by plotting ET as a function of the surface temperature minus 1.5 m air temperature for the data of Tables 5 and 6 under conditions of two different wind speeds (figure not shown). As the surface-to-1.5 m air temperature difference increases, atmospheric instability increasingly enhances sensible heat transport leaving less energy for ET, resulting in a concave downward curve. With an increase in wind speed, stability effects are damped and the ET vs. temperature difference relationship becomes more linear. Without a stability correction, these curves would be exactly linear. Of course, larger surface-to -1.5 m air temperature differences are fundamentally caused by low availability of water for ET.

The bottom line on any technique making use of remotely sensed surface temperatures is how nearly resulting estimates equal ground truth measurements. On this score our results are still somewhat inconclusive as our remote estimates were ~ 0 to 25% lower than our Bowen ratio-energy balance ground truth measurements.

There are a variety of possible reasons for this discrepancy. The method for remote sensible heat flux density estimates was found to be extremely sensitive to

Table 4. Distribution of evapotranspiration per unit land area (column 4), and proportional regional evapotranspiration (column 7), expressed as latent heat flux density (ℓE), based on the proportional area in each color code class of Fig. 1 for the pasture scene using resistance method, Apr. 28, 1978 from 1200-1230 h EST. Other variables related to the color code classes are surface-to-air temperature difference (ΔT), sensible heat flux density (H), and Bowen ratio (β).

		Flux density		Proportional area and flux			
Color	ΔT	H	ℓE	Area	H	ℓE	β
	°C	W m^{-2}			W m^{-2}		
Tan	16.5	168	319	0.233	39.2	74.3	0.53
Black	14.9	152	335	0.242	36.8	81.1	0.45
Aqua	11.5	117	370	0.251	29.4	92.8	0.32
Pink	8.2	83	404	0.165	13.8	66.6	0.21
Yellow	4.9	50	437	0.066	3.3	28.8	0.11
Dark blue	1.5	15	472	0.022	0.3	10.4	0.03
Orange	-1.8	-18	505	0.021	-0.4	10.6	-0.04
Totals				1.000	122.4	364.6	0.34

parameters such as the displacement height and the geometric mean height. Without consideration of the displacement height, sensible heat flux density estimates bared little relation to ground truth values; the grass surface at Davis, CA (Morgan et al., 1971; Pruitt et al., 1973) was short enough not to require its use.

Also, since the differential version of the diabatic influence functions was used, no explicit use of the roughness length Z_0 was made. It is possible that even if actual profiles over clipped grass and profiles over pasture (with or without displacement height corrections) are nearly the same, heat transport would be affected by the roughness of the underlying surface.

Stability-corrected integral profile—Method 3

Both stability (*Ri*) and roughness (Z_0) had an effect on the computed r_a values. At a Z_0 of 0.01 m, the ratio of r_a in the most unstable case (ΔT = 17.2°C) to r_a in the neutral case (ΔT = 0°C) was 0.476/0.587, or 0.81. In the neutral stability case (ΔT = 0°C), the relative values of r_a decreased with increasing Z_0 (0.712, 0.587, 0.477, 0.416, and 0.376, for Z_0 of 0.005, 0.01, 0.02, 0.03, and 0.04 m, respectively). The sensitivity of ET by this method to Z_0 (as mediated by the influence on r_a) was computed for values of Z_0 between 0.005 m to 0.04 m and plotted (Allen et al., 1980; figure not shown).

Table 7 shows values of sensible and latent heat flux densities as a function of *Ri*, Eq. [23]. The temperature gradient shown in this table was $T_s - T_a$ where T_a was at 10 m. The sensible heat flux density and latent heat flux density is shown in Table 7. Total fluxes were computed based on proportional areas (Tables 4, 5, and 6). These computations showed much higher values of H and lower values of ℓE for the 28 April pasture than computed in Table 4. The computed overall β was 1.47 as

Table 5. Evapotranspiration calculations from different surface temperatures for the pasture scene of 28 Apr. 1978 (1222-1225 h EST) under relatively low windspeed (U_{10} = 4.37 m s^{-1}) using stability corrected heat flux densities derived from temperature profiles.

Color	T†	ΔT‡	ΔU§	*Ri*§	{SCF}¶	H††	ET‡‡	AF§§
	°C		m s^{-1}			W m^{-2}		
Tan	43.3	2.21	0.74	-0.1580	57.6	296	191	0.233
Black	40.6	1.86	0.80	-0.1150	48.8	227	260	0.242
Aqua	37.2	1.44	0.87	-0.0721	40.1	157	330	0.251
Pink	33.9	1.03	0.94	-0.0458	33.2	101	386	0.165
Yellow	30.6	0.61	1.02	-0.0231	27.5	54	433	0.066
Dark blue	27.2	0.19	1.10	-0.0062	22.8	15	472	0.022
Orange	23.9	-0.22	1.17	+0.0064	18.6	-15	502	0.021

Regional ET = $\sum ET_{(color)} AF_{(color)}$ = 303 W m^{-2} Regional H = $\sum H_{(color)} AF_{(color)}$ = 184 W m^{-2}

Portable Chamber ET = 414 W m^{-2} for bermudagrass and 302 W m^{-2} for pangolagrass.

Constants used Eq. [48]-[58] in calculations: T_a = 25.6°C, U_{10} = 4.37 m s^{-1}, U^* = 0.253 m s^{-1}, D = 0.0 m, Z_0 = 0.01 m, ΔZ = 1.2 m, Z_{gm} = 0.671 m.

†Midpoint of temperature range of color on thermal scene.

‡Calculated from regression: $\Delta T_t = 0.125\ (T_s - T_a)$; upward heat flux is positive.

§Calculated iteratively; see text for definition of *Ri*.

$\Delta U = [(U^*\ \Delta Z)/(k\ Z_{gm})](1 - 16\ Ri)^{-1/3}$, unstable case, $\Delta U = [(U^*\ \Delta Z)/(k\ Z_{gm})](1 + 16\ Ri)^{1/3}$, stable case.

¶Stability correction factor {SCF} = $20.9\ (1-60\ Ri)^{.074}(1-16\ Ri)^{.667}$, unstable case, {SCF} = $20.9\ (1+95\ Ri)^{-.11}(1 + 16\ Ri)^{-.667}$, stable case.

††H = {SCF} $((Z_{gm}/\Delta Z)^2)\Delta U\ \Delta T$.

‡‡ET = ℓE = Rn - S - H = 582 - 95 - H = 487 - H, W m^{-2}.

§§AF = Fractional area in each surface temperature class.

Table 6. Evapotranspiration calculations from surface temperatures for the citrus grove scene of 26 Apr. 1978 (1432-1435 h EST) under relatively high windspeed (U_{10} = 12.1 m s^{-1}). Stability corrected sensible heat flux densities that were derived from temperature profile data were used to calculate latent heat flux densities ET from short vegetation, and a leaf-to-air resistance model was used to calculate sensible heat flux density, then ET, from tall vegetation.

	Short height vegetation							
Color	T_s†	ΔT_t†	ΔU_t†	*Ri*†	{SCF}†	H†	ET‡	AF§
	°C	°C	m s^{-1}			W m^{-2}	W m^{-2}	
Tan	42.2	2.24	2.98	-.00993	23.9	499	-51	0.000
Black	39.4	1.89	3.01	-.00825	23.4	416	32	0.003
Aqua	36.1	1.47	3.04	-.00630	22.8	319	129	0.108
Pink	32.8	1.06	3.06	-.00446	22.3	226	222	0.139
Y/P	31.1	0.85	3.08	-.00356	22.0	181	267	0.069
Yellow	29.4	0.64	3.09	-.00264	21.7	134	314	0.198
Dark blue	26.1	0.22	3.12	-.00090	21.2	46	402	0.032
Orange	22.8	-0.19	3.15	+.00077	20.6	-39	487	0.011
	Tall height vegetation							
Color	T_s†	ΔT_T¶				H#	ET‡	AF§
PK	32.8	8.4				363	85	0.047
Yellow	29.4	5.1				220	228	0.129
Blue	26.1	1.8				76	372	0.146
Orange	22.8	-1.6				-67	515	0.118

Regional ET = $\Sigma_{height} \Sigma_{color} ET_{(height, color)} AF_{(height, color)}$ = 292 W m^{-2}. Constants used in Eq. [48]-[58] calculations: T_a = 24.3°C, U_{10} = 12.1 m s^{-1}, U* = 0.701 m s^{-1}, D = 0.0 m, Z_o = 0.01 m, Δz = 1.2 m, Z_{gm} = 0.671 m.

†Calculated in the same way as for pasture scene, Table 5.

‡ET = ℓE = Rn - S - H = 435 - (-13) - H = 448 - H, W m^{-2}.

§AF = Fractional area in each surface temperature class of either short or tall vegetation.

¶$\Delta T_T = T_s - T_a$.

#$H = (\rho C_p/r_a)\Delta T_T$, where $r_a = 6.6\ (U_{10}/2)^{1/2}$ = 26.6 s m^{-1}.

compared to 0.34 in Table 4. In general, the r_a values were about half of the bulk aerial resistance, r_B, computed by using Eq. [22]. The aerial resistance should be considered in two parts, especially for this type of short grass vegetation. The r_a values computed by assuming $Z_H = Z_o$ = 0.01 m are really turbulent transport values, and do not include the bulk boundary layer resistance.

Half-hourly data on 28 Apr. 1978, were used to compute Z_H values. Temperature profiles were smoothed by plotting air temperature vs. log height. Values at Z = 10 m and Z = 0.3 m were extracted and T* computed from the following equation (Kanemasu et al., 1979).

$$T^* = k\ (T_{0.3} - T_{10})/[\ell n(10) - \ell n(0.3) - \Psi_{2,10} + \Psi_{2,0.3}] \qquad [60]$$

The stability functions at 10 m and 0.3 m were taken from Table 7, depending upon the $T_s - T_{10}$ temperature difference. The value of Z_H was determined by substituting values of T_s (surface temperature from radiation thermometer data) into the above type of equation:

$$Z_H = \exp\ [\ell n(10) - (k/T_*)\ (T_s - T_{10}) - \Psi_{2,10}] \qquad [61]$$

The arithmetic mean of 15 profile determinations of Z_H was 0.178 × 10^{-3} m, the geometric mean was 0.0273 × 10^{-3} m, and the mode was 0.0286 × 10^{-3} m. The values computed ranged from 0.919 × 10^{-3} m to 0.516 × 10^{-9} cm. This wide scatter was likely due to the fact that temperature profiles and surface radiation temperatures were read only each 15 min.

Table 7. Computations of r_a, ℓE, H, and β from stability-corrected profile integral methods using meteorological input data from 28 Apr. 1978 at 1245 h EST with the thermal scene obtained at 1222-1225 h EST (Fig. 1).

					$Z_H = Z_o$ = 0.01 m				Z_H = 0.0001 m			
Color	ΔT	*Ri*	Ψ_1	Ψ_2	U*	r_a	H	ℓE	β	r_a	H	ℓE	β
	°C				m s^{-1}	s m^{-1}	W m^{-2}	W m^{-2}		s m^{-1}	W m^{-2}	W m^{-2}	
Black	17.2	-0.219	0.488	0.889	0.316	47.6	417	129	3.23	84.1	236	310	0.76
Aqua	13.3	-0.169	0.409	0.770	0.312	49.2	312	234	1.33	86.1	178	368	0.48
Pink	10.0	-0.127	0.337	0.630	0.309	50.8	227	319	0.71	88.1	131	415	0.32
Yellow	6.7	-0.085	0.251	0.478	0.305	52.7	147	399	0.37	90.4	86	460	0.18
Dark blue	3.3	-0.042	0.142	0.273	0.300	55.3	69	477	0.14	100.0	41	505	0.08
Orange	0	0	0	0	0.294	58.7	0	546	0	103.3	0	546	0
Totals							325	221	1.47		185	361	0.51

Since wind speed profiles were not measured, there was no way to determine Z_0 directly. However, through the definition of $T^* = H/(\rho C_p U^*)$, Z_0 could be calculated from T^* values obtained from air temperature profile data, from H values obtained from the Bowen ratio-energy balance apparatus, and from wind speed measured at 10 m. Rearranging Eq. [24] gives:

$$Z_0 = \exp\,[\ell n(10) - k\, U_{10}/U^* - \Psi_2]. \qquad [62]$$

Fourteen temperature profiles from 830 to 1530 h EST on 28 April were analyzed with H and U_{10} data. The arithmetic mean value of Z_0 was 0.0416 m, the geometric mean value was 0.00161 m, and the mode was 0.00412 m. The values ranged from 0.325 m to 0.035×10^{-12} m. Here again, low frequency of observations, including wind speed at 10 m, probably contributed to the scatter of data.

From the above analyses, a value of $Z_H = 0.0001$ m was selected to recompute r_a, H, and RE by the integral profile stability corrected method, Eq. [26]. Computations were made for Z_0 values of 0.005, 0.01, 0.02, 0.03, and 0.04 m, but only the values for $Z_0 = 0.01$ m are shown in Table 7. Computations were made for the whole scene of 28 Apr. 1978. The values of r_a based on $Z_H = 0.0001$ m were ~2× as large as those based on $Z_0 = 0.01$ m. They should correspond more nearly to the sum of r_t and r_B the turbulent resistance, and the bulk boundary layer resistance. The values ranged from 84.1 s m^{-1} at $Ri = -0.219$ to 103.3 s m^{-1} for $Ri = 0$, and compare well with the value of 113 s m^{-1} obtained from $T_s - T_{10}$ and H measurements.

The total scene H, ℓE, and β values on 28 April were 185 W m^{-2}, 361 W m^{-2}, and 0.51 respectively. These values compare well with those of Table 4. Therefore, this method looks promising when accurate values of Z_H can be obtained.

Another alternative approach of computation of H and ℓE by the integral profile stability method would be to determine T_0, an air temperature at Z_0, by some method, and then compute $T_0 - T_a$, Ri, Ψ_1, Ψ_2, and r_a based on these temperature and height differences. However, this method does not have the advantage of using surface-derived temperatures directly.

The surface temperatures measured by the airborne scanner and the radiation thermometer are probably not the theoretical temperatures at Z_H, but they appear to be suitable for use in computing fluxes of sensible heat and latent heat.

Comparisons of Whole-Day and Short-Term Evapotranspiration

Whole-day ET by the profile Bowen ratio measurements gave mean and standard deviations for RE of 7.31 ± 1.73 MJ m^{-2}, respectively, for 7 d of the spring dataset (Table 3). In comparison, values of computed chamber ℓE (0700-1900 h EST) for bermudagrass and pangolagrass, and profile Bowen ratio (0700-1800 h EST) on 27 April were 8.51, 5.39, and 7.98 MJ m^{-2}, respectively, and on 28 April were 10.11, 6.83, and 9.05 MJ m^{-2}, respectively. Thus, the profile Bowen ratio values were intermediate between the more developed bermudagrass and the less developed pangolagrass chamber values. By soil water balance over the 5-d period from 27 April to 1 May the mean daily value of ℓE was 7.72 MJ m^{-2} in comparison with 7.63 ± 1.94 MJ m^{-2} by the profile Bowen ratio. Thus, whole day ET by the profile Bowen ratio was comparable with both chamber techniques and soil water balance values. The mean and standard deviation for ℓE was 6.50 ± 0.42 MJ m^{-2} for the 7 d of data by the profile Bowen ratio method from 17 October to 3 November (Table 3), however, we had no chamber or soil water balance data for comparison.

Table 8 shows comparisons of short-term ET data by various methods near 1430 h EST on 26 April and near 1230 h EST on 28 April corresponding to the times of the Daedalus 1250 data from the aircraft overflights. On 26 April, only method 2 (stability-corrected heat flux density) was compared with the profile Bowen ratio measurements. Method 2 gave ℓE values of 257 W m^{-2} for the pasture scene only, and 292 W m^{-2} for the pasture plus citrus grove scene of Fig. 2, in comparison with the profile Bowen ratio ℓE of 270 W m^{-2} (Fig. 3) measured at the micrometeorological instrumentation site. the range of deviation from the profile Bowen ratio method was from -5% to +8%. Overall, the pasture plus citrus scene would be expected to have a higher ET than the pasture scene alone even though the thermal image of the irrigated citrus of Fig. 2 indicated a higher temperature and hence lower stomatal conductance and lower ET than the wet areas or the areas with tall natural vegetation.

Table 8. Summary of ET methods for short-terms on 28 April (pasture scene) and 26 April (pasture and citrus scene).

Date	Time interval	Rn	S	ℓE	H	β	Reference to text
1978	h EST			---------- W m^{-2} ----------			
28 Apr	1200-1230	582	95	365	122	0.34	Table 4 (Method 1)
28 Apr	1222-1235	582	95	303	184	0.61	Table 5 (Method 2)
28 Apr	1222-1235	596	95	331	170	0.51	Table 7 (Method 3, $Z_H = 0.0001$ m)
28 Apr	1222-1225	596	95	221	325	1.47	Table 7 (Method 3, $Z_H = 0.01$ m)
28 Apr	1200-1230			414			Fig. 6, Chamber (bermudagrass)
28 Apr	1200-1230			302			Fig. 6, Chamber (pangolagrass)
28 Apr	1230	582	95	350	137	0.39	Fig. 5, Bowen ratio-energy balance
26 Apr	1432-1435	435	-13	292	156	0.53	Table 6 (Method 2) pasture plus citrus
26 Apr	1432-1435	435	-13	257	191	0.74	Table 6 (Method 2) pasture only
26 Apr	1430	435	-12	270	177	0.66	Fig. 3, Bowen ratio-energy balance

On 28 April, applications of remotely sensed data for the pasture scene (Fig. 1) yielded ensemble short-term midday ℓE values of 365 W m^{-2} for method 1 (temperature profile and aerodynamic resistance), 303 W m^{-2} for method 2 (stability-corrected heat flux density), and 331 and 221 W m^{-2} when Z_H was estimated at 0.0001 m and 0.01 m, respectively, for method 3 (stability-corrected integral profile) in comparison with 414 and 302 W m^{-2} for chamber measurements of bermudagrass and pangolagrass, respectively, and 350 W m^{-2} for the profile Bowen ratio-energy balance method (Table 8). Method 1 values were higher than the profile Bowen ratio measurements, and method 2 values were lower. The range of method 3 values indicated that values of Z_H need to be known rather precisely in order to accurately estimate ET. Again, the chamber ℓE value for bermudagrass was larger (and the value for pangolagrass was smaller) than the profile Bowen ratio value. Neglecting the method 2 value obtained with the larger Z_H, the estimated short-term ET by remote sensing methods deviated from the profile Bowen ratio method by -13% to +4%.

The most important aspect of the remotely sensed methods for ET is that ℓE values can be attributed to various surfaces with a range of surface temperature classes. As such, the surface temperatures shown in Figs. 1 and 2 as defined in Table 1 can actually represent a distribution of rates of evapotranspiration as determined in Tables 4, 5, 6, and 7.

In the years since 1978, much progress has been made in using remotely sensed data for ET and hydrometeorlogy (Jackson et al., 1887; Moran et al., 1989; Schmugge et al., 1998, 2002; French et al., 2003; Kustas et al., 2003; Magliulo et al., 2003; Norman et al., 2003; and Suleiman and Crago, 2004). Moran et al. (1989) found that estimates of ℓE from Landsat Thematic Mapper data differed from Bowen ratio and aircraft-based estimates by <12%, which is similar to the range of differences found by our remotely sensed techniques and the profile Bowen ratio method. Moran et al. (1989) also pointed out the potential problem associated with the fact that aerodynamic and radiometric temperatures might not be the same for crop canopies, and that this problem could be compounded in the case of partial vegetative cover (a condition that likely occurred for the highest radiative surface temperatures in our study). French et al. (2003) used aircraft mounted thermal infrared multispectral scanner along with a two-surface energy balance model (soil and vegetative surfaces) to predict ℓE, H, and S in comparison with ground-based eddy correlation measurements. Based on their data, percentage biases of the predicted ℓE vs. the eddy correlation measurements were ~13% for uniform pastures and 30% for patchy pasture, with 20% for the overall scene at El Reno, OK. Norman et al. (2003) developed a system to predict surface energy fluxes, particularly ET, at a small scale by disaggregating low-resolution remote sensing data such as from GOES using high spatial resolution data from other remote sensing systems. They reported a root mean square deviation between model estimates and measurements of 40 W m^{-2}, which is comparable with observational accuracy of micrometeorological flux measurements. Presumably this technology would allow ET estimates over much great expanses of landscape which should be useful for hydrometeorology purposes. Finally, it appears that the accuracy of our estimates of ET are comparable, if not quite as good, as some of the modern techniques.

ACKNOWLEDGMENTS

This research was conducted by the Univ. of Florida, Institute of Food and Agricultural Sciences and USDA-ARS in cooperation with the National Aeronautics and Space Administration, Kennedy Space Center and the South Florida Water Management District, as part of a Florida Water Resources Management Project, NASA RTOP (UPN 177-55-91). Supported in part by NASA Contract No. NAS10-9348 with the Univ. of Florida.

Special thanks are due to T. C. Davis, Jr., NASA-KSC Project Manager and D. Pope, NASA-KSC Engineer, for arranging for airborne thermal scanner data collection by NASA and aerial false-color infrared photography by the Florida Dep. of Transportation; to Dr. J. W. Jones for assistance in analyzing chamber ET data, to Univ. of Florida technicians A. F. Cook for conducting a vegetation survey, and H. E. Hannah and F. G. Johnson for assistance in setting up micrometeorological and data acquisition systems, and primary data acquisition; and to USDA-ARS technicians W. H. Henry and Karen Hokkanen for assistance in secondary data analyses.

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Bioassays on Glyphosate Residue Toxicity and Photodegradation on Polyethylene Mulch

James P. Gilreath and Bielinski M. Santos*

ABSTRACT

Glyphosate (*N*-(phosphonomethyl) glycine) bioassays were conducted to determine the concentration of glyphosate needed for plant injury, and the extent of photodegradation over varying sunlight and humidity exposure periods. In the dose-response bioassay, foliage of tomato (*Lycopersicon esculentum* Mill.) plants was dipped into glyphosate eluant solutions at 0, 50, 100, 150, 200, 250 and 500 mg L^{-1}. In the photodegradation bioassay, black low-density polyethylene film was mounted on boards and glyphosate was sprayed at 1.14 kg ha^{-1}. Sunlight-exposure lengths were 0, 1, 2, 3, 4, 5, 7, 9, 11, 13, and 15 d. Boards were removed from the field at sunset. Mulch eluants were obtained and tested on tomato plants. In the dew exposure bioassay, procedures were similar to those for the photodegradation bioassay, except that sunlight exposure lengths of 0, 1, 2, 4, 6, and 8 d combined with either board removal at the end of each day and placed in a dark shelter or boards that remained on the ground at all times. Sampling mulch procedure, solution volume, time of exposure, plant material and other experimental procedures were similar to those for the photodegradation bioassay. Finally, the simulated rainfall bioassay followed similar procedures and rainfall effect was simulated by sprinkler irrigation (0, 6.5, 12.8, 19.1, 25.4, 31.7, and 38.0 mm). In the dose-response bioassay, with 50 mg L^{-1} of glyphosate, there was a reduction of 73% in tomato fresh plant weight. In the photodegradation bioassay, 15 d after application, there was still enough glyphosate to reduce biomass accumulation. In the dew exposure bioassay, plant injury decreased with time. However, after 8 d of dew exposure plants were still 16% below the control. In the simulated rainfall bioassay, there were no differences between the fresh weight of the control treatment and all treatments that received sprinkler irrigation. The results indicated that low glyphosate concentrations could cause significant tomato seedling injury, suggesting that glyphosate farm spraying equipment and industrial packing lines must be cleaned and tested to avoid contamination.

INTRODUCTION

Glyphosate is the most-used herbicide in the world. This is a non-selective molecule that blocks the synthesis of the aromatic amino acids, tryptophane, tyrosine, and phenylalanine (Duke, 1985). Under field conditions, this herbicide is used to spray weeds in crop preemergence or on direct row-middle applications (WSSA, 2002). The latter is widely used in polyethylene-mulched vegetables and ornamentals, where glyphosate is applied to kill the foliage of weeds, such as nutsedges (*Cyperus* spp. L.), which can grow through the film. This practice is justified because usually 2 to 3 wk pass from the time the mulch is placed on the planting beds to the transplant. Crops are usually established within 48 h of glyphosate application.

The label of this herbicide indicates that there is no soil residuality of this molecule, which is rapidly broken down by microbial activity (WSSA, 2002). However, direct observations in vegetable grower fields with plastic mulch have shown plant injuries similar to those by glyphosate, especially when rainfall has occurred within 72 h after application. The initial hypotheses of these trials are: a) resolubilization of glyphosate molecules on the mulch surface occurs causing plant injury, and b) sunlight decomposes glyphosate molecules on the mulch surface reducing plant injuries. The objectives of these studies were to determine: a) the concentration of glyphosate needed for plant injury, and b) the extent of photodegradation over varying sunlight and humidity exposure periods.

MATERIALS AND METHODS

Dose-Response Bioassay

Two trials were conducted under greenhouse conditions from October 2000 to January 2001 at the Gulf Coast Res. and Educ. Center (REC), Univ. of Florida in Bradenton. Seven glyphosate concentrations (0, 50, 100, 150, 200, 250, and 500 mg L^{-1}) were prepared from distilled water. Treatments were arranged in 10, randomized complete blocks. These glyphosate rates were selected based on recommended rates for preplant situations, where 1.14 kg ha^{-1} are diluted in 520 L ha^{-1}, rendering a concentration of 2180 mg L^{-1} (Stall and Gilreath, 2002).

'Solimar' tomato seedlings in the two, true-leaf stage were selected as indicator plants because their sensitivity to glyphosate. Each seedling comprised an experimental unit. Foliage of tomato plants were dipped into a 250 mL of respective treatment solutions for 10 s. These seedlings were placed in trays to allow foliage drying and were positioned such that individual plants would not touch each other. One day after application, plants were transplanted into 1 L (15-cm wide) containers filled with a commercial potting medium. Fresh plant weights were collected at 29 and 56 d after treatment for each trial, respectively. The relationship between glyphosate concentration and plant fresh weights was examined by regression analysis and individual treatment means were separated by standard errors. Data from two trials were combined, since there was no significant ($P > 0.05$) trial × treatment interaction.

Photodegradation Bioassay

Field trials were conducted from October to December 2000 at the Gulf Coast REC. Average maximum and minimum temperatures during the trials were 23.7 and 7.2°C, respectively, and no significant rain events

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James P. Gilreath and Bielinski M. Santos. Gulf Coast Res. and Educ. Center, Univ. of Florida, Bradenton, FL 34203. This research was supported by the Florida Agric. Exp. Stn. and is approved for publication as Journal Series No. N-02401.

*Corresponding author (bmsantos@ifas.ufl.edu).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:21-24 (2004).

occurred. Black low-density polyethylene film was mounted on 2.5-m long by 0.3-m wide boards. Glyphosate was sprayed with a tractor-mounted boom, at 1.14 kg ha^{-1} with 8004 nozzles (Spraying Systems Co., Wheaton, IL) calibrated to deliver 520 L ha^{-1}. Eleven treatments were distributed in 10, randomized complete blocks. Sunlight-exposure lengths were 0, 1, 2, 3, 4, 5, 7, 9, 11, 13, and 15 d. Each board constituted an experimental unit. At every sunset, boards were removed from the field and placed inside a dark shelter until the next day.

For each sunlight-exposure length, 900 cm^2 of polyethylene film were removed from each board, placed in a 250-mL beaker with 50 mL of distilled water, and agitated for 30 min to dissolve the residual glyphosate. Foliage of Solimar tomato seedlings in the two-true leaf stage was dipped into the eluants for 10 s, then the same procedure as outlined above for the dose-response bioassay was followed to transplant single plants in containers. Fresh plant weights were collected at 32 d after treatment. The relationship between sunlight exposure lengths and plant fresh weights were examined by regression analysis and individual treatment means were separated by standard errors. Data form two trials were combined, since there was no significant ($P > 0.05$) trial × treatment interaction.

Dew Exposure Bioassay

Field trials were conducted in the same location and time as for the photodegradation bioassay. The procedure to prepare mulch film was similar to that previously described. Glyphosate was sprayed with a tractor-mounted boom, at 1.14 kg ha^{-1} with 8004 nozzles calibrated to deliver 520 L ha^{-1}. Eleven treatments were established in 10, randomized complete blocks. Treatments were sunlight exposure lengths of 0, 1, 2, 4, 6, and 8 d combined with either boards removal at the end of each day and placed in a dark shelter or boards that remained on the ground at all times. Film sampling, solution volume, time of exposure, plant material, and other experimental procedures were similar to those for the photodegradation bioassay. Likewise, data collected was examined with regression analysis to determine the relationship between sunlight exposure lengths and plant fresh weights for treatments with dew and without dew exposure. Data form two trials were combined, since there was no significant ($P > 0.05$) trial by treatment interaction.

Simulated Rainfall Bioassay

Field trials were conducted in the same location and time as for the photodegradation bioassay. The procedure to prepare mulch film was similar to that previously described. Glyphosate was sprayed with a tractor-mounted boom, at 1.14 kg ha^{-1} with 8004 nozzles calibrated to deliver 520 L ha^{-1}. Eight treatments were established in 10, randomized complete blocks. Rainfall effect was simulated by sprinkler irrigation and started within 1 h after treatment. Treatments were 0, 6.5, 12.8, 19.1, 25.4, 31.7, and 38.0 mm of overhead irrigation to the boards. Film sampling, solution volume, time of exposure, plant material, and other experimental procedures were similar to those for the photodegradation bioassay. Likewise, data collected was examined with regression analysis to determine the relationship between simulated rainfall on glyphosate applied treatments and plant fresh weights. Data from two trials were combined, since there was no significant ($P > 0.05$) trial × treatment interaction.

RESULTS AND DISCUSSION

Dose-Response Bioassay

An exponential model described the relationship between glyphosate concentration and tomato fresh plant weight ($Y = 3.63 + 19.75\ e^{(-x/41.00)}$, $R^2 = 0.97$), where plant fresh weight decreased sharply at the lowest glyphosate concentrations and leveling off afterwards (Fig. 1). With 50 mg L^{-1} of glyphosate, there was a 73% reduction in tomato fresh plant weight. An average 90% fresh weight reduction was obtained with 150 mg L^{-1} of glyphosate.

Photodegradation Bioassay

A power model characterized the relationship between days after glyphosate application and tomato fresh plant weight ($Y = 3.24 + 0.005x^{2.53}$, $R^2 = 0.92$), with slow increases in fresh weight as length of exposure increased (Fig. 2). However, 15 d after application, there was still enough glyphosate to significantly reduce biomass accumulation. The average value for the control treatment was 28.6 g plant^{-1} in contrast with 8.0 g for 15 d of sunlight exposure.

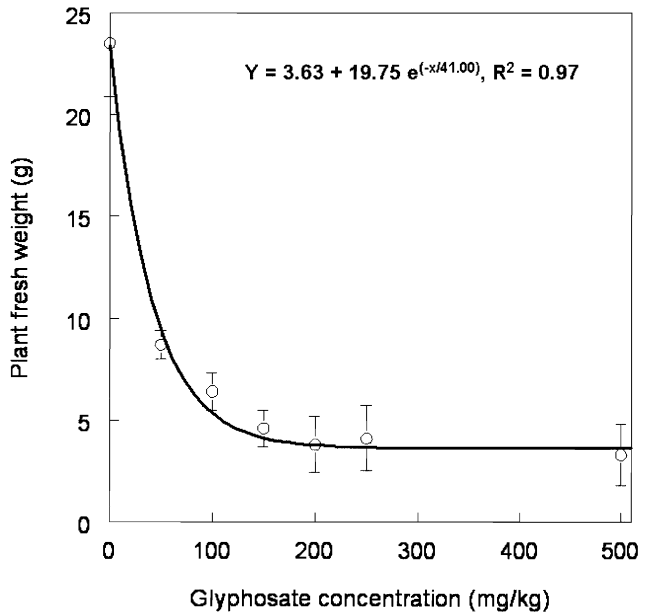

Fig. 1. Effect of glyphosate concentration on tomato plant fresh weight. Bars on the predicted curve are standard errors.

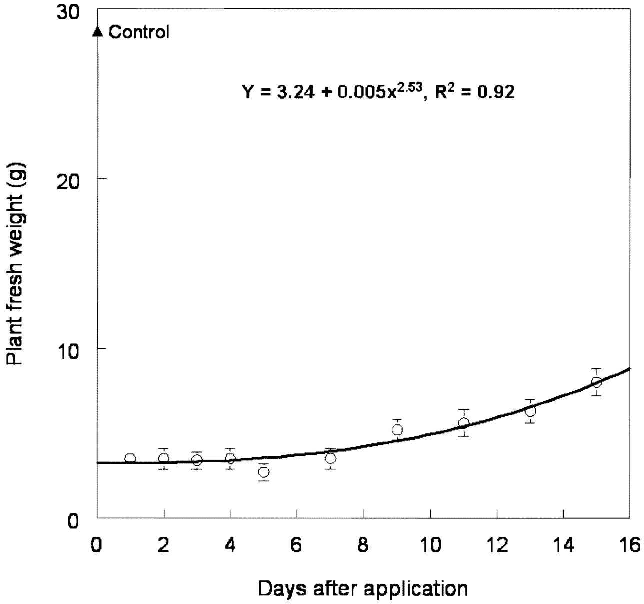

Fig. 2. Effect of length of sunlight exposure with glyphosate-applied mulch on tomato plant fresh weight. Bars on the predicted curve are standard errors.

Dew Exposure Bioassay

These trials were best described by a quadratic equation ($Y = -4.24 + 6.48x - 0.38x^2$, $R^2 = 0.93$) for treatments that were under dew exposure, whereas no significant regression was found for treatments that did not receive dew effect (Fig. 3). Within the range of days of exposure considered by the trials, the highest fresh biomass obtained was 24 g, which was significantly different from the control (28.6 g), which was 84% of the control biomass.

Simulated Rainfall Bioassay

The data collected indicates an exponential relationship between simulated rainfall and tomato fresh plant weight ($Y = 15.65 - 13.57\, e^{(-x/0.0231)}$, $R^2 = 0.94$) (Fig. 4). There was a sharp increase on tomato fresh plant weight as simulated rainfall rose from 0 to 6.5 mm, representing around 85% biomass increase. Fresh biomass remained stable beyond 6.5 mm of rainfall. There were no differences between the fresh weight of the control treatment and all treatments that received sprinkler irrigation.

The data indicated that glyphosate residues could be a potential source for injury to tomato transplanted in polyethylene mulch beds. This finding is supported by the results of the dose-response bioassay, where eluants with 50 mg L^{-1} were enough to reduce tomato biomass accumulation. This concentration is >40 times lower than the regular glyphosate concentration applied in on-farm transplanting. Also, this finding might be particularly important for the industry, which frequently uses the same packaging lines to fill different herbicide containers, including glyphosate, reducing the risks of contamination of other herbicides with potentially injurious glyphosate concentrations.

Another important finding suggests that photodegradation of the herbicide takes >15 d if the molecule is not allowed to enter in contact with dew, irrigation or rainfall. This is particularly important from the grower's standpoint, since it is a common practice transplanting the crop within 72 h after glyphosate application. On the other hand, dew and rainfall proved to be important mechanisms to reduce herbicide toxicity. In the case of dew combined with photodegradation, the herbicide

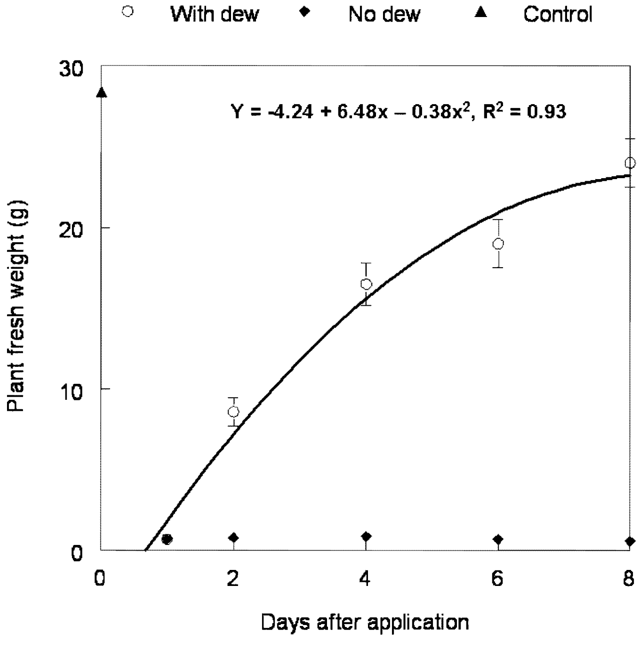

Fig. 3. Effect of length of dew exposure and sunlight with glyphosate-applied mulch on tomato plant fresh weight. Bars on the predicted curve are standard errors.

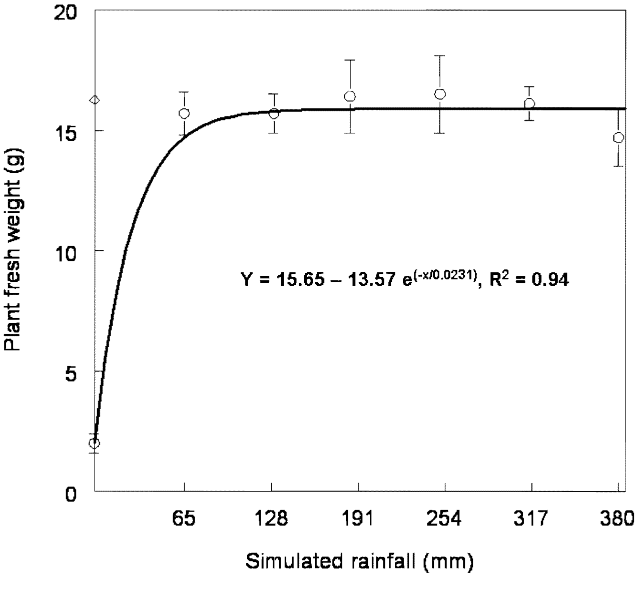

Fig. 4. Effect of simulated rainfall with glyphosate-applied mulch on tomato plant fresh weight. Bars on the predicted curve are standard errors.

injuries were reduced as time of exposure increased. Rainfall, as simulated by sprinkler irrigation, showed to be an effective mode to wash the herbicide away from mulch surfaces.

More extensive studies have to be conducted to determine the minimum concentration at which plants are injured by glyphosate. Also, these bioassays could be expanded to other species where glyphosate residues could be a concern. The findings discussed herein agreed with the mechanisms discussed by previous research on another non-selective herbicide, such as paraquat (1,1'-dimethyl-4,4'-bypridinium dichloride), where eluants collected from plastic mulch caused significant plant injuries (Gilreath and Duranceau, 1986).

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Influence of Plant Height on Dry Biomass Yield and Nutrient Value of *Aeschynomene Evenia*

P. Mislevy* and F. G. Martin

ABSTRACT

Aeschynomene evenia C. Wright (evenia) is a short-lived perennial tropical legume grown by Florida cattlemen. Little information is available regarding above ground dry biomass (DB) yield and nutritive value changes with plant maturity. This experiment was conducted during 1996 and 1997 to determine the influence of harvest treatments (plant height in 15-cm intervals from 15 to 210 cm) on yield, above ground whole-plant (AGWP) nutritive value, and nutritive value of each harvest treatment when separated into 15-cm sections. Dry biomass yield followed a curvilinear relationship in 1996 and an increasing linear relationship with plant height in 1997. Generally, 6 wk was required for evenia plants to attain the first 15 cm of growth followed by a growth rate of 15 cm weekly. Above ground whole-plant crude protein (CP) and in vitro organic matter digestion (IVOMD) decreased linearly from 227 to 92 g kg^{-1} and from 703 to 309 g kg^{-1}, respectively as plant height increased. Based on sectional analyses of the plants, the top 60 cm or 35% of each harvest treatment >60 cm in height had >80 and 550 g kg^{-1} CP concentration and IVOMD, respectively. These data indicate DB yield will maximize at about 12 Mg ha^{-1} with acceptable (100 g kg^{-1}) AGWP CP up to a 210-cm plant height. However, plants did not retain acceptable IVOMD and dropped below 550 g kg^{-1} at a plant height >90 cm. This would suggest plants harvested for hay, silage, or green chop should not be allowed to attain a height >90 cm. Since plants were harvested only one time, no inference regarding grazing can be determined.

Evenia is a short-lived, upright legume that is related to American jointvetch (*A. americana* L.) and grows rapidly on most improved, moist subtropical soils. This legume can be grown on cultivated soil or in association with a perennial grass. Once established, evenia will develop rapidly, producing high quality forage readily accepted by cattle (Kretschmer et al., 1994; Adjei, 2003). However, Chambliss and Kalmbacher (1999) indicated evenia is not immediately palatable to cattle, requiring time for cattle to adapt. Both evenia and American jointvetch exhibit rapid growth rate when coupled with improper grazing management and can quickly develop into a fibrous, low quality forage rejected by livestock (Mislevy et al., 1981; Hodges et al., 1982; Kalmbacher et al., 2002). This may be why cattlemen are slow to incorporate this legume into their pastures. Evenia and American jointvetch can both be harvested for hay and silage, however neither process works very well. Mislevy et al. (1982) found that mature American jointvetch harvested for silage contained a mucilaginous material and produced low quantity (4.5 Mg ha^{-1}) and low nutritive value forage ranging from 420 to 500 g kg^{-1} IVOMD and 87 to 127 g kg^{-1} CP. Low quality evenia hay could be the result of leaf shaddering during the hay making process. When harvested at the immature stage both evenia and American jointvetch produce excellent quality forage (Mislevy et al., 1981; Mislevy and Martin, 2001). Little management information is available on evenia, especially as plants grow beyond 60 to 90 cm.

The purpose of this paper was to monitor changes in DB yield, AGWP nutritive value and the variation in nutritive value of plants based on 15-cm sections at each harvest treatment as evenia plants matured.

P. Mislevy, Range Cattle Res. and Educ. Center, Ona, FL 33865-9706; F. G. Martin, Statistics Dep., Univ. of Florida, Gainesville, FL 32611-0840. This research was supported by the Florida Agric. Exp. Stn. and is approved for publication as Journal Series No. N-02479.
*Corresponding author (pmislevy@ifas.ufl.edu).
Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:24-29 (2004).

MATERIALS AND METHODS

Evenia was seeded in mid-April 1996 and 1997 at 20 kg ha^{-1} (seed removed from hull) into a clean-tilled seed bed using a grain drill. Seeding was immediately followed by a light disking (2.5-cm deep, with disk-angle removed) and firm packing. The soil was a sandy, siliceous, hyperthermic Ultic Alaquod (Pomona fine sand) at the Range Cattle Research and Education Center, Ona. Fertilization rate was 0-15-55 kg ha^{-1} N-P-K plus 3.4 S, 1.7 Cu, Zn, Mn, Fe, (sulfate forms) and 0.17 kg ha^{-1} B.

The experimental design was a randomized complete block with four replications. Within each block, a randomly selected plot (1.5 by 6.2 m) was harvested each time the average height of the plants in the plot increased by 15 cm. The first harvest was made when plants were 15-cm tall and the last one was made when the plants were 210-cm tall which made a total of 14 harvests. Two separate forage samples were collected at each plant height. To determine DB yield and AGWP nutritive value, a 0.5 by 4.6 m strip was cut to a 7.5-cm stubble height. To determine the difference in nutritive value of plants based on relative maturity as estimated by plant height, plants (n = 10-25) from the unharvested portion of the plots were hand clipped to the soil surface. These plant samples were cut into 15-cm sections and each section was analyzed for CP and IVOMD.

Forage samples were dried at 60°C, ground, and analyzed for total N concentration (Gallaher et al., 1975; Hambleton, 1977). Crude protein concentration was calculated as 6.25 × N. Additionally, IVOMD content was determined for forage samples by the two-stage procedure of Tilley and Terry (1963) modified by Moore and Mott (1974).

Dry biomass yield, CP, and IVOMD were analyzed separately by year using PROC GLM (SAS, 1989) with the model statement appropriate for a randomized complete block. When significant differences ($P < 0.01$) were found the data were further investigated by estimating the regression relationship between plant height and response.

RESULTS AND DISCUSSION

Biomass Yield

Significant ($P < 0.05$) differences were found among plant heights for above ground whole-plant DB yield, CP, and IVOMD. Dry biomass followed a curvilinear and linear relationship with plant height in 1996 and 1997, respectively (Fig. 1). Forage yield of evenia, when harvested at ≤30 cm was very low averaging ~0.5 Mg ha^{-1} during both 1996 and 1997. As plant height increased from 45 to 150 cm, forage yield increased from 2 to 6 Mg ha^{-1}. However, as plants approached maturity (165-210 cm) forage yield increased sharply from 6 to 12 Mg ha^{-1}.

Following germination, growth rate of evenia plants was fairly slow. They required 6 wk to attain an initial 15 cm of plant height, followed by a growth rate of 15 cm weekly (Fig. 1). For each additional 15 cm increase in plant height, DB yield increased an average of 0.87 Mg ha^{-1}. With adequate moisture and fertility, this growth rate can continue until early-mid October. However, plants managed under a grazing system will continue vegetative growth through November. This is quite the opposite to American jointvetch which will continue making good growth only until mid-October, regardless of management system. At this time, day-length has shortened sufficiently to cause termination of growth and leaf drop (Mislevy, 1986).

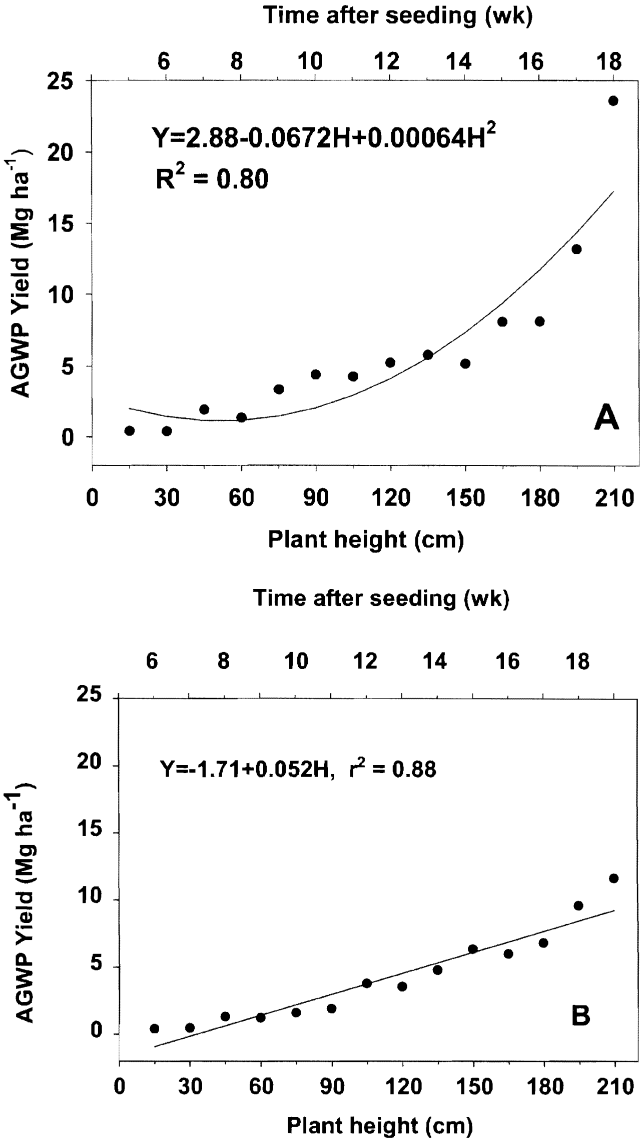


Fig. 1. Dry biomass (DB) yield response of above ground whole-plant (AGWP) evenia harvested at plant height ranging from 15 to 210 cm during (A) 1996 and (B) 1997. Each data point represents forage yield averaged over four replications. H in the equation is plant height.

FORAGE NUTRITIVE VALUE

Above ground whole-plant samples

Crude protein concentration and IVOMD decreased linearly as plant height increased from 15 to 210 cm during both 1996 and 1997. Protein concentration during 1996 and 1997 ranged from a high of 210 and 290 g kg^{-1} respectively, for immature plants to 100 and 87 g kg^{-1}, respectively, for mature, seed producing plants (Fig. 2). On average, CP decreased 5.3 and 14.6 g kg^{-1} in 1996 and 1997, respectively, for each 15 cm increase in plant height between 15 and 210 cm. Even at the low end of the CP range, evenia would be more than adequate for lactating mature beef cattle of moderate milk production (NRC, 1984).

From a grazing management standpoint, it is difficult to provide grazing information since plants were only harvested one time. However, it would be best to graze the initial harvest of evenia when plants are 30 cm followed by regrowth harvests of 60 to 90 cm (Mislevy and Martin, 2001). Plants at this stage averaged 220 g kg^{-1} CP and generally 80 to 90% of the plant would be consumed by the grazing animal. Although plants >75 cm may average > 120 g kg^{-1} CP, 50 to 75% of the DB yield at this mature stage would be rejected by mature cattle.

Above ground whole-plant IVOMD ranged from 735 g kg^{-1} for 15-cm tall plants to 268 g kg^{-1} for 210 cm plants when averaged over 2 yr (Fig. 3). The digestibility of AGWP decreased linearly at 30 and 37 g kg^{-1} for each 15 cm increase in plant height in 1996 and 1997, respectively. If plants were grazed prior to reaching 75-cm height, IVOMD would have averaged ~600 g kg^{-1} or more during 1996 and 1997. Allowing plants to attain a height >75 cm resulted in low digestibility that ranged from 300 g kg^{-1} to 540 g kg^{-1} in 1996 and from 210 to 540 g kg^{-1} in 1997. These data indicate evenia plants taller than ~90 cm would not be desirable for green chop or silage, due to low IVOMD.

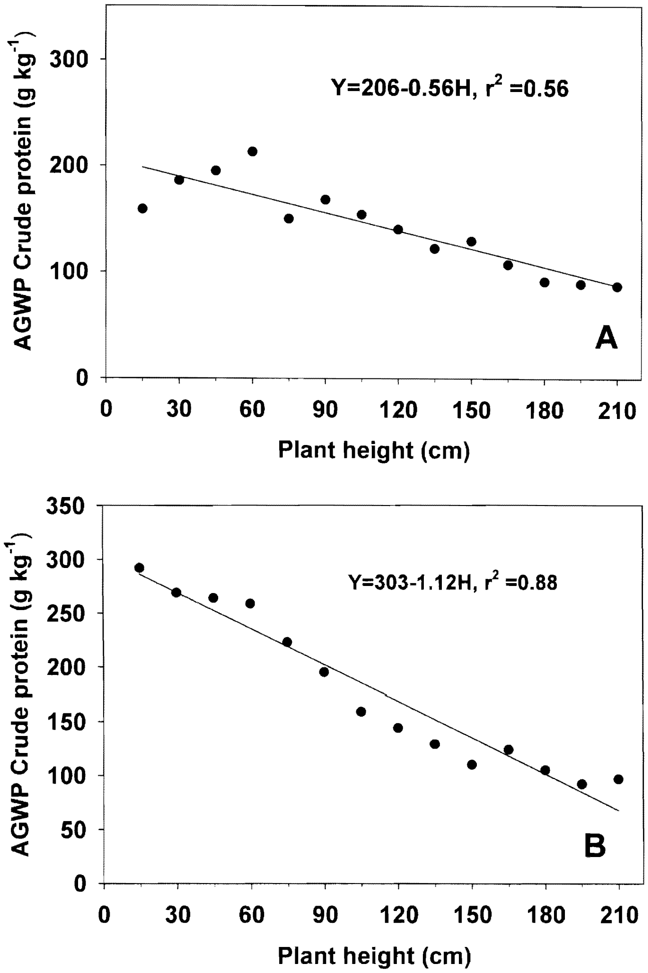


Fig. 2. Crude protein (CP) concentration response of above ground whole-plant (AGWP) evenia harvested at plant height ranging from 15 to 210 cm during (A) 1996 and (B) 1997. Each data point represents AGWP CP averaged over four replications. H in the equation is plant height.

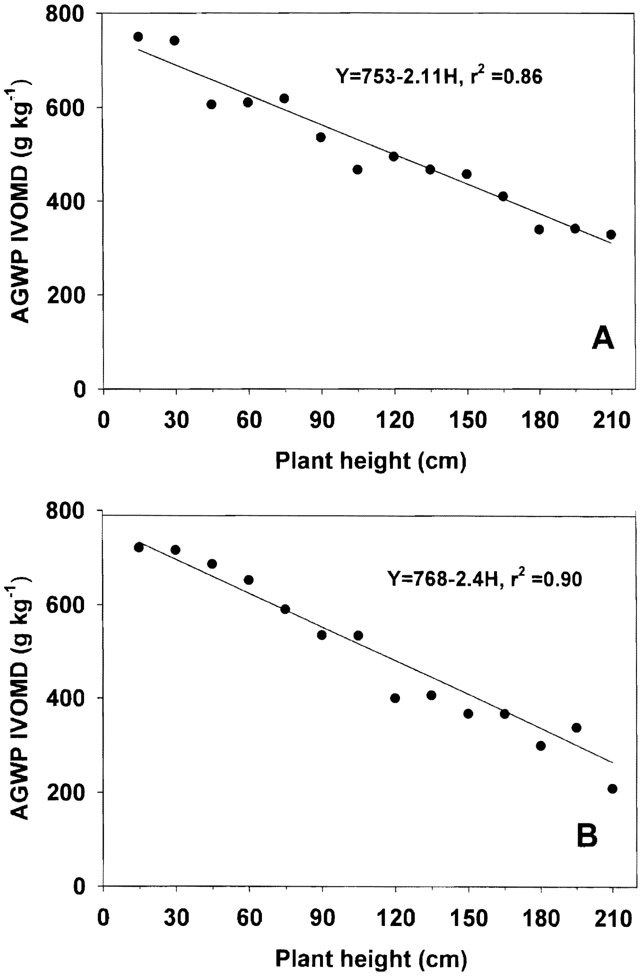


Fig. 3. In vitro organic matter digestion (IVOMD) response of above ground whole-plant (AGWP) evenia harvested at plant height ranging from 15 to 210 cm during (A) 1996 and (B) 1997. Each data point represents AGWP IVOMD averaged over four replications. H in the equation is plant height

Plant sections

Crude protein concentration was always the highest at the upper-most terminal part of the plant, which consists of the most immature forage (Fig. 4a). Average CP of the terminal 15-cm section of the plant was 274 g kg^{-1} during 1996 and 297 g kg^{-1} during 1997. Moving down the plant to the second and third 15-cm sections, CP averaged 228 and 176 g kg^{-1}, respectively in 1996 and 269 and 228 g kg^{-1} respectively during 1997 (Figs. 4a and 4b).

Time after seeding (wks)

A

CP g/kg 1996
CP < 80 g/kg

Plant sections (cm)	0	6	7	8	9	10	11	12	13	14	15	16	17	18	19
196-210															226
181-195														234	215
166-180													276	195	188
151-165												262	224	186	168
136-150											271	231	177	136	130
121-135										286	234	183	151	140	113
106-120									324	231	214	161	154	98	79
91-105								286	247	212	172	114	114	75	54
76-90							273	244	203	129	125	81	74	67	54
61-75						280	266	172	142	119	94	71	62	58	44
46-60					308	211	179	117	106	88	55	53	44	50	37
31-45				301	261	128	140	62	58	66	57	47	44	38	36
16-30			287	214	157	88	86	46	54	55	52	51	42	41	34
0-15		216	198	118	94	67	57	54	52	52	58	54	43	41	47
Plant height (cm)	0	15	30	45	60	75	90	105	120	135	150	165	180	195	210

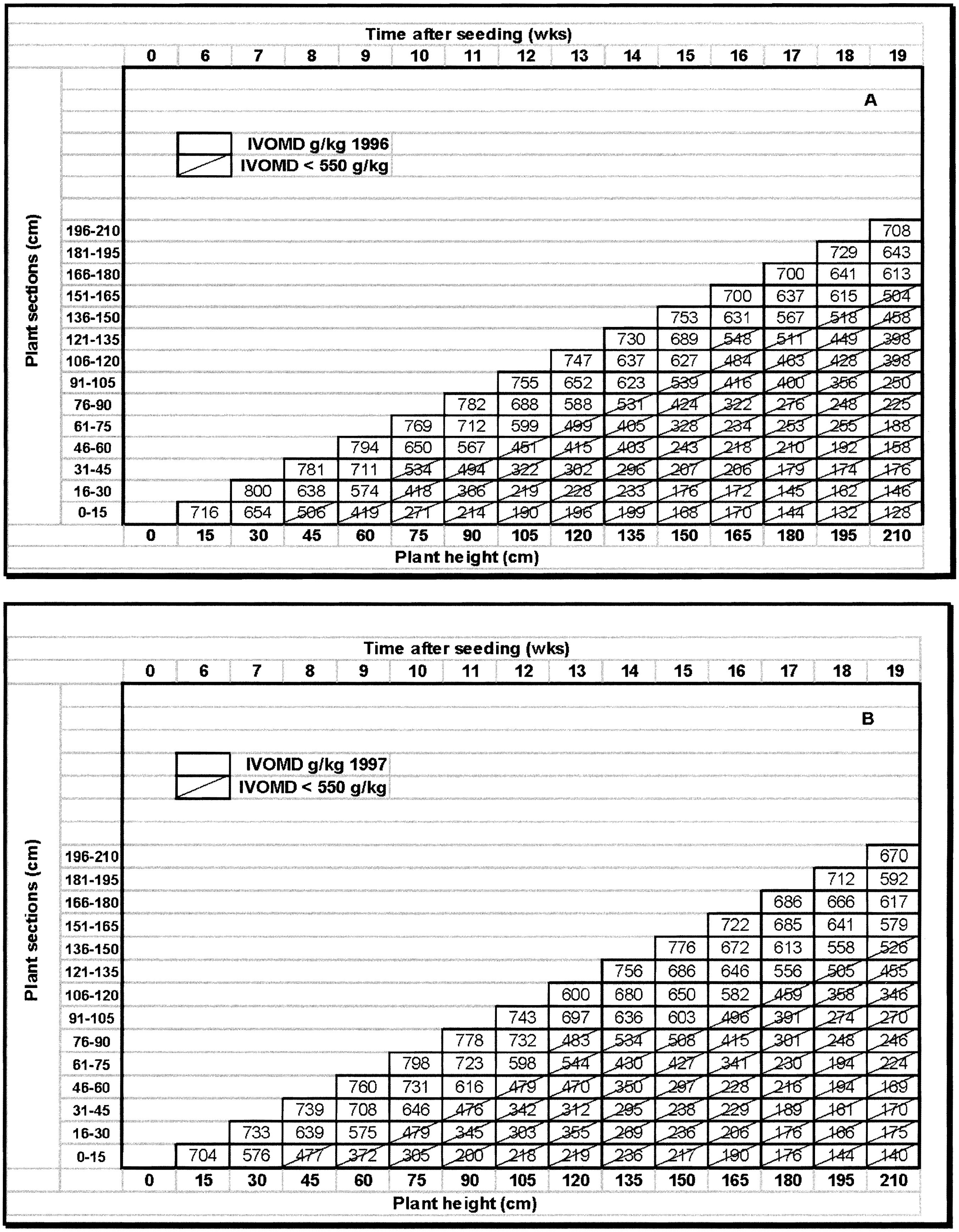
Time after seeding (wks)

B

CP g/kg 1997
CP < 80 g/kg

Plant sections (cm)	0	6	7	8	9	10	11	12	13	14	15	16	17	18	19
196-210															246
181-195														281	215
166-180													297	267	224
151-165												302	292	256	204
136-150											313	302	267	228	174
121-135										308	294	271	214	174	144
106-120									294	258	242	250	167	122	107
91-105								268	285	249	222	188	118	88	60
76-90							344	258	177	196	170	138	81	63	58
61-75						339	314	184	185	139	131	103	56	53	49
46-60					310	312	220	138	161	100	76	61	57	42	39
31-45				324	282	270	156	90	106	69	54	53	48	42	38
16-30			306	239	208	187	94	70	121	64	58	57	49	44	39
0-15		231	177	166	115	93	56	52	58	64	57	56	57	43	42
Plant height (cm)	0	15	30	45	60	75	90	105	120	135	150	165	180	195	210

Fig. 4. Crude protein (CP) concentration of evenia plants sectioned at 15-cm intervals for plant height ranging from 15 to 210 cm during (A) 1996 and (B) 1997. Time after seeding (wk) is shown for comparison with plant height. Each section represents 10-25 plants.



A

☐ IVOMD g/kg 1996
▨ IVOMD < 550 g/kg

Time after seeding (wks)	0	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Plant sections (cm)															
196-210															708
181-195														729	643
166-180													700	641	613
151-165												700	637	615	~~504~~
136-150											753	631	567	~~518~~	~~458~~
121-135										730	689	~~548~~	~~511~~	~~449~~	~~398~~
106-120									747	637	627	~~484~~	~~463~~	~~428~~	~~398~~
91-105								755	652	623	~~539~~	~~416~~	~~400~~	~~356~~	~~250~~
76-90							782	688	588	~~531~~	~~424~~	~~322~~	~~276~~	~~248~~	~~225~~
61-75						769	712	599	~~499~~	~~405~~	~~328~~	~~234~~	~~253~~	~~255~~	~~188~~
46-60					794	650	567	~~451~~	~~415~~	~~403~~	~~243~~	~~218~~	~~210~~	~~192~~	~~158~~
31-45				781	711	~~534~~	~~494~~	~~322~~	~~302~~	~~296~~	~~207~~	~~206~~	~~179~~	~~174~~	~~176~~
16-30			800	638	574	~~418~~	~~366~~	~~219~~	~~228~~	~~233~~	~~176~~	~~172~~	~~145~~	~~162~~	~~146~~
0-15		716	654	~~506~~	~~419~~	~~271~~	~~214~~	~~190~~	~~196~~	~~199~~	~~168~~	~~170~~	~~144~~	~~132~~	~~128~~
Plant height (cm)	0	15	30	45	60	75	90	105	120	135	150	165	180	195	210

B

☐ IVOMD g/kg 1997
▨ IVOMD < 550 g/kg

Time after seeding (wks)	0	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Plant sections (cm)															
196-210															670
181-195														712	592
166-180													686	666	617
151-165												722	685	641	579
136-150											776	672	613	558	~~526~~
121-135										756	686	646	556	~~505~~	~~455~~
106-120									600	680	650	582	~~459~~	~~358~~	~~346~~
91-105								743	697	636	603	~~496~~	~~391~~	~~274~~	~~270~~
76-90							778	732	~~483~~	~~534~~	~~508~~	~~415~~	~~301~~	~~248~~	~~246~~
61-75						798	723	598	~~544~~	~~430~~	~~427~~	~~341~~	~~230~~	~~194~~	~~224~~
46-60					760	731	616	~~479~~	~~470~~	~~350~~	~~297~~	~~228~~	~~216~~	~~194~~	~~169~~
31-45				739	708	646	~~476~~	~~342~~	~~312~~	~~295~~	~~238~~	~~229~~	~~189~~	~~161~~	~~170~~
16-30			733	639	575	~~479~~	~~345~~	~~303~~	~~355~~	~~269~~	~~236~~	~~206~~	~~176~~	~~166~~	~~175~~
0-15		704	576	~~477~~	~~372~~	~~305~~	~~200~~	~~218~~	~~219~~	~~236~~	~~217~~	~~190~~	~~176~~	~~144~~	~~140~~
Plant height (cm)	0	15	30	45	60	75	90	105	120	135	150	165	180	195	210

Fig. 5. In vitro organic matter digestion (IVOMD) of evenia plants sectioned at 15-cm intervals for plant height ranging from 15 to 210 cm during (A) 1996 and (B) 1997. Time after seeding (wk) is shown for comparison with plant height. Each section represents 10-25 plants.

This equates to an average of 46 g kg^{-1} decline in CP between each of the top four plant sections in 1996 and 36 g kg^{-1} during 1997. Generally, the top 60 to 90 cm of evenia plants contain forage CP concentration in the range of 80 to 300 g kg^{-1}. This type of forage would contain adequate protein for lactating beef cattle (NRC, 1984).

Unlike CP the IVOMD of evenia plants decreased rapidly with plant height. Average IVOMD of the top 15 cm of plant for all harvest treatments was 747 g kg^{-1} in 1996 and 727 g kg^{-1} in 1997 (Fig. 5). Forage digestibility of the second and third plant sections from the top averaged 660 and 580 g kg^{-1}, respectively, during 1996 and 676 and 600 g kg^{-1} in 1997. The IVOMD dropped an average of 84 g kg^{-1} in 1996 and 64 g kg^{-1} in 1997 between each of the top three 15-cm sections. Basically, the IVOMD of the top 45 cm of evenia is high quality ranging from 737 to 590 g kg^{-1}. Cutting the plant 60 cm or lower from the top generally produces low quality forage (Fig. 5).

In conclusion, these data indicate that evenia plants require about 6 wk after germination to attain the first 15 cm of plant height, followed by a growth rate of 15 cm wk^{-1}. Evenia plants should be harvested or grazed at ≤90 cm. A single harvest at this height generally produced low DB yield averaging <5 Mg ha^{-1}. However, whole plant CP and IVOMD will range from 150 to 300 g kg^{-1} and 520 to 750 g kg^{-1}, respectively. Allowing plants to grow beyond 90 cm results in increased DB yields, adequate CP for mature cattle, but poor (<500 g kg^{-1}) IVOMD content. Analyzing plant samples at 15-cm sections revealed that the top 60 to 90 cm of evenia plants contain forage CP concentration >80 g kg^{-1}. High IVOMD (590 to 737 g kg^{-1}) was found only in the top 45 cm of plant growth, followed by a rapid decrease to ≤520 g kg^{-1}. Evenia harvest management studies described in an earlier paper by Mislevy and Martin (2001) showed that the removal of initial harvest at 30 cm and all regrowth harvests at 60 cm produced a seasonal average of 5.6 to 6.0 Mg ha^{-1} of high nutritive value forage.

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Germinable Seed in the Soil Seed Bank of Five Bahiagrass-Legume Pastures

R. S. Kalmbacher

ABSTRACT

Soil in five bahiagrass (*Paspalum notatum* Flügge)-legume pastures in central Florida was sampled for germinable seed prior to summer rains in February 2002. Three pastures contained 1, 5, or 10-yr-old stands of *Aeschynomene evenia* C. Wright (evenia). A fourth pasture contained 15-yr-old *A. americana* L. (americana), and the fifth contained 8-yr-old *Desmodium heterocarpon* (L) DC (carpon). Seedlings of all plants were identified, counted, and removed from flats in a glasshouse as they emerged in 5 cycles of wetting and drying over a 20-mo period. Averaged over all pastures, there was a total 9538 germinable seed m^{-2} representing 48 species plus the combined Cyperaceae and Juncaceae, which constituted the largest entity with an average 6653 seed m^{-2}. Bahiagrass ranked 3rd in density of germinable seed with an average 566 seed m^{-2} (equivalent of 17.2 kg seed ha^{-1}), 98% of which germinated in Cycle 1. Evenia seed ranked 5th in density with 52, 553, and 335 seed m^{-2} in 1, 5, and 10-yr-old stands, respectively (2.8, 29.7, and 18 kg seed ha^{-1}). Density of americana (rank 13) and carpon (rank 6) averaged 124 and 857 seed m^{-2}, respectively (6.7 and 11.2 kg seed ha^{-1}). Of the total americana seed, 68 and 21% germinated in Cycles 1 and 2. Germination of evenia and carpon seed was 25 and 39%, respectively, in Cycle 1, but it reached a peak in Cycle 2 with 47 and 57%, respectively. Seeds of common weeds were present in all pasture soils, but did not constitute a major portion of the seed bank. These data demonstrate the importance of management to build seed reserves of forage plants. The presence of weed seed indicates the need for good management to maintain strong stands of desirable forages capable of suppressing weeds.

Buried seed constitutes a reserve of dormant individuals capable of replenishing losses incurred by mature vegetation (Thompson, 1978). Referred to as soil seed banks, buried seed has been the focus of considerable plant ecology research summarized by Leck et al. (1989). Soil seed banks are of importance in pasture agronomy because seed reserves determine future vegetation, the outcome of which can be favorable if forages are established from buried seed or unfavorable if weeds infest pasture. Australian researchers have been particularly keen to recognize the practical importance of buried seed for replenishing tropical legumes (Jones and Evans, 1977; Gardner, 1981; Wilson et al., 1982; McIvor and Gardner, 1991). They recognize soil seed banks as an important factor in botanical stability of pasture systems (Tothill and Jones, 1977) and in the dynamics of plant communities (Jones and Mott, 1980).

There is no information on seed reserves in pasture soils in Florida, yet soil seed banks are especially important because annuals such as *Aeschynomene* spp. are dependent on seed reserves for regeneration every summer. Also, perennial legumes such as *Desmodium* sp. die and must be replaced for pasture stability. Bahiagrass, the state's most important pasture grass, is often killed by tawny mole cricket (*Scapteriscus vicinus* Scudder), and seed reserves could play an important role in replenishing this grass. The purpose of this study was to provide basic information about seed reserves in bahiagrass pastures containing one of two annual *Aeschynomene* spp. or one perennial *Desmodium* sp.

MATERIALS AND METHODS

Research was conducted at the Univ. of Florida, Range Cattle Res. and Educ. Center (REC) at Ona where five Pensacola bahiagrass pastures, all of which were at least 20-yr-old, were sampled on 15-18 Feb. 2002. At this time, seed reserves would be close to their peak prior to advent of rainfall which would bring about germination. In three pastures, evenia had been sown 1- (pasture 95-4), 5- (pasture 95-6), or 10-yr (pasture 27 east) prior to sampling. A fourth pasture contained americana (pasture 27 west) which was ~15 yr-old. The fifth pasture (48) contained carpon which was 8-yr-old at the time of sampling. The soil in all *Aeschynomene* pastures was Pomona fine sand (sandy, siliceous, hyperthermic Ultic Alaquods), and soil in the carpon pasture was an Ona fine sand (sandy, siliceous, hyperthermic Typic Alaquods).

Sampling the soil seed bank was done in 25, equally spaced 1-m^{2} quadrats along a 100-m transect in each pasture. At each quadrat, 6, 10-cm diam soil cores were extracted with a golf-green cup cutter to a depth of ~10 cm. The top 25 mm was sliced from each core and saved (including litter), and the lower portion discarded. The top 25 mm was selected because it contains >95% of the seed (Young et al., 1981; McIvor, 1987). The six cores for each quadrat were composited and air-dried to ~25 g water kg^{-1} soil. Samples (~600 g each) were spread evenly (~10 mm thick) over a 25-mm layer of clean builder's sand in 30- by 30-mm trays. The 125 trays were randomly arranged by pasture in a glasshouse. A traveling sprayer uniformly applied water three to six times daily depending on day length and temperature. Watering began on 10 Apr. 2002 and continued to 8 July (Cycle 1), then watering ceased allowing the soil in trays to dry. The surface layer was thoroughly disturbed during drying. Watering commenced on 25 Oct. 2002 and continued to 2 Jan. 2003 (Cycle 2) followed by drying and disturbance. Similarly, Cycle 3 (3 Apr.-11 June 2003), Cycle 4 (2-22 Sept. 2003), and Cycle 5 (3 Nov.-8 Dec. 2003) were conducted. The length of each cycle was based on emergence. As long as seed emerged, the cycle was continued. Alternating periods of wet and dry were used instead of one continuous wet cycle which may underestimate the size of germinable seed banks (Orr, 1999).

Seedlings were identified, counted, and removed from each tray every 7 to 10 d or longer at the end of a cycle when germination was reduced. Seedlings that could not be identified were transplanted to pots where they grew until they flowered and could be identified.

R. S. Kalmbacher, Range Cattle Res. and Educ. Center, Ona, FL 33865-9706. This research was supported by the Florida Agric. Exp. Stn. and is approved for publication as Journal Series No. N-02476.

*Corresponding author (rskalmbacher@ifas.ufl.edu).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:30-36 (2004).

Plants were identified at the Univ. of Florida Herbarium. Cyperaceae and Juncaceae were combined due to the difficulty of their identification. When scientific names are given in the text without authorities, they can be found in Table 1.

Data were summarized with the means procedure of SAS (1985). Calculations of seed mass for evenia and americana were based on 1.87×10^5 of unhulled seed kg^{-1} (Hodges et al., 1982); for carpon, 7.7×10^5 seed kg^{-1} (Kretschmer et al., 1979); and for bahiagrass, 6.6×10^5 seed kg^{-1} (Martin and Leonard, 1965).

RESULTS

Over all five pastures, there was an average 9538 seed m^{-2} that germinated over the 20-mo period (Table 1). Except for the 1-yr-old evenia pasture 95-4, which had a total of 6644 seed m^{-2}, pastures were similar in total germinable seed ranging from 9742 to 10 568 seed m^{-2}. There were 48 species represented plus the combined Cyperaceae and Juncaceae. Two plants could not be identified as they did not flower. One was a winter annual (17th), which was abundant in pasture 27, and the other was an infrequent grass (39th).

Bahiagrass and Legumes

Bahiagrass had the 3rd greatest density of germinable seed in the soil of all pastures with an average 566 seed m^{-2} (Table 1). The variation among pastures (s_d = 134 seed m^{-2}) was relatively low compared with that of other plants. Except for evenia pasture 27, which was somewhat higher in bahiagrass seed density compared with other pastures, bahiagrass had 456 to 590 seed m^{-2}. Bahiagrass seed was relatively well distributed within all pastures as seed occurred in 100% of quadrats, however, standard deviations for seed density over quadrats within a pasture were high averaging 376 seed m^{-2}. Seed reserves were the equivalent of 13.9 to 25 kg seed ha^{-1} (Table 2).

Legume density was relatively great, especially for carpon in pasture 48 (Table 1). Americana was an exception in pasture 27, where its density was only 124 seed m^{-2}. None of the legumes had 100% frequency of occurrence, indicating a mosaic pattern for legumes across the pastures. Seed reserves of legumes ranged from 2.8 kg seed ha^{-1} in the 1-yr old evenia pasture 95-4 to 29.7 seed ha^{-1} in the 6-yr old evenia pasture 95-6 (Table 2). In the 10-yr old evenia pasture 27, the seed bank contained 18 kg seed ha^{-1}. In americana pasture 27, where this legume was sown ~15 yr ago, there was 6.7 kg seed ha^{-1}. Americana was also found infrequently in evenia pastures 95-4 and 27 (Table 1). The 8-yr-old carpon pasture had 11.2 kg carpon seed ha^{-1}.

There were several legumes of minor occurrence in these pastures (Table 1). 'Shaw' vigna (*Vigna parkeri*) was found in the 6-yr-old evenia pasture 95-4, where it was sown at 3 kg ha^{-1} in June 2001 (Adjei, personal communication, 2002). 'Savanna' *Stylosanthes guianensis* was sown in the 1-yr-old evenia pasture in 1996 and 1997 (Kalmbacher et al., 2002). Seed persisted in the soil from the initial sowings or from seed from the scattered plants. Savanna seed was also found in the 10-yr-old evenia pasture 27. White clover (*Trifolium repens*) seed was found in the 1-yr-old evenia pasture where it had been sown in the 1950s.

Almost all (98%) of the germinable bahiagrass seed was accounted for in Cycle 1 (Table 3). Most of the americana seed germinated in Cycles 1 (68%) and 2 (21%). Germination of evenia and desmodium seed was high in Cycle 1 (25 and 39%, respectively), but it reached a peak in Cycle 2 (47 and 57%, respectively). Cycles 3 and 5 had substantially less germinable legume seed than the first two cycles. In Cycle 4 there was a slight increase in germinable seed compared with Cycles 3 and 5.

Pasture Weeds

Seed of Cyperaceae and Juncaceae constituted the largest entity in the soil seed bank (Table 1). Their seed was found in every quadrat in all five pastures. Goatweed (*Scoparia dulcis*) ranked 2nd in total density and was found in all pastures. Pigweed (*Amaranthus spinosus*), which ranked 12th in density, was found in four pastures. Its distribution was not uniform, but had high density in quadrats where it occurred. For example, in evenia pasture 95-6, it occurred in 16% of the quadrats, and averaged 141 seed m^{-2} over the pasture. Vaseygrass (*Paspalum urvillei*), common bermudagrass (*Cynodon dactylon*), and smutgrass (*Sporobolus indicus*) ranked 14th, 19th, and 20th in density. Vaseygrass seed was found in all pastures, while seed of the other grasses were found in three pastures. Among the pastures, seed density of these three grasses was not uniform. Evenia pasture 95-6 had greater densities than other pastures. Dog fennel (*Eupatorium capillifolium*) ranked 21st in density and was found in all pastures.

Other Abundant Plants

The family Rubiaceae was well represented with *Hedyotis corymbosa* (ranking 4th), *Hedyotis uniflora* (ranking 11th), *Diodia virginiana* (ranking 23rd), and *Spermacoce assurgens* (ranking 38rd). *Hedyotis* spp. were found in all pastures, but their density was quite variable among pastures. Smartweed (*Polygonum punctatum*) and cudweed (*Gnapthalium pennsylvanicum*) ranked 7th and 15th, respectively, in seed density and were found in all pastures, sometimes with high density. Seeds of annuals, such as false pimpernel (*Linaria dubia),* and the unknown winter annual (probably toadflax [*Lineria* sp.]) which emerged in Cycle 2, were found in four pastures and could be abundant in pastures where they occurred.

DISCUSSION

Bahiagrass and Legumes

An interesting finding was the relatively large reserve of germinable bahiagrass seed in the soil. An average 566 seed m^{-2} (Table 1) was equivalent to 17.2 kg seed ha^{-1} (Table 2). Our bahiagrass seed density was similar to

Table 1. Density and frequency of occurrence of germinable seed in soil as determined from seedling counts. Densities are totals over five germination cycles (10 Apr. 2002-8 Dec. 2003). Entries are ranked in descending order according to total (over pastures) density.

		Pasture 27				Pasture 48		Pasture 95			
		A. americana		*A. evenia*		*D. heterocarpon*		*A. evenia*†		*A. evenia*‡	
		Freq§	Density	Freq	Density	Freq	Density	Freq	Density	Freq	Density
Rank	Plant	%	no. m^{-2}	%	no. m^{-2}	%	no. m^{-2}	%	no. m^{-2}	%	no. m^{-2}
1	Cyperaceae & Juncaceae	100	8517	100	8098	100	3408	100	5235	100	8005
2	*Scoparia dulcis* L	80	102	92	370	100	4759	88	727	100	82
3	*Paspalum notatum* (Flügge)	100	456	100	788	100	484	100	508	100	590
4	*Hedyotis corymbosa* (L.) Lam.	84	595	68	135	80	475	4	1	28	8
5	*Aeschynomene evenia* C. Wright	0	0	96	335	0	0	80	52	92	555
6	*Desmodium heterocarpon* (L) DC.	4	1	0	0	80	857	0	0	0	0
7	*Polygonum punctatum* Elliott	28	72	76	329	60	50	16	7	24	21
8	*Linaria dubia* (L.) Pennell	36	51	28	15	92	312	12	3	0	0
9	*Oxalis florida* Salisb.	76	224	20	21	40	13	48	27	44	38
10	*Ludwigia octovalvis* (Jacq.) Raven	16	4	68	127	28	18	0	0	0	0
11	*Hedyotis uniflora* (L.) Lam.	28	14	8	3	84	124	8	3	20	10
12	*Amaranthus spinosus* L.	0	0	8	5	4	3	4	1	16	141
13	*Aeschynomene americana* L.	92	124	8	3	0	0	4	1	0	0
14	*Paspalum urvillei* Steud.	8	4	8	2	20	8	20	18	60	72
15	*Gnapthalium pennsylvanicum* Willd.	68	65	64	18	32	7	12	3	12	3
16	*Ludwigia* sp.	12	13	48	63	16	3	4	3	8	9
17	Unknown forb (sterile winter annual)	52	77	68	41	0	0	12	3	8	3
18	*Trifolium repens* L.	0	0	0	0	0	0	0	0	32	77
19	*Cynodon dactylon* L.	20	5	8	2	0	0	8	2	48	38
20	*Sporobolus indicus* (L.) R. Br.	12	4	4	1	0	0	0	0	28	31
21	*Eupatorium capillifolium* (Lam.) Small	16	3	16	4	24	7	32	12	40	9
22	*Eleusine indica* (L.) Gaertn.	8	2	20	6	32	8	36	9	16	3
23	*Diodia virginiana* L.	0	0	4	2	4	2	4	1	12	17
24	*Sacciolepsis indica* (L.) Chase	0	0	4	8	44	17	0	0	0	0
25	*Linaria dubia* (L.) Pennell	0	0	28	15	0	0	12	3	0	0
26	*Stylosanthes guianensis* (Aubl.) SW	0	0	16	5	0	0	36	10	0	0
27	*Bidens alba* (L.) DC.	8	3	8	4	12	3	4	1	0	0
28	*Teucrium canadense* L.	12	3	4	5	0	0	0	0	0	0
29	*Chamaesyce hypericifolia* (L.) Millsp.	4	1	20	5	4	1	4	1	0	0
30	*Commelina diffusa* Burm. f.	0	0	0	0	0	0	4	1	12	6
31	*Chenopodium ambrosioides* L.	0	0	0	0	0	0	20	6	0	0
32	*Sesbania macrocarpa* Muhl.	0	0	0	0	0	0	0	0	16	6
33	*Ambrosia artemisiifolia* L.	0	0	8	2	0	0	4	1	4	3
34	*Vigna parkeri* Bak.	0	0	0	0	0	0	0	0	24	6
35	*Linaria canadensis* (L.) Chaz.	0	0	4	1	12	4	0	0	0	0
36	*Hydrocotyle verticillata* Thunb.	0	0	0	0	0	0	4	1	8	2

†Pasture 95-4 was sown to *A. evenia* 1 yr prior to sampling soil seed bank.

‡Pasture 95-6 was sown to *A. evenia* 6 yr prior to sampling soil seed bank.

§Percentage of 25 quadrats in the 100-m long transect in each pasture in which the specie was found.

Table 1. **(Continued) Density and frequency of occurrence of germinable seed in soil as determined from seedling counts. Densities are totals over five germination cycles (10 Apr. 2002-8 Dec. 2003). Entries are ranked in descending order according to total (over pastures) density.**

		Pasture 27				Pasture 48		Pasture 95			
		A. americana		*A. evenia*		*D. heterocarpon*		*A. evenia*†		*A. evenia*‡	
		Freq§	Density	Freq	Density	Freq	Density	Freq	Density	Freq	Density
Rank	Plant	%	no. m^{-2}	%	no. m^{-2}	%	no. m^{-2}	%	no. m^{-2}	%	no. m^{-2}
37	*Rotalia ramosior* (L.) Koehne	0	0	0	0	4	1	4	2	0	0
38	*Spermacoce assurgens* Ruiz. & Pavon	0	0	0	0	0	0	0	0	4	3
39	Unknown grass	0	0	4	1	4	2	0	0	0	0
40	*Solanum chenopodioides* Lam.	4	1	0	0	0	0	0	0	8	2
41	*Digitaria floridana* Hitchc.	0	0	4	1	4	1	0	0	0	0
42	*Pluchia* sp.	0	0	0	0	0	0	4	1	4	1
43	*Drymaria cordata* (L.) Willd. ex Roem. & Schult	0	0	8	2	0	0	0	0	0	0
44	*Axonopus furcatus* (Flugge) Hitchc.	0	0	4	1	0	0	0	0	0	0
45	*Baccharis halimifolia* L.	0	0	4	1	0	0	0	0	0	0
46	*Ludwigia peruviana* (L.) Hara	0	0	0	0	0	0	4	1	0	0
47	*Rhexia virginica* L.	0	0	0	0	4	1	0	0	0	0
48	*Descurainia pinnata* (Walt.) Britt.	4	1	0	0	0	0	0	0	0	0
49	*Physalis cordata* Mill	0	0	0	0	0	0	0	0	4	1
Total			10 342		10 414		10 568		6 644		9 742

†Pasture 95-4 was sown to *A. evenia* 1 yr prior to sampling soil seed bank.

‡Pasture 95-6 was sown to *A. evenia* 6 yr prior to sampling soil seed bank.

§Percentage of 25 quadrats in the 100-m long transect in each pasture in which the specie was found.

Table 2. Germinable seed of major forages in the soil seed bank within *Aeschynomene evenia-*, *A. americana-*, or *Desmodium heterocarpon-*bahiagrass pastures. Total over five cycles spanning 20 mo.

Pasture†	Years since sowing‡	Bahiagrass	Legume§
		kg ha^{-1}	
Evenia (95-4)	1	15.5	2.8
Evenia (95-6)	6	17.1	29.7
Evenia (27)	10	25.0	18.0
Americana (27)	15	13.9	6.7
Desmodium (48)	8	14.7	11.2

†Pasture designation at the Range Cattle REC in parenthesis.

‡All pastures were bahiagrass and legumes had been seeded at various times.

§For *Aeschynomene*, this is unhulled seed.

densities of the perennial grasses *Chloris gayana* Kunth. (660 seed m^{-2}) and *Urochloa mosambicensis* (Hack.) Dandy (410 seed m^{-2}) reported by McIvor and Gardener (1991). In annual grasslands, grass seed densities are quite large and can reach >100 000 seed m^{-2} at their peak before the growing season (Young et al., 1981).

Bahiagrass seed reserves were depleted very quickly as almost all of the seed germinated in Cycle 1 (Table 3). This is consistent with the findings of Jones et al. (1991) who reported that most of the seed of grasses (except *Eleusine indica*) germinated in the first of eight cycles. However, considering the relatively high seed dormancy of harvested and stored bahiagrass seed (West and Marousky, 1989), it seems that a relatively large portion of the bahiagrass seed reserves would germinate in later cycles. Nothing is known about the age of the bahiagrass seed reserves in the soil, but the minimum age would be ~6 mo (July 2001 seed). Perhaps there is little relationship between dormancy of commercial seed held in storage and seed buried in soil.

Legume seed densities found in this study are comparable to other reported tropical legume seed densities. Mean density of 25 *Stylosanthes guianensis* accessions averaged 330 seed m^{-2} (McIvor et al., 1979). *Desmodium intortum* (Mill.) Urb. seed ranged form 150 to 500 seed m^{-2} (Jones and Evans, 1977). *Macroptilium atropurpureum* (DC.) Urb. seed density in eight pastures ranged from 21 to 520 seed m^{-2} (Tothill and Jones, 1977). Legume seed density can be extremely high as was the case for *Stylosanthes hamata* (L.) Taub. which averaged 8180 seed m^{-2} in surface litter plus 6110 seed m^{-2} in the 0 to 10 cm of soil (Gardener, 1981). Peak density of *S. hamata* averaged 2190 seed m^{-2} (McIvor and Gardener, 1991). *Aeschynomene falcata* (Poir.) DC. seed reserves averaged 4000 seed m^{-2} (Wilson et al., 1982). Seed of *Lotononis bainesii* Baker averaged 4600 seed m^{-2} (Jones and Evans, 1977).

Seed densities are highly variable over years (Beale, 1974; Young et al., 1981; McIvor, 1987; McIvor and Gardener, 1991). Documentation of seed density is a state or point-in-time measurement (Jones and Mott, 1980). This is a limitation of the present study in that it presents the seed status in 1 yr. Several years are needed and reserves need to be related to pasture management and weather.

How much of a legume seed reserve is sufficient in order to provide plants each year? One approach is to relate seed in the soil to sowing rates (Champness and Morris, 1948). Since un-hulled *Aeschynomene* is sown at 22 to 28 kg ha^{-1} (Chambliss and Kalmbacher, 1999), evenia pasture 95-6 would have sufficient reserves with evenia pasture 27 approaching sufficiency (Table 2). The seed reserves of carpon in pasture 48 would likewise be sufficient since carpon is sown at the recommended 5.6 to 11.2 kg ha^{-1} (Adjei and Kretschmer, 1999).

One problem with basing sufficiency of seed reserves on sowing rates is that legume seed often germinates over a long period due to hard-seed characteristics (Quinlivan, 1971). While hard seed allows the build-up of seed reserves and protects against depletion of the reserve, only a portion of the seed reserve is activated following rainfall events which promote germination. Data in Table 3 indicates that no more than 55% of the legume seed reserves germinated in any cycle. Although this experiment was in a glasshouse environment, it is interesting that legumes germinated at different seasons (Table 3). *Aeschynomene*, a summer annual, does not appear to fit the model of dormancy of summer annuals with strict temperature and seed physiology mechanisms that regulate germination (Baskin and Baskin, 1985).

A second problem is that only a small portion of seed in the soil live to germinate. Cook (1980) estimates that ~90% of seeds in the soil seed bank die before germination and emergence. Beale (1974) found that only

Table 3. Germinable seed of *Aeschynomene americana, A. evenia, Desmodium heterocarpon,* and bahiagrass from the soil seed bank over five cycles spanning 20 mo. Soil was sampled 15-18 Feb. 2002.

	Americana	Evenia			Desmodium	Bahiagrass
Cycle (Date)	Pasture 27	27	95-4	95-6	48	Mean†
				no. m^{-2}		
1 (10 Apr.-8 July '02)	84	82	15	135	335	553
2 (25 Oct. '02-2 Jan. '03)	26	135	19	286	473	11
3 (3 Apr.-11 June '03)	2	5	1	32	17	2
4 (2-22 Sept. '03)	11	103	17	73	25	0
5 (3-24 Nov. 2003)	1	10	0	29	7	0
Total	124	335	52	555	857	566

†Mean over five bahiagrass-legume pastures.

11% of seed in the soil showed up as seedlings. California annual grasslands provide an example where predation, senescence, and unknown causes eliminate 75% of the 200 000 total seed m^{-2} found at peak density (Young et al., 1981). Agronomists are well aware of the high mortality of seedlings. In the example above, a total of 50 000 seedlings m^{-2} emerge annually, but 74 to 86% of the seedlings were lost with insufficient rain early in the season. Because losses are so great, Gardner (1981) indicated reserves of *S. hamata* should be 13 000 seed m^{-2} in order to supply the 30 to 100 seed m^{-2} for maximum production of that legume. Estimates of sufficiency levels of forage seed in Florida pastures are needed.

The difference in evenia seed densities between the 1-yr-old pasture 95-4 and the 6-yr-old pasture 95-6 demonstrates the importance of management to build a seed reserve. An accumulation of seed in the soil is favored by disturbance and low levels of stress (Thompson, 1978). Stress is defined as factors that limit the ability to produce seed. This means vacating cattle from pastures that were recently sown to legumes prior to flowering and allowing seed set. Older pastures should be periodically allowed to restore seed reserves. Gardner (1981) indicated that legumes have different strategies that result in the build-up of seed in the soil. With americana, carpon, and other legumes that are short-day plants, pasture closure is relatively convenient at the end of the growing season. With evenia, it is difficult as it is day-neutral and flowers and sets seed throughout the summer (Kretschmer et al., 1994).

Greater time since legumes were introduced into pastures does not always mean larger legume seed reserves. Beale (1974) found that seed reserves are not always correlated with pasture age. In the present study, pastures were not managed similarly, and there was no conscious effort to build a seed reserve. The 10 and 15-yr old evenia and americana pastures had been periodically chopped or disked in the spring to promote legume regeneration. A dry spring or early summer with intermittent showers could lower soil seed reserves due to multiple flushes of seed germination followed by seedling death. These two pastures were sometimes not grazed until after seed set, while in other years they were grazed throughout summer. The 6-yr-old evenia pasture 95-6 was grazed with 1.5 head ha^{-1} from July to October in the first 3 yr after it was sown (Kalmbacher et al., 2002). The carpon pasture 48 was rotationally grazed with ~1.5 cow-calf pairs ha^{-1} from March to October (Pate and Kalmbacher, 2000), so it was grazed when carpon was flowering and setting seed. Research on the effect of pasture management on legume seed reserves in Florida is needed.

Pasture Weeds

Seed of sedges and rushes are often a major portion of the soil seed bank in pastures (Champness and Morris, 1948; McIvor, 1987; McIvor and Gardener, 1991). *Cyperus compressus* L., *C. polystachyos* Rottb., *C. retrosus* Chapm., and *C. surinamensis* Rottb. are a few of the major Cyperaceae commonly found in pasture at the Range Cattle REC (Kalmbacher and Martin, 1998). For Juncaceae, *Juncus marginatus* Rostk. is very common in flatwoods pastures (Kalmbacher, unpublished data). Colloquially referred to as "watergrass" by Florida ranchers, sedges and rushes are very strong competitors with forage plants during establishment. Sedges and rushes could be found in all five pastures in this study, but not in proportion to their immensity in the seed bank. Seed in the soil seed bank often bares little resemblance to vegetation at the surface (Cook, 1980).

Goatweed seed was very abundant in the soil. It is generally not a competitive weed in pasture, but plant density can be high (~25-50 plants m^{-2}). Common bermudagrass and smutgrass are two major grass weeds in Florida pasture. Dog fennel is one of the most common broadleaf pasture weeds throughout the South and is the major broadleaf weed in Florida pasture. A few plants of each of these weeds, especially goatweed, could be found in all five pastures. None of these plants constituted a major portion of the present pasture flora because of a strong stand of bahiagrass. Because of their presence in the soil, each weed is a potential problem if bahiagrass is weakened or the canopy reduced by disking or chopping, mole cricket damage, burning, and overgrazing. Increasing stocking density increased the amount of non-forage species in the soil seed bank (Jones et al., 1991).

Other Abundant Plants

Many of the non-forage, non-weedy plants whose seed was abundant in the soil seed bank were small forbs. General characteristics of this group are: annuals; prolific seed producers; and non competitive. Apparently, seedlings have a low survival rate in pasture as the plants are not abundant. Other reports on seed banks in pasture have indicated the presence of similar species. Of 45 forb species, *Hedyotis galioides* F. Muell. was the most abundant seed in pasture with 2500 seed m^{-2} (McIvor, 1987). Peak germinable seed reserves of *Erodium botrys* (Cav.) Bertol. (28 000 seed m^{-2}) and *Stellaria media* (L.) Cyrillo (14 600 seed m^{-2}) demonstrate that similar, diminutive forbs can be very abundant in soil (Young et al., 1981).

SUMMARY AND CONCLUSIONS

Germinable seed of bahiagrass, evenia, americana, and carpon were found in soil along with seed of at least 46 other species. The seed reserves of bahiagrass were the equivalent of 17.2 kg seed ha^{-1}, 98% of which germinated in the first of five cycles. Seed reserves of evenia were 2.8 kg seed ha^{-1} in a pasture 1 yr after seeding the legume, but reserves were 29.7, and 18 kg seed ha^{-1} in 5 and 10-yr-old evenia pastures, indicating the need to build legume seed reserves. Seed reserves of americana and carpon desmodium were the equivalent of 6.7 and 11.2 kg seed ha^{-1}, respectively. While all seed reserves were similar to seeding rates of respective species, it is not known if these reserves are adequate for pasture stability.

The soil seed bank contained very large amounts of Cyperaceae and Juncaceae seed (6518 seed m^{-2}). Seed of other plants that are often weed problems in Florida pastures were present in all pastures. These seed constitute a potential threat to pastures in the event that poor management and pest problems allows for their establishment.

This was the first study of seed reserves in Florida pastures, and it raises more questions than it provides answers. Detailed studies of soil seed reserves, their patterns of survival, emergence, and replenishment are needed. The equilibrium of grasses and legumes in pastures is not natural, but is maintained by management. While much has been learned about management of forages for livestock production in Florida, little is known about management effects on soil seed reserves.

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Adapting the CROPGRO Model to Predict Growth and Composition of Tropical Grasses: Developing Physiological Parameters

S. J. Rymph, K. J. Boote*, A. Irmak, P. Mislevy, and G. W. Evers

ABSTRACT

It would be valuable to have management tools for predicting forage growth, nutrient quality, soil water balance, and N leaching. The objective of this research was to adapt the CROPGRO V4.0 growth simulation model in order to predict growth and tissue N concentration of bahiagrass (*Paspalum notatum* Flugge) in response to daily weather, N fertilization, and harvest management. To remain consistent with other crops the model simulates, the source code was not modified. The model's species and cultivar files were modified for bahiagrass, based first on literature information, and secondly, on optimization against field data. Herbage growth and N concentration data from a 2-yr experiment at Ona, FL and a 3-yr experiment at Eagle Lake, TX were used for optimization and model testing. The model, with literature-based estimates of photosynthetic rate, temperature sensitivities, and tissue compositions, predicted growth and composition reasonably well, confirming that C and N balances can be predicted from literature-inputs. Optimization of temperature sensitivities and target tissue N levels improved predictability. Because CROPGRO was developed for annual grain crops, the model was not able to predict winter dormancy, nor could it predict regrowth from a reserve pool if all the foliage had been killed, as in a freeze. Simulations persist through the winter if the freeze-kill inputs are turned off, but this led to unsatisfactory (excessive) water and soil N uptake in late-winter and early spring when the real crop was dormant. While this version can be used with some cautions, we conclude that the CROPGRO source code must be modified to add a dormancy routine, add a stolon storage organ to allow regrowth, and include daylength effects regulating partitioning of reserves to stolons.

INTRODUCTION

CROPGRO is a mechanistic model that predicts yield and composition of crops based on plant, soil, management, and weather inputs. As such, it appears well suited for modeling forage growth and nutrient quality. In addition, the ability to simulate soil water and N balances, soil organic matter—residue dynamics, and pest/disease damage increases the utility of CROPGRO as a tool for evaluating potential environmental consequences of management changes. The generic, process-oriented design has allowed CROPGRO to be adapted to model a variety of different species including soybean (*Glycine max* L.), peanut (*Arachis hypogaea* L.), and dry bean (*Phaseolus vulgaris* L.) (Boote et al., 1998a; Boote et al., 1998b). Recent adaptations include tomato (*Lycopersicon esculentum* Mill.) (Scholberg et al., 1997) and faba bean (*Vicia faba* L.). Adaptation is accomplished by changing a set of parameters and relationships describing the species' response to environmental variables. The procedure is described in Boote et al. (2002).

Kelly (1995) previously attempted to adapt CROPGRO to model the growth of bahiagrass with the objective of using the model as a component of a system for simulating peanut cropping systems. Simulation results were incorporated into an economic model to predict the sustainability and profitability of the cropping systems. The species, cultivar, and ecotype files developed were later released as a "pasture" model in DSSAT v 3.5 (ICASA, 1998). Our application of this model to simulate data sets of bahiagrass hay production revealed consistent overprediction of dry matter (DM) yields, particularly in the cooler months. More rigorous applications and objectives for the use of the model impose different standards of accuracy, and our proposed use as a practical planning and teaching tool requires a more accurate prediction capability and a more realistic representation of the seasonal patterns of growth of bahiagrass. The objective of this study was to more rigorously parameterize and test the CROPGRO V4.0 growth simulation model for ability to predict growth and tissue N composition of bahiagrass in response to daily weather, N fertilization, and harvest management.

MATERIALS AND METHODS

To derive model parameters for describing bahiagrass growth and composition, the adaptation procedure of Boote et al. (2002) was followed. Where possible, parameters describing the basic processes of photosynthesis, respiration, N assimilation, and plant development in bahiagrass were derived from the literature. Other parameters describing basic biochemical processes were assumed to be conserved or similar among species, and are thus the same across all CROPGRO species files. Examples of such parameters are glucose requirement costs for synthesizing protein, carbohydrate, lipid, lignin, organic acid, and mineral, as well as cost to mobilize N from senesced proteins (Penning de Vries et al., 1974).

Where processes or parameters were perceived to be unique to perennial forage species, parameter estimates were interpolated from literature pertaining to other tropical perennial grass species or selected through sensitivity analysis of the bahiagrass model.

We also developed an optimized set of parameters using a custom-built optimization program. In the program, the user specifies a minimum and maximum acceptable value for each parameter and the desired number of steps between those limits for up to five parameters. Simulations were run using all possible combinations of the specified parameters. Results from each set of parameters were statistically analyzed for mean of simulated results, slope and intercept of a fitted regression line of predicted

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S. J. Rymph and K.J. Boote, Agronomy Dep., Univ. of Florida, Gainesville, FL 32611-0500; A. Irmak, Dep. Agricultural & Biological Engineering, Univ. of Florida, Gainesville, FL 32611-0570; P. Mislevy, Range Cattle Res. and Educ. Center., Univ. of Florida, Ona, FL 33865; and G. W. Evers, Texas A & M Univ., Overton, TX 75684. This research was supported by the Florida Agric. Exp. Stn., and is approved for publication as Journal Series No. N-02538.

*Corresponding author (kjb@ifas.ufl.edu).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:37-51 (2004).

and observed data, r^2, d-index of agreement, and root mean square error (RMSE). Results from all runs were saved to an output file and the combination with the lowest RMSE was listed at the end. The output file was then exported to an Excel spreadsheet, parsed, and sorted from highest (best fit) to lowest d-index rating. The d-index, RMSE, and consistency with literature, were all considered in selection of the optimized parameters.

Description of Data Sets Used to Test Model Performance and Fit Parameters

Two data sets (Ona, FL and Eagle Lake, TX) were selected for fitting parameters and testing the optimized model. A brief listing of growing conditions will be given here. A more complete description of each data set may be found in their respective cited articles.

The study at Ona, FL was part of a three-species study of forage protein response to N fertilization and cutting date (Johnson et al., 2001). The experiment was conducted at the University of Florida Range Cattle Research and Education Center (REC) (27°25'N, 81°55'W; elevation 27.4 m) on a Pomona fine sand (sandy siliceous, hyperthermic Ultic Alaquod). 'Pensacola' bahiagrass received five fertilizer treatments (0, 39, 78, 118, and 157 kg N ha^{-1} $cutting^{-1}$) supplied as ammonium nitrate applied on 5 May and on the day after each cutting except for the October harvest. Staging harvests marking the beginning of each growing season were made on 5 May 1997 and 4 May 1998 with successive harvests every 28 d until October. Herbage yield and crude protein concentration were measured for all but the staging harvests. Daily weather data were acquired from the REC's weather station. Temperatures rarely dropped below 0°C in the winter. Rainfall totaled 1142 mm in 1997 and 2110 mm in 1998.

The Eagle Lake, TX experiment was part of a larger study of N contributions of arrowleaf (*Trifolium vesiculosum* Savi) and subterranean clovers (*Trifolium subterraneum* L.) over-seeded on Pensacola bahiagrass conducted during 1979, 1980, and 1981. The study was located in Southeastern Texas at the Texas Agricultural Experiment Station (29°37'N, 96°22'W; elevation 46 m) on a Crowley fine sandy loam (fine montmorillonitic, thermic, Typic Albaqualfs) soil. Treatments included fertilizer applied at annual rates of 0, 84, 168, 252, or 336 kg N ha^{-1}. The fertilizer was split into three equal applications made ~ 1 April, 1 June, and 1 August of each year. All plots were harvested monthly from May through October. Herbage yield and crude protein were reported. Daily weather data were acquired from the Experiment Station's weather station. Freezing temperatures were not uncommon with minimum temperatures as low as -9°C. Rainfall was typically less than for Ona, with annual precipitation of 1354 mm, 765 mm, and 1223 mm for 1979, 1980, and 1981, respectively.

The two data sets were split for optimization and testing. The two lowest N treatments and the two highest N treatments from each site were used in the optimization process. The middle N treatments from both data sets were reserved for testing the literature-based and optimized species files. The rationale behind the splitting scheme was to maximize the range of N fertilization and number of observed data pairs (108) available for the optimization process. At the same time the test data sets would be most indicative of how the model will perform under more typical "mid-range" N fertilization. The primary objective for the optimization process was to minimize RMSE for the prediction of herbage yield (leaf + stem) or herbage N concentration (DM basis) depending on the variables being optimized.

Preparation of Datasets

There were no data available regarding initial plant mass or soil conditions for either experiment, so actual initial crop condition could not be input into the model. Instead, we estimated the initial conditions by running each simulation for one full growing season/winter cycle prior to the measured seasons, and the simulated crop stand was staged (cut) to the same stubble height as used in the measured experiments. Actual weather data were used for the prior year. Fertilization during the prior simulated year was assumed the same as the medium N fertilization treatment for each site (78 kg N ha^{-1} $cutting^{-1}$ at Ona, and 168 kg N ha^{-1} yr^{-1} at Eagle Lake).

To compare simulated and observed growth, the simulated and observed results had to be expressed on a common basis. The field studies reported yield as herbage mass (leaf + stem) harvested above a base cutting or stubble height while simulation results reported yield as the total amount of leaf and stem. The difference between the two is the amount of leaf and stem mass in the stubble left after each harvest. Using the results of other studies (Beaty et al. 1968; Pedreira and Brown, 1996; Rymph and Boote, 2002), we developed estimates of post-harvest stubble mass for the different cutting heights used in the Ona and Eagle Lake experiments. These estimated stubble masses were added to the reported harvest yields to estimate total leaf + stem mass observed for these experiments. Estimates for stubble mass left under 3.5 cm, 5 cm, 7.5 cm, and 10 cm cutting heights were 1500, 1800, 2400, and 3000 kg DM ha^{-1}, respectively. These values may apply only to Pensacola bahiagrass, as newer varieties with more upright growth habits may have considerably less stubble mass (Pedreira and Brown, 1996). This tactic basically creates a consistent season-long offset, but correctly computes the increment of forage produced.

Initial testing of the model revealed some characteristics of the CROPGRO program code that were not compatible with a perennial forage. FREEZ1 and FREEZ2 are parameters describing temperatures where all leaves fall off, or the entire crop dies, respectively, due to cold. We found that after a FREEZ1 event occurred, there was no regrowth of new leaves, causing plants to exhaust all reserves on maintenance respiration and then dying. The problem was related to the strategy used to end photosynthesis of grain legumes after a foliage-killing freeze event. Since our goal was to leave the source code unchanged, and to modify only the "read-in" species input file as done for other CROPGRO species, we set both FREEZ1 and FREEZ2 to -25°C, essentially disabling the FREEZ1 function but allowing the simulation to continue through the winter. Additionally, we simulated frost damage of leaves by partially defoliating the crop each January using the PEST routine.

Literature as Source of Model Parameters

This section will be confined to parameters that are unique to perennial subtropical grasses or required redefinition or alteration in concept. A complete list of parameter values is provided in Table 1.

Photosynthesis Parameters

CROPGRO users have two options for predicting daily assimilate production: an hourly leaf-level option and a daily canopy option. The leaf-level photosynthesis option predicts hourly photosynthetic rates for sunlit and shaded leaf area by simulating the dynamics of Rubisco activity and electron transport and integrates them within the hourly hedgerow approach to yield a daily assimilation rate. The daily canopy option is the more simplistic approach, predicting photosynthate production as an asymptotic light response to daily solar radiation levels. Both options include adjustments for current temperature, CO_2 concentration, and leaf N concentration. For completeness, Table 1 includes parameters for the daily canopy option, but we will not discuss those here because they are not physiologically derived and model performance was equivalent for the hourly and the daily options after optimization.

The leaf-level photosynthesis option, while more complex than the daily canopy option, incorporates several conserved processes for which parameters may be directly measured. Leaf quantum efficiency (QE) is typical of these conserved parameters/processes. Quantum efficiency (parameter name PGEFF) or quantum yield is defined as the initial slope of the CO_2 assimilation vs. absorbed PAR response. A value of 0.0541 μmol CO_2 μmol^{-1} absorbed photons (Ehleringer and Björkman, 1977) is typically used in CROPGRO for all C_3 species, including soybean. While the same biochemical processes are used in both C_3 and C_4 photosynthesis, the leaf cellular CO_2 concentrating effect of the C_4 system increases the QE slightly. Differences in efficiency exist between the three variations of the C_4 photosynthetic pathway (NAD-ME, NADP-ME, and PCK-type) with NADP-ME species exhibiting the highest QE with an average QE of 0.065 μmol CO_2 μmol^{-1} absorbed photons (Ehleringer and Pearcy, 1983). We selected this value for our bahiagrass species file (Table 1). This value appears to be quite robust as it falls well within the range of QE values solved from bahiagrass canopy photosynthetic light response data (0.054-0.081 μmol^{-1} absorbed photons), and reported QE values (0.062 to 0.075 μmol CO_2 μmol^{-1} absorbed photons) for another NADP-ME species, sugarcane (*Saccharum* spp.) (Meinzer and Zhu, 1998).

One inconsistency that remains is the relationship between temperature and QE. In C_3 plants, as temperature increases, the solubility of CO_2 decreases relative to the solubility of O_2, lowering QE of C_3 species at high temperatures. Because of the high CO_2 concentration surrounding Rubisco in bundle sheath cells of C_4 plants, the actual temperature effect on QE is negligible. However, the temperature effect on QE is an outcome of the C_3 Rubisco kinetics in the model code and was left unchanged because there are no external input parameters to modify the response. This is only a minor problem, as the temperature sensitivity on light-saturated photosynthesis is much more important and is set as described in the next paragraph.

The other parameter required is light-saturated leaf assimilation (LFMAX) for leaves at high N concentration, 30°C, and a given specific leaf weight. We based our estimate of LFMAX (and PGREF) on a maximum leaf photosynthetic rate of ~40.0 μmol CO_2 m^{-2} (leaf) s^{-1}, solved from bahiagrass canopy light response data. Relative differences between cultivars are modeled by changing the ratio of LFMAX (maximum leaf photosynthetic rate for the cultivar) to PGREF (maximum leaf photosynthetic rate for the species). As Pensacola was the reference bahiagrass cultivar on which the species parameters are based and was the cultivar measured, PGREF = LFMAX = 1.760 mg CO_2 m^{-2} s^{-1} = 40.0 μmol CO_2 m^{-2} (leaf) s^{-1}.

The amount of photosynthetic enzymes in the leaf affect photosynthetic rate as well. Generally, higher N concentrations in the leaves are correlated with higher levels of these enzymes and higher photosynthetic capacity. Bahiagrass and other C_4 grasses are generally considered to have low concentrations of N in the leaves, yet maintain high photosynthetic rates. Thus, optimal N concentration for photosynthesis of bahiagrass is likely to be lower than for soybean. We could find no reports of the minimum N concentration required for photosynthesis (FNPGN(1)), so we defined this lower threshold of the N response function from the lowest reported living leaf N concentration of 7.6 g N kg^{-1} leaf (Beaty and Tan, 1972). Sugimoto and Nikki (1979) observed a curvilinear increase in bahiagrass leaf photosynthetic rate as leaf N concentration increased from 20 to 30 g N kg^{-1}, after which the rate remained nearly constant from 30 mg N g^{-1} to 40 g N kg^{-1}. Hence, we chose a quadratic shape to define the response of bahiagrass photosynthesis to leaf N concentration, with zero rate at 7.6 g N kg^{-1}, increasing up to optimum rate at 30 g N kg^{-1} (FNPGN(2)), and maintaining a plateau at higher N concentration. The 30 g N kg^{-1} optimum was also used for LNREF, the N concentration at which PGREF is defined for the species.

The high concentration of CO_2 around Rubisco in the bundle sheath chloroplasts permits high photosynthetic rates at higher temperatures than typically observed in C_3 plants. Although the mechanism is not well understood, C_4 species generally also have a greater sensitivity threshold for low temperature reduction of photosynthetic rate than C_3 species (Long 1983; 1999). Thus, bahiagrass should have a base temperature required for photosynthesis that is higher than soybean and it should have higher optimum and maximum (highest temperature at which photosynthesis occurs) temperatures as well. Several studies have been conducted to quantify the cardinal temperatures for tropical and subtropical C_4 grasses (Ludlow and Wilson,

Table 1. Bahiagrass parameter values for the CROPGRO species file. Initial values were derived from the literature. Optimized values were derived from optimization runs made based on the preliminary values.

Parameter	Initial value (literature)	Optimized value	Units
PARMAX	60.0	140.0	mol PFD m^{-2} d^{-1}
PHTMAX	90.0	180.0	g CH_2O m^{-2} d^{-1}
CCMP	5.0		ppm
FNPGN(1-4)	0.75, 3.0, 10.0, 10.0	1.0, 3.0, 10.0, 10.0	% N
TYPPGN	quadratic		
FNPGT(1-4)	12.0, 25.0, 38.0, 50.0	20.0, 25.0, 30.0, 50.0	°C
TYPPGT	linear		
XLMAXT	-5.0, 7.0, 35.0, 45.0, 55.0, 60.0	-5.0, 10.0, 26.0, 45.0, 57.0, 60.0	°C
YLMAXT	0.0, 0.0, 1.0, 1.0, 0.0, 0.0	0.0, 0.0, 1.0, 1.0, 0.0, 0.0	relative
FNPGL(1-4)	7.0, 18.0, 45.0, 57.0	7.0, 18.0, 45.0, 57.0	°C
TYPPGL	quadratic		
PGEFF	0.065		mol CO_2 mol PFD^{-1}
SLWREF	0.0035		g m^{-2}
LNREF	3.0		% N
PGREF	1.76		mg CO_2 m^{-2} s^{-1}
PROLF I, G, and F	0.22, 0.11, 0.05	0.15, 0.05, 0.04	fraction
PROST I, G, and F	0.11, 0.07, 0.033	0.125, 0.04, 0.022	fraction
PRORT I, G, and F	0.101, 0.040, 0.022		fraction
PLIP LF, ST, RT	0.025, 0.020, 0.020		fraction
PLIG LF, ST, RT	0.04, 0.06, 0.07		fraction
PCAR LF, ST, RT	0.602, 0.697, 0.702	0.672, 0.682, 0.702	fraction
CMOBMX	0.025		fraction d^{-1}
NMOBMX	0.05		fraction d^{-1}
NVSMOB	1.00		scalar
XLEAF	0.0, 1.5, 2.0, 3.0, 5.0, 7.0, 30.0		V-stage
YLEAF	0.45, 0.5, 0.6, 0.4, 0.25, 0.2, 0.2		fraction
YSTEM	0.05, 0.05, 0.1, 0.1, 0.05, 0.05, 0.05		fraction
FRSTMF	0.05		fraction
FRLFF	0.20		fraction
FRLFMX	0.60		fraction
FINREF	144		cm^2 g^{-1}
SLAREF	285		cm^2 g^{-1}
SIZREF	2.0		cm^2 $leaf^{-1}$
VSSINK	0.0		V-stage
SLAMAX	350		cm^2 g^{-1}
SLAMIN	200		cm^2 g^{-1}
XVGROW	0.0, 5.0, 10.0, 15.0, 20.0, 25.0		V-stage
YVREF	0.0, 10.0, 20.0, 30.0, 40.0, 50.0		cm^2 $plant^{-1}$
XSLATM	-50.0, 00.0, 10.0, 30.0, 60.0		°C
YSLATM	0.25, 0.25, 0.25, 1.00, 1.00		fraction
FREEZ1, FREEZ2	-25.0, -25.0		°C
ICMP	0.8		mol PFD m^{-2} d^{-1}
TCMP	25		days
XSTAGE	0.0, 5.0, 9.0, 50.0		V-stage
XSENMX	3.0, 5.0, 10.0, 50.0		V-stage
RTDEPI	20		cm
RFAC1	5000		cm^2 g $(root^{-1}$
RTSDF	0.02		fraction d^{-1}
RWUEP1	1.5		scalar
Vegetative TB, T1, T2, TMax	9.0, 32.0, 40.0, 45.0		°C
Early Reproductive TB, T1, T2, TMax	10.0, 28.0, 32.0, 45.0		°C
Late Reproductive TB, T1, T2, TMax	10.0, 28.0, 32.0, 45.0		°C
XVSHT (1-10)	0.0, 1.0, 4.0, 6.0, 8.0, 10.0, 14.0, 16.0, 20.0, 40.0		V-stage
YVSHT (1-10)	0.0150, 0.0265, 0.0315, 0.0330, 0.0345, 0.0330, 0.0310, 0.0255, 0.0170, 0.0030		m $(internode)^{-1}$
YVSWH (1-10)	0.0150, 0.0255, 0.0310, 0.0320, 0.0330, 0.0315, 0.0295, 0.0230, 0.0125, 0.0005		m $(internode)^{-1}$

1971; Wilson, 1975; Unruh et al., 1996); unfortunately none included bahiagrass. Our interpretation of these results is that the optimum range for leaf photosynthesis for a subtropical grass species should be between 35°C and 45°C, with a base temperature around 7°C and a maximum critical temperature for zero rate near 55°C.

Low night temperatures may also have a prolonged effect on photosynthesis, affecting photosynthetic rate after temperatures have returned to the optimal range. CROPGRO uses another set of temperature parameters, FNPGL(1-4), to describe the effect of minimum night temperature on the subsequent day's light-saturated leaf photosynthetic rate. West (1973) observed that *Digitaria decumbens* Stent. (*D. eriantha* Steud.) grown at 30°C and subjected to just one night at 10°C and returned to 30°C, showed a 40% decrease in photosynthetic rate compared to plants held continuously at 30°C. Based on this, we set the minimum temperature (no photosynthesis on the day after experiencing this temperature—FNPGL(1)) to 7°C, optimum night temperature (no effect on subsequent day's photosynthesis—FNPGL(2)) to 18°C, with a quadratic (curvilinear) response between these points (Table 1).

Root Parameters

Bahiagrass poses an additional challenge to modeling its growth using CROPGRO because a significant proportion of total plant mass is represented by stolon mass and CROPGRO does not include a stolon organ in its structure. To include stolons in the stem fraction would have confounded the computation of protein/N removed at harvest and further complicated the estimation of stubble mass. Thus we redefined "roots" in the model to include both stolons and roots. This "redefinition" without a code change required considerable modification of the growth and senescence parameters relative to those used for other species modeled by CROPGRO. The largest adjustment was for the root length density (RFAC1) parameter (cm of root length per g of root). Stolons are much thicker than roots and may represent more plant mass than the roots. Additionally, nutrient uptake per length of stolon (if any) is likely to be much lower than for roots, further decreasing their "effective" length as a root. Based on the relative proportions of stolons and roots reported by Rymph and Boote (2002), RFAC1 was reduced to 5000 cm g^{-1}, 33% lower than the value used for soybean roots.

As stolon mass is routinely mobilized to support new growth, the maximum senescence rate (RTSDF) of the combined organs was increased from 0.01 to 0.02 d^{-1} (1 to 2% d^{-1}). In preliminary simulations this allowed a maximum predicted root mass of 10000 kg root DM ha^{-1}, in the range of the combined stolon and root mass observed by Boote et al. (1999) (10 660 to 15 370 kg ha^{-1}) and Rymph and Boote (2002) (7160 to 15 740 kg ha^{-1}).

Carbon and Nitrogen Mobilization Parameters

Another area where modeling perennial forages and annual grains differ, is nutrient mobilization. The basic concept is the same, but the timing and purpose differ. Nutrient reserves in annual grain crops are generally mobilized from vegetative tissue for filling seed. Although many perennial forages such as Pensacola bahiagrass may set seed, they are generally harvested at a younger stage of maturity and C and N reserves are used primarily to speed vegetative regrowth after a harvest or in the spring. Since perennial forages must be able to mobilize C and N reserves repeatedly from stolon/crown tissues over several growing seasons, the rate and extent and source of nutrient mobilization may be quite different from that observed in annual grain crops. Reports from Skinner et al. (1999), estimating N and total nonstructural carbohydrate (TNC) mobilization in blue grama grass [*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.] during regrowth after cutting, showed quite high rates of nutrient mobilization from crown tissue. On average, 36% of the available N pool was mobilized within 7 to 10 d of cutting. This translates into ~5% d^{-1} or a maximum available N mobilization rate (NMOBMX) of 0.05 (fraction d^{-1}). Total nonstructural carbohydrate mobilization was also reported, but the measured TNC concentrations were 2.5 to 3 times the levels found in bahiagrass and we could not adapt them to our purpose with any confidence. With no data to support TNC changes during bahiagrass re-growth, CMOBMX (fraction per day) was taken from the default soybean file (Table 1).

Vegetative Partitioning Parameters

During vegetative growth, the model partitions new growth among leaf, stem, and roots as a function of the vegetative stage of the crop (V-stage). This is another area where the concept of V-stage is different for perennial forage crops. Annual crops, as well as seedling forages, progress through the sequential increase in leaf numbers in a relatively orderly fashion. Established perennial forages, however, are periodically "re-staged" by harvests and frosts, interrupting the orderly pattern. As a seedling, bahiagrass could reach a V-stage of 4 to 6 (four or six fully-expanded leaves) with a relatively small root mass and few, if any stolons. An established stand of bahiagrass, with a relatively large root and stolon system capable of mobilizing significant amounts of nutrients, could also have the same V-stage rating of 4 after a harvest. In the CROPGRO model, partitioning of subsequent growth is handled identically in both scenarios. A unifying assumption in both cases is that if V-stage is low (<4 to 6), the priority for partitioning is towards growing leaf mass and area to establish photosynthetic capacity. As V-stage increases, more DM may be partitioned to stolon and root. Additionally, since stolon and root mass were combined, partitioning of new growth between organs required modification from the proportions used for soybean.

While partitioning in seedlings may be measured by changes in leaf, stem, and root mass over time, the presence of older, senescing material in established plants prevents such a simple determination. Assuming that the model would be used most often to predict growth of established stands, we developed the partitioning parameters to mimic observed patterns of regrowth, rather than purely based on seedling growth. Parameter values were estimated prior to optimization using growth patterns reported by Rymph (2004) and Boote et al. (1999) and then refined by running simulations and manually adjusting the parameters to match growth patterns and relative magnitudes of each organ (leaf, stem, or root) (Table 1).

Leaf Growth and Senescence Parameters

Complications caused by repeated re-setting of the V-stage of the crop within a growing season required minor modifications of leaf growth-related parameters. As the V-stage of the plants is reset after each harvest, there is potential for V-stage to be quite low for a perennial grass with numerous growing points in stolons. The VSSINK function allows photosynthesis and leaf expansion to be limited by sink strength rather than assimilate supply. While potentially appropriate for a small seedling, this function is not appropriate to represent re-growth of an older perennial plant. To prevent potential limitations to growth in older plants, the VSSINK parameter was disabled by assigning a value of zero.

Senescence parameters were modified very little from Kelly's pasture model. The time constant for senescence (TCMP) was set to 25 thermal days based on the weekly counts of dead leaves and weather from the data of Rymph and Boote (2002). The light compensation point trigger for leaf senescence (ICMP), which triggers leaf senescence due to shading of lower leaves was set to 0.8 mole-quanta m^{-2} d^{-1}, the same as soybean. Similarly, the V-stage trigger for senescence (when 12% of the plant's leaf number is assumed to have been senesced) (XSTAGE) was lowered from 14 leaves for soybean to 9. This was necessary because of the relatively low number of leaves on a bahiagrass plant compared to a soybean plant.

Phenology Parameters and Harvesting Routines

The resetting of V-stage after a harvest is done in the PEST routine, using either the MOW function or a combination of the HARV and HRVS functions, and no modification of the species file is required. To implement the MOW function, the user supplies the harvest date(s) and the amount(s) of stubble mass to remain after harvest. On the harvest date, CROPGRO then calculates the proportion of shoot mass removed, then leaf mass, stem mass, and V-stage are each reduced by that proportion. The HARV and HRVS functions work similarly except that the user sets the proportion of herbage mass to be removed (HARV) separately from the proportion of V-stage lost (HRVS).

The sawtooth pattern of the simulated growth in Fig. 1a illustrates harvest events triggered by the MOW harvest function of the model's PEST routine. The first harvest of each year "staged" the crop for subsequent yield analysis and no data were recorded on that day. Thereafter, the MOW harvest brings the herbage mass back to a baseline corresponding to the stubble mass, with all mass above that point being the harvestable increment. The PEST routine was also used to arbitrarily to create a forced defoliation event in early January of each winter to simulate defoliation by frost.

The influence of temperature on the rate of phenological development of bahiagrass is not well documented in the literature. Therefore, we set the cardinal temperatures for base (no new leaf appearance), optimum (maximum rate of leaf addition), and maximum (upper failure temperature) points (Table 1), based on our experiences growing bahiagrass (K. J. Boote, personal communication, 2003).

RESULTS

Testing of Literature-Based Parameters

Testing of the preliminary, literature-based species file was encouraging with d-index values of 0.843, 0.605, and 0.925 for accumulated herbage mass (leaf + stem), herbage N concentration, and accumulated herbage N, respectively (Table 2). It is important to highlight that CROPGRO has an extensive soil N balance simulation including mineralization of soil organic matter and root N uptake that contribute to the herbage N yield and N concentrations discussed here. Despite the moderate d-index values for simulated N concentration, the r^2 was low at 0.18, indicating that prediction of tissue N concentration was an initial weak point. The higher d-index value for herbage N yield than for either herbage mass or herbage N concentration represents the effect of underestimation of yield coincident with an overprediction of N concentration.

Reviewing the predicted pattern of growth, however, showed excessive rates of winter and spring growth (Fig. 1a). Water and N demand associated with this excessive growth caused elevated water and N stress throughout the spring and early summer (Fig. 1a), reducing predicted growth in May and June. The principle cause of this discrepancy was model failure to simulate winter dormancy. Compounding this was the lack of a working freeze damage routine which allowed an artificially high leaf area index (LAI) and photosynthetic capacity through much of the winter. CROPGRO has no provisions for modeling dormancy, so we attempted to duplicate the dormancy effect through other methods. This problem will require new model code differing from the standard CROPGRO.

To reduce winter growth rate as shown in Fig. 1b, we used the PEST routine in CROPGRO to reduce daily photosynthesis production by 70% from 23 October through 30 March. This approach directly reduces photosynthetic rate but does not concurrently reduce transpiration because LAI is not changed. (Failure to concurrently reduce photosynthesis and transpiration can be viewed as an error in the PEST coding, but we did not change it.) Coincident with this change, the periods of water and N stress were shortened considerably (Fig. 1b), but not as much as would have occurred if transpiration was also reduced. Statistically, there were minimal improvements in the fit of summer herbage production after this modification (Table 2). This approach resulted in slight improvements in d-index values for herbage yield and accumulative herbage N (Table 2). The first two predicted harvests were still considerably below the observed growth (Fig. 1b) and were associated with simulated water stress. The PEST option

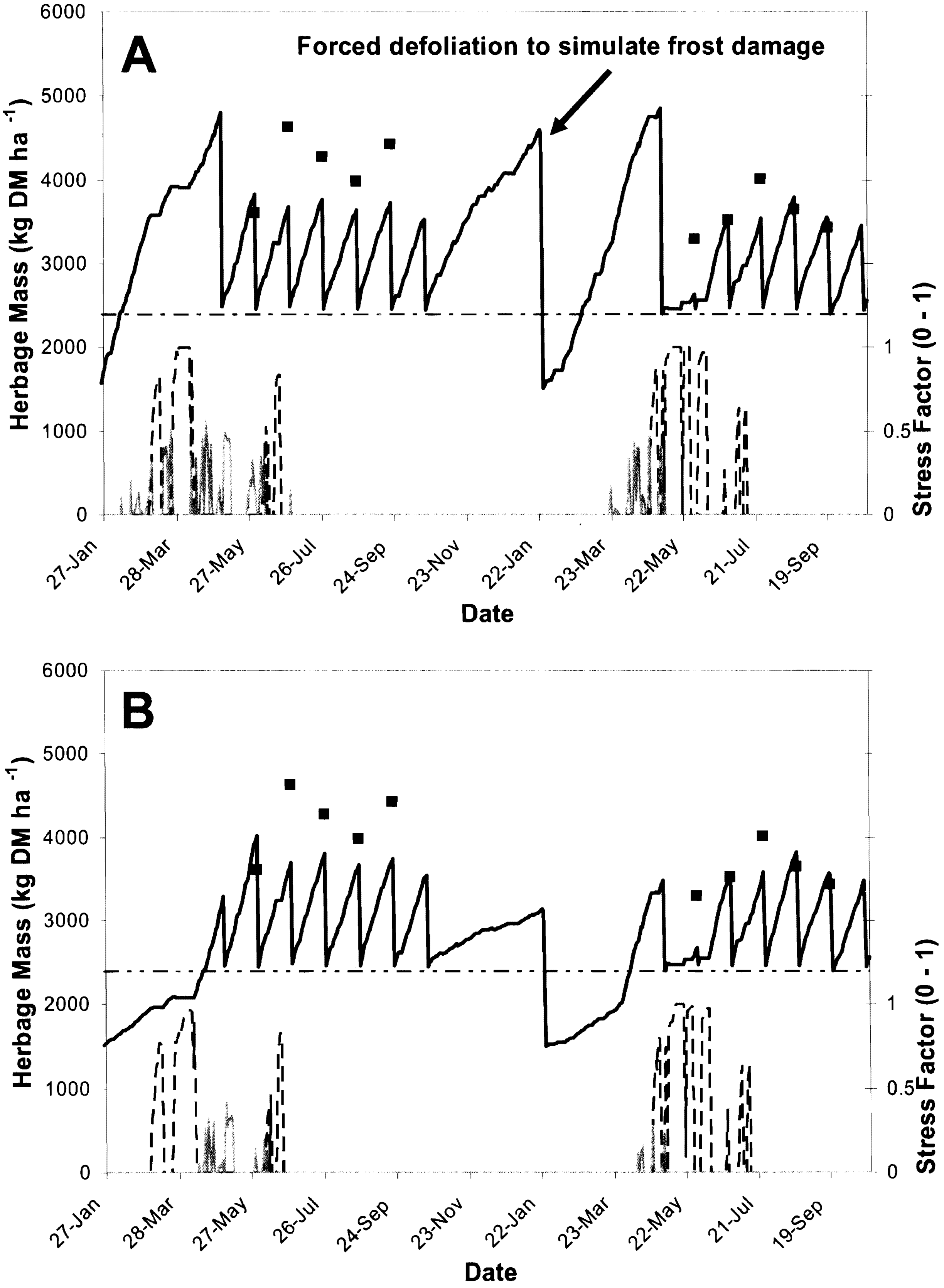

Fig. 1. Observed herbage mass (■), predicted herbage mass (solid line), water stress (dashed line), and N stress (gray line) of bahiagrass grown with 78 kg N ha^{1} $cutting^{1}$ at Ona, FL, using preliminary (literature-based, non-optimized) species file and the leaf-level photosynthesis option, with (A) No adjustment to winter growth, or (B) 70% reduction in photosynthetic rate and partial defoliation (frost) over the winter. Predicted stress factors are based on a 0-1 scale with 0 = no stress/normal growth rate and 1 = severe stress/no growth. The broken horizontal line denotes the stubble mass left in the field after each harvest.

Table 2. Performance of CROPGRO using various species files and winter-growth reduction schemes to predict statistics of herbage yield (kg ha^{-1}), herbage N concentration (g N kg^{-1} DM), and herbage N yield (kg N ha^{-1}).

Source data/Winter adjustment	Photosyn. model option	Target variable	Mean	Slope	Intercept	D-Index	r^2	RMSE
	Observed	Herbage	3215					
		N conc.	18.6					
		Herbage N	60.1					
Literature species file, with no winter growth reduction	Leaf	Herbage	3119	0.611	1154	0.843	0.54	557
		N conc.	20.1	0.603	8.9	0.605	0.18	5.8
		Herbage N	65.0	1.005	4.57	0.925	0.77	14.5
	Canopy	Herbage	2944	0.605	999	0.851	0.68	536
		N conc.	22.8	0.603	11.54	0.531	0.19	6.9
		Herbage N	69.21	0.990	9.7	0.907	0.78	16.13
Literature species file, with winter growth reduction	Leaf	Herbage	3119	0.624	1113	0.856	0.58	533
		N conc.	21.1	0.648	9.0	0.582	0.18	6.3
		Herbage N	68.2	1.085	3.0	0.926	0.83	14.9
	Canopy	Herbage	2944	0.626	931	0.856	0.68	534
		N conc.	24.1	0.657	11.9	0.482	0.19	8.0
		Herbage N	73.4	1.096	7.6	0.890	0.82	18.6
Optimized species file, with winter growth reduction	Leaf	Herbage	3214	0.649	1129	0.860	0.58	528
		N conc.	18.2	0.426	10.32	0.676	0.19	4.3
		Herbage N	60.0	0.774	13.5	0.935	0.78	11.7
	Canopy	Herbage	2923	0.713	631	0.847	0.62	587
		N conc.	21.6	0.438	13.4	0.600	0.22	5.1
		Herbage N	64.0	0.803	15.8	0.935	0.80	12.0

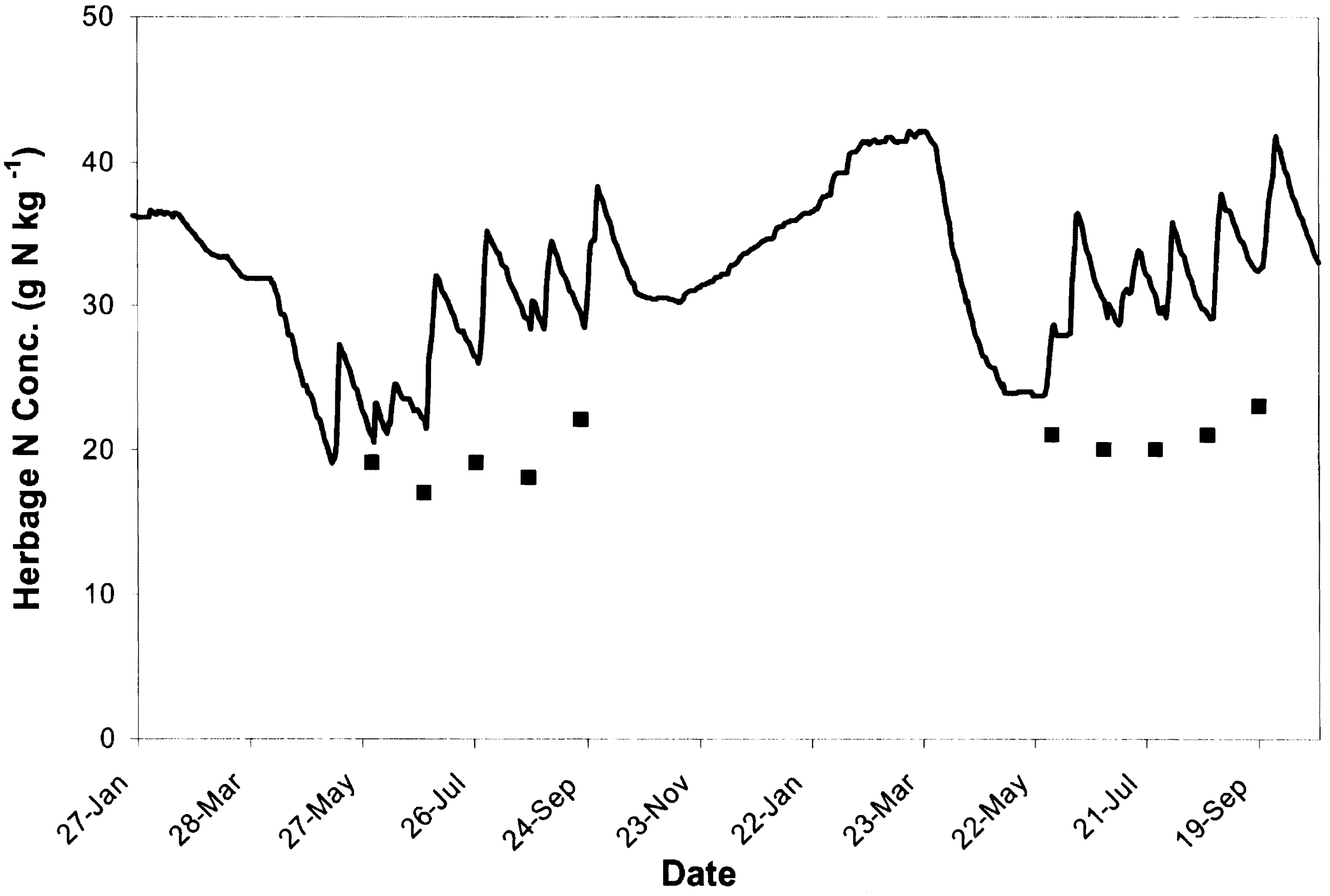

Fig. 2. Observed herbage N concentration (■) and predicted herbage N concentration of bahiagrass grown with 78 kg N ha^{-1} cutting^{-1} at Ona, FL, using the preliminary (literature-based, non-optimized) species file and the leaf-level option (solid line).

of reducing photosynthesis had restricted root growth (and this limited subsequent water uptake) even while this option did not reduce simulated transpiration (or conserve soil water) except indirectly through the lower LAI resulting from slowed growth.

Two mechanisms were responsible for the early season water and N stress. In reducing photosynthesis in the PEST routine, the normal photosynthetic rate and transpiration rate was calculated, and then the photosynthetic rate was reduced by the designated percentage. Transpiration, however, was not reduced, so water uptake continued at the normal (now excessive) rate, depleting soil water. The only "reduction" in transpiration was due to the lowered LAI coming from the slowed growth. Also, lower photosynthesis (from the PEST option to reduce photosynthesis in winter) along with continued root senescence had reduced root mass considerably by the end of the winter/early spring period (data not shown). Thus, while more water and nutrients may have been available in the soil, the diminished root system had a reduced capacity to exploit them, suppressing growth in May and June. While statistical fit was not improved, we used this winter photosynthesis reduction strategy in all optimization and testing runs because the patterns of nutrient stress were more realistic than before.

Based on literature-inputs only, the fit of herbage N concentration was not as good as prediction of herbage yield (Table 2). Herbage N concentration was consistently over-predicted at Ona (Fig. 2). During winter regrowth, after the simulated frost defoliation, herbage N concentration exceeded 40 g N kg^{-1}, equivalent to 250 g crude protein (CP) kg^{-1}, higher than the "maximum" leaf and stem CP concentration set by PROLFI and PROSTI. This is related to the N allocation problem in the code mentioned earlier that prohibited leaf regrowth after a FREEZ1 event. As the goal of the present effort was to calibrate the parameters without changing source code, this problem could not be addressed.

For Eagle Lake, predicted herbage N concentration appeared to follow a more accurate pattern despite greater variation in the observed values (Fig. 3). Prediction of herbage N concentration was more balanced, being both over- and under-predicted. The improved prediction pattern may be related to the lower fertilizer levels used at Eagle Lake and the lower yields for that site compared with Ona.

Optimization of Model Parameters

Since we were unable to accurately predict the spring growth pattern, data for the June harvests at Ona and the May harvests at Eagle Lake were excluded from the optimization process. The rationale for culling these data was that the model was consistently predicting early

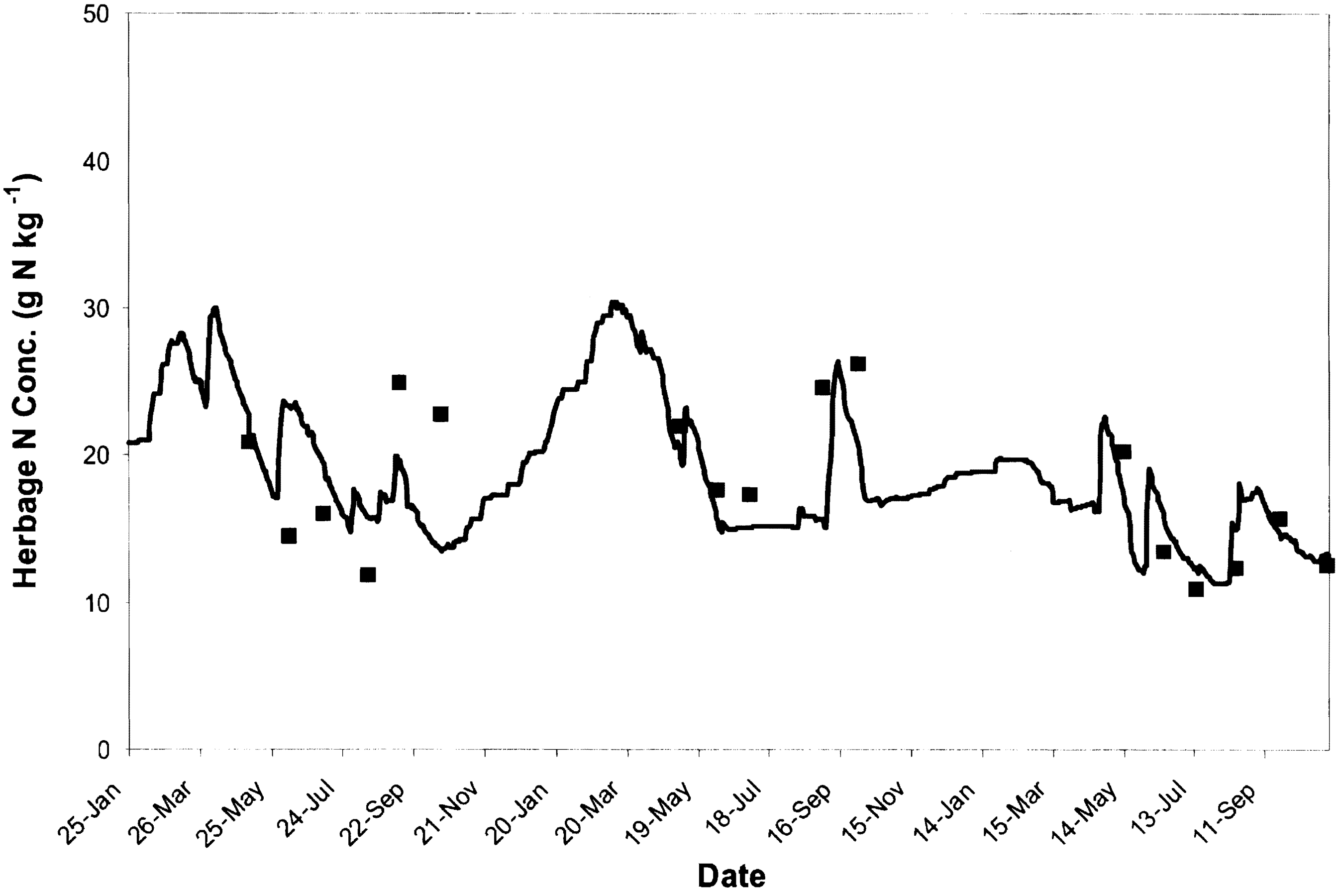

Fig. 3. Observed herbage N concentration (■) and predicted herbage N concentration for bahiagrass grown with 168 kg N ha^{-1} yr^{-1} at Eagle Lake, TX, using the preliminary (literature-based, non-optimized) species file and the leaf-level option (solid line).

season N and water stress when there was none. Keeping those data points in the optimization would influence the final parameter values in order to compensate for the predicted stresses. This left 52 data pairs for calibration. No data were excluded from the data sets used to test the performance of the model. Testing runs used all of the observed data available for the site/fertility combinations used (27 data pairs). The distinction being made here is that we wanted to develop the most accurate parameters for the model through optimization (hence leaving out the early season data) while presenting a fair evaluation of the performance of the model through testing (by including all data).

Our strategy was to first optimize the temperature parameters of the leaf-level photosynthesis option to establish proper seasonal patterns of growth, then refine the prediction by optimizing parameters that affect the growth response to N. Since the critical leaf N response parameters apply to both the leaf and daily canopy photosynthesis options, we deferred optimization of the temperature parameters and the PARMAX and PHTMAX parameters for the daily canopy photosynthesis option until the last step.

The optimization for temperature parameters used only the two highest N fertility treatments from each experiment, assuming that nutrients would not be limiting growth for those treatments. The two highest and two lowest N fertilization treatments from each study were used in optimizing the N parameters as this presented the broadest range of conditions.

Testing of Optimized Parameters

Optimization slightly improved the predicted winter growth pattern (Fig. 4), but the fit of summer production of herbage was generally not improved (Table 2) with nearly identical d-index values for both optimized and literature-based species files. Nitrogen stress was reduced in the optimized simulations (Fig. 4); however, water stress was still extensive in the spring, resulting in a continued poor prediction of first cutting regrowth at Ona, particularly in the second growing season. To compensate for the failure of the model to properly simulate winter dormancy, the optimization process promoted combinations of somewhat abnormal parameter values to improve the fit, especially for the daily canopy option (Table 2). Overall, the model tended to over-predict herbage yield at lower yields and under-predict at higher yields (slopes < 1.0), whether for the leaf-level photosynthesis option (Fig. 5a) or the daily canopy option (Fig. 5b). Generally, the model predic-

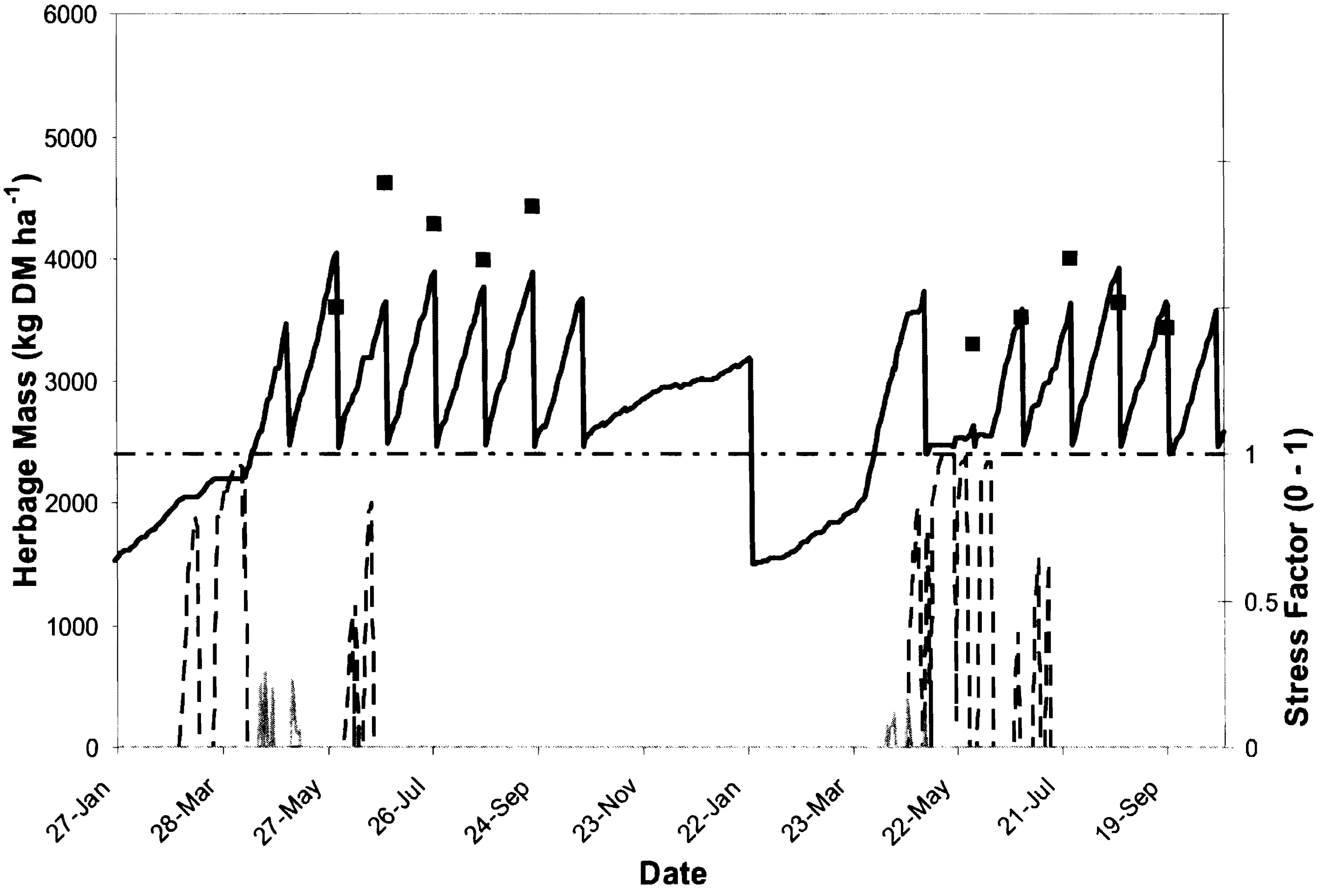

Fig. 4. Observed herbage mass (■), predicted herbage mass (solid line), water stress (dashed line), and N stress (gray line) of bahiagrass grown with 78 kg N ha^{-1} cutting^{-1} at Ona, FL, using the leaf -level photosynthesis option and the optimized species file with 70% reduction in photosynthetic rate over the winter months. Predicted stress factors are based on a 0-1 scale with 0 = no stress/normal growth rate and 1 = severe stress/no growth. The broken horizontal line denotes the stubble mass left in the field after each harvest.

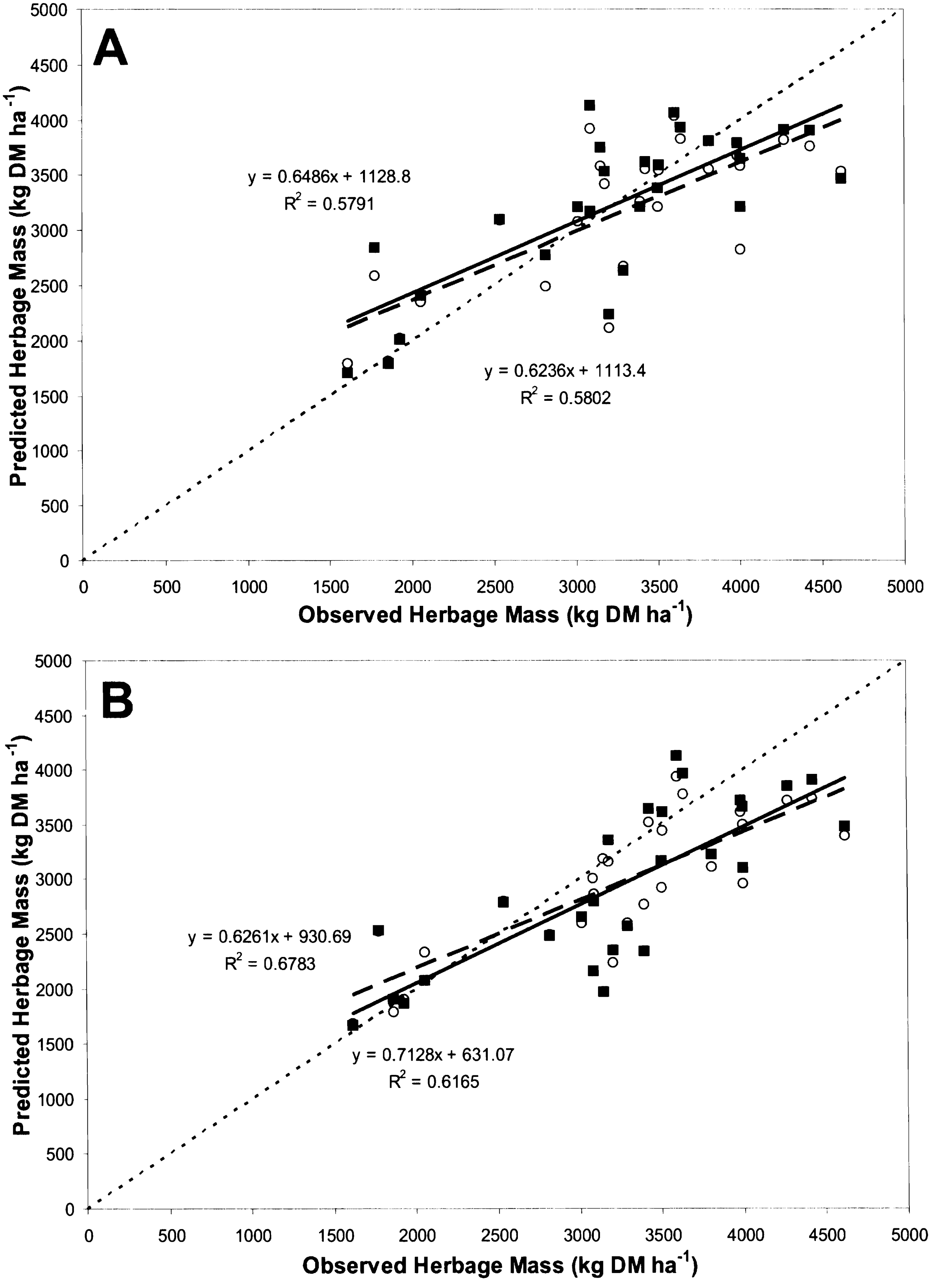

Fig. 5. Predicted vs. observed herbage mass of bahiagrass grown with 78 kg N ha^{-1} cutting^{-1} at Ona, FL, and grown with 168 kg N ha^{-1} yr^{-1} at Eagle Lake, TX, using (A) the leaf-level photosynthesis option, or (B) the daily canopy photosynthesis option. Both options included a reduction of 70% reduction of photosynthetic rate over the winter. Plots for both the preliminary (literature-based, non-optimized) (○) and optimized (■) species files are presented. Linear regression lines for preliminary (dashed line), and optimized (solid line) species files are presented with their corresponding equations and r^2 values along with a line designating a theoretical 1:1 relationship (dotted line).

tions accounted for about two-thirds of the variation in the observed herbage production, as indicated by the r^2 of 0.58 to 0.61 and d-indices of 0.85 to 0.86 (d-indices also approximate percentage of variation accounted for).

Fit of herbage N concentration predictions improved considerably after optimizing parameters related to the target N levels for the foliage as well as optimizing N effects on leaf-level photosynthesis (Table 2, Fig. 6 and 7). The d-index rating improved considerably after optimization, however, the r^2 values remained low (Table 2). Predicted herbage N concentration was still consistently overpredicted at Ona, but the magnitude of overprediction was reduced (Fig. 6) by optimization toward lower PROLFI, PROLFG, PROSTI, and PROSTG parameters (Table 1). The pattern of predicted herbage N concentration for Eagle Lake remained realistic after optimization (Fig. 7). However, the values predicted using the optimized parameters were generally lower than those using the literature-based parameters (Fig. 3). The difference between predicted and observed herbage N concentration was also reduced (Fig. 8a, b), indicating a more consistent prediction. There was a tendency for the model to over-predict herbage N concentration, especially for the daily canopy option (Fig. 8b). Despite the improvement in herbage N concentration prediction, fit of predicted herbage N yield showed little improvement (Table 2), but the fit had been quite good to begin with.

DISCUSSION

Performance of the literature-based parameters was good, especially related to predicting herbage yield and herbage N yield. The prediction of herbage N concentration needed improvement. There appeared to be some features of CROPGRO that may have made significant contributions to the errors in predicting both herbage N concentration and herbage yield. The absence of a dormancy routine to control vegetative growth during the winter and spring had a profound effect toward depletion of early season N and water availability, which contributed to subsequent underprediction of herbage during May and June. The absence of a storage organ such as a stolon contributed to this problem by confounding effects of changing proportions of stolon and root mass. Additionally, quirks related to modeling of freeze damage and patterns of refilling of N in old tissues complicated matters even more. Imposing a 70% reduction in potential daily photosynthesis during the winter months compensated for some of the problems, albeit in an artificial way.

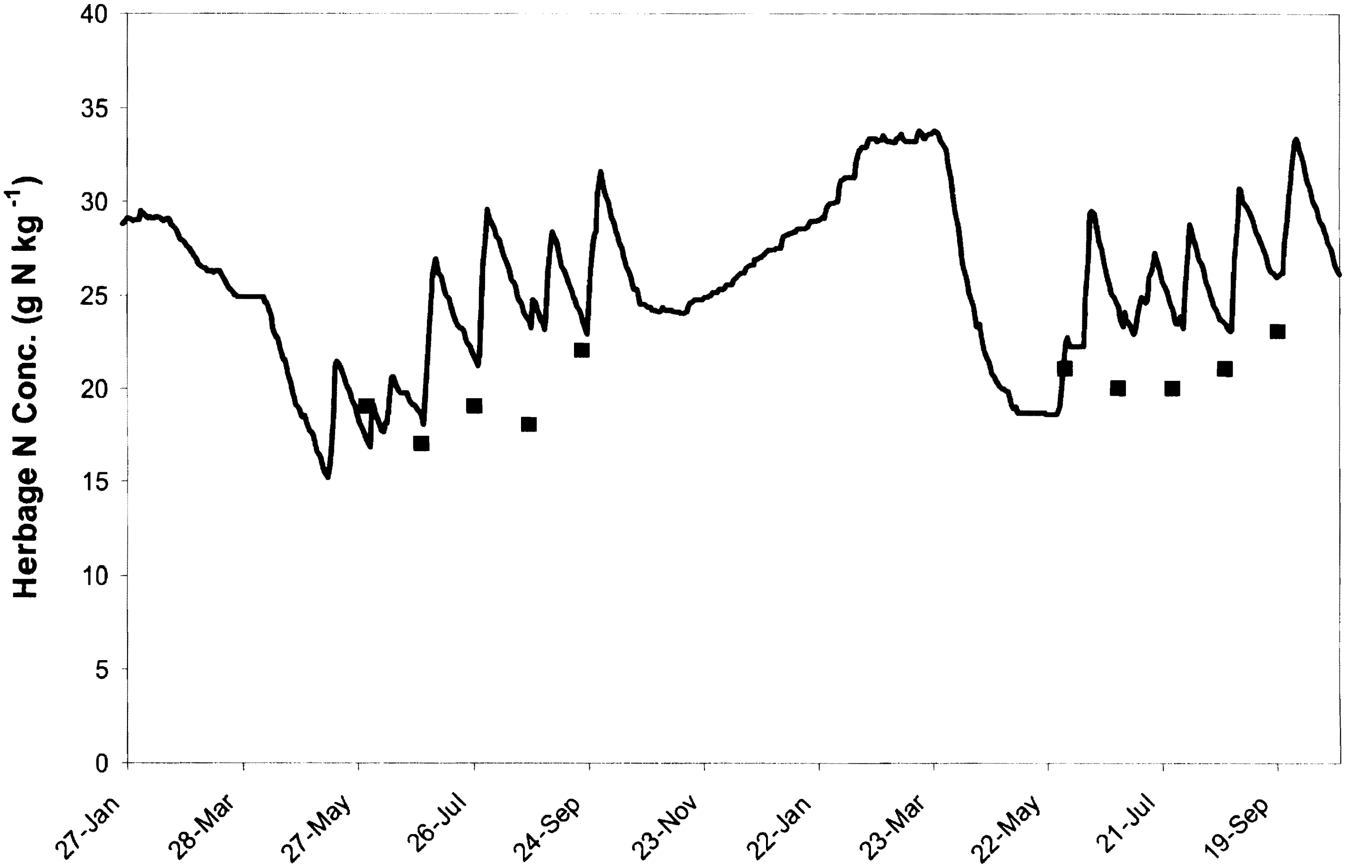

Fig. 6. Observed herbage N concentration (■) and predicted herbage N concentration of bahiagrass grown with 78 kg N ha^{-1} cutting^{-1} at Ona, FL, using the optimized species file and the leaf-level option (solid line).

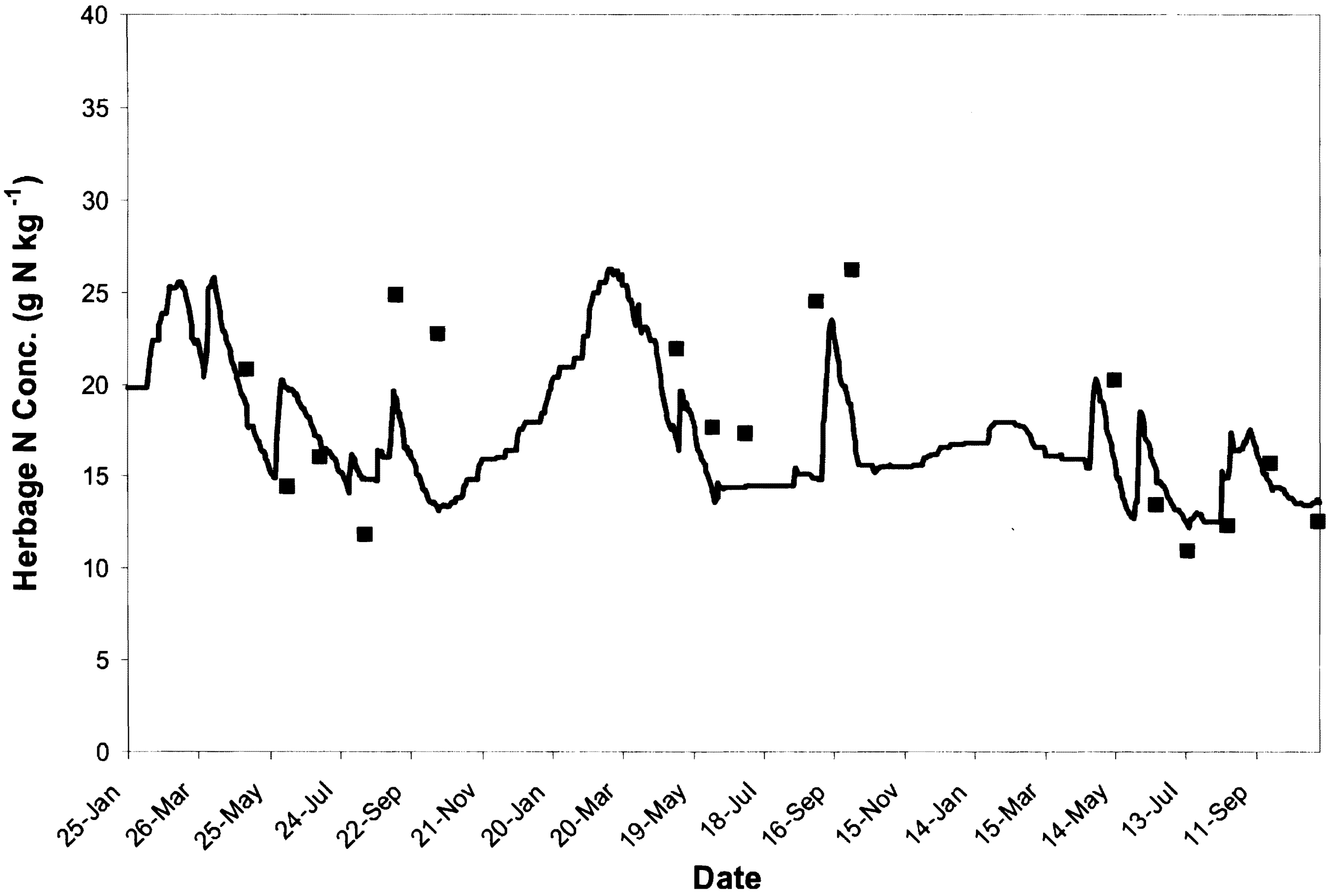

Fig. 7. Observed herbage N concentration (■) and predicted herbage N concentration of bahiagrass grown with 168 kg N ha^{-1} yr^{-1} at Eagle Lake, TX, using the optimized species file and the leaf-level option (solid line).

Optimization improved the fit compared to simulations using the literature-based parameters. Problems with too much winter growth and with excessively high leaf N concentration were somewhat reduced using the optimized parameters. However, some of the optimized parameters are at the edges of their biological range as a result of compensating for missing or problem components in the model code. The optimization was more an exercise in compensating for the model than in divining more accurate parameter values. The adjustments in the "target" tissue N compositions were not completely realistic, but offset for N balance and N mobilization problems in the model. The increase in base temperature from 7 to 10°C for leaf photosynthesis was a reasonable change, but the changes to the temperature functions for the daily canopy option were not realistic. The increases in the PARMAX and PHTMAX for the daily canopy option suggest linear response to solar radiation, again a reasonable change.

In order to better mimic the biology of perennial, subtropical grasses, modifications must be made to the model concepts and code. Essential among these changes is the addition of a dormancy routine. Evidence for this required dormancy mechanism is available from Sinclair et al. (2003) and Gates et al. (2001) who demonstrated an important role of daylength in controlling dormancy. Hints for the mechanism for reducing leaf and stem growth during dormancy can be found in Rymph and Boote (2002) and Boote et al. (1999) where significant shifts in allocation of new growth from shoots to stolons were observed in the fall. Adding a mechanism controlled by daylength to reduce partitioning and mobilization to the shoot while increasing allocation to the stolon would complement the maturity, temperature, and stress mechanisms already present in CROPGRO. Greater allocation to root and less to shoot and leaf area during the short days of winter would have minimized transpirational water loss, yet allowed good root growth to provide for subsequent N and water uptake in May and June.

Addition of stolons as a storage organ would also allow more realistic prediction of the patterns of accumulation and depletion of roots, and would avoid confounding root mass and nutrient uptake parameters to compensate for the presence of stolons in the root mass. Providing a storage organ not only provides a sink to store the excess assimilate that is currently allocated to leaves and stems in the winter, but it would also supply a source of nutrients for regrowth after frosts, in the spring, and after harvests. This would prevent the current situation of the plants dying after a frost and allow for more rapid regrowth in the spring.

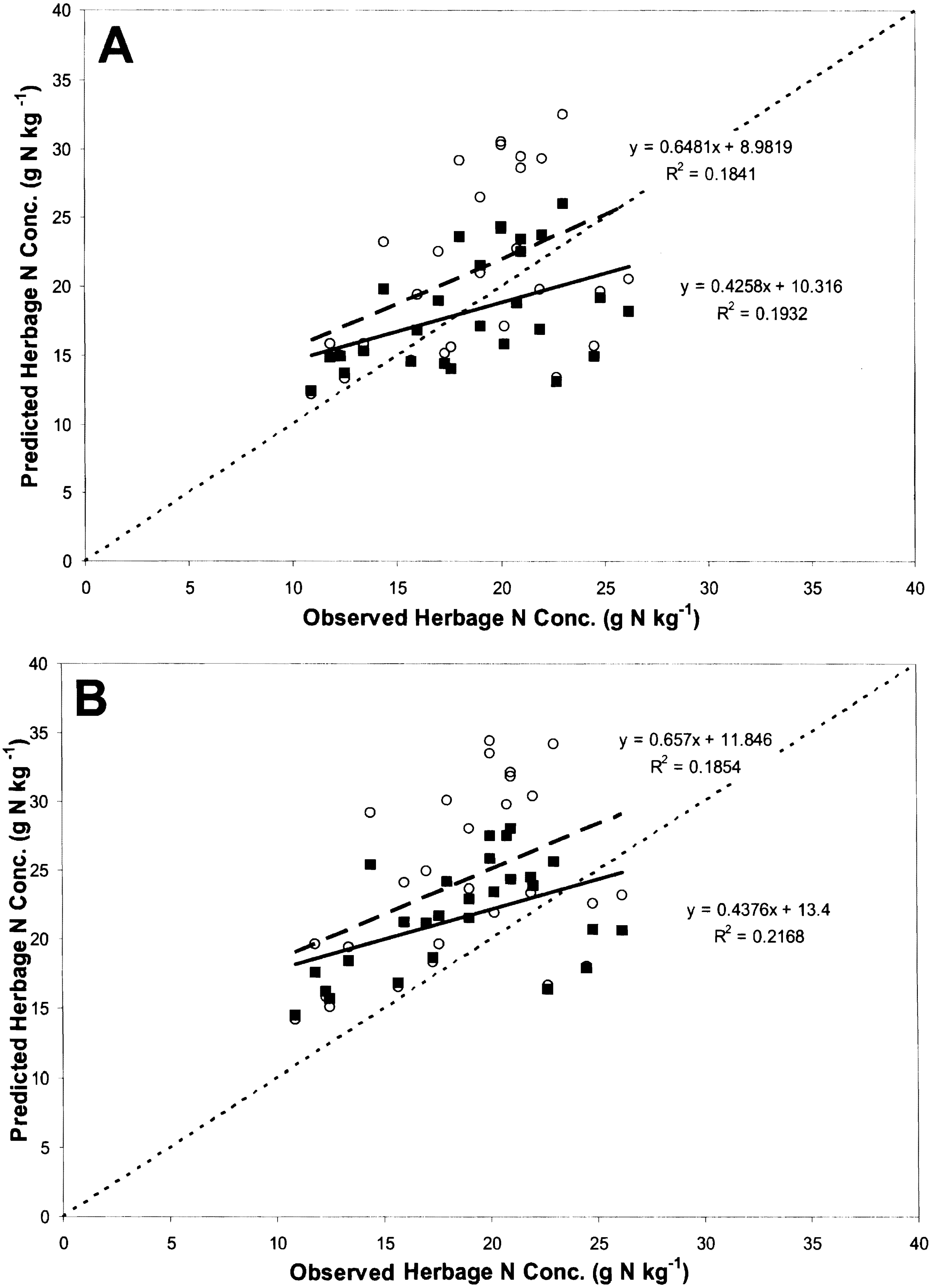

Fig. 8. Predicted vs. observed herbage N concentration (g kg^{-1}) of bahiagrass grown with 78 kg N ha^{-1} cutting^{-1} at Ona, FL, and grown with 168 kg N ha^{-1} yr^{-1} at Eagle Lake, TX, using (A) the leaf-level photosynthesis option, or (B) the daily canopy photosynthesis option. Both options used a 70% reduction in photosynthetic rate over the winter months. Plots for both the preliminary (literature-based, non-optimized) (○) and optimized (■) species files are presented. Linear regression lines for preliminary (dashed line), and optimized (solid line) species files are presented with their corresponding equations and r^2 values along with a line designating a theoretical 1:1 relationship (dotted line).

Other elements of the model, such as the freeze damage scheme and the partitioning of N to replenish old leaves, likely stem from past approaches to modeling an annual grain crop compared with a perennial forage. Situations such a low leaf mass after a harvest coupled with large amounts of available N from the roots and stolons are not generally encountered in the life cycle of an annual grain crop, but are dominant features of the pattern of growth of a perennial grass. These differences are better addressed through adapting the model code than by adjusting species parameters.

Consideration of these differences notwithstanding, the overall performance of both the literature-based and optimized parameters is good. If used carefully, the optimized leaf and canopy models should perform well. More testing would be in order if these models were to be used extensively. As mentioned earlier, further optimization will only improve our ability to compensate for the model code, not improve the quality of the parameters. Taking steps such as running the simulation for a year prior to the measured growing seasons to establish initial conditions, addition of defoliation events to simulate frosts, and addition of photosynthesis reduction schemes to reduce winter growth will be as critical as changing parameter values in establishing a good fit of model predictions to observed data. The bulk of future efforts should be directed at changing the model code to more accurately reflect the life cycle of perennial grasses.

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SOIL AND WATER SECTION

Interactive Effect of Lime and Nitrogen on Bahiagrass Pasture

Martin B. Adjei* and Jack E. Rechcigl

ABSTRACT

Information is lacking on the long-term effect of University of Florida's recommendation for application of N (no P or K) on grazed bahiagrass (*Paspalum notatum* Flugge) pastures in south Florida on forage dry matter (DM) yield, nutritive value, and pasture botanical composition. This experiment consisted of four, annual, sub-plot, fertilizer treatments: 1) 67 kg N ha^{-1} (N); 2) 67-12-56 kg N-P-K ha^{-1} (NPK); 3) 67-12-56 kg N-P-K ha^{-1} plus 22 kg ha^{-1} of micronutrients mix (NPKM); and 4) control (no fertilizer), superimposed on two main-plot treatments: lime vs. no-lime to maintain a pH > 5.0 vs. < 4.5, respectively, from 1998 to 2002. The experiment was repeated under grazing conditions on four locations in central Florida. Although fertilized plots consistently yielded 20 to 30% more DM annually, and had greater crude protein (CP) concentration than the control, there were no yield nor CP differences ($P > 0.05$) between the N and NPK or NPKM treatments at three of the four sites. Mean annual forage yield increased from 6.5 Mg ha^{-1} with the N treatment to 7.2 Mg ha^{-1} with NPK or NPKM treatments on the deep sandy soil at Pasco Co., but CP remained similar among fertilized treatments. Forage IVOMD was generally unaffected by fertilizer or lime treatments, but tissue Ca, P, and K increased for amendments containing these elements. The percentage of bahiagrass stand that was yellow and/or dead and invaded by weeds in Hardee Co. averaged (5 yr) 5% for the control and 2 to 5% for the limed plots whether or not they were fertilized. The greatest ($P < 0.01$) deterioration in bahiagrass pasture (69% dead with weeds and only 31% green) occurred when grass was not limed but N-fertilized annually. While the N fertilizer alone may have long-term useful application to many bahiagrass pastures on flatwoods soils with spodic horizon close to the surface, the need for a fertilizer containing N, P and K on deep sandy soils may be warranted. Additionally, in acid-soil situations, it is better to lime to maintain the pH at 5.0 before N fertilization.

Nitrogen is the most limiting nutrient to warm-season grass production in Florida. Blue (1970) reported that oven-dry forage yields of bahiagrass were 3 to 4 Mg ha^{-1} without applied N and 12 Mg ha^{-1} or more for 224 kg N ha^{-1}. Likewise, N uptake in perennial grass forage from Leon fine sand (Aeric Alaquod) ranged from 30 to 50 kg ha^{-1} without applied N in contrast to quantities exceeding 200 kg ha^{-1} where high rates of N were applied.

McCaleb et al. (1966) studied the effect of P (0-30 kg P ha^{-1} in eight increments), and K (0-280 kg K ha^{-1} in 56 kg ha^{-1} increments) on yield, seasonal growth, and percentage ground cover of Pangola digitgrass (*Digitaria eriantha* Steud.) and 'Pensacola' bahiagrass for 3 yr and observed that P and K influenced growth and ground cover of digitgrass more than bahiagrass. Bahiagrass yield in that study was not improved by P fertilization, and a response to K fertilization was not obtained at rates > 27 kg K ha^{-1} annually, even with 134 kg N ha^{-1} application. Based on standard fertility soil test of that study, Univ. of Florida fertilizer recommendation at that time would have been 23 kg P ha^{-1} and 89 kg K ha^{-1} (Jones et al., 1974).

Blue (1970) showed that ~70% of the P applied to a limed Leon fine sand pasture during an 18-yr period had remained in the surface soil. A subsequent study (Rodulfo and Blue, 1970) showed that bahiagrass responded to added P when grown in the surface horizon of a virgin soil, but did not respond to P when grown in the surface horizon of soil from a previously fertilized pasture. A study across nine south Florida counties showed that, unlike N application, yield increases from P and K applications to bahiagrass pasture in grazed situations were not cost-effective (Sumner et al., 1991). This finding, was collaborated by the work of Rechcigl et al. (1992) and eventually led to the deletion of P and K from Univ. of Florida fertilization recommendations for south Florida pastures (Kidder et al., 2002).

Soil acidity is a major yield-limiting factor for many forage crops grown in the southeastern USA (Adams, 1984). Excess exchangeable Al, the result of low pH, stunts root systems, reducing nutrient and moisture uptake and forage yields (Rechcigl et al., 1985). In Florida, bahiagrass is predominantly grown on Spodosols, which are naturally acidic (pH < 5.0). Rechcigl et al. (1995) demonstrated the importance of dolomitic lime for bahiagrass production when they reported a 25% yield increase by broadcast addition of 4.48 Mg ha^{-1} of lime to raise the soil pH from 4.2 to 5.0. The application of lime above 4.48 Mg ha^{-1} increased pH to 5.5 but did not improve yield further.

The objective of this study was to evaluate the long-term interactions between annual N vs. NPK or NPKM applications and dolomitic liming to pH 5.0 on bahiagrass production, nutritive value, and pasture botanical composition under grazing conditions.

MATERIALS AND METHODS

The experiment was part of a broader study to re-evaluate P fertilizer recommendations for warm-season pasture grasses in south Florida and the results of the first 2 yr are published (Adjei et al., 2000). Separate experiments were conducted in Hardee, Manatee, and Pasco Co. The soils were a Pomona fine sand (sandy, silicious, hyperthermic, Ultic Alaquod) in the Hardee

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M. B. Adjei, Range Cattle Res. and Educ. Center, Ona, FL, 33865-9706; J. E. Rechcigl, Gulf Coast Res. and Educ. Center, Bradenton, FL, 34203. This research was supported by the Florida Agric. Exp. Stn. and is approved for publication as Journal Series No. N-02529.
*Corresponding author (mbadjei@ifas.ufl.edu).
Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:52-56 (2004).

and Pasco Co. ranch sites and Immokalee fine sand (sandy, siliceous, hyperthermic Arenic Alaquod) in Manatee Co. Pastures on the Range Cattle Research and Education Center (RCREC), Hardee Co. (pastures 71A and 87) had not received P or K for about 10 yr prior to this experiment. All sites were portions of bahiagrass pastures that had apparently experienced serious damage by tawny mole crickets (*Scapteriscus vicinus* Scudder) in 1996. Soil was sampled from each site during winter of 1997 for pH and plant nutrient analyses. Before total pasture renovation, portions of damaged pasture were planted to strips (15.2 by 60.8 m each) of several warm season grasses in three randomized complete blocks. Two strips of Pensacola bahiagrass, established from seed (22.4 kg ha^{-1}) within each of the replicates at each site, were used for the limed vs. non-limed treatment comparisons. The remainder of the damaged pasture at each site was later renovated and seeded to Pensacola bahiagrass to allow for cattle grazing. Uniform fertilizer (30-6-30 N-P-K kg ha^{-1}) was used to promote grass establishment in 1997. Dolomitic lime (2-3 Mg ha^{-1}, depending on site) was applied to all grass strips except for the non-limed bahiagrass strips in February 1998 to raise the initial soil pH to ~5.5. Subsequently, soil pH was maintained at ~5.0 for limed strips, requiring annual soil testing and the application of ~2.24 Mg ha^{-1} of dolomite every 3 to 4 yr for the limed treatment (Mylavarapu and Kennelley, 2002). The non-limed bahiagrass strips had an initial average pH of ~4.5 and received no dolomite during or after grass establishment in 1997.

Four fertilizer treatments were superimposed on 15.2 by 15.2 m sections of grass strips as subplots. Fertilizer treatments were: 1) 67 kg N ha^{-1} (N); 2) 67-12-56 kg N-P-K ha^{-1} (NPK); 3) 67-12-56 kg N-P-K ha^{-1} plus 22 kg ha^{-1} of F 503 G® micronutrients mix (NPKM); and 4) control (no fertilizer). The F 503 G® micronutrients, produced by Frit Industries, Inc., Ozark, AL, had the following guaranteed analysis: 24 g B kg^{-1}; 24 g Cu kg^{-1}; 144 g Fe kg^{-1}; 60 g Mn kg^{-1}; 0.6 g Mo kg^{-1}; and 66 g Zn kg^{-1}. Fertilizer treatments were applied to the same plots between March and May (depending on site), 1998 and in March, yearly, from 1999 to 2002. Soil was sampled from each plot at the end of each year's growing season (December-February) from 1997-2002 and analyzed for pH, lime requirement test and Mehlich I extractable P, K, Ca, Mg Zn Cu and Mn (Mylavarapu and Kennelley, 2002).

An area in each bahiagrass plot was cut to 5-cm stubble and a 1.0 by 1.0-m wire exclusion cage was placed on the cut area to protect forage re-growth from cattle. Grass re-growth was harvested at 35-d intervals at the 5-cm stubble height until late fall each year. Cages were moved to a newly mowed area of a plot after each harvest to allow for the impact of grazing. Due to variable fertilizer application dates in 1998, there were six forage harvests on pasture 71A and five on pasture 87 at the RCREC, five at the Pasco site, and three harvests on the Manatee site. For the 1999 to 2002 seasons, fertilizer was applied in March-April to all sites and five to six harvests were obtained from each site. Sub-samples of harvested forage were dried at 60°C to constant weight to determine forage DM yield and were ground for laboratory analyses. Selected ground forage samples representing spring, summer, and fall were analyzed for CP (Gallaher et al., 1976; Hambleton, 1977) and in vitro organic matter digestion (IVOMD) (Moore and Mott, 1974). Sub samples of the same selected ground forage were ashed, dissolved in 0.30 *M* HCl and filtered. Tissue concentrations of P, K, Ca, Mg, Zn, Cu, and Mn were determined (Mylavarapu and Kennelley, 2002).

Method of grazing varied with site. At the Hardee sites, a herd of 50 brood cows was allowed to mob-graze the 8-ha pastures, for 4 to 7 d before each forage harvest date and then removed. At the Manatee site which was sold in early 2001, the grazing schedule was less frequent (45 d), but the stocking rate during the grazing period was > 12 cows ha^{-1}. At the Pasco site where the experiment was also terminated at the end of 2000 season, cow-calf pairs grazed the site with ~30 calves creep grazing ahead of the cows.

The percentage ground cover of each 15.2 by 15.2 m plot that was green, yellow or dead and invaded by weeds was estimated each May. We marked two parallel line transects (6 m apart) across the middle of a plot and randomly placed a 1-m^2 wooden frame at three points along each transect which then covered 6 m^2 or 20% of plot area for each estimate. The wooden frame was divided by strings into 100, 100 cm^2 sections and the number of cells occupied by each category of ground cover was counted at each point on the transect and then averaged for a plot.

Due to premature termination of study at some sites, data were analyzed separately for each site as a split split-plot in time using a mixed–effect model that included the fixed effects of lime (main plot), fertilizer (subplot), year (sub subplot), and their interactions, and harvests as a repeated measure with the rep × lime, rep × lime × fertilizer, rep × lime × fertilizer × yr as the respective random effects (SAS, 1999). Least-square means for main and simple effects were separated with the PDIFF (LSD) option.

RESULTS AND DISCUSSION

With the exception of the Pasco Co. site, soils were initially very acidic (pH < 4.5) (Table 1) and required liming (except the non-limed bahiagrass strips) to raise

Table 1. The initial (1977) 15-cm soil surface pH, and fertility status of experimental sites.

Site	pH	P[†]	K[‡]	Ca	Mg[§]	Zn	Cu	Mn
				mg kg^{-1}				
71A	4.3	4	30	420	48	1.0	0.31	0.07
87	4.4	3	27	105	20	1.6	0.61	1.2
Pasco	5.1	2	29	270	29	1.4	0.03	1.4
Manatee	4.4	7	37	590	49	#	#	#

[†] <10 mg P kg^{-1} soil, very low; 10 to 15, low; 16 to 20, medium; 31 to 60, high (Kidder et al., 2002).

[‡] <20 mg K kg^{-1} soil, very low; 20 to 35, low; 36 to 60, medium; >60, high.

[§] <15 mg Mg kg^{-1} soil, low; 15 to 30, medium; >30, high.

#Not determined.

the pH to ~5.5. The initial P soil test in the surface 15 cm was very low for all sites and the initial K ranged from low to medium. The initial Cu status of Pasco site was extremely low.

Dry Matter Yield

Bahiagrass forage dry matter yield fluctuated widely from year to year, however, the effects of dolomitic lime and fertilizer application on yield were generally consistent across years. On pasture 71A in Hardee Co., and at the Pasco and Manatee Co. sites, yield was not affected by applying dolomitic lime ($P > 0.35$) and there was no lime × fertilizer interaction (Table 2). This result was probably due to the ability of the non-limed plots to retain pH ~4.5 for the entire 3-5 yr period. Lime treatment increased bahiagrass forage yield by 24% across fertilizer treatments on pasture 87 (Table 3) where the non-limed, fertilized plots showed a pH decline to < 4.3 early during the 5 yr. The yield improvement was similar to the increase in yield due to dolomite application reported by Rechcigl et al. (1995).

Fertilizer effects on yield were consistent across harvest dates, years, and liming treatments (fertilizer × harvest date, fertilizer × year, fertilizer × lime: $P > 0.11$) and significant at all sites (Tables 2 and 3). Yield increases on fertilized plots compared to the non-fertilized control ranged from 18% at the Manatee Co. site to 31% at the Pasco Co. site, but differences among fertilized plots varied with site. On the two Hardee Co. pastures, there were hardly any differences in forage yield among the N, NPK, and NPKM fertilizer treatments (Tables 2 and 3), and yields from N and NPKM were also similar for the Manatee site (Table 2). The lack of response of Pensacola bahiagrass pasture production to P and K fertilizer on Spodosols agrees with previous information (Sumner et al., 1991) and is attributed to a combination of nutrient recycling from manure of the grazing cattle and the ability of permanent grass roots to retrieve nutrients from the spodic horizon (Rechcigl et al., 1992). To the contrary, a positive yield trend in favor of P and K application in the initial years at the Pasco Co. site became magnified during the 3 yr study, leading to significant ($P < 0.02$) yield differences between the N only fertilizer on one hand and the NPK or the NPKM treatments on the other for that site. The Pasco Co. site had a slightly elevated, deep, moderately well-drained sandy soil belonging to the Pomona series, which could have prevented easy access by roots to the spodic horizon.

Table 2. The effect of fertilizer treatments on mean annual bahiagrass dry matter production across lime treatments.

Fertilizer treatment†	South-central Florida sites		
	Hardee Co. (71A)‡	Pasco Co.	Manatee Co.
	Mg ha^{-1}		
N	11.4 ab§	6.5 b	7.2 b
NPK	11.9 a	7.1 a	7.8 a
NPKM	11.2 b	7.3 a	7.3 b
Control	9.4 c	5.3 c	6.3 c

†N = 67 kg N ha^{-1}, NPK = 67-12-56 kg N-P-K ha^{-1}, NPKM = 67-12-56 kg N-P-K ha^{-1} plus 22 kg ha^{-1} of F 503 G® micronutrients mix, and control = no fertilizer.

‡5-yr mean for Hardee Co. and 3-yr mean for Pasco Co. and Manatee Co.

§Means in column for each site followed by the same letters are not different ($P > 0.05$) according to LSD.

Table 3. The effect of lime and fertilizer applications on annual bahiagrass dry matter production (5-yr mean) on pasture 87at the Range Cattle Res. Educ. Center in Hardee Co.

Fertilizer treatment†	No-lime‡	Lime	Mean
	Mg ha^{-1}		
N	6.8	8.5	7.7 a§
NPK	7.2	9.1	8.2 a
NPKM	6.7	9.3	7.5 a
Control	5.6	6.3	6.0 b
Mean	6.6 B	8.1 A	

†N = 67 kg N ha^{-1}, NPK = 67-12-56 kg N-P-K ha^{-1}, NPKM = 67-12-56 kg N-P-K ha^{-1} plus 22 kg ha^{-1} of F 503 G® micronutrients mix, and control = no fertilizer.

‡No lime = pH ≤ 4.5, lime = pH ≥ 5.0.

§Means in column followed by same lowercase letters or means in row followed by same uppercase letters are not different ($P > 0.05$) according to LSD.

Nutritive Value

Forage CP concentration increased ($P < 0.01$) by ~15 g kg^{-1} by the application of any of the N-containing fertilizers compared with the control on all sites (Table 4). This forage CP enhancement due to applied N was reduced somewhat on limed compared with non-limed plots of Hardee Co. pasture 71A, resulting in a significant lime × fertilizer interaction ($P < 0.05$). Improvement of forage IVOMD with any of the N fertilizer treatments was consistent only at the Pasco Co. site (Table 5).

Tissue concentrations of minerals varied markedly by site and season, but some general trends emerged regarding the effects of lime and fertilizer treatments (data not tabulated). Tissue Ca concentration increased ($P < 0.001$) when dolomite was applied compared with no dolomite application and the gap widened with time. To the contrary, the effect of dolomite on tissue Mg concentration was mixed. The NPK and NPKM treatments decreased tissue Ca concentration probably due to some Ca being tied up in the soil by P application, but Mg concentration was usually highest ($P < 0.001$) for the N only fertilizer compared to the other treatments. Overall, however, the range of tissue Ca (26-44 g kg^{-1}) and tissue Mg (25-45 g kg^{-1}) were within plant sufficiency levels (Kincheloe et al., 1987).

Although the range of tissue P was narrow (24-32 g kg^{-1}), P concentrations were generally increased ($P < 0.0001$) by the NPK and NPKM treatments compared to the N only and the non-fertilized control. Likewise, tissue K was increased from 110 g kg^{-1} to >185 g kg^{-1} with the application of NPK and NPKM fertilizers. The effect of lime on tissue Zn, Cu, and Mn concentrations were non-significant ($P > 0.10$) and the trend towards greater tissue concentrations with the NPKM treatment was also non-

Table 4. The effects of lime and fertilizer applications on bahiagrass crude protein concentration in south-central Florida.

	South-central Florida sites						
	Hardee, 71A		Pasco			Hardee, 87	Manatee
Fertilizer treatment†	No lime‡	Lime	No Lime	Lime	Mean		
	g kg^{-1}						
N	120 a§	109 a	119	116	118 a	124 a	115 a
NPK	116 a	109 a	124	119	122 a	118 a	119 a
NPKM	118 a	108 a	118	119	119 a	117 a	116 a
Control	101 b	97 b	105	103	104 b	104 b	100 b
Mean	114	105	116 A	114 B			

†N = 67 kg N ha^{-1}, NPK = 67-12-56 kg N-P-K ha^{-1}, NPKM = 67-12-56 kg N-P-K ha^{-1} plus 22 kg ha^{-1} of F 503 G® micronutrients mix, and control = no fertilizer.

‡No lime = pH ≤ 4.5, lime = pH ≥ 5.0.

Significant ($P < 0.05$) lime, fertilizer, and lime × fertilizer effects on Hardee 71A, lime and fertilizer effects ($P < 0.05$) but no interaction ($P > 0.25$) on Pasco site and only fertilizer effect ($P < 0.05$) on Hardee 87 and Manatee sites.

§Means (simple or main) in columns followed by same lowercase letters or means in row within site followed by same uppercase letters are not different ($P > 0.05$) according to LSD.

significant ($P > 0.07$). At the Pasco Co. site, where lime affected tissue Fe concentration ($P < 0.03$), the tissue Fe level was reduced from 91 to 87 mg kg^{-1}. On three of the four sites, Fe tissue concentration was least for the non-fertilizer control but greatest for the N and NPK treatments.

Vegetative Ground Cover

Because of premature termination of experiments at other sites, this portion of discussion is restricted to the two Hardee Co. sites. At the beginning of grazing in 1998, all bahiagrass plots had excellent stand with ~100% ground cover (Table 6), having been established only the previous year. By 2000, bahiagrass ground cover on plots had started to sort out into lime vs. non-limed components based on the fertilizer treatment. The interaction ($P < 0.02$) between lime and fertilizer treatments became more pronounced with passage of time. In 2002, minimal damage to bahiagrass pasture (1-4% loss or 96-99% green, Table 6) was observed in spring at both Hardee Co. sites for plots that were limed whether or not they received fertilizer or for non-limed plots that were not fertilized. Damage was most severe (up to 69% loss or 31% green) when bahiagrass was not limed but fertilized repeatedly with N (any of the fertilizer treatments containing N). The combination of acid soil (pH < 4.5) and N fertilizer seemed to weaken the bahiagrass root-stolon system and caused severe chlorosis in the early spring regrowth. The weakening of root system probably facilitated stand loss due to mole cricket infestation in the long-term. In hindsight, the interaction between lime and N fertilizer on ground cover was not duplicated for forage DM yield partly because an effort was made to locate exclusion cages on remaining bahiagrass portions of each plot.

CONCLUSIONS

Mean (3-5 yr) annual bahiagrass forage DM yield and crude protein concentration on typical Flatwoods soils improved equally with N, NPK, or NPKM fertilizer application compared to the non-fertilized control except on the deep sandy ridge where the addition of P

Table 5. The effect of fertilizer application on bahiagrass in vitro organic matter digestibility in south-central Florida.

Fertilizer treatments†	South-central Florida sites			
	Hardee 71A	Hardee 87	Pasco	Manatee
	g kg^{-1}			
N	472 a‡	468 ab	490 a	485 ab
NPK	466 ab	469 ab	491 a	491 a
NPKM	467 ab	471 a	486 a	486 ab
Control	461 b	457 b	471 b	475 b

†N = 67 kg N ha^{-1}, NPK = 67-12-56 kg N-P-K ha^{-1}, NPKM = 67-12-56 kg N-P-K ha^{-1} plus 22 kg ha^{-1} of F 503 G® micronutrients mix, and control = no fertilizer.

‡Means in columns followed by same lowercase letters are not different ($P > 0.05$) according to LSD.

Table 6. The Lime × fertilizer × year interaction means for percentage live, green bahiagrass ground vegetative cover in Hardee Co.

Fertilizer treatment†	Hardee, 71A				
	1998	2000		2002	
	Initial	No lime‡	Lime	No lime	Lime
	%				
N	100 a	88 b	99 a	85 b	99 a
NPK	99 a	82 c	99 a	81 b	98 a
NPKM	100 a	80 c	98 a	75 c	99 a
Control	100 a	96 a	99 a	94 a	99 a
	Hardee, 87				
N	100 a	80 b	99 a	61 b	99 a
NPK	100 a	75 b	100 a	31 c	99 a
NPKM	100 a	78 b	99 a	64 b	96 a
Control	100 a	97 a	99 a	97 a	98 a

†N = 67 kg N ha^{-1}, NPK = 67-12-56 kg N-P-K ha^{-1}, NPKM = 67-12-56 kg N-P-K ha^{-1} plus 22 kg ha^{-1} of F 503 G® micronutrients mix, and control = no fertilizer.

‡No lime = pH ≤ 4.5, lime = pH ≥ 5.0.

§Means in column under each site followed by the same letters are not different ($P > 0.05$) according to the LSD.

and K to N made a statistical difference. In general, forage digestibility was less sensitive to differences in fertilization. Repeated N fertilization without adequate lime application to bahiagrass pastures in south-central Florida can induce early-spring yellowing and may predispose bahiagrass to loss by tawny mole cricket. In acid soil situations, it is better to maintain the pH at 5 or greater before N-fertilization.

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Fungi in Coastal Tableland Soils of Northeastern Brazil: Preliminary Results

Q. R. Araujo*, J. L. Bezerra, F. G. Faleiro, K. M. T. Bezerra, P. V. Menezes,
A. S. G. Faleiro, A. V. Ogram, A. Al-Agely, and N. B. Comerford

ABSTRACT

Soil compaction causes reduced agricultural production due to limited root development resulting in reduced water and nutrient access. This is particularly true of soils of the Brazilian tablelands (~200 000 km^2) that are characterized by a naturally occurring compact subsoil horizon. Most of these soils have a coeso layer with a density that limits agricultural production. Deep plowing has been the main treatment to alleviate this problem. This study was carried out to identify some fungi associated with an Argissolo Amarelo coeso (Ultisol) in the coastal tableland, in northeastern Brazil (16°10' to 16°30'S and 39°05' to 49°40' W). The fungi were evaluated on soil samples from cultivated areas under natural forest, rubber tree (*Hevea brasiliensis* Willd.), pasture, and annual crops at 0 to 15 cm and 35 to 50 cm depths. The predominant groups (*Penicillium* spp and Dematiaceae), were analyzed by Random Amplified Polymorphic DNA (RAPD) molecular markers. Other identified groups included *Monilia*, *Aspergillus* and Eurotiaceae. The soil under annual cropping showed a trend to higher diversity of fungi. The presence of fungi in the coeso horizon illustrates the biological activity that occurs in a compact subsoil horizon and a probable interaction with the organic C. These preliminary results suggest that the presence, quantity, and activity of associated fungi and bacteria and root dynamics be studied to better understand the environmental and agricultural functioning of this subsurface horizon.

INTRODUCTION

The coastal tablelands of northeastern Brazil support one of Brazil's population centers as well as a diverse matrix of natural, managed, and poorly managed ecosystems. Unique to this region are the coastal tablelands that, in many parts of the region, have a naturally occurring, dense subsoil horizon (Rezende, 2000) called a coeso. This horizon presents a challenge to soil management for crop production because the coeso has a documented deleterious influence on root development (Araujo, 2000). Subsoiling has been used to improve this

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Q. R. Araujo, CEPLAC/Cocoa Res. Center and State Univ. Santa Cruz, CP 07, 45600-970, Itabuna, Bahia, Brazil; J. L. Bezerra, F. G. Faleiro, K. M. T. Bezerra, P. V. Menezes and A. S. G. Faleiro, CEPLAC/ Cocoa Res. Center, CP 07, 45600-970, Itabuna, Bahia, Brazil; N. B. Comerford, A. V. Ogram and A. Al-Agely, Soil and Water Science Dep., Univ. of Florida, Gainesville, FL 32611-0290, USA. This paper represents a initial part of the sabbatical research, of the first author, supported by CAPES-Coordenação de Aperfeiçoamento de Pessoal de Nível Superior, Brasília, Brazil.
*Corresponding author (quintino@cepec.gov.br).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:56-59 (2004).

horizon, however its expense is prohibitive for most small landowners. Rezende (2000) noted the necessity to develop biological methods for subsoil enhancement.

Biological activity is or has been present in these horizons as evidenced by soil organic C levels that approach 5.9 g C kg^{-1} soil (unpublished data). Very little is known about the microbial populations in these soils. One of the steps in understanding the microbial activity, particularly in the coeso horizon, is to document their microbial populations. The purpose of this study was to provide a preliminary look at the presence and relative abundance of select fungal populations in both the surface and subsurface soil horizons.

MATERIALS AND METHODS

Soil samples came from horizons of soil profiles found under four different land use areas in the Bahia, Brazil. The first land use was native forest that was characterized as coastal Atlantic rain forest, with ~2000 mm of rain yr^{-1}. The second land use was a rubber tree plantation and the third land use was a managed pasture of *Brachiaria decumbens* Stapf. The final land use was crop land that was currently supporting Mandioca (*Manihot esculente* Crantz) managed under a best management practice of returning as much organic material as possible to the soil follow harvesting.

Two soil horizons were sampled, including four replications, the surface A horizon (0-15 cm) and the coeso layer (35-50 cm). All soil profiles were Argissolo Amarelo Distrófico coeso (Brazilian soil system classification), based on Leão and Melo (1989) and EMBRAPA (1999), which are Ultisols according to Soil taxonomy (Soil Survey Staff, 1975). All study areas were in close approximation to each other being found at the Pau-Brasil Ecological Station located at 16°10' to 16°30'S and 39°05' to 49°40'W.

For fungal analysis, 1 mL of solution from fresh soil of each horizon-land use combination were placed in Petri dishes with a potato dextrose agar (PDA) + Rose of Bengal + antibiotic medium. The PDA was 200 g potato (*Solanum tuberosum* L.), 12.5 g dextrose, and 17.5 g agar. The Rose of Bengal was added at 0.05 g L^{-1} of PDA. The antibiotic was a suspension of streptomycin: 750 mL water sterile + 1 g antibiotic, using 50 mL suspension for 500 mL of PDA. The samples were incubated at 25°C. The number of colonies per gram of soil was evaluated after 3 d and again after 1 wk. Colony numbers were calculated by dividing the number of colonies measured per plate by the dilution factor (Fernandez, 1993). Nine fungal isolates were identified during these measurements. These isolates had been previously characterized and classified on the basis of their morphological characteristics.

Mycelia mass of each isolate was produced in petri dishes containing a PDA liquid medium. It was this mass that was the material for genomic DNA extraction. The extraction methodology was optimized according to Doyle and Doyle (1990). After extraction, the DNA concentration was estimated by spectroscopy at 260 nm (Sambrook et al., 1989). Bands of genomic DNA were separated by electrophoresis in a 8 g kg^{-1} agarose gel. The DNA samples were diluted to a concentration of 10ng μL^{-1}.

DNA from each isolate was amplified by the RAPD procedure (Doyle and Doyle, 1990). The amplification was accomplished in a 25 µL solution containing 10 mM Tris-HCL (pH 8.3), 50 mM KCl, 2 mM MgCl2, 100 mM each of deoxi-nucleotides (dATP, dTTP, dGTP and dCTP), 0.4 mM of a "primer" (Operon Technologies, Inc., Avenue, CA, U.S.A.), a unit from the enzyme TAQ polymerase and ~30 ng of DNA. Fifteen decamers primers were utilized for obtaining RAPD markers. The amplifications were performed in a thermo circle programmed for 40 cycles, each constituted by the following sequence: 15 s to 94°C, 30 s to 35°C and 90 s to 72°C. After 40 cycles, the final extension phase was for 7 min at 72°C. Finally, the temperature was maintained at 4°C. After amplification, 3 µL of a mixture of bromophenol blue (2,5 mL L^{-1}), glycerol (600 mL L^{-1}) and water (397.5 mL L^{-1}) were added to each sample.

The RAPD markers were converted into a binary matrix and genetic distances between the different isolates were calculated based on the coefficient of similarity (D) of Nei and Li (1979), utilizing the Genes Program (Cruz, 1997). The matrix of genetic distances was used (i) for graphic dispersion in two-dimensional space based on minimizing the differences between the original genetic distances and the graphic distances (Cruz and Viana, 1994) and (ii) for group analyses to show the percent of similarity.

RESULTS AND DISCUSSION

The soil fungi cultured from the samples included the genera *Penicillium*, *Aspergillus* and *Monilia*; and the families Dematiaceae and Eurotiaceae. The number of colonies found in each land use is illustrated in Fig. 1. *Penicillium* was the dominant type found, followed by Dematiaceae. *Monilia* and Eurotiaceae were not common.

Penicillium was present in all land uses and at both soil depths (Fig. 2). In contrast, Dematiaceae was present in the A horizon of all of the land uses, but was less common in the subsoil horizon. *Aspergillus* occurred in the surface and subsoil of both pasture and annual crops, but was only present in surface soil of the rubber tree plantation and the subsoil of natural forest. Euroti-

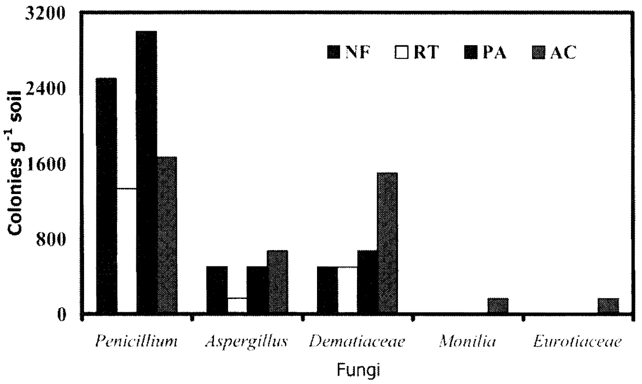

Fig. 1. Number of fungal colonies over two soil depths identified in an Argissolo Amarelo coeso under different land uses (NF—natural forest; RT—rubber tree; PA—pasture; AC—annual crop).

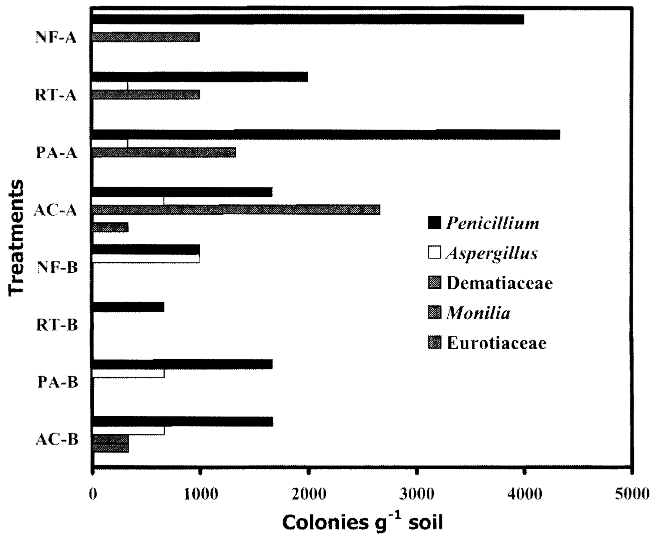

Fig. 2. Number of fungal colonies by treatment (NF—natural forest; RT—rubber tree; PA—pasture; AC—annual crop; A and B horizon) in an Argissolo Amarelo coeso.

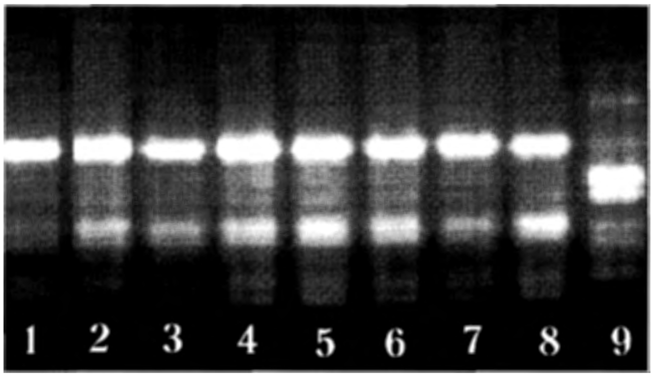

Fig. 3. Products of amplification of genomic DNA of isolates of *Penicillium* (1-8) and *Dematiaceae* (9) of fungi of an Argissolo Amarelo coeso generated with the utilization of the decamer primer L8.

aceae was least common, being present only in the subsoil of the annual crops. The annual crops had a trend to show a higher diversity of fungi.

The genetic evaluation was done on the predominant fungi, *Penicillium* and Dematiaceae, considering also the first one occurred in all land-use treatments and studied depths. The seven primer decamers used in this study, generated a total of 68 RAPD markers, with an average of 9.7 primer^{-1}. Figure 3 shows the amplification standard of DNA samples for nine isolates (1-8 referring to *Penicillium* and 9 referring to Dematiaceae) obtained with the use of the OPL-8 primer. There was a clear difference among *Penicillium* and Dematiaceae isolates.

The genetic distances of *Penicillium* were lower than those between this group and the Dematiaceae (Table 1). *Penicillium* had a tendency toward a greater similarity between those that originated in the B-horizon. However, the area under the rubber trees did not follow the same trend. In general, fungi found in the A horizon had a genetic distance between 0.012 and 0.073. The distance for those in the B-horizon ranged from 0.062 to 0.100. The shortest distance was recorded for Dematiaceae, which was 0.794 to the *Penicillium* Pasture-A horizon.

The grouping analysis illustrated the differences between isolates (Fig. 4). There were clearly two groups that primarily represented the difference between *Penicillium* and Dematiaceae. It was possible to verify that the RAPD markers showed not only the differentiation between the isolates of the peculiar groups, but also recorded the diversity of isolates into the same group.

Considering the possible action of PDA medium to fast growing fungi, like *Aspergillus* and *Penicillium*, other media could be also recommended to compare the fungal occurrence in the coeso soils.

The presence of fungi in the coeso horizon illustrates that biological activity occurs in a presumably hostile soil environment. The presence of soil organic C in this same horizon reaching as much as 5.9 g C kg^{-1} (Araujo, unpublished data) further suggests more biological activity in this naturally compacted horizon than its physical properties suggest. On the basis of these preliminary results, we suggest that the presence, quantity and activity of associated fungi, bacteria and roots dynamics should be studied to better understand this soil subsurface horizon in this region of high biodiversity.

Table 1. Matrix of genetic distances among nine isolates of fungi of an Argissolo Amarelo coeso, calculated on the basis of 68 RAPD markers.

Ident.†	1	2	3	4	5	6	7	8	9
1	0								
2	0.082	0							
3	0.070	0.060	0						
4	0.034	0.048	0.035	0					
5	0.034	0.070	0.057	0.023	0				
6	0.048	0.086	0.098	0.060	0.082	0			
7	0.047	0.036	0.048	0.012	0.034	0.073	0		
8	0.071	0.062	0.073	0.036	0.059	0.100	0.049	0	
9	0.806	0.826	0.800	0.803	0.808	0.794	0.800	0.853	0

†1. *Penicillium* sp/Natural forest/A horizon, 2. *Penicillium* sp/Natural forest/B horizon, 3. *Penicillium* sp/Rubber tree/A horizon, 4. *Penicillium* sp/Rubber tree/B horizon, 5. *Penicillium* sp/Pasture/A horizon, 6. *Penicillium* sp/Pasture/B horizon, 7. *Penicillium* sp/Annual crop/A horizon, 8. *Penicillium* sp/Annual crop/B horizon, 9. Dematiaceae/Annual crop/B horizon.

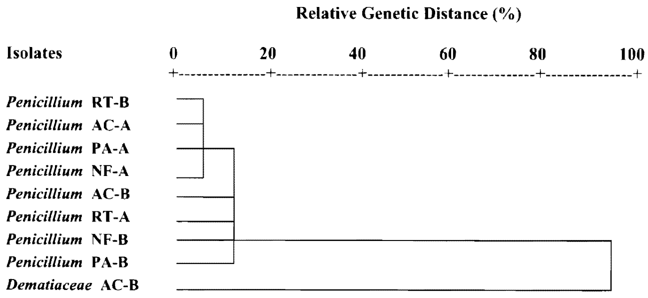

Fig. 4. Grouping analysis of nine isolates of fungi of an Argissolo Amarelo coeso, based on the matrix of genetic distances (NF—natural forest; RT—rubber tree; PA—pasture; AC—annual crop; A and B horizon). They were utilized for the calculation of the genetic distances of 68 RAPD markers.

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Characterization and Classification of Some Soils in the Lowlands of Northern Belize

Paul R. Bloom*, James R. Crum, and Mary E. Pohl

ABSTRACT

Seven pedons were sampled along a transect across the drainages of two adjacent rivers in northern Belize, an agriculturally and archaeologically significant region of Central America. The pedons represent soils of wide extent in the region. The parent materials are hard and soft siliceous lime deposits that are low in heavy minerals. Some of the limy parent materials contain gypsum. The annual rainfall is 1500 mm, but the potential evapotranspiration (PE) is high, and the rainfall in the 4-mo dry season is low. Carbonate leaching in some of the soils is limited by seasonal saturation and the two soils sampled in the floodplain of the Hondo River have gypsum accumulations. The pedons that show evidence of clay translocation or clay weathering are those with better drainage and lower water holding capacity due to a silty clay loam or coarser texture. The soils were classified as Calciustolls, Fluvaquents, Endoaquepts, Haplustolls, and Argiustolls. Plant-available K is high, and available P is low in all of the soils. The two soils formed in alluvial materials have sufficient B, but extractable B is low in the non-alluvial soils. Plant available Zn is low in four of the soils. The necessity for shifting cultivation by traditional agriculturists was explained by the need to accumulate P, Zn, and B in the fallow as well as to maintain organic N. Artificial drainage of the riverine margin soil, which has high native fertility, but is subject to frequent flooding, could provide for permanent cropping in the dry season.

The primary agricultural region of Belize is in the tropical lowlands of the north along the adjacent drainages of the Hondo and New Rivers (Fig. 1) (Wright et al., 1959; King et al., 1992). Dominant agricultural systems at present include permanent cropping to sugarcane (*Saccharum officinarum* L.) and shifting cultivation of maize (*Zea mays* L.).

Northern Belize and the adjacent lowlands of Quintana Roo, Mexico, were important to the ancient Maya. Archeological evidence suggests that this region supported a relatively dense Maya Indian population starting as early as ca. 3400 B.C. (Pohl et al., 1996) with numerous ceremonial centers after 600 A.D., including the large site of Nohmul near the present-day community of Douglas (Fig. 1) (Hammond, 1985). The ancient Maya were active in shifting cultivation, but they also practiced permanent cultivation in drained alluvial soils (Pohl and Bloom, 1996) and possibly on raised planting beds in swamps (Turner and Harrison, 1983).

Only limited information on soil properties is available for the region. The soils of Belize were surveyed by Wright et al. (1959), and a soil map at a scale of 1:250,000

P. R. Bloom, Dep. Soil, Water, & Climate, Univ. of Minnesota, 1991 Upper Buford Circle, St. Paul, MN 55108-6024; J. R. Crum. Dep. Crop and Soil Sciences, Michigan State Univ., 160C Plant and Soil, East Lansing, MI 48824-1325; and M. E. Pohl, Dep. of Anthropology, Florida State Univ., P.O. Box 7772, Tallahassee, FL 32306-7772.
*Corresponding author (prb@umn.edu).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:59-72 (2004).

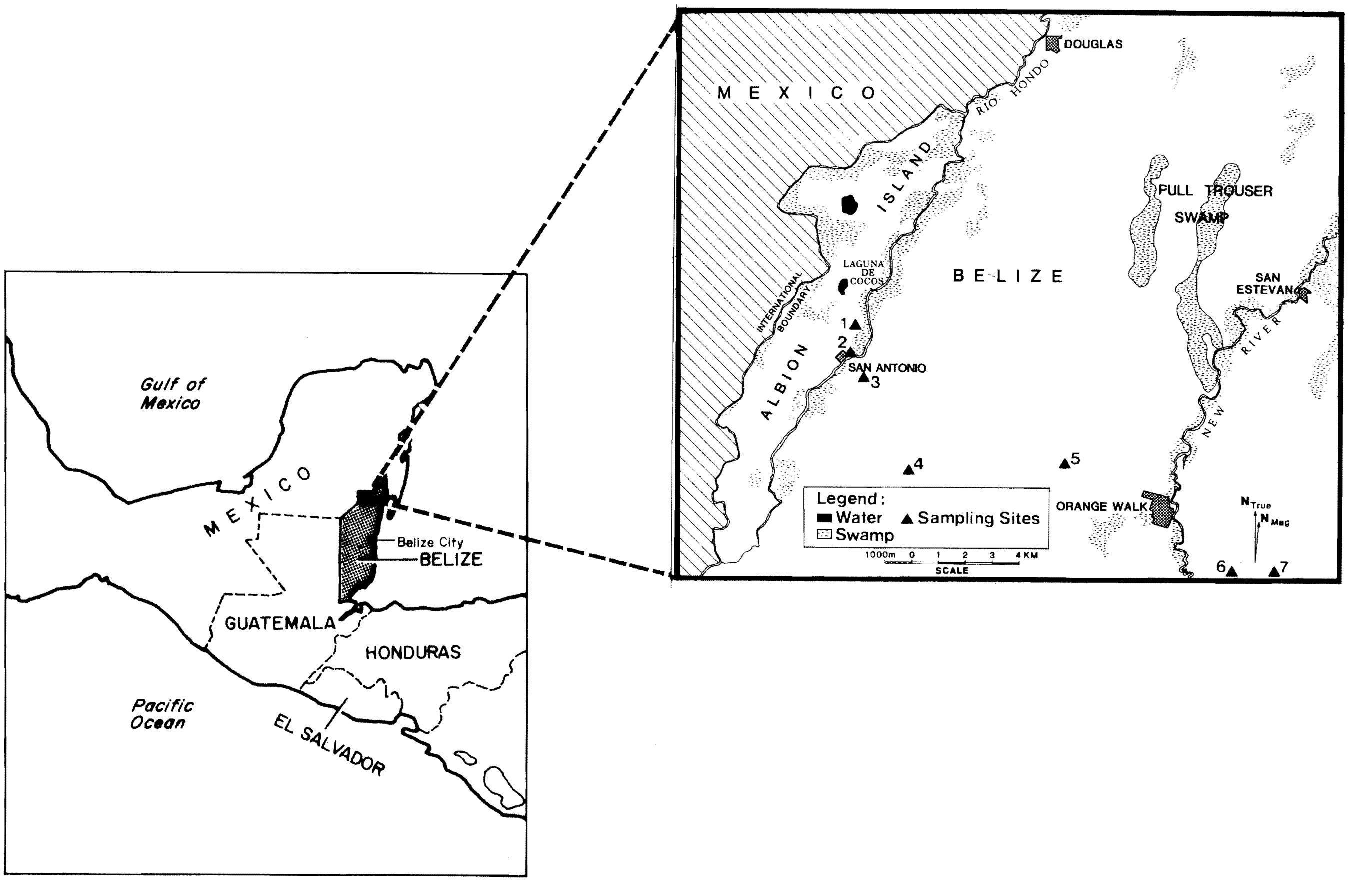

Fig. 1. Study area in northern Belize showing the site of the pedons.

was published. More recently King et al. (1992) published a "Land System" map of Belize that includes some soil data and interpretations for land use. The genesis of soils formed in alluvial materials cropped by the ancient Maya along the Rio Hondo has been investigated in detail (Bloom et al., 1983; Bloom et al., 1985b; Pohl et al., 1990; Pohl and Bloom, 1996). The existing information, however, is insufficient for detailed classification of the soils of the region according to the most recent Soil Taxonomy (Soil Survey Staff, 1999) and interpretation of the soil survey information for agricultural production is limited by the limited laboratory data.

The objectives of the present study are to characterize the major soil types in some of the lowlands of northern Belize, interpret the data with respect to the most recent edition of the Soil Taxonomy (Soil Survey Staff, 1999), and assess the soil fertility status. These data should aid archaeologists in reconstructing past land use; pedologists in understanding soil morphology and genesis; and agricultural scientists in developing strategies for increasing productivity in the region.

MATERIALS AND METHODS

Description of the Study Area

The study area was located in the drainages of the adjacent Hondo and New Rivers (Figs. 1 and 2). This region of Belize (18°0'N; 88°49'W) is bordered on the north and west by Mexico, and on the east by the Caribbean Sea. The lowlands of northern Belize and adjacent Quintana Roo, Mexico are a low-lying shelf in an embayed area on the eastern side of the Central American isthmus (Wright et al., 1959). The bedrock of this low-lying coastal plain is composed of both soft and hard Oligocene and Pliocene siliceous limestone and gypsum. Southwest of the study area, the shelf has been uplifted to form the Maya Mountains. The highest point in the study area is in the center of Albion Island, 47 m above sea level, while the lowest point is along the Rio Hondo, 2 m above sea level (Fig. 2). Albion Island, which is composed limestone, is formed by the bifurcation of the Rio Hondo into two channels (Fig. 1). The main channel, the western channel, forms the border with Mexico, but the eastern channel flows only during intense rainfall events (Stein, 1990).

Albion Island has many Karstic features including sinkholes, solution cavities, and springs. Gypsum outcrops can be found (Antoine et al., 1982) and analysis of a spring near Pedon 1 (Fig. 1) showed the water to be saturated with respect to gypsum (Stein, 1990). Karstic activity has also been significant during the evolution of the lower parts of the landscape. Darch (1983) reported an underground water channel near Pulltrouser Swamp (Fig. 1).

From geologic survey data, Dixon (1956) concluded that the soils of northern Belize are weathered

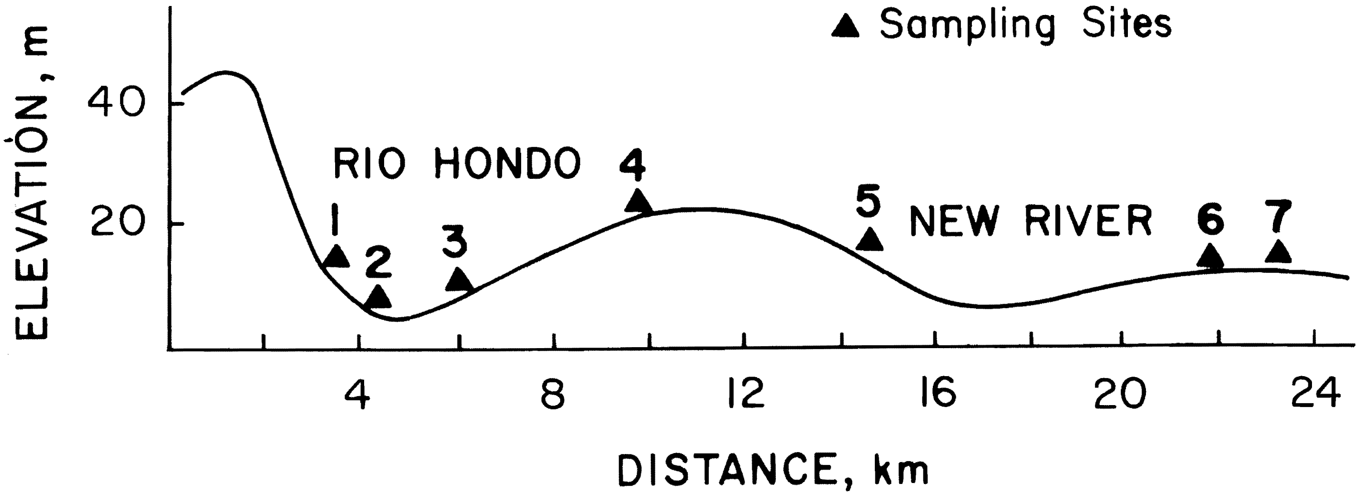

Fig. 2. Topographic cross-section showing the relative elevation of the pedons.

in situ from bedrock and not from erosional sediments mantling the bedrock. Wright et al. (1959), however, concluded that wave activity during the late Pliocene or early Pleistocene was a factor in the deposition of sandy erosional sediments especially in the vicinity of Pedons 6 and 7 (Figs. 1 and 2).

The Koppen-Geiger system of climate classification designates the climate of northern Belize as Aw; tropical with a dry season during the winter months (Kendrew, 1953). The mean monthly temperature ranges from 24 to 27°C, and the mean monthly rainfall ranges from 35 to 280 mm (Fig. 3) (Wright et al., 1959; King et al., 1992). The annual precipitation is 1500 mm (Johnson, 1983). The summer-wet season has two peaks when rainfall exceeds the potential PE, and soil recharge can occur (Fig. 3). A distinctive dry season occurs from January through April, when PE greatly exceeds precipitation (King et al., 1992). Comparison of the rainfall with PE in Fig. 3 shows that PE exceeds rainfall for more than 120 days. The depletion of soil water that occurs during the dry season exceeds the potential for recharge during the wet season. Thus, except in wet lowlands, the soil moisture regime is expected to be ustic.

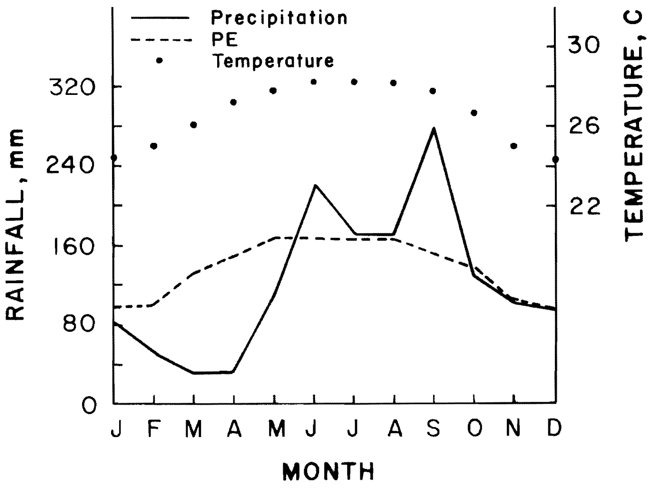

Fig. 3. Mean monthly precipitation and rainfall data for Orange Walk Town, Northern Belize. Potential evapotranspiration (PE) calculated by the method of Thornthwaite and Mather (1957).

Soil Sampling

Seven pedons were sampled along a 20-km transect originating from Albion Island in the Rio Hondo and extending southeast to a site 6 km southeast of the New River (Figs. 1 and 2). The pedons were chosen to represent mapping units described by Wright et al. (1959) that archeological evidence and inference suggest are representative of soils used by the ancient Maya for subsistence (Pohl et al., 1996). Most of these soils also are important for modern agriculturalists (Wright et al., 1959; King et al., 1992). Choice of the exact pedon sites was made in the field based on the apparent representative nature of the site. The local names we use for the soil pedons are from the map of Wright et al. (1959) and with exception of the Hondo soil the names are coincident with the soil subsuites published by Baillie et al. (1993). Baillie et al. (1993) adapted the mapping units of Wright et al. (1959) to develop a three-tiered hierarchical classification system of suites, subsuites and series. In general, they used the mapping units of Wright et al. (1959) in defining the subsuites. They stated that Wright et al. (1959) did not map in sufficient detail to define soil series and thus they only defined their taxa to the level of suite. In this system suites are defined mainly in terms of parent materials but color and mineralogy was also used. Fine-textured calcareous soils, which are common the study area, are separated into different suites based on the probable age and mineral impurities in parent limestones, except for the Tintal suite, which, consists of recent calcareous alluvium. In the system of Baillie et al. (1993), subsuites are similar to soil complex mapping units used in the USA and suites are similar to soil associations.

King et al. (1992) sampled soils in northern Belize, mostly along major roads, and using the system of Baillie et al. (1993) they published the subsuite class for each sample site. They also provide some pit descriptions and some laboratory data. In their Land Systems map they indicate the major soil subsuites within each Land System, but they did not map soil boundaries. They attempted to correlate their subsuites with Soil Taxonomy (1st ed.) (Soil Survey Staff, 1975) at the Great Group level and found that different pedons of a subsuite were often classified in different taxa. In our application of Soil Taxonomy (Soil Survey Staff, 1999) we classified each pedon to the family level, but we made no attempt to find the variation within each mapping unit of Wright et al. (1959).

Pedon 2 was sampled in September 1980, during the middle of the wet season, and the other pedons were sampled in June 1982, during the early part of the wet season. The pedons were described and sampled using standard methods (Soil Survey Staff, 1999).

Laboratory Analysis

Organic C was determined by dichromate oxidation with reflux (Franzmier et al., 1977). Soil pH was determined both in 1:1 water and 0.01 *M* $CaCl_2$ (Peech, 1965). Calcium carbonate equivalent (CCE) was determined by weight loss after addition of 1 *M* HCl (USDA, 1984) and gypsum was determined by acetone precipitation of H_2O extracts (USDA, 1984). Water contents at 33 kP and 1500 kP were determined using a pressure plate apparatus (USDA, 1984).

Calcium carbonate removal from the calcareous samples was accomplished using a sodium acetate buffer, adjusted to pH 4.0 with acetic acid (Rabenhorst and Wilding, 1984). All samples were treated with H_2O_2 to remove organic carbon, and wet sieving was used to separate the sand fractions. Clay and silt contents were determined by sedimentation (Day, 1965). Clay-sized carbonate (CSC) was determined by the method of Bloom et al. (1985a).

Mineralogy of the clay-sized fraction (<2 μm) was determined by x-ray diffraction (Jackson, 1956). After Mg and K saturation, clay suspensions were plated on glass slides to induce preferred orientation. To the Mg saturated samples, 100 ml L^{-1} glycerol was added for detection of expandable clay minerals. The slides were then scanned at 4 deg 2θ min^{-1} on a Philips APD-3600 (Philips Electronic, Eindhoven, Netherlands) using Ni filtered Cu-K_α radiation with a compensating slit. Quantitative analysis was based on background-corrected normalized areas under the peaks. Standard clay mixtures containing montmorillonite, kaolinite, and quartz as described by Crum (1984) were used for calibration. The quantity of clay was calculated using the straight-line model software supplied by the instrument's manufacturer (Jenkins et al., 1983) and the data are reported as % of the total clay.

Electrical conductivity of saturated soil paste extracts was determined for selected samples according to the method of Richards (1954). Total N was determined by Kjeldahl digestion followed by steam distillation. Exchangeable bases were determined in 1 *M* NH_4OAc extracts of samples that did not contain carbonates, and $BaCl_2$-TEA acidity was determined on carbonate free samples by the method of Peech (1965). Plant-available P was determined using the method of Olsen and Sommers (1982), B was determined after extraction with hot water, and available Cu, Mn, and Zn were determined using DTPA extraction (Norvell and Lindsay, 1978).

RESULTS AND DISCUSSION

Characterization and Classification

Nearly all of the soil horizons, with the exception of some horizons from Pedons 6 and 7, had dominant Munsell soil color chromas ≤1 (Table 1). In part this fact is due to poor internal drainage and saturation of subsurface soil horizons, but it is also a reflection of the low content of ferromagnesian minerals in the parent materials of these soils. A subsoil sample at 53-84 cm from Pedon 3 contained only 14 g kg^{-1} Fe_2O_3 and 5 g kg^{-1} MgO (unpublished data). Subsoils from Pedons 6 and 7, contained more Fe in the parent material and develop higher chroma matrix colors when not gleyed (Table 1). A 20 to 43 cm sample from Pedon 7 contained 38 g kg^{-1} Fe_2O_3 and a 71-132 cm sample from Pedon 6 contained 34 g kg^{-1} Fe_2O_3 (unpublished data).

Wright et al. (1959) stated that the soils of the region have parent materials low in Fe and Al. Powder x-ray diffraction analysis of sand, silt, and clay fractions of the sedimentary soil from Pedon 2 showed that the only detectable primary mineral was quartz. The dissolution of carbonates from the soil parent materials resulted in a light-gray mineral residue. Lack of color in the minerals making up the matrix of the soils caused difficulties in interpretation of the degree of gleying. Soil Taxonomy (Soil Survey Staff, 1999) states that the "g" suffix should be used to indicate horizons with "intensive gleying". Gleying is generally indicated by low-chroma colors except that, "horizons of low chroma in which the color is due to uncoated sand or silt particles are not considered gleyed." The only pedons in which color unambiguously indicated gleying were Pedon 3 which has a Bg horizon having a Munsell color of N 6/0 and Pedon 7 with a Bg horizon with colors of 2.5 YR 8/1 (Table 1). In the other soils we chose to assign g suffix for horizons with hues of 2.5 Y or bluer, values ≥5, and chromas = 1.

Pedon 1

Pedon 1, a representative of the Louisville subsuite (Pembroke suite), was sampled on a nose slope, back slope erosional landscape position. The Louisville soil is commonly used for maize production under shifting cultivation (Wright et al., 1959; King et al. 1992) and the sampling site had been cropped sometime in the past, but there was no evidence that the site had been recently cleared for agricultural production. The present vegetation is secondary regrowth of a deciduous forest dominated by Sapodilla (*Achras zapota* L.) and mahogany (*Swietenia macrophylla* King), both calcophyllic species.

The parent material is soft limestone locally known as sascab. The pedon we sampled was very high in gyp-

Table 1. Morphological properties of pedon horizons. See Fig. 1 for location of pedons.

			Mottles†								
Horizon	Lower depth	Color (moist)	Abund., size & contrast	Color (moist)	Texture	Structure‡	Consist. (moist)	Effervescence#	Roots††	Boundary‡‡	Other features
Pedon 1 (Louisville)											
A	13	10YR 2/1	none		c	2mgr	fi	ev	mm	cw	many 10YR 8/1 $CaCO_3$ concretions
B	28	10YR 5/1	none		c	2msbk	fi	ev	mm	cw	many 10YR 8/1 $CaCO_3$ concretions
Cr	102	10YR 8/1	f2p	7.5YR 6/8	—	1msbk	fr	ev	ff		—
Pedon 2 (Hondo)											
A	9	10YR 3/1	none		c	2msbk	s	e	mm	cs	few shell fragments
A2	19	10YR 5/1	none		c	1cpl	s	e	mm	cs	very few shell fragments; common 10YR 8/1 gypsum crystals
Bg1	28	2.5Y 5/1	none		c	1cpl&sbk	s	e	mm	gs	very few shell fragments
Bg2	43	10YR 6/1	none		c	1cpl	s	e	mf	gs	very few shell fragments
Bg3	60	2.5Y 5/1	none		c	1cpl&sbk	s	es	mf	gs	few shell fragments common 2.5Y 7/1 $CaCO_3$ concretions; pottery shards at 52 cm.
B	81	10YR 5/1	c2d	10YR 5/4	c	1cpl&sbk	s	e	ff	gs	common shell fragments
BCg	108	10YR 4/1	f2d	10YR 5/9	c	1csbk	s	e	ff	as	very few shell fragments
Cg	116	10YR 4/1	none		c	0m	s	e	ff	cw	many whole shells & shell fragments
Pedon 3 (Pucte)											
A	8	10YR 2/1	none		c	2mgr	fi	—	mf	as	—
Bg	30	N 6/0	none		c	2mabk	fi	—	cm	aw	common N 6/0 stress surfaces
BCg	48	2.5Y 8/1	none		c	2mabk	fi	es	fm	aw	common 2.5Y 8/1 stress surfaces
Cr1	102	10YR 8/1	f1d	10YR 5/8	—	1msbk	fi	ev	fc	—	many 10YR 8/1 gypsum crystals
Cr2	140	10YR 8/1	none		—	—	—	ev	—	—	many 10YR 8/1 gypsum crystals
Cr3	168	10YR 8/1	none		—	—	—	ev	—	—	many 10YR 8/1 gypsum crystals
Cr4	196	10YR 8/1	none		—	—	—	ev	—	—	many 10YR 8/1 gypsum crystals
Pedon 4 (Lazaro)											
A	28	7.5YR 3/1	f1d	7.5YR 5/8	sc	3fabk	vfi	—	cf	cs	—
B1	53	10YR 4/1	c1d	7.5YR 5/8	c	3mabk	fi	—	cf	cw	—
B2	84	10YR 5/1	c2d	7.5YR 5/8	c	3mabk	fi	—	cf	cw	many 10YR 5/1 stress surfaces
B3	104	10YR 5/1	m3d	2.5Y 7/1	c	2cabk	fi	—	ff	aw	many 10YR 5/1 stress surfaces
IIBCg	140	5Y 7/1	c2p	10YR 6/8	c	1cabk	fi	e	ff	as	many 5Y 7/1 stress surfaces
IICr	152	10YR 8/1	c1d	10YR 6/8	—	2msbk	fi	ev	—	—	many 10YR 2/1 concretions
Pedon 5 (Pixoy)											
AP	23	7.5YR 2/1	none		fsl	2mgr	fi	—	cf	as	—
A	41	7.5YR 2/1	none		scl	2mabk	fi	—	cm	cw	—

†Mottles: Abundance, f—few, c—common, m—many. Size; 1—fine, 2—medium, 3—coarse. Contrast; f—faint, d—distinct.

‡Structure grade: 0—structureless, 1—weak, 2— moderate, 3—strong. Size: f—fine, m—medium, c—coarse. Type; gr—granular, abk—subangular blocky, sbk—angular blocky, pl—platy, pr—Prismatic, m—massive.

¶Consistence: fr—friable, fi—firm, vfi—very firm.

#Effervescence: e—slight, es—strong, sv—violent.

††Roots: Abundance: f—few, c—common, m—many. Size; f—fine, m—medium, c—coarse.

‡‡Boundary: c—clear, g—gradual, d—diffuse, s—smooth, w—wavy, I—irregular, b—broke.

Table 1. (Continued)Morphological properties of pedon horizons. See Fig. 1 for location of pedons.

			Mottles†								
Horizon	Lower depth	Color (moist)	Abund., size & contrast	Color (moist)	Texture	Structure‡	Consist. (moist)	Efferves-cence#	Roots††	Boundary‡‡	Other features
B1	53	10YR 4/1	c2d	2.5Y 6/1	scl	3mabk	fi	—	fc	cw	few 10YR 4/1 stress surfaces
B2	84	10YR 6/1	m3d	2.5Y 6/1	scl	2mpr&abk	fi	—	ff	dw	few 10YR 6/1 stress surfaces
BCg1	109	2.5Y 7/1	f3p	10YR 6/8	scl	2cpr&abk	vfi	—	fm	aw	common 2.5Y 5/1 stress surfaces
BCg2	137	2.5Y 7/1	f2p	10YR 6/8	scl	2mpr&abk	vfi	es	fc	cw	many 2.5Y 6/1 stress surfaces
Cr	165	2.5Y 7/2	m3d	10YR 8/1	—	2fsbk	vfi	ev	ff	—	many 7.5Y 2/1 stress surfaces
							Pedon 6 (Jobo A)				
Ap	28	10YR 2/2	none	—	ls	2mgr	fr	—	cf	as	—
E	33	10YR 4/2	none	—	ls	1fgr	fr	—	cf	as	—
IIBt1	48	7.5YR 5/6	c3p	2.5YR 3/6	sc	2msbk	fi	—	cf	cw	common 7.5YR 4/6 clay films; common 10YR 8/1 barite crystals
IIB1	71	10YR 6/6	m3d	10YR 7/1	scl	2mabk	vfi	—	fm	cw	few 10YR 5/3 clay films; common 10YR 8/1 barite crystals, common 2.5YR 3/6 plinthite
IIB2	91	10YR 7/1	m3d	10YR 7/8	scl	2mpr&abk	vfi	—	fm	cw	common 10YR 8/1 barite crystals; common 2.5Y 3/6 plinthite; few 10YR 5/3 stress surfaces
IIBCg	132	2.5Y 8/1	c3p	10YR 7/8	sc	1mpr&abk	vfi	—	fm	gw	common 10YR 8/1 barite crystals; common 2.5Y 3/6 plinthite; common 10YR 5/3 stress surfaces
IIC	203	10YR 6/8	m3p	2.5Y 8/1	scl	0m	vfi	—	fm	—	few 2.5Y 3/6 plinthite
							Pedon 7 (Jobo B)				
A	20	10YR 5/2	c1d	7.5YR 6/8	fsl	2msbk	fi	—	cf	aw	—
Bg1	43	2.5Y 7/1	m2p	7.5YR 6/8	sc	2msbk	fi	—	ff	cw	—
Bg2	71	2.5Y 8/1	c2p	7.5YR 6/8	scl	1mpr&2mabk	fi	—	ff	cw	common 2.5Y 8/1 stress surfaces
BCg	109	2.5Y 8/1	f2p	7.5YR 6/8	cl	1mpr&2mabk	Fi	e	ff	gw	common 10YR 2/1 concretions; common10YR 8/1 carbonate coatings; common 2.5Y 8/1 stress surfaces
IICg	178	2.5Y 8/1	f1p	7.5YR 6/8	c	1cpr	vfi	ev	ff	—	common 10YR 2/1 concretions; common 10YR 8/1 carbonate coatings; many 2.5Y 8/1 stress surfaces

†Mottles: Abundance, f—few, c—common, m—many. Size; 1—fine, 2—medium, 3—coarse. Contrast; f—faint, d—distinct.

‡Structure grade: 0—structureless, 1—weak, 2— moderate, 3—strong. Size: f—fine, m—medium, c—coarse. Type; gr—granular, abk—subangular blocky, sbk—angular blocky, pl—platy, pr—Prismatic, m—massive.

¶Consistence: fr—friable, fi—firm, vfi—very firm.

#Effervescence: e—slight, es—strong, sv—violent.

††Roots: Abundance: f—few, c—common, m—many. Size; f—fine, m—medium, c—coarse.

‡‡Boundary: c—clear, g—gradual, d—diffuse, s—smooth, w—wavy, I—irregular, b—broke.

sum ($CaSO_4.2H_2O$) and calcium carbonate ($CaCO_3$) and these two materials accounted for 97% of the material in the Cr horizon (Table 2). The soil is weakly developed with much $CaCO_3$ occurring throughout the solum, both as fine lime and harder illuvial concretions and colluvial fragments of coral limestone. There is no indication of impeded drainage, yet the organic matter content is high (Table 3). The stability of the organic matter is a reflection of the high clay content and high calcium status of this soil.

Pedon 1 was classified as Typic Cacliustolls (Table 4). Some of the Louisville soils that are very shallow to hard carbonate rock are likely in the lithic great group.

Pedon 2

Pedon 2, a representative of Hondo mapping unit described by Wright et al. (1959) was located within the floodplain of the Rio Hondo only 30 m from the riverbank. Wright et al. (1959) mapped the soils adjacent to the Rio Hondo and the New River as Hondo, but Baillie et al. (1993) did include Hondo in their list of subsuites. They did describe the Tintal suite, which includes all the poorly drained alluvial soils along the Rio Hondo and New River and indicate that the areas where Wright mapped the Hondo soil are dominated by their Sibal subsuite. The Sibal soils are described as being high organic matter mineral soils or peats and that have very high organic matter in the top 50 cm. Our pedon had only 37 mg organic C kg^{-1} in the surface horizon (Table 3) and fits well into the Hondo Clay unit described by Wright et al. (1959).

The sample site is located in an area that was cultivated by the Maya by the third century B.C. To facilitate agricultural production the Maya constructed drainage ditches connecting to the river, which has resulted in plots 12- to 20-m wide, of varying lengths (Bloom et al., 1983). The ancient fields have been covered by 1.5 m of calcareous sediments, and yet the ancient drainage network is reflected in the present landscape. The elevation difference from the center of the ancient plots to the bottom of the ditches is currently ~0.5 m. The native vegetation is high marsh forest dominated by bribri (*Inga edulis* Mart.) along with provision tree (*Pachira aquatica* Aubl.), cocoplum (*Chrysobalanus icaco* L.), and bullet tree (*Bucida buceras* L.). These species are all tolerant of soil saturation. The present vegetation at the sampling site is grass, because this site was cleared of trees by the people of the nearby village for mosquito control and animal grazing.

The soil is poorly drained, very high in clay, and has a high Ca status (Table 2). When the pedon was sampled in September 1980, free water was encountered at 40 cm from the surface, and it was necessary to use a pump during sampling. During the dry season, the river (and associated free water) drops by about 1 m (Bloom et al., 1983). The high chroma mottles at 60 to 108 cm (Table 1) are evidence of a fluctuating zone of saturation. Another indication of saturation during the formation of this soil is the presence of freshwater mollusk shells throughout the soil. The high CCE in the 43 to 81 cm and 108 to116-cm horizons results from high concentrations of shells deposited under the wet conditions that occurred during the deposition of the soil's parent material.

This soil has over 900 g clay ($CaCO_3$ and gypsum-free basis) kg^{-1} with a gypsic horizon occurring between 9 and 60 cm (Table 2). In this environment, where the river water is high in dissolved $CaSO_4$, the montmorillonitic clays flocculate and act more like silts. Data from two other Hondo pedons in the same area (Pohl and Bloom, 1996) suggest that some of the plots cultivated by the ancient Maya have an even greater accumulation of gypsum. In the remnant ditches there is only a small accumulation of gypsum at the surface, and no gypsic horizon is present. The Hondo soil has only a weakly developed structure.

Pedon 2 contained many Maya pottery shreds (Table 1). At depths below the solum, evidence for cultivation of maize was found (Bloom et al., 1983). Pedon 2 was classified as Mollic Fluvaquents (Table 4). Given the current limits in the Soil Taxonomy (Soil Survey Staff, 1999) it is not possible to reflect the gypsic horizon in the taxonomic class.

Pedon 3

Pedon 3, a representative of the Pucte subsuite (Tintal suite), was sampled at a slightly higher elevation of the Rio Hondo floodplain than Pedon 2. The Pucte soil has drainage limitations and is not extensively used for agriculture, but sugarcane was growing near the sampling site. The native vegetation is a low marsh forest dominated by the bullet tree, which is locally known as the pucte tree. This wetland forest has also an abundance of white poisonwood (*Cameraria belizensis* Standl.) and black poisonwood [*Metopium brownei* (Jacq.) Urban]. Being in a higher position, the Pucte soil has a slightly more developed structure compared to the Hondo soil. This fact is shown by the medium angular blocky structure in the B horizon. Complete weathering of carbonates has occurred to 48 cm. Underlying the solum is a soft limy deposit high in gypsum. The data (Table 2) show this material to be ~90% calcium carbonate plus gypsum.

Deposition caused by floods associated with hurricanes contributes some alluvium to Pucte soils. Flood frequencies in the area are not well documented, but in the 10 yr previous to our 1982 sampling, local villagers observed three floods that inundated Pedon 3. During one of the floods the water rose to ~3 m above normal wet season high water. The gleying in the B horizon and the high chroma mottles in the BCg are a consequence of the periodic saturation. Gypsum and carbonates, however, have not accumulated in the A and B horizons as in the Hondo soil. This fact suggests that leaching is active in Pucte soils. Pedon 3 was classified as Fluventic Endoaquepts.

Pedon 4

Pedon 4, representing the Lazaro subsuite (Guineagrass suite), was sampled in a pasture on the Yo Creek agricultural field station. The native vegetation is cohune palm *Attalea cohune* (Mart.) forest. Wright et al. (1959) reported that the parent material for this soil is soft siliceous limestone. Baillie et al. (1993) stated that the

Table 2. Physical and mineralogical properties of pedon horizons. See Fig.1 for location of pedons.

		Particle size					Moisture				Clay mineralogy		
	Horizon	Sand	Silt	Clay	CSC†	Texture	33 kPa	1500 kPa	CCE‡	Gypsum	Smectite	Kaolinite	Quartz
		%					mg kg^{-1}		%				
Pedon 1 (Louisville)													
13	A	23.5	28.5	40.0	21	C	369	260	59	—	51	44	5
28	B	18.6	31.0	50.3	26	C	324	201	71	—	55	39	6
102	Cr	—	—	—	—	—	—	—	15	82	—	—	—
Pedon 2 (Hondo)													
9	A	1.7	6.4	89.9	—	C	—	—	13	1.4	56	39	5
19	A2	1.0	9.6	89.4	—	C	—	—	3	21.7	60	36	4
28	Bg1	0.4	8.7	90.9	—	C	—	—	3	16.9	—	—	—
43	Bg2	1.0	6.4	92.6	—	C	—	—	2	16.5	—	—	—
60	Bg3	1.3	4.5	94.2	—	C	—	—	35	5.1	—	—	—
81	B	1.9	3.8	94.3	—	C	—	—	35	1	—	—	—
108	BCg	0.8	4.5	94.7	—	C	—	—	4	1	—	—	—
116	Cg	0.3	2.8	96.9	—	C	—	—	20	1	—	—	—
Pedon 3 (Pucte)													
8	A	27.2	10.2	62.6	—	C	620	410	0	—	61	31	8
30	Bg	27.0	6.5	66.5	—	C	552	391	0	—	60	30	10
48	BCg	22.8	5.4	71.8	—	C	588	413	4	—	—	—	—
102	Cr1	—	—	—	—	—	—	—	23	41	—	—	—
140	Cr2	—	—	—	—	—	—	—	6	76	—	—	—
168	Cr3	—	—	—	—	—	—	—	10	82	—	—	—
196	Cr4	—	—	—	—	—	—	—	11	77	—	—	
Pedon 4 (Lazaro)													
28	A	46.7	13.8	39.5	—	SC	306	232	0	—	61	21	18
53	B1	43.7	12.3	44.0	—	C	—	—	0	—	—	—	—
84	B2	40.7	11.1	48.2	—	C	340	260	0	—	59	19	22
104	B3	39.6	11.1	49.3	—	C	—	—	0	—	—	—	—
140	IIBCg	26.7	15.5	57.8	2	C	476	330	5	—	56	21	23
152	IICr	—	—	—	—	—	—	—	79	—	—	—	—
Pedon 5 (Pixoy)													
23	Ap	76.7	9.2	14.1	—	FSL	134	92	0	—	53	28	19
41	A	67.2	8.2	24.6	—	SCL	204	138	0	—	—	—	—
53	B1	62.0	6.0	32.0	—	SCL	—	—	0	—	55	24	21
84	B2	60.1	6.3	33.6	—	SCL	226	16.8	—	—	—	—	—
109	BCg1	61.7	6.3	32.0	—	SCL	—	—	0	—	59	20	21
137	BCg2	62.9	9.4	28.2	2	SCL	—	—	7	—	—	—	—
165	Cr	—	—	—	—	—	—	—	69	—	—	—	—
Pedon 6 (Jobo A)													
28	Ap	81.8	11.4	6.8	—	LS	70	38	0	—	17	42	41
33	E	83.8	10.8	5.4	—	LS	—	—	0	—	—	—	—
48	IIBt1	48.5	8.8	42.7	—	SC	263	177	0	—	—	—	—
71	IIB1	59.9	8.1	32.0	—	SCL	—	—	0	—	31	65	4
91	IIB2	63.3	4.6	32.1	—	SCL	173	122	0	—	—	—	—
132	IIBCg	55.3	7.5	37.2	—	SC	—	—	0	—	50	47	3
203	IIC	61.7	5.4	32.9	—	SCL	—	—	0	—	—	—	—
Pedon 7 (Jobo B)													
20	A	67.3	16.5	16.2	—	FSL	135	82	0	—	33	42	25
43	Bg1	48.6	11.8	39.6	—	SC	278	205	0	—	—	—	—
71	Bg2	50.2	15.2	34.6	—	SCL	—	—	0	—	37	20	43
109	BCg	44.8	17.4	37.8	1	CL	257	189	0	—	40	18	42
178	IICg	23.4	31.4	45.2	3	C	—	—	27	—	—	—	—

†Clay sized carbonates.
‡Calcium carbonate equivalent.

quartz sand component resulted either from "an impurity in the limestone or a later mixed-in surficial deposit". Clay contents increase and sand contents decrease with depth (Table 2). The silt to sand ratio, however, is constant (0.28 ± 0.1) from the surface to 104 cm and then increases greatly to 0.59. This fact suggests a lithological

Table 3. Chemical properties of pedon horizons. See Fig.1 for location of pedons.

Lower depth	Horizon	1:1 pH H_2O	1:1 pH $CaCl_2$	CEC	B.S.	E.C.	P Olsen	K	O.C. Total	N Total	B†	DTPA‡ Cu	DTPA‡ Mn	DTPA‡ Zn
cm		-------pH------		cmol$_c$kg^{-1}	%	dS m^{-1}	-----------------mg kg^{-1}-----------------							
Pedon 1 (Louisville)														
13	A	7.5	7.3	—	—	0.90	3.16	137	37	3.4	0.85	0.93	4.04	0.39
28	B	7.6	7.5	—	—	0.72	2.44	92	19	1.4	0.64	0.45	2.08	2.70
102	Cr	7.5	7.5	—	—	2.35	0.69	—	—	—	—	—	—	—
Pedon 2 (Hondo)														
9	A	—	—	—	—	3.40	1.61	195	46	6.0	1.19	0.77	3.34	0.18
19	A2	—	—	—	—	3.40	3.26	130	12	—	1.28	2.84	4.10	0.27
28	Bg1	—	—	—	—	—	—	—	—	—	—	—	—	—
43	Bg2	—	—	—	—	—	—	—	—	0.6	—	—	—	—
60	Bg3	6.8	—	—	—	—	—	93	—	—	—	—	—	—
81	B	7.1	—	—	—	—	—	—	—	—	—	—	—	—
108	BC	7.2	—	—	—	—	—	—	—	—	—	—	—	—
116	C	7.4	—	—	—	—	—	195	—	—	—	—		
Pedon 3 (Pucte)														
8	A	7.6	7.4	90.9	98.2	1.42	3.05	1911	64	3.5	2.26	1.27	4.16	1.92
30	Bg	7.4	7.4	69.4	98.8	3.15	0.58	1638	6	4	3.13	0.46	3.63	0.33
48	BCg	7.4	7.5	—	—	3.39	0.57	—	—	—	2.35	0.12	2.10	0.12
102	Cr1	7.7	7.6	—	—	3.18	0.58	—	—	—	—	—	—	—
140	Cr2	7.7	7.7	—	—	3.14	—	—	—	—	—	—	—	—
168	Cr3	7.8	7.8	—	—	4.09	—	—	—	—	—	—	—	—
196	Cr4	8.0	7.8	—	—	4.81	—	—	—	—	—	—	—	—
Pedon 4 (Lazaro)														
28	A	6.2	5.9	41.3	90.5	—	0.59	897	11	1.1	0.90	0.27	9.90	0.73
53	B1	6.2	5.7	42.3	90.3	—	0.59	312	5	0.3	0.31	0.11	4.90	0.01
84	B2	6.0	5.8	45.0	92.7	—	0.58	390	5	—	—	—	—	—
104	B3	7.3	7.0	55.3	100	—	0.57	390	4	—	—	—	—	—
140	IIBCg	7.5	7.4	—	—	—	0.59	—	—	—	0.70	0.08	0.91	0.01
152		7.9	7.6	—	—	—	0.55	—	—	—	—	—		—
Pedon 5 (Pixoy)														
23	Ap	7.3	6.9	23.5	96.5	—	1.14	195	9	1.5	0.22	0.36	7.48	0.01
41	A	6.5	6.1	25.9	91.2	—	0.57	117	1.0	—	—	—	—	—
53	Bg1	6.1	5.5	31.5	89.5	—	0.60	156	0.3	2	0.36	0.08	0.44	0.22
84	Bg2	5.6	5.0	26.6	89.1	—	0.58	117	3	—	—	—	—	—
109	BCg1	5.4	5.2	26.0	91.3	—	0.57	78	1	—	—	—	—	—
137	BCg2	7.6	7.2	—	—	—	0.54	156	2	—	0.18	0.19	1.38	0.01
165	Cr	7.6	7.4	—	—	—	0.54	—	—	—	—	—	—	—
Pedon 6 (Jobo A)														
28	Ap	6.7	6.5	10.1	73.4	—	1.33	156	12	9	0.24	0.26	4.74	1.06
33	E	6.4	5.8	04.0	74.3	—	0.44	78	4	—	—	—	—	—
48	IIBt	6.4	5.2	25.5	78.1	—	0.55	390	7	0.5	0.21	0.10	0.12	0.01
71	IIB1	5.3	4.7	19.2	77.5	—	0.54	351	2	—	—	—	—	—
91	IIB2	4.9	4.4	17.8	76.9	—	0.53	234	2	—	—	—	—	—
132	IIBCg	5.0	4.6	27.8	82.2	—	0.56	390	2	—	0.09	0.41	0.09	0.18
203	IIC	5.7	5.4	17.3	90.5	—	0.56	390	—	—	—	—	—	—
Pedon 7 (Jobo B)														
20	A	5.2	4.7	14.4	78.5	—	0.53	195	6	0.5	0.26	0.15	2.37	0.01
43	Bg1	5.2	4.7	29.6	86.1	—	0.56	312	3	0.2	0.31	0.13	1.12	0.01
71	Bg2	5.6	5.6	24.5	93.3	—	0.58	351	3	—	—	—	—	—
109	BCg	7.3	7.3	33.3	99.4	—	0.57	429	2	—	0.44	0.21	1.66	0.01
178	2Cg	7.6	7.5	—	—	—	0.56	—	—	—				

†Hot water extraction.
‡DTPA extraction (Norvell and Lindsay, 1978).

discontinuity at the 104-cm depth. Higher sand content in surface soils is common in the region and may reflect the influence of beach-forming processes during the sea level recession in the late Pliocene and early Pleistocene. Beach deposits at the 55-m elevation (Wright et al., 1959) mark the high point of the sea level. There is also evi-

Table 4. Soil taxonomic classification of pedons.

Soil Subsuite	Pedon	Classification
Louisville	1	Fine-loamy, carbonatic, isohyperthermic, Typic Cacliustolls
Hondo	2	Very fine, montmorillonitic, isohyperthermic, Mollic Fluvaquents
Pucte	3	Very fine, montmorillonitic, isohyperthermic, Fluventic Endoaquepts
Lazaro	4	Fine, montmorillonitic, isohyperthermic, Aquic Haplustolls
Pixoy	5	Fine-loamy, siliceous, isohyperthermic Aquic Haplustolls
Jobo A	6	Fine, mixed, isohyperthermic, Psammentic Argiustolls
Jobo B	7	Fine, mixed, isohyperthermic, Typic Endoaquepts

dence for a halt in the retreat of the sea at ~15 m, an elevation not much different from that of Pedon 4 that we estimated to be about 20 m (Fig. 3).

The Lazaro soil has a high capacity to store plant-available water well into the dry season. Our estimate of the water storage capacity in the A and B horizons of Pedon 4, based on the water retention data in Table 2 is 180 mm. This value is greater than the total of the rainfall in excess of PE that falls in June and September and the Lazaro can store the excess rainfall for plant growth well into the dry season (Fig. 3).

The Lazaro soil has a mollic epipedon and morphologic properties indicative of swelling clays. Slickensides were observed in the lower B horizons (>200 mL L^{-1}), but there was no evidence of mixing due to crack formation during the dry season. The clay content increases gradually with depth down to the B3 horizon and there is a discontinuous increase between the B3 and IICgl (Table 2). The increase with depth to the B3 may be influenced by illuviation, but there is no suggestion of formation of a zone of accumulation. The existence of high chroma mottles in the A, B1, and B2 horizons suggests that during the wet season this soil is wet enough to cause the reduction and mobilization of Fe. More intense reduction is indicated by the low chroma mottles in B3.

The pH and base saturation of the A, B1, and B2 in the Lazaro soil indicate a depletion of base cations reducing the base saturation to 90% in these horizons (Table 3). There is little indication of clay translocation, and the stable ratio of smectite to kaolinite with depth (Table 2), suggests that there has been little or no weathering of clay minerals in this soil.

The mottling of the surface suggests that the surface soil may sometimes be saturated. Water balance calculations and landscape position suggest that saturation is never close enough to the surface to create aquic conditions. However, the mottling may be due to temporary saturation during periods of very high rainfall. Rainfall events associated with hurricanes could readily fill the macropores with water causing conditions appropriate for Fe reduction in this clayey soil even before the interior of the peds are fully wetted.

The low chroma mottles in the B3 horizon are sufficient to place this soil in the aquic great group. However, the abundance of well developed slickensides suggests vertic activity and that the soils could be in the vertic great group. We classified the Pedon 4 as Aquic Haplustolls because there is no evidence of cracking that extends to the surface. An alternative classification is Vertic Haplustolls.

Pedon 5

Pedon 5, a representative of the Pixoy subsuite (Guineagrass suite), was located in a sugarcane field in a rolling landscape. The Pixoy soil is extensively used for agricultural production. Wright et al. (1959) mapped the native vegetation as high marsh forest. The most common tree is the Botan palm, but the forest also has an abundance of black poisonwood, white poisonwood, and bullet tree. Pedon 5, like Pedon 4, is developed in soft siliceous limestone (Wright et al., 1959; Baillie et al. 1993), but Pedon 5 has lower clay and higher sand contents (Table 2).

Pedon 5 has better internal drainage than Pedon 4, but evidence of periodic saturation occurs in the BCg horizons, which appeared to be gleyed and to contain a few high chroma mottles (Table 1). In addition low chroma mottles were found in the B1 and B2 horizons.

Wright et al. (1959) believes that the higher sand content of the siliceous limestone in the parent material of the Pixoy soil contributes to the higher sand content compared with the Lazaro soil. The constancy of the silt/sand ratios throughout the solum (Table 2) supports the assumption that the sand content is inherited from the parent material. The clay data suggest some clay translocation from the surface into the B horizons. The structural development is moderate with generally < 200 mL L^{-1} slickensides in the B horizons (Table 1).

Translocation of clay occurred without the weathering of the smectite. The ratio of smectite to kaolinite (calculated from the data in Table 2) is constant with depth. One factor that helps to inhibit smectite weathering is the relatively high pH of the surface soil (Table 2). The pH (H_2O) decreases from 7.3 in the Ap to 5.4 in the BCgl and then rises to 7.6 in the lower calcareous horizons.

The relatively high surface pH is evidence for calcium biocycling by calcophyllic vegetation. Calcophyllic vegetation is also abundant on the Louisville, Hondo, and Pixoy soils, but weathering is insufficient to develop acid subsoils in these soils.

Like Pedon 4, we classified Pedon 5 as Aquic Haplustolls (Table 4). This pedon does not have the abundance of slickensides that Pedon 4 has but does have low chroma mottles.

Pedons 6 and 7

These pedons are representative of the Jobo subsuite (Altun Ha suite). Pedons 6 and 7 were sampled at adjacent sites in a pasture. These soils are developed on hard siliceous limestone (Wright et al., 1959). The siliceous components are flint and chert fragments with possible contribution of old beach deposits (King et al., 1992). Pedon 6 (Jobo A) was located on an upland swell and the Pedon 7 (Jobo B) in an upland depression. These two soils have quite different characteristics due to landscape position.

The native vegetation for Jobo soils is low marsh forest similar to the Pucte soil. At the site of Pedon 7, however, the soil is very infertile, and without much vegetation. Both soils have weak to moderate prismatic and angular blocky structure (Table 1), but Pedon 6 shows much more development with an argillic horizon and segregated Fe (probably plinthite) throughout the B and C horizons.

The possibility of leaching is much greater for the Jobo soils than for Pedons 4 and 5 because these soils are coarser in texture and have lower water holding capacity. In Pedon 7, however, leaching is severely inhibited by a seasonal saturation. In this soil, gleying is evident in the B horizons, and high chroma mottles were seen in both the A and B horizons (Table 1).

The high chroma mottles in the argillic horizon in Pedon 6 (Table 1) are evidence that it is sometimes saturated. The horizon below the argillic does not contain high chroma mottles suggesting that the mottling of the argillic horizon is due to perched water. Mottling and gleying of the BCg horizon are evidence for seasonal saturation in the lower part of the solum. At the time of sampling, however, no free water was observed in the pits.

Both Pedons 6 and 7 have relatively coarse-textured surface horizons. In Pedon 6 there is a clear indication of clay translocation and the formation of an argillic horizon (Table 2). The particle size data (Table 2) also suggest the possibility of clay translocation in Pedon 7. For both pedons, the clay content of the surface soil is too low to be explained solely by clay eluviation. Some of the discrepancy could be due to the clay weathering (discussed below), but most probably the very low clay content is influenced by deposition of sandy material. The surficial deposits in Pedons 6 and 7 may be from material deposited by wave action nearby during the late Pliocene or early Pleistocene (Wright et al., 1959). A likely source is the redeposition from the Puletan loamy sand, which was formed in a beach deposit on a higher landscape position 1000-m south of Pedons 6 and 7.

Pedons 6 and 7 are the most acid of the soils sampled. Pedon 6, like Pedon 5, has a decreasing pH with depth, and the Jobo A soil, like the Pixoy, is influenced by the biocycling of Ca by calcophyllic vegetation. This characteristic contrasts with the Jobo B which is very acid in the A horizon because of the lack of biocycling of Ca. The acidity of the surface horizon of Pedon 7 suggests leaching has strongly influenced soil development, despite the seasonal impeded drainage.

The increase in the smectite to kaolinite ratio with depth in Pedons 6 and 7 (calculated from data in Table 2) suggests the possibility of clay weathering in these soils. The previously discussed evidence for surficial deposition, however, complicates this interpretation.

Crystals identified by x-ray diffraction as barite were found in the B horizons of Pedon 6. Crum and Franzmeier (1980) and Lynn et al. (1971) found this mineral in Ultisols and Alfisols of the southern U.S. that have low pH but high base saturation. Stoops and Zavoleta (1978) found barite in a Typic Haplustult of Peru. Although Pedon 6 has a mollic epipedon, this soil has a low pH (5.0) and a high base saturation (>75%) throughout the horizons in which the barite is found.

We classified Pedon 6 as Psammemtic Argiustolls and Pedon 7 as Typic Endoaquepts. The Jobo mapping unit appears to be a complex with Argiudolls on the swells and Endoaquepts in the depressions.

Clay cation exchange capacity (CEC) and clay content

The CEC data (Table 3) suggest either that the quantitative x-ray diffraction procedure used to determine the clay quantities in Table 2 underestimates the quantity of smectite in the soil or that the smectite is, in fact, vermiculite. Estimates of smectite CEC from soil CEC data and clay data (Tables 2 and 3) result in CEC values too high for montmorillonite or beidellite. For example, in the Lazaro Bg2 horizon (CEC = 45 cmol_c kg^{-1}) the clay content is 48%, and the smectite content of the clay fraction is 590 g kg^{-1}. If the CEC of organic matter is estimated to be 200 cmol_c kg^{-1}, kaolinite 0.5 and quartz 0 (Bohn et al., 1985), the CEC of the smectite is 150 cmol_c kg^{-1}. A similar estimate for the Pucte B horizon yields a CEC of 170. The 150 value is at the upper limit for smectite and lower limit for vermiculite. Although these very high values likely reflect an underestimate the quantity of smectite by the x-ray procedure, it probable that the smectites in these soils have high charge densities.

Soil fertility and soil conditions for plant growth

The four soils on the westerly end of the transect (Louisville, Hondo, Pucte and Lazaro) are all clayey with high CEC (Table 3), high water holding capacity (Table 2), and generally higher fertility status compared with the Pixoy and Jobo soils. The Pucte and Hondo are the soils that have the highest overall fertility status. The Hondo soil, however, has severe limitations due to poor drainage, and the Pucte also has limits for wet season crop production. Jobo soils in depressions (Jobo B) also suffer from some drainage limitations.

Some salt accumulation of has occurred in both the Hondo and Pucte soils as indicated by the electrical conductivity of saturated paste solutions (Table 3). Leaching of the Pucte soil has reduced the conductivity of the A horizon relative to the subsurface horizons. Saturated paste conductivities in the range of 3 to 4 dS m^{-1} were measured below the A horizon in Pedon 3 and throughout Pedon 2. This salt accumulation is sufficient to severely limit sensitive crops such as beans (*Phaseolus vulgaris* L.) and can reduce sugarcane production by 10 to 25%, but it would not adversely affect any other of the major crops grown in the region (Bohn et al., 1985). The Louisville soil has a higher conductivity in the C1 (2.35 dS m^{-1}) than in the A horizon because of the gypsum in this horizon, but this should not have much effect on crop growth.

The water storage in the Pucte and Lazaro soils, calculated from the difference between 35 kPa and 1500 kPa moistures (Table 2), is enough for deeply rooted-plants to have sufficient water well into the dry season (Fig. 2). The Louisville soil sampled in Pedon 1 is more subject to drought than many Louisville soils because of its shallow solum (Wright et al., 1959). The Pixoy, Jobo A and Jobo B soils have less water storage capacity because they are coarser textured. Water deficit on the Hondo soil is not a problem because of continual saturation within the top 1.5 m of the solum.

The Louisville, Hondo, and Pucte soils have higher contents of organic N than the other soils sampled (Table 3). Hondo and Louisville soils have a good capacity for supplying N for low input agriculture such as shifting cultivation, which is practiced extensively in the region. Organic N and C analyses of Pedons 1 and 2 show that surface soil organic C is about 40 g kg^{-1} (Table 3) with a C/N ratio in the range of 8 to 11. The Louisville soil is favored by shifting cultivators because of its high fertility and relatively good drainage (Wright et al., 1959). Also, the better soils in the plain between the two rivers, Lazaro, Pixoy and JoboA, are used but for sugarcane and cattle production and are not available to shifting cultivators. The Pucte soil has high surface organic C, but the C/N ratio in Pedon 3 was 18, suggesting some limitation in N availability. Compared to the Louisville, Hondo, and Pucte soils, the organic C and N contents are much lower in the other soils. The least fertile soil is the Jobo B which has only 6 g C kg^{-1} in the A horizon.

Calcium and Mg are the dominant exchangeable cations in all of the soils (data not shown), and they are in good supply for plant growth. All of the soils also have high levels of exchangeable K with soil test values >125 mg kg^{-1} (Table 3). A soil test value of 125 mg K kg^{-1} is sufficient for high production of most crops (Doll and Lucas, 1973). High K was found in the subsoil as well as in the surface horizons. The data of Wright et al. (1959) shows that sugarcane grown on the Louisville soil does not respond to K fertilization. King et al. (1992) suggest that the soils in the study area are generally high in exchangeable K.

The high K may be due to due to small inputs of volcanic ash. Ford and Rose (1995) found Classic-era Mayan ceramics of the lowlands of Belize are high in biotitic volcanic ash. Volcanoes in Guatemala produce ash high in biotite, and Ford and Rose (1995) speculate that volcanic eruptions of in Guatemala supplied ash to the study area ca. 600 to 900 A.D. Also, CEC is high and leaching is not intense, so with biocycling exchangeable K can be maintained at a high concentrations.

Phosphorus appears to be the most limiting of the macronutrients. Wright et al. (1959) reported that P is the limiting nutrient for the acid, sandy soils near the Jobo A and Jobo B pedons. He also reported a dramatic response of sugar cane to P on a Louisville soil. All of the soils we sampled had bicarbonate extractable P < 5.0 mg kg^{-1} (Table 3), which is indicative of severe deficiency (Thomas and Peaslee, 1973). The Louisville, Hondo and Pucte soils probably have sufficient P in the top 30 cm of the soil for shifting cultivation, but the other soils, especially the Lazaro and Jobo B, are extremely low in available P. The Jobo B and Lazaro soils have no surface accumulation of available P, suggesting that biocycling and other biological processes have not been sufficient for the accumulation of available P at the surface. This explanation is reasonable for the Jobo B since we saw little plant growth on this soil. Micronutrients may also be a problem for plant growth in some of the soils. Zinc is low, especially on the Pixoy and Jobo B soils where DTPA extractable Zn was only 0.01 mg kg^{-1}. Soils with <0.5 mg kg^{-1} of DTPA Zn may have not enough Zn for sensitive crops (Viets and Lindsay, 1973). The Louisville and Hondo soils have DTPA Zn in the range of 0.2 to 0.4 in the surface horizons suggesting possible deficiencies. Soil test B indicates possible deficiencies for sensitive crops in some of the soils. Plant species vary greatly in their requirement for B, but generally 1.0 to 5.0 mg kg^{-1} of extractable B is recommended to allow normal growth of plants (Reisenauer et al., 1973). The Hondo and Pucte soils are in this range, but the Lazaro and Louisville soils had slightly <1.0 mg kg^{-1}. The possibility of B deficiency is even greater in the Pixoy, Jobo A, and Jobo B soils where extractable B was <0.4 mg kg^{-1}. Copper deficiency is not a potential problem except perhaps in the Jobo B soil where DTPA extractable Cu was 0.15 mg kg^{-1} in the surface soil. Deficiencies are expected for sensitive species if the DTPA Cu <0.2 mg kg^{-1} (Viets and Lindsay, 1973). All of the soils are high in Mn.

CONCLUSIONS

The soils in the lowlands of northern Belize have developed from calcareous coastal deposits. These soils are weakly developed as a result of: (1) the intensity and length of the dry season, which places these soils in the ustic moisture regime, (2) seasonal saturation in many of the soils, (3) colluvial deposition of limy material (Louisville Pedon), and (4) the high water holding capacity of the clayey textured soils, which limits leaching. These soils contain high activity smectite clay and have high CEC. The only soils with clear evidence for clay translocation or clay weathering are the Pixoy and Jobo soils, which developed on relatively coarse materials that have lower water holding capacities.

With the exception of the Jobo soils, the native fertility is high, and the study area has a high potential for agricultural production by traditional, low-input methods. Phosphorus is likely the most limiting nutrient on the better soils, but Zn and B may also be limiting for some crops. The Hondo soil has very high fertility, due to frequent alluvial inputs, but has severe limitations due to seasonal flooding and poor drainage much of the year. The Pixoy soil also has alluvial inputs but less frequently than the Hondo soil, and the drainage limitations are not as severe as in the Hondo soil. The Jobo B has severe limitations both due to drainage and very low fertility. With the exception of the Jobo B and Hondo soils, crop production by traditional shifting cultivation methods is possible. Relatively short fallow periods should be sufficient to accumulate readily available organic N for maize, and the burning of the woody fallow should supply sufficient P (plus B and Zn if needed).

The soil resources in the study area provide a resource base that can support a relatively high population density compared with other areas in the tropics where the soils are highly leached and long fallow periods are needed. These characteristics help to explain the high population density of the Maya in the Late Classical period.

The Hondo soils would require artificial drainage for agricultural production and even then could only be cropped in the dry season. With frequent inputs of river sediment, the Hondo soil could be used for permanent cropping. Drainage could increase production on Pucte soils, and modern cultivators do use artificial drainage in Pucte soils.

The ancient Maya use of the Hondo and similar wetland soil resources is controversial. The present-day surface patterns of mounds and swales connecting the Hondo soils to the Rio Hondo suggest that this soil, and similar wetland soils, may have been used in the past for cultivation. Extensive archaeological excavation along the Hondo and New rivers of northern Belize revealed that the Maya did construct canals to drain wetland soils in some areas (Pohl and Bloom, 1996). The evidence suggests, however, that the Maya dug these canals in the Late Formative or Preclassic period, beginning in about the third century B.C. The research found little evidence that these soils contributed to the support of Maya civilization during the Classic florescence (Pohl et al., 1996; Pope, et al., 1996).

ACKNOWLEDGMENTS

We thank Milegua F. Layese, Richard Rust, and H.U. Neue, for reviewing the manuscript, and James C. Bell for assisting in the classification of the soils.

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Development of Methodologies for Characterization of Slow-Release Fertilizers

J. B. Sartain*, W. L. Hall, R. C. Littell, and E. W. Hopwood

ABSTRACT

Presently there is no official means of verifying the labeling claims placed on slow-release fertilizers. The slow-release task force of the Association of American Plant Food Control Officials (AAPFCO) requested that a soil incubation methodology be developed for estimating nutrient release over time which would correlate with a laboratory nutrient extraction method such that a slow-release source can be extracted in the laboratory and the values used to predict the long-term release of nutrients. To this end, incubation lysimeters constructed of 7.5-cm diam. by 15-cm long PVC tubes were filled with 1710 g uncoated sand, 90 g Arredondo fine sand (loamy, siliceous, hyperthermic, Grossarenic Paleudult) and 450 mg of N from selected slow-release N sources. Lysimters were leached at 7, 14, 28, 42, 56, 84, 112, 140 and 180 d incubation with 0.1 mL L^{-1} citric acid. Soluble N as NO3, NH4 or urea were determined from the leachates. In addition, the materials were extracted using an increasingly aggressive extraction procedure which involved the pumping of extracting solutions through jacketed chromatography columns containing a 30 g sample of the slow-release material. Extraction involved four stages: 1) 2h @ 25°C with water; 2) 2h @ 60°C with 2 mL L^{-1} citric acid; 3) 16 h @ 60°C with 2 mL L^{-1} citric acid; and 4) 54 h @ 60°C with 2 mL L^{-1} citric acid. Through non-linear regression the N release rate was expressed with an R^2 of 0.99 as: Nt = asym - (asym-int)*e-rate*t; where 't' equals time in days, 'Nt' equals percent N release by time t, 'asym' equals the maximum level of N released (or the asymptote of the curve), 'int' equals the intercept, and 'rate' is the rate of increase parameter. The CV of accelerated laboratory extraction procedure was 3.2%, and the anticipated N release rate of a slow-release N material was predicted with an accuracy of 90%. Additional verification of release rate parameters is needed, but this methodology for estimating N release, extracting N from slow-release N materials and then predicting that N release is scientifically valid and one that can be used for verifying labeled claims.

During the past 50 yr a number of slow-release fertilizers have been developed for use in speciality fertilizer markets. These are collectively referred to as 'enhanced efficiency' materials by the AAPFCO (Terry, 2003). In general, these materials have been characterized relative to their nutrient release rates, mechanisms of nutrient release and factors affecting nutrient release (Carrow et al., 2001). The commercial development of slow-release materials has been based on several unique technologies. Each technology was addressed in terms of the regulation and analysis of the specific material. At the time of each development this approach was adequate based on the limited number of products. However, as the number of products increased, the individualized approach to regulation became less effective. This problem is world-wide as summarized by Trenkel (1997). Previous development of technology for characterizing these new slow-release materials has lead to inconsistencies in the analytical methods needed to effectively evaluate the materials, claims and performance. Despite many new technologies, there have not been any new methods of analysis accepted for use by the Association of Analytical Chemists International (AOACI, 2000) since 1970. An accepted methodology is needed that will estimate the nutrient release from various materials over time to establish the long term release of the product. In addition, a laboratory extraction method is needed that can be used to evaluate the material in the short term and then verify the actual nutrient release in the long term. Thus, the objectives of this study were (1) to develop an incubation methodology to determine the nutrient release rate of various slow-release fertilizers; (2) to develop a laboratory extraction procedure that can be used to progressive extract the target nutrient; and (3) to establish a relationship between the two methodologies such that the laboratory extraction procedure can be used to predict the long term release of the product.

J. B. Sartain and E. W. Hopwood, Univ. of Florida, Soil and Water Sci. Dep. Gainesville, FL 32611; W. L. Hall, IMC Global Operations, Mulberry, FL 33860; R. C. Littell, Univ. of Florida, Statistics Dep. Gainesville, FL 32611. This research was supported by the Florida Agric. Exp. Stn. and is approved for publication as Journal Series No. N-02494.

*Corresponding author (jbs@ifas.ufl.edu).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:72-75 (2004).

MATERIALS AND METHODS

Soil Incubation N Release Methodology

Incubation lysimeters were constructed using a 30-cm section of 7.5-cm diam. PVC tubing fitted with fiberglass mat across the lower end that was held in place by a PVC cap. The cap was drilled and fitted with a barbed plastic fitting and a tygon tube was attached to an Erlenmeyer flask with sidearm for evacuating the leachate under vacuum. An additional cap was used on the upper end and sealed to prohibit volatile loss. A mixture of uncoated quartz sand (1710 g) and a surface layer (0 to 5-cm depth) of Arredondo fine sand (90 g) was mixed with the equivalent of 450 mg N from each fertilizer source. Soil was added to the sand and N-source mixture to insure that nitrifying bacteria were present and that the system was biologically active, similar to natural conditions that the fertilizer sources would experience when applied to the soil. Evidence of biological activity can be verified through the detection of nitrate-N. Since the N form in isobutylidene diurea (IBDU) is urea, the detection of NO$_3$ in the leachate is verification of an active biological system in which nitrification is taking place (Schmidt, 1982). The mixture was then placed in the incubation lysimeters and brought to 100 mL L^{-1} moisture (~80% water holding capacity) by adding 180 mL of 0.1 mL L^{-1} citric acid. Citric acid was added to stabilize the pH of the mixture and to serve as an energy source for the bacteria. A 50 mL beaker containing 20 mL of 0.2 M H$_2$SO$_4$ was placed in the head space of the incubation lysimeter as an ammonia trap. The solution in the ammonia trap was replaced and analyzed for NH$_4$ by titration with 0.1 M NaOH every 7 d. After 7, 14, 28, 56, 84, 112, 140, and 180 d each lysimeter was leached with one pore volume of 0.1 mL L^{-1} citric acid (500 mL) using a vacuum manifold for 2 min (exact tension unknown). Leachate volume was recorded and an aliquot was taken for urea (Mulvaney and Bremner, 1979), NH$_4$ (O'Dell, 1993a.) and NO$_3$ (O'Dell, 1993b) analysis. In previous versions of the incubation methodology prior to the addition of the citric acid, leachate pH increased to >9, and volatile ammonia was detected. Since no volatile ammonia was detected in the ammonia trap during any of the incubation periods, the three forms of N detected in the leachate were summed for an estimate of the total N released with time. Thirteen slow-release N sources, including Nitroform® (United Industries, St. Louis, MO), Nutralene,® (United Industries, St. Louis, MO), Polyon® (Pursell Technologies Inc, Sylacauga, AL), IBDU® (United Industries, St. Louis, MO), and Milorganite® (Milwaukee Sewage Commission, Milwaukee, WI) were used. Information on properties and mechanisms of N release for these slow-release N sources can be found in Sartain and Kruse (2001). Ammonium nitrate was also included as a soluble N source to evaluate the precision of the release system. In excess of 96% of the N applied as ammonium nitrate was recovered in the first two leachates.

Accelerated Laboratory Extraction Procedure

An unground 30 g sample of slow-release N fertilizer was exposed to increasingly aggressive extraction procedures. Each extraction step was designed to isolate nutrients that release or become available over longer periods when compared with a reference, rapidly available nutrient fertilizer. Extraction apparatus consisted of vertical jacketed chromatography columns enclosing inner columns of 2.5 cm by 30 cm and a constant temperature water circulation manifold with pump system capable of maintaining a constant flow rate of 4 L min^{-1}. In-line thermometers were used to monitor and adjust the temperature. Each column was filled from the bottom with 475 mL of extracting solution. During extraction solution flow was upward. It was reversed for sample collection when all of the solution was pumped from the column by pumping air into the column. Four increasingly aggressive extraction sequences were utilized: 1) 2h @ 25°C with water; 2) 2h @ 60°C with 2 mL L^{-1} citric acid; 3) 16 h @ 60°C with 2 mL L^{-1} citric acid; and 4) 54 h @ 60°C with 2 mL L^{-1} citric acid. The extracts were then analyzed for total N (AOACI, 2000).

RESULTS AND DISCUSSION

Biological Activity

Cumulative amounts of NO$_3$-N, NH$_4$-N, and urea-N leached from the incubation lysimeters containing IBDU during a 180 d period are presented in Fig. 1. Nitrate-N was detected in the first 7-d leachate and continued to increase in magnitude for 140 d, after which no additional NO$_3$-N was detected. This result suggests that the urea-N in the IBDU was being converted rapidly to the NO$_3$-N form. Ammonium-N was present in the leachate for the first 42 d and urea-N was detected in only the 7-d leachate. Apparently following a short lag of 7 d, the urea N was converted to either NO$_3$-N or NH$_4$-N. Thus, it appears that the sand/soil/N-source mixture was biologically active, and adequate aeration was being maintained for nitrification to occur. The leachate pH was between 5.5 and 7.5 during the 180 d incubation period and no volatile ammonia was detected in the ammonia traps in the lysimeter head space.

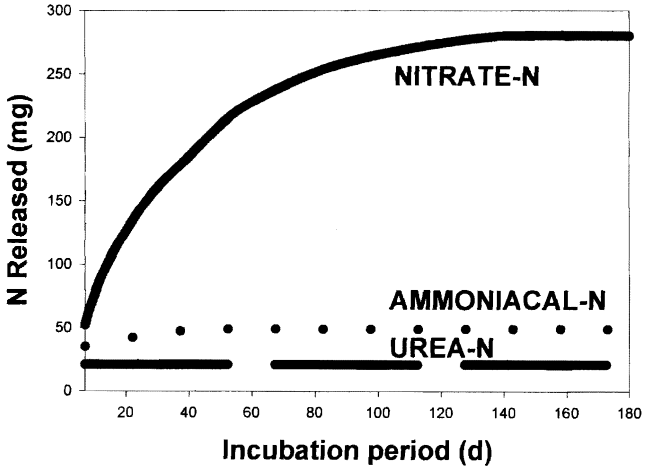

Fig. 1. Forms of N released from IBDU during 180 d incubation period.

Nitrogen Release Profile

The quantity of N detected in the leachate collected at the progressive sampling intervals was used to estimate the N-release profile for the source materials with time. Percentages of N released during 180 d of incubation for ammonium nitrate, Polyon, Nutralene and Milorganite are shown in Fig. 2. Ninety four percent of the 450 mg N applied as ammonium nitrate was accounted for in the first 7-d leachate, and by the second (14 d) 96% of the N was recovered. The polyurethane-coated Polyon slow-release N material released ~80% of the applied N within 112 d. Very little additional N was detected in the leachate of lysimeters containing Polyon after 112 d of incubation. Nutralene, a methylene urea for which the N release is based on biological activity, released N at a slower rate than did Polyon during the first 56 d of incubation. However, as was observed with Polyon very little additional N was released following 112 d of incubation. Milorganite, an anaerobically digested sewage sludge that requires biological activity for N mineralization, released only ~40% of the applied N during the 180 d incubation period, and the rate of release was much less than that of Polyon.

Approximately 20% of the total N in each of the slow-release materials was detected in the first 7 d leachate, except for Nutralene, which released 37% of the applied N in the first 7 d (Fig. 2). By 14 d incubation the rate of N release from the N sources began to diverge and different release profiles began to emerge. At 84 d incubation, 93, 90, and 82% of the total N released from Polyon, Nutralene and Miloganite, respectively, had been released. Very small quantities of additional N were released from all of the N sources during the last 70 d of incubation except for Nitroform, which released an additional 12% of its total N during this period (data not shown). Based on these findings, incubation periods >112 d may not be necessary for most slow-release N sources other than some of the methylene ureas and possibly some of the coated sources.

Correlation of Soil Incubation N Release and Accelerated Lab Extraction

Non-linear regression curves were fitted to the N release data separately for each replicate of N source (SAS, 1985). The assumed functional form of the soil incubation release curve is the non-linear equation:

$$N_t = \text{asym} - (\text{asym} - \text{int}) \cdot e^{\text{rate} \cdot t} \qquad \text{Eq. [1]}$$

where 't' equals time in days, 'N_t' equals percent N release by time t, 'asym' equals the maximum level of N released (or the asymptote of the curve), 'int' equals the intercept, and 'rate' is the rate of increase parameter. As with most regression curves, it should not be used to predict outside the range of the data; that is, outside the time interval of 7 to 180 days. In particular, the intercept of the "true" curve would be zero. Equation (1) was fitted to the release data for each of the 39 samples (three samples for each 13 fertilizer products) using the NLIN procedure in SAS.

The accelerated laboratory procedure results in four extractions, E1, E2, E3, and E4. The objective is to predict the time release curve described by equation (1); that is, for a given sample of a fertilizer product, to estimate 'asym', 'int', and 'rate' based on the data E1, E2, E3, and E4. This was done by using a multiple regression model in which E1, E2, E3 and E4 were used as "explanatory" variables, and 'asym', 'int', and 'rate' are "dependent" variables.

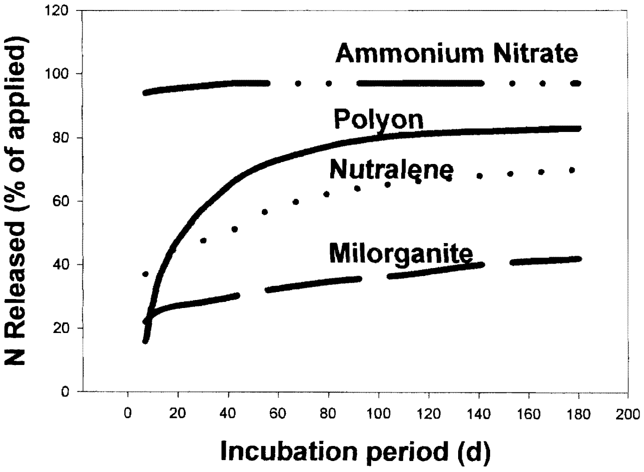

Fig. 2. Percentage of applied N released from one soluble and three slow-release N sources during 180 d incubation period.

Thus there are three multiple linear regression equations to predict each time release curve:

$$\begin{aligned} \text{asym} &= a_0 + a_1E1 + a_2E2 + a_3E3 + a_4E4 \\ \text{int} &= b_0 + b_1E1 + b_2E2 + b_3E3 + b_4E4 \qquad \text{Eq. [2]} \\ \text{Rate} &= c_0 + c_1E1 + c_2E2 + c_3E3 + c_4E4 \end{aligned}$$

In application, samples of fertilizer products from which both the time release and accelerated laboratory extraction data were obtained were used to establish the equations. The first step was to fit equation (1) to the time release data for each sample, and save the values 'asym', 'int', and 'rate'. In the second step the values of 'asym', 'int', and 'rate' and values of E1, E2, E3, and E4 for the accelerated extractions were used to fit equations (2). Then, for a fertilizer product whose time release curve was desired, values of E1, E2, E3, and E4 were obtained and inserted into the fitted equations (2) to yield predictions of asym, int, and rate. Finally, the predicted values of 'asym', 'int', and 'rate' were used to construct the estimated timed release curve for the fertilizer product. Time release data and accelerated extraction data for three samples of each of 13 fertilizer products were used to evaluate the proposed methodology. Equation (1) was fitted to time release data for each of the 39 samples, and values of 'asym', 'int', and 'rate' were obtained. An R^2, equal the sum of squared deviations about the non-linear regression divided by the sum of squared deviations for the mean, was computed for each sample. The R^2 values were > 0.99 for all but four of the samples. The other R^2 values were 0.93, 0.96, 0.96, and 0.98. Thus the curve fits the observed time release data exceedingly well. Curves for samples of the same product were similar, but curves for different products could be quite different.

Equations (2) were fitted to obtain predictions of time release curve based on the accelerated extraction data. Indicator variables for the product type were also used as independent variables in the fitted equations to account for characteristics due to the product type. In order to check the predictive ability of equations (2), data from replication 1 of each of the 13 products were not used in the fits. The time release curve predicted by equation (1) was computed with the actual time release curve for each sample. Predictive ability was assessed by computing the R^2 -type statistics equal to (SS1 - SS2)/ SS1, where SS1 equals the sum of squared differences between points on the fitted time release curve and the overall mean, and SS2 equals the sum of the squared differences between points on the fitted time release curve and pointed on the predicted time release curve. Thus, this statistic measures how much better the predicted time release curve agrees with the fitted time release curve than a straight line through the mean agrees with the fitted time release curve. A value of 1 indicates the predicted curve is exactly the same as the fitted curve, and a value of 0 indicates that the predicted curve fits no better than a horizontal line. It is possible for the statistic to be negative, when the horizontal line actually agrees with the fitted curve better than the predicted curve.

As an example, for Polyon this relationship was found to fit the replication 2 and 3 soil incubation nitrogen release data with an $R^2 = 0.995$ (Fig. 3). Predictions of the non-linear regression parameters were computed from the accelerated laboratory extraction data for all replications. R^2 replication 2 for the non-linear regression of the accelerated laboratory extraction data was 0.99 (Fig. 3). Comparisons of non-linear regression curves with soil replicate 1 indicated how well the accelerated laboratory extraction data predicted the actual N release curve when release data were not known. This comparison for Polyon using replicate 1 data produced an $R^2 = 0.90$ (Fig. 4). This suggests that the accelerated laboratory extraction data can predict the N release from Polyon with time with an accuracy of 90%. This is recognized as a strong relationship considering the limited data points employed as well as the sampling and analytical variances. The relationship is specific to the material being evaluated, but as more data are generated it is hoped that a general relationship can be identified. Based on the initial results, at least a grouping of the slow release N sources relative to material type may be achievable.

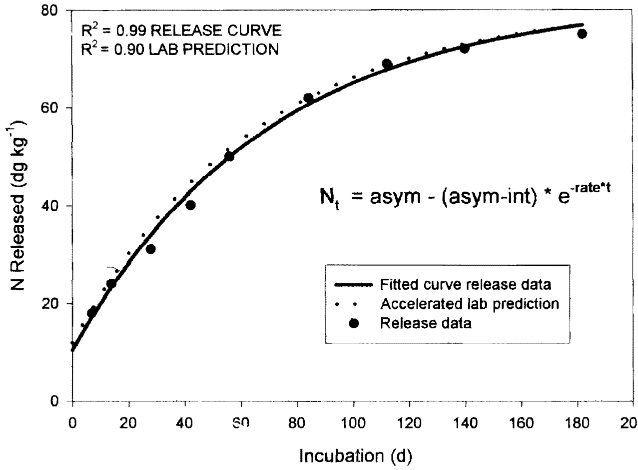

Fig. 3. Relationships between soil incubation N release and accelerated laboratory extraction data for Polyon using replicate 2 and 3.

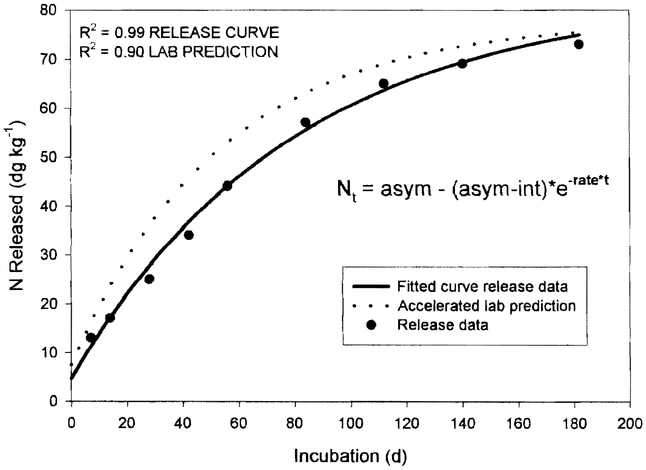

Fig. 4. Laboratory extraction data from replicate 1 were used to predict N released from Polyon during a 180 d period.

CONCLUSIONS

It appears that the accelerated laboratory extraction procedure can be used to predict the N release rate of slow-release N sources with acceptable accuracy ($R^2 > 0.90$). The accelerated laboratory extraction procedure is reproducible, having an average CV= 3.2%. The soil incubation N release methodology has a CV = 9.1% and can be expressed as a non-linear regression function ($N_t = \text{asym} - (\text{asym-int}) * e^{-\text{rate}*t}$) with an $R^2 = 0.99$. Nitrification is occurring due to the predominance of nitrate N in the leachates of urea source materials, which suggests that the soil incubation lysimeters are being maintained in an aerobic manner that is micro biologically active.

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Evaluation of Physical and Chemical Methods for Alleviating Soil-Water Repellency in Turfgrass in Florida

George H. Snyder* and John L. Cisar

ABSTRACT

Soil water repellency creates a difficult management problem for turfgrasses grown on sand soils. Studies were conducted in Florida to evaluate physical incorporation of soil amendments and chemical surfactant applications to overcome water repellency in sand soils cropped with bermudagrass [*Cynodon dactylon* (L.) Pers.] turf. In an attempt to improve water penetration and distribution in highly water repellent native sand soil, the following treatments were applied separately: rototilled incorporation of several rates of an organic (Greenlife Pine Bark Soil Conditioner) and inorganic (finely-divided Emathlite clay) soil amendment, rototilling alone, and surface applications of wetting agents (AquaGro, Water Mate, and Solare 25). Visual examination of dye-stained profiles was superior to infiltration measurements for treatment evaluation. Plots receiving the clay amendment at ≥30 g kg^{-1} gave satisfactory moisture distribution through an 11-yr evaluation period, whereas those receiving other treatments retained their characteristic water repellency. A single application of the wetting agents (AquaGro, Water Mate, and Solare 25) at 3.2 to 5.1 mL m^{-2} followed by 5 and 10-cm irrigations, or 5 applications at 3.2 mL m^{-2} each over a period of 8 wk with 50-cm rain and irrigation during this period did not improve moisture distribution. A second surfactant study investigated five surfactants (Primer, Aqueduct, Aquifer, Respond, and LescoFlo) and a control for alleviating soil water repellency on a constructed sand-based green. Treatments were applied twice at 1 wk intervals after localized dry spots (LDS) were apparent on the green. Compared to the control, surfactants provided more rapid improvement in turf quality and reduced the LDS in plots, and reduced water-drop penetration time up to 4 wk after application.

INTRODUCTION

Soil water repellency has been reported in various places throughout the world. For example, it has been reported in Australia (Bond, 1964), Florida (Jamison, 1946; Wander, 1949), England (Hill, 1934), California (Krammes and DeBano, 1965), and New Zealand (Vant Woudt, 1954). The authors have observed it in the Bahamas, Hawaii, Puerto Rico, Ireland, and Colombia. But few investigators have extensively studied this phenomenon.

Water repellent soils remain dry after rainfall and irrigation. Generally, irregular dry regions remain in the soil mass and all water passes through vertical channels between these dry regions.

To determine the presence of water repellent soil in the field, the water drop test often is used. A drop of water is placed on a sample of soil to see if the water remains in the form of a drop on the soil surface, indicating a water repellent soil (Fig. 1).

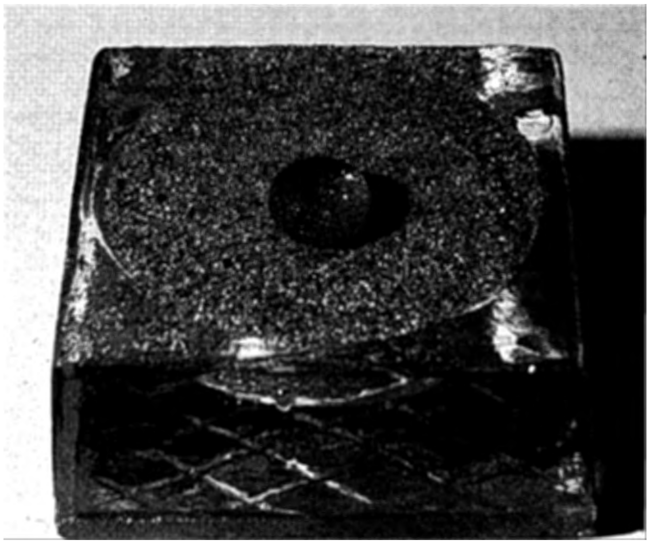

Fig. 1. Water drop on unconsolidated water repellent sand.

The factor causing the repellency has not been well determined, but it is assumed to be a waxy or oily layer on the soil particles. Savage (1969) found an alifatic hydrocarbon and attributed water repellency to it. Bond and Harris (1964) attribute the repellency to fungal mycelium or its metabolites, and Bond and Hammond (1970) presented scanning electron micrographs showing organic coating on water repellent sand grains.

The factors which favor water repellency are poorly defined at present. Wander (1949) concluded that moderate pH (5.8 or higher) and high Mg are required for its development, although Hill (1934) observed it when ammonium sulfate fertilizer was used, which could lead to very acid soil and perhaps reduce soil Mg. Bond (1969) did not consider pH and Ca level to be important factors. It appears that the repellency is favored by long dry periods and by sand texture (Bond, 1969). Water repellency of organic soils is probably caused by factors much different from those causing repellency in mineral soils, and is not discussed herein.

Generally, it is difficult to determine the degree to which water repellency affects crop production, but it is clear that it reduces the water holding capacity of the soil. Bond (1972) documented cases of much reduced seed germination in water repellent soils. DeBano et al. (1967) demonstrated how mud slides in California are encouraged by a layer of water repellent soil below the surface. Water repellency in turfgrass leads to visually very obvious LDS which reduce turf quality.

The principle of water repellency also can be beneficial. Using Dow-Corning 772 water repellent (Dow-Corning, Midland, MI) to create a layer of water repellent soil over a fertilizer band, the senior author has

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Distinguished Professor, Emeritus. Univ. of Florida, Everglades Res. and Educ. Center, Belle Glade, FL 33430, and Professor, Univ. of Florida, Ft. Lauderdale Res. and Educ. Center, Ft. Lauderdale, FL 33314, respectively. This research was supported by the Florida Agric. Exp. Stn., and is approved for publication as Journal Series No. N- 02537. Contribution published in

*Corresponding author (ghs@ifas.ufl.edu).

Soil Crop Sci. Soc. Florida Proc. 63:76-84 (2004).

been able to reduce fertilizer leaching and by this increase corn production (Snyder and Ozaki, 1971; Snyder et al., 1974).

Since water repellency is most often observed in sand soils, containing little organic matter or clay, an experiment was designed to see if adding organic matter and clay would overcome the repellency of a fine sand in Ft. Lauderdale, FL. In addition, studies were conducted using surfactants, also called wetting agents, which reduce the surface tension of water, and have been suggested for wetting water repellent soils and reducing LDS symptoms in turfgrass (Cisar et al., 1999).

METHODS AND MATERIALS

Soil Amendment Study

At the University of Florida, Ft. Lauderdale Plantation Field Laboratory, a shredded pine bark (Greenlife Pine Bark Soil Conditioner, Greenlife Products Co., West Point, VA) was rototill-incorporated in mid-August 1968 in plots 3 m by 3 m to a depth of 15 cm at rates of 20, 50, 100, or 200 mL L^{-1} in a Margate fine sand (siliceous, hyperthermic Mollic Psammaquent). A finely-divided Ca-montmorillonite clay (Emathlite VMP-3000, Mid-Florida Mining Co., Lowell, FL) was similarly incorporated at 10, 30, and 50 g kg^{-1} at the same time. A rototilled plot, which only received soil mixing, and a check plot that was not mixed were included in the study. All of the treatments were replicated in three randomized complete blocks. Bermudagrass re-established itself and was conventionally maintained as a turfgrass. In February 1969, following a dry period, the plots were evaluated for water infiltration rate. A steel ring 15-cm diam. was pressed 5 cm into the soil of each plot, leaving 5 cm above the surface of the soil. Water was poured into the ring and maintained at a depth of 2.5 cm. The quantity of water entering the soil during each 5-min interval was noted until 2400 mL of water (136 mm) penetrated the soil. Then the ring and a 15-cm diam. by 28-cm deep cylinder of soil below the position of the ring was removed. The cylinder of soil was split lengthwise to reveal the profile. This profile was sprinkled with a dust composed of finely-ground kaolinite clay containing Rhodamine B dye (10 mL L^{-1}) that turned red in contact with moist soil and remained white in contact with dry soil (Bond, 1964). Photographs were made of the profiles. The samples were returned to their places in the plots. The same method of evaluation was used in May 1969, except the rate of infiltration was not recorded. In addition to visually examining extracted soil cores, a moisture detector (Fig. 2) based on the Moisture Scout® (Soil Test, Inc., Evanston, IL) but with 18.5-cm probes, insulated except at their tips, was used to locate regions of dry soil below the infiltration rings, and at other times after rainfall and irrigation. Periodic water drop tests confirmed that the dry soil located with the moisture detector was water repellent. Selected plots were evaluated in this manner, or by visually examining the soil profile with dye, for 11 yr after incorporation of the amendments. Treatments that previously had failed to alleviate water repellency were not evaluated throughout the full study period. Turfgrass clipping weights taken with a tee mower were measured from May to September 1970, 2 yr following amendment incorporation. Data were analyzed by the SAS ANOVA or GLM procedures, with mean separation indicated by LSD ($P < 0.05$) (SAS, 1985).

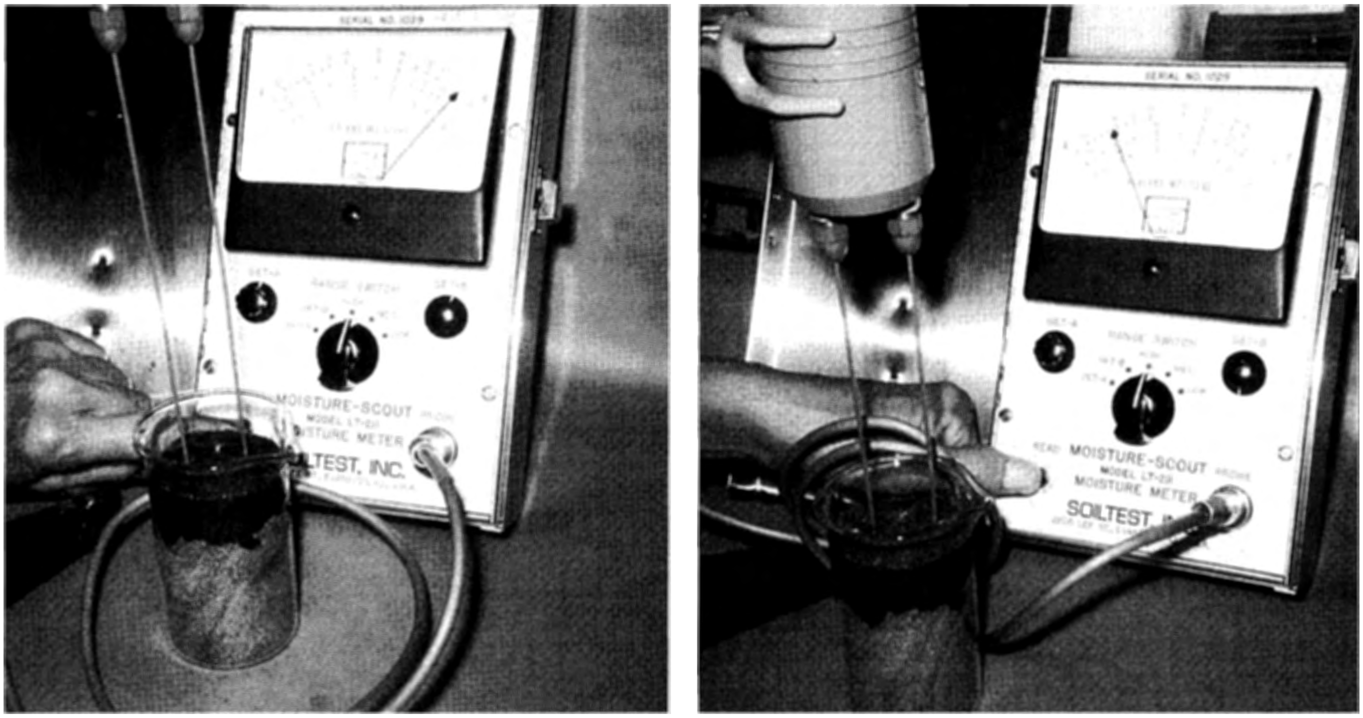

Fig. 2. Moisture probe device used to detect dry regions in the soil. Left: Probe tips in moist soil in top layer in beaker providing a high reading (needle to right), and Right: probe tips in dry soil in lower layer in beaker providing a low reading (needle to left).

Surfactant Experiments—Native Soil

A wetting agent experiment was conducted on a circular plot of Margate fine sand with a radius of 4.5 m, divided like a pie into 12 pieces, making three replications of four treatments. The treatments were: AquaGro at 5.1 mL m^{-2} (Aquatrols, Inc., Cherry Hill, NJ), Water Mate at 3.2 mL m^{-2} (Weyerhaeuser Co., Tacoma, WA), Solar 25 at 5.1 mL m^{-2} (Swift & Co., Chicago, IL), and a check plot which received no wetting agent. These materials were sprayed on the plot surfaces in March, 1969, using ~700 mL m^{-2} solution and were followed by 5 cm of irrigation from a full-circle sprinkler head placed in the center of the plot. The plots then were evaluated as previously described by visually examining removed cylinders of soil, and by using the moisture detector. The following day a second 5 cm of irrigation was applied and the plots were again evaluated. About 2 mo later, the same materials were applied to the same plots at 3.2 mL m^{-2} each 2 wk for 10 applications. Rainfall was supplemented when necessary with irrigation to apply a total of 6 cm wk^{-1}. During the course of the study there was 126 cm of rainfall and irrigation. The plots were evaluated weekly with the moisture detector and several times during the study cylinders of soil were removed and stained for visual evaluation.

In another experiment conducted adjacent to the above in April, 1969, 12 infiltration rings were pressed into the soil. To each ring was added 463 mL (2.6 cm) of AquaGro at 0 to 12.5 ml L^{-1}. The time required for the water to completely penetrate the soil was recorded and the profiles were examined to observe the distribution of the water within the profile. Data were analyzed for regression by the SAS GLM procedure (SAS, 1985).

Surfactant Experiments—Constructed Golf Green

The experiment was conducted during a spring dry season on a United States Golf Association (USGA) specification cv. Tifdwarf bermudagrass (*Cynodon dactylon* × *C. transvaalensis* Burtt-Davy) green at the Ft. Lauderdale Res. and Edu. Center that had over 50% LDS. Detailed physical characteristics and organic matter content of the green have been reported by Cisar et al. (1999). Surfactant treatments consisted of Aqueduct (Aquatrols, Inc., Cherry Hill, NJ) at 2.5 mL m^{-2}, Aquifer (Aqua-Aid, Inc., White Marsh, MD) at 2.5 mL m^{-2}, Lesco-Flo (LESCO, Rocky River, OH) at 2.5 mL m^{-2}, Primer (Aquatrols, Inc., Cherry Hill, NJ), at 1.9 mL m^{-2}, and Respond (United Horticultural Supply, Inc., Fremont, NH) at 1.0 mL m^{-2}. A control treatment receiving no surfactant also was included in the study. There were six randomized, complete blocks of all treatments. The surfactants were applied on 5 and 12 Apr. 1999, with a CO_2 backpack-type sprayer to 1 m^{-2} plots sprayed with a final volume of 80 mL m^{-2}. Only the surfactant Respond was labeled to require irrigation (0.6 cm) immediately after spraying. Following the first application, all plot areas received routine irrigation of 0.6 cm daily.

Turfgrass quality and percent appearance of LDS were determined throughout an ~2-wk period. Rainfall for the period totaled 0.2 cm. Between 22 Apr. and 3 May 1999, daily irrigation was reduced to 0.3 cm to encourage the re-appearance of LDS symptoms. Rainfall totaled 0.2 cm during this period. Once LDS symptoms were observed, daily irrigation was increased to 0.6 cm and turfgrass performance was once again determined between 3 and 7 May 1999. Treatments were evaluated for their effect on turf quality and LDS. On 10 May, daily irrigation was reduced to 0.3 cm to encourage LDS symptoms and the effect of treatment on turfgrass quality and percentage LDS was again determined. Rain during the period totaled 2.3 cm. Soil cores were removed from plots for evaluation of water drop penetration time (WDPT) before the first surfactant application on 5 April, and post-treatment on 22 Apr. and 6 May 1999. WDPT was determined by placing a 36 µL drop of deionized water on the soil core at 1-cm intervals to a depth of 6 cm and determining the time required for complete entry into the soil. All data were subjected to ANOVA procedures and significant means were identified using Duncan's Multiple Range Test (SAS, 1985).

RESULTS AND DISCUSSION

Soil Amendment Study

Differences in clipping weights were not observed on 14 of the 16 clipping dates from 5 May through 1 Sept. 1970 (data not presented). On the two dates for which significant differences were observed, the greater clipping weights were obtained in the clay-amended plots (Table 1).

Although the mean time required for 13.6-cm infiltration ranged from 22 to 46 min, there were not significant ($P < 0.05$) differences among treatments in the rate of infiltration in February 1969, 6 mo after amendment incorporation (data not presented). But clear differences were observed in the distribution of water in the profiles below the area of infiltration (Fig. 3). For clay amendment at 30 and 50 g kg^{-1}, water was distributed throughout the profile. By contrast, in plots receiving pine bark, or in unamended plots, regions of dry soil generally were encountered. Considerable difference in infiltration rate was noted among check plots, which appeared to be related to the chance movement of infiltrating water down channels, and not due to wetting of the entire soil mass (Fig. 4). The same phenomenon was observed for the pine bark treatments (not shown). Similar conclusions were drawn from additional profile examinations over time, and from the

Table 1. Effect of amendment on clipping weights at two dates in 1970 when significant treatment effects were observed.

Treatment	8 July	24 July
	g $plot^{-1}$	
Pine bark (200 mL L^{-1})	9.9	10.3
Fine clay (10 g kg^{-1})	14.2	16.4
Fine clay (30 g kg^{-1})	14.8	16.3
Fine clay (50 g kg^{-1})	22.2	21.9
No amendment, soil mixed	9.2	9.7
No amendment, soil undisturbed	8.4	8.5
LSD ($P < 0.05$)	4.6	3.8

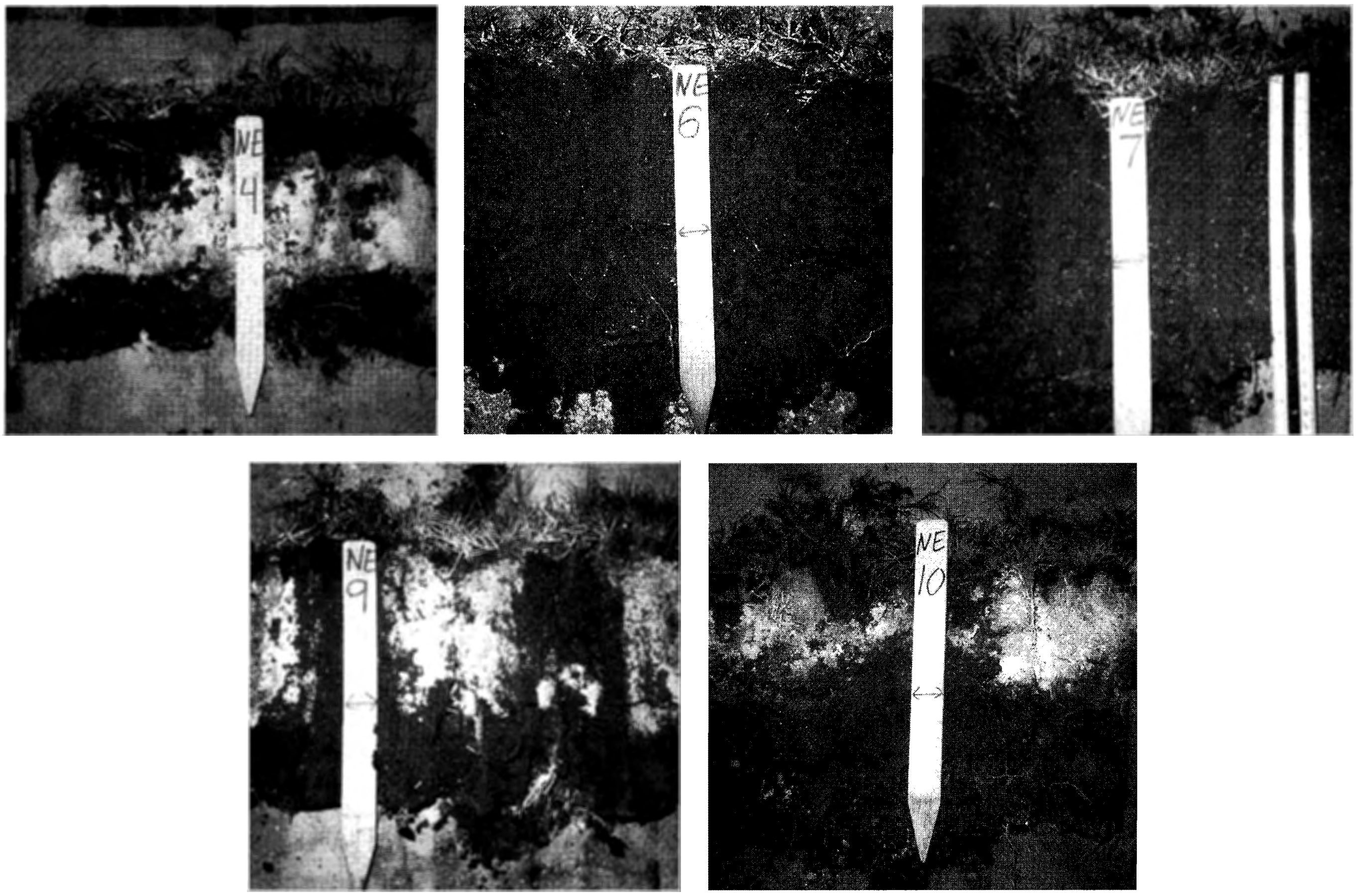

Fig. 3. Areas of dry soil following water infiltration showing in white for the treatments: (top, left to right) Pinebark at 200 mL L^{-1}, clay at 30 g kg^{-1}, clay at 50 g kg^{-1}, (bottom, left to right) soil mixed by rototilling, and soil undisturbed. Dark regions are moist.

moisture probe evaluations throughout the first 6 yr of the study (Table 2). No dry areas were found for clay incorporation at 50 g kg^{-1}. Eleven years after clay incorporation (March 1979), no large areas of dry, water-repellent soil were observed in plots receiving 30 and 50 g clay kg^{-1} soil, and none at all were observed at 50 g clay kg^{-1} soil, whereas the check plots were very dry and highly water repellent (Table 3).

It is emphasized that the presence or absence of water repellent soil in the plots did not influence the rate of infiltration in this study. Being a Mollic Psammaquent, the Margate soil had considerable organic matter in the top 2 to 3 cm, but had little below this layer. The infiltration rate, which was ~12 cm h^{-1}, could have been controlled primarily by this layer. Below this, the unamended soil probably had an infiltration rate of 40 cm h^{-1}, when moist, so that although the water only moved in a few vertical channels in the plots not receiving clay, these channels were easily able to carry all the water coming from the upper 2 to 3 cm. Nevertheless, it is important to observe that although the water moved into the soil, large portions of soil were left dry. So the water holding capacity of the entire soil mass was reduced in direct proportion to the volume of soil left dry. In addition, it is interesting to note that in the water repellent soil, infiltration into the initially dry soil increased with time (Fig. 4, top), whereas in most dry soils initial infiltration is rapid and then decreases somewhat over time (Brady and Weil, 1999). It appears that in the water repellent soil, infiltration is slow until a water-conducting channel forms and then the rate of infiltration increases.

Surfactant Experiment—Native Soil

Even after repeat applications of surfactant to the native fine sand soil, dry regions remained in all the plots regardless of treatment (Fig. 5). Increasing the concentration of AquaGro wetting agent in infiltrating water in the second experiment reduced infiltration time from 28 to 1.3 min (Table 4), but a large portion of soil below the ring remained dry in all cases (Fig. 6). Thus it appeared that the wetting agent increased water movement through channels between dry, water repellent areas of soil, but did not greatly improve water movement into these areas. In each examination, when the soil was found dry after an irrigation, it also was found to be water repellent by the water-drop test.

Valoras et al. (1969) have demonstrated that some wetting agents are superior for initially wetting a water repellent soil, while others are more beneficial for re-wetting the soil. AquaGro is one of the latter, and is strongly retained by the soil. We have no data of this type for the other materials used. If the soils were once wetted, and the wetting agents were then applied, perhaps some of

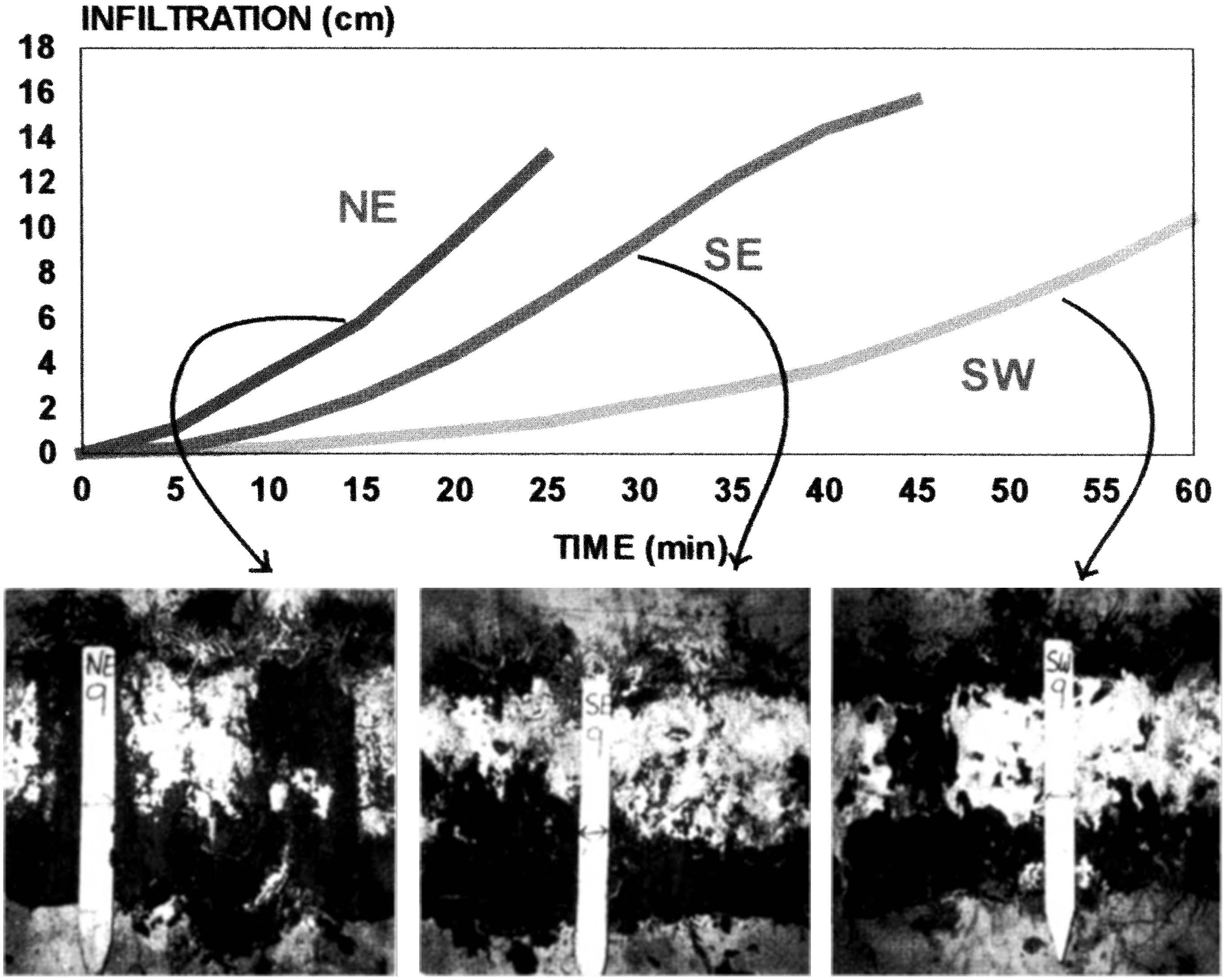

Fig. 4. Top: Infiltration rate varied considerably among replications of the unamended, but mixed, soil. Bottom: Substantial regions of the soil profile remained dry after infiltration (white areas), indicating that water movement occurred in specific channels within the profile rather than throughout the profile.

these materials would be moved into the soil and then be beneficial for re-wetting the soil after drying. Clearly, in these studies, when the water once moved downward in the form of vertical channels, the remaining soil remained dry. It is important to note that the mere entry of water into the soil does not show that the soil is wetted completely. One must examine the profile to determine whether the entire mass of the soil is wetted.

Table 2. Frequency of dry spot occurrence on various dates over a 5-yr period following amendment incorporation.

Treatment	16 Dec 1968	29 Apr 1969	9 Mar 1970	10 May 1973
	%			
Pine bark (20 mL L^{-1})	45	30	100	—
Pine bark (50 mL L^{-1})	75	60	86	—
Pine bark (100 mL^{-1})	65	60	100	100
Pine bark (200 mL L^{-1})	75	60	100	100
Fine clay (10 g kg^{-1})	0	0	33	50
Fine clay (30 g kg^{-1})	0	33	20	26
Fine clay (50 g kg^{-1})	0	0	0	0
No amendment, soil mixed	40	90	100	90
No amendment, soil undisturbed	85	57	100	93
LSD ($P < 0.05$)	50	42	26	28

Table 3. Visual estimation of the soil profile area remaining dry in Mar. 1979, 11 yr after amendment incorporation.

Fine clay g kg^{-1}	Replication A	Replication B	Replication C
	Dry area %		
0	100	100	100
10	0	50	0
30	20	0	10
50	0	0	0

Surfactant Experiments—Constructed Golf Green

Prior to the first surfactant application on 5 Apr. 1999, LDS symptoms were severe in the experimental area (data not presented). On 14 Apr. 1999, 2 d after the second application of the surfactants, Respond and Primer treated plots had less LDS than the control plots (Table 5). Irrigation was reduced on 22 April from 0.6 to 0.3 cm d^{-1}. On 25 April, there were no differences in LDS among treatments, and LDS averaged 53%. However, on three dates in early May, following resumption of irrigation at 0.6 cm d^{-1} on 3 May, less LDS was observed for Primer than for the control, and less LDS was observed for Aquifer than for the control on two dates (Table 5). No significant differences were observed thereafter.

In contrast to the native Margate soil, which is a moderately deep (50-100 cm) fine sand, the USGA specification green has a textural discontinuity (finer texture above, coarser texture below) at a depth of 30 cm. For this reason, more moisture is retained in the soil profile, particularly in the lower portion nearer the textural discontinuity, than would otherwise occur for a deeper soil of the same texture. The WDPT, which indicates water repellent soil, was much less at depths of >5 cm (Tables 6-8), probably because the soil at this depth does not endure the severe drying conditions that encourage water repellency. Root growth in closely-mowed greens generally is fairly shallow, so most moisture is withdrawn by the turf from the upper several centimeters of the soil and water repellency tends to be more of a problem in this region. The pre-treatment WDPT values were consistent with these trends (Table 6). Following application of the surfactants, significant WDPT reductions were observed for some surfactants in the upper few centimeters of the soil profile (Tables 7, 8). Relative to the control, the greatest and most consistent reductions were observed for Primer and Aqueduct.

Table 4. Time for penetration of 2.6 cm of water containing a range of concentrations of AquaGro wetting agent.

Concentration mL L^{-1}	Time min
0	28
0.00125	12.5
0.005	19.6
0.025	13.3
0.075	13.0
0.125	12.0
0.25	13.0
0.5	10.8
1.25	3.5
2.5	2.3
5.0	2.3
12.5	1.3
Regression analysis	
Linear	*†
Quadratic	*

†* is $P < 0.05$.

Applying the Wetting Agent Study Results

Golf course greenskeepers managing turfgrass on USGA greens often are faced with poor quality turfgrass from water stress and soil water repellency. They attempt to limit irrigation to create challenging putting performance on greens. However, once LDS occurs, they then often will make frequent applications of water and/or surfactants to encourage turf recovery from water stress. Based on our research, greenskeepers appear to have several choices for obtaining turfgrass recovery. Applying sufficient irrigation alone will alleviate stress

Fig. 5. Dry, water repellent soil (shown as white areas) remaining after 10 applications of wetting agent (left to right: AquaGro, Water Mate, Solar 25) and 126 cm irrigation and rainfall.

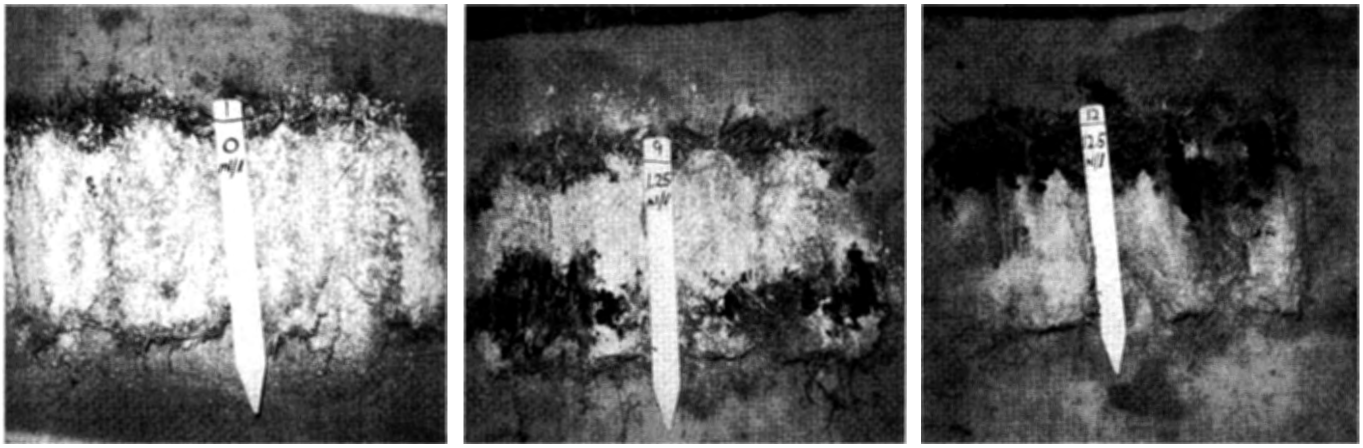

Fig. 6. Dry, water repellent soil (shown as white areas) following infiltration of 2.6 cm water containing (left to right) 0, 1.25, and 12.5 mL Aqua-Gro L^{-1}.

and result in improved turf quality and reduce LDS symptoms over time. Surfactants can, in certain cases, provide more rapid improvement. The surfactants evaluated in this experiment ranged from products with suggested routine monthly applications intervals, such as Primer, to LescoFlo, a product that has a recommended application interval of 4 mo. Cisar et al. (1999) reported that application of surfactants before the onset of soil water repellency symptoms can provide better turfgrass quality and reduced LDS incidence. This experiment suggests that greenskeepers can get some benefit from any of the tested surfactants to alleviate the stress and symptoms of soil water repellency. The surfactant benefit in this specific experiment was short term; ≤4 wk. Furthermore, WDPT results suggested that the surfactants were having their greatest effect at the soil surface and in the upper 3 cm of the soil profile of a USGA green.

Table 5. Effect of surfactant application on percentage localized dry spot (LDS) in a golf green during Apr. and May 1999.

	Date (month/day)									
Treatment	4/5	4/7	4/14	4/25	5/3	5/4	5/6	5/7	5/17	5/18
	%									
Aqueduct	67	61 a†	16 ab	53	61 bc	23 ab	20 ab	13	34	43
Lescoflo	63	60 a	18 ab	73	86 a	42 a	31 a	18	38	60
Aquifer	63	63 a	10 ab	48	59 ab	18 b	10 b	7	23	43
Respond	62	40 b	1 b	41	78 ab	34 ab	24 ab	14	25	43
Primer	66	46 ab	6 b	55	47 c	13 b	12 b	12	34	53
Control	62	55 ab	26 a	48	82 ab	44 a	27 a	11	29	43
Significance	ns‡	§	§	ns	**	*	*	ns	ns	ns

†Means within a column with the same letter are not significantly different by the Duncan's Multiple Range Test ($P > 0.05$).

‡ns, $P > 0.1$.

§*, ** are $P < 0.1$, 0.05, and 0.01, respectively.

Table 6. Pre-surfactant application water drop penetration time (WDPT) in seconds on soil cores taken from a golf green on 5 Apr. 1999.

	Depth						
Treatment	0	1	2	3	4	5	6
	cm						
Aqueduct	105	146	161	117	47	31	36
LescoFlo	100	174	127	122	36	26	10
Aquifer	124	288	208	115	35	16	3
Respond	123	139	131	143	26	12	13
Primer	141	208	145	104	46	9	1
No surfactant	170	226	204	98	60	23	30
Significance	ns†	ns	ns	ns	ns	ns	ns

†ns, $P > 0.10$.

Table 7. Effect of surfactant application on water drop penetration time (WDPT) in seconds on soil cores taken from a golf green on 22 Apr. 1999.

	Depth						
Treatment	0	1	2	3	4	5	6
	cm						
Aqueduct	36 c†	66 c	113 ab	96	58	37	7
LescoFlo	171 ab	205 a	208 a	145	73	36	17
Aquifer	66 bc	107 bc	112 ab	75	55	20	7
Respond	216 a	235 a	144 ab	105	74	53	4
Primer	28 c	67 c	51 b	83	64	42	6
No surfactant	228 a	195 ab	214 a	170	146	36	12
Significance	**‡	**	*	ns	ns	ns	ns

†Means within a column with the same letter are not significantly different by the Duncan's Multiple Range Test ($P > 0.05$).
‡ns, $P > 0.1$.
§*, ** are $P < 0.05$ and 0.01, respectively.

Table 8. Effect of surfactant application on water drop penetration time (WDPT) in seconds on soil cores taken from a golf green on 6 May 1999.

	Depth						
Treatment	0	1	2	3	4	5	6
	cm						
Aqueduct	52 b†	66 b	78	72	45	25	28
LescoFlo	73 ab	151 a	120	97	35	28	2
Aquifer	85 ab	61 b	33	39	43	20	12
Respond	116 a	193 a	103	52	32	11	3
Primer	31 b	62 b	24	25	24	14	0
No surfactant	86 ab	137 ab	119	63	50	16	4
Significance	*‡	**	ns	ns	ns	ns	ns

†Means within a column with the same letter are not significantly different by the Duncan's Multiple Range Test ($P > 0.05$).
‡ns, $P > 0.1$.
§*, ** are $P < 0.05$ and 0.01, respectively.

CONCLUSIONS

Soil amendments and surfactants were used in an attempt to overcome the water repellency of a Margate find sand and a USGA green. The longest-term results were obtained by the incorporation of clay at 30 to 50 g kg^{-1}. Dry regions remained in the soil mass after rainfall and irrigations except when treated with the clay. Surfactants provided short-term alleviation of LDS and water repellency in turf. A hydrophilic clay provides an attraction for water that encourages its movement into dry areas as unsaturated flow, thus breaking down water repellency. Surfactants reduce the affinity of water for soil particles, which decreases movement of water as unsaturated flow throughout a water repellent soil mass. However, reduction of water surface tension can improve penetration of water as saturated flow into specific channels in soil, thereby increasing the infiltration rate even thoughthe entire soil mass may not be wetted.

ACKNOWLEDGMENT

Dr. David Hubbel, former Professor of Microbiology in the Soil and Water Science Dep. at the University of Florida, maintained an active interest in soil water repellency throughout much of his career. He strongly encouraged the senior author to present his findings on the subject at a Soil and Crop Science Society of Florida annual conference. This paper is presented in memory of David, his encouragement and his friendship. Technical assistance was provided by Ms. Carrie Martin, Mr. David Pitkins, Ms. Karen Williams, and Mr. Norman Harrison.

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Stormwater Runoff from Phosphatic Clay Soil-Treatment and Estimated Cost

J. A. Stricker

ABSTRACT

The objective was to increase awareness of water quality issues related to phosphatic clay soils, determine if a stormwater treatment system could be designed for the interior of a clay settling area, and to estimate the cost of installing the system. As part of the mining process, phosphatic clay is pumped into settling areas ranging from 121 to 324 ha (300-800 acre). Once reclaimed, clay settling areas have potential for intensive crop production. Before cropping, drainage systems consisting of wide beds with ~2% slopes are needed on flat areas. Earlier research demonstrated that stormwater runoff from cropped areas with ~2% slope was high in suspended solids and associated P. An engineering consulting firm selected a representative reclaimed clay settling area and designed both passive and chemical water treatment systems. The engineering firm determined that an Environmental Resource Permit (ERP) from the Southwest Florida Water Management District (SWFWMD) and Florida Dept. of Environmental Protection (FDEP) would be required. Both water quality and quantity criteria must be met to secure an ERP. An on-line treatment system was designed that met ERP criteria. In addition, should water quality standards for P be established for the Peace River, a chemical treatment system was designed. The cost of the on-line treatment system totaled \$27 000 or \$210 ha^{-1} (\$85 acre^{-1}). Estimated cost for the chemical treatment system, including supplying electrical power, was \$95 000. Total cost for the two systems was \$122 000 or \$951 ha^{-1} (\$385 acre^{-1}). The additional cost of installing a stormwater treatment system could be a determining factor for a landowner making a decision to develop a clay settling area for intensive agriculture.

INTRODUCTION

Phosphate was first discovered in the Peace River near Arcadia, FL in 1881 and mining has continued since that time (Hood, 1984). Phosphate ore occurs in a matrix of sand, clay, and phosphate in about equal proportions. Before mining, the phosphate matrix is covered with overburden which is made up of sand and clay ranging in thickness from 1.8 to 18 m (6-60 ft). In the mining process, large draglines remove the overburden from the top of the phosphate matrix and deposit it in adjacent mined areas. The dragline then scoops up the matrix and deposits it in a pit beside the mine cut. High pressure water is then used to make a slurry of the matrix. The matrix slurry is pumped to a beneficiation plant where the clay is separated and pumped to settling areas at 30 to 50 g L^{-1} solids. The sand is pumped to fill mine cuts, and the phosphate ore is stockpiled in preparation for shipping. By the end of 1998, a total of 119 180 ha (294 500 acre) had been mined in Florida (Stricker, 2000). Clay settling areas cover ~40% of the mined area or ~48 560 ha (120 000 acre) (Roger Martin & Steve Partney, FL. DEP, Bureau of Mine Reclamation, Tallahassee, 5 Jan. 2000, personal communication).

Individual clay settling areas vary from 121 to 324 ha (300-800 acre). After the phosphatic clay is pumped to the settling area, water is decanted and reused. The clay consolidates to 120 to 150 g L^{-1} solids in 3 to 30 mo (Zang and Abarelli, 1995). Depth of the clay can vary from 1 m to >18 m (3 -60 ft). Phosphatic clay consists mostly of particles <2 µ in size with about half <0.2 µ. Phosphate minerals, mainly apatite, make up the medium-size fractions while clay minerals, mainly montmorillonite, make up the finer fractions. Composition of phosphatic clay includes 500 to 600 g clay L^{-1}, 300 to 400 g quartz L^{-1}, and 20 to 50 g heavy minerals L^{-1} and miscellaneous (Hawkins, 1973).

A 10-yr research program (Hanlon et al., 1996) proved that phosphatic clay soil can support intensive agricultural production. Phosphatic clay soil is highly fertile with high water holding capacity compared with native sandy soils. A wide variety of crops may be produced with no additional fertilization for most legumes and only N fertilizer for non-legume crops. Surface drainage is needed because of slow infiltration rate and

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J. A. Stricker, Univ. of Florida, Polk Co. Coop. Ext. Ser., Bartow, FL 33831-9005

This research was supported by the Florida Agric. Exp. Stn. and a grant from the Florida Institute of Phosphate Research and the Polk County Board of County Commissioners and is approved for publication as Journal Series No. N-02495.

Correspondence: jstricker@ifas.ufl.edu.

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:84-88 (2004).

the resulting tendency for water to pond on the surface. To achieve drainage on flat areas, construction of a landform referred to as a macrobed was found most effective (Hanlon et al., 1994). Although the actual design for macrobeds is flexible, the macrobeds built as part of the research program were 61 m (200 ft) wide with a center height of 46 to 61 cm (1.5-2 ft). The resulting slope on the macrobeds was 1.5 to 2%.

Stormwater runoff from phosphatic clay soil with ~2% slope was studied for a 2-yr period with two cropping systems. One had permanent bermudagrass *Cynodon dactylon* L. cover and the second a corn (*Zea mays* L.)/wheat (*Triticum aestivum* L.) rotation (Haman et al., 2001). Drainage for each 1.2 ha (3 acre) field was isolated and directed to discreet discharge points. The discharge points were equipped with flumes to measure the quantity of discharge and sampling equipment for water quality determination.

A settling pond was built to collect runoff from both fields using current USDA-NRCS design criteria. Automated sampling equipment was installed at inflow and outflow ends of the pond to sample for water quality analysis.

Only three runoff events were recorded from the bermudagrass field. The first two events were temporally related. Because the first rain event had an impact on the runoff from the second event, it was not possible to separate the two rain events for proper analysis. The other runoff event contained elevated concentrations of sediment and nutrients compared to the first. Additional runoff events were recorded for the cornfield. Measurements of N were low and below regulatory concern, however, sediment and P from the cornfield were 2 to >6 times the concentration found in the runoff from the bermudagrass field. The P was found to be associated with suspended solids in the water column. When a runoff event occurred, both sediment and total P were of environmental concern. Sediment and total P from the corn/wheat rotation field was higher than that from the bermudagrass field. If phosphatic clay soil is to be used for intensive row crop production, a system for mitigating the environmental impact will be needed.

The settling pond provided little retention time and did nothing for water quality improvement. Retention time was too short to permit natural settling. Suspended clay solids in runoff water, should they be released, would be of environmental concern.

Chemical treatment would likely improve water quality of stormwater runoff by coagulating clay particles, allowing them to settle out of the water column. Three compounds were studied: ferric chloride, ferric sulfate, and alum. It was determined that all compounds were effective in total phosphorus (TP) removal <1 mg kg^{-1} using basic chemical techniques. Alum was found to be the most effective coagulant.

Phosphatic clay soils are fertile and have good water holding capacity with potential for intensive agriculture production. At this time only a small area of phosphatic clay soil is being used for intensive agricultural production, mainly vegetable production. Should a large area of phosphatic clay soil be placed into production there is a possibility that stormwater runoff could result in water quality impacts from turbidity and related P. Should this occur, regulatory action would likely follow. Landowners should be made aware of this possibility and steps that can be taken to mitigate adverse impacts. Potential cost for installing water treatment systems will be an important consideration for landowners planning to develop phosphatic clay soils for intensive agriculture.

The objectives of this study were (1) develop information to help landowners and their advisors understand possible water quality impacts from crop production on phosphatic clay soils. (2) determine if a stormwater treatment system could be designed for the interior of a clay settling area and (3) estimate the cost to design and build both a passive treatment system and a chemical treatment system.

MATERIALS AND METHODS

Pickett & Associates, Inc. from Bartow, FL, a consulting firm with extensive experience working with clay settling areas, designed a mitigation system and estimated the cost for installation. The goal was to improve runoff water quality from a phosphatic clay settling area under intensive agricultural production to meet environmental standards for the water to be released to the waters of the state.

A representative clay settling area was sought for the study. Several visits were made before choosing a clay settling area at the former Mobil Fort Meade Mine, containing ~175 ha (432 acre). This was a medium-sized settling area referred to as Clay Pond PR-5. Clay Pond PR- 5 had been reclaimed and abandoned according to rules set forth in Chapter 62-672 F.A.C. To be abandoned, a gravity-drained outlet breach was constructed at the lowest elevation in the reclaimed interior. The breach elevation was designed to drain the interior and prevent impounding water against the remaining perimeter earthen dike walls during a 25 yr storm. Mobil breached the Clay Pond PR-5 dike and located a rock-lined trapezoidal swale in the southwest corner. Drainage from the settling area goes into the Peace River, a short distance away.

Pickett & Associates determined that to mitigate turbidity and associated P in stormwater runoff, water will need to be retained on site for a period of time, depending on treatment method used. Construction of stormwater retention capacity within the settling area will require a restriction of the outflow breach. Restricting the outflow breach will result in additional permit requirements from SWFWMD and Florida DEP. At this time, no specific precedent has been established. Representatives from Pickett & Associates met with SWFWMD and the Florida DEP about re-establishing water impounding capability in an officially abandoned clay settling area. Both SWFWMD and Florida DEP indicated that a ERP, in compliance with Chapter 62-343 F.A.C., would be required should water impounding capability be re-established.

RESULTS AND DISCUSSION

According to ERP regulations, criteria are specified for both quantity and a quality of offsite discharge for a

25 yr frequency storm event. No offsite impacts may be caused by the quantity of discharge. In addition, retention capacity for 25 mm (1 in) of runoff must be maintained to assure quality of the discharge.

To meet the quality criteria two retention methods are available, on-line treatment and wet retention. Either of the two methods could be applied to a typical clay settling area. A reinforced concrete structure with a rectangular weir, and a small orifice located below the weir crest, would be utilized for either method. The orifice would allow the retained stormwater to drain down at a controlled rate so retention capacity may be restored for the next storm event.

Requirements for a wet retention system include a combination of retention pond and wetlands to provide water quality treatment. A minimum of 35% littoral zone is required, based on the impounded area at the control elevation (bottom of orifice). Other requirements include: the littoral zone cannot be deeper than 1.1 m (3.5 ft) at the control elevation, wet retention treatment volume must be retained for 120 h, no more than one-half the total volume may be discharged in the first 60 h.

Although the on-line treatment system utilizes a retention pond for water quality improvement, it does not utilize a wetland and is not subject to depth restrictions. The outlet structure for the on-line treatment system is similar to the one used for the wet detention system. The main differences between the two structures are in the elevation and dimension of the overflow crest and bleed-down orifice. The total treatment volume must be available for 72 h for the on-line treatment system. Because a smaller pond area and shorter retention period is required compared with the wet retention system, the on-line treatment system was selected for this project.

Based on research results from Haman et al., 2001, it is possible that the on-line treatment system alone will not remove the suspended solids and associated P from the stormwater discharge. As a result, a system for chemical treatment was also designed for the clay settling area site. An equipment vendor, AMJ Equipment Corporation, Lakeland, FL, was contacted by Pickett & Associates and asked, based on details of the retention system, to provide a cost quotation for adding alum treatment system to the retention pond. Equipment is shown in Table 1. The treatment system is designed to add 4.25 g L^{-1} of alum to stormwater runoff as the runoff enters the retention pond. Estimated cost for designing, equipping, and installing a chemical treatment system was $65 000.

To operate the chemical treatment system, electrical power is needed at the site. It was assumed that for most clay settling area sites a powerline would have to run for 3.2 km (2 miles). As a result the cost for 3.2 km of powerline at $9375 km^{-1} or a total of ~$30 000 was used for this study.

Reclamation of a phosphatic clay settling area begins with the construction of a perimeter ditch, around the inside of the dike, connected to an outfall drain. Lateral ditches are cut into the clay surface with high flotation equipment to drain into the perimeter ditch. Once drained, the clay begins to consolidate. After ~2 to 3 yr, the clay will have consolidated to the point where it will support conventional farm equipment. The next step in reclamation is to push down the perimeter dike to produce a widened remnant with graded inside and outside slopes of around 1 m drop for every 4 m of horizontal distance (4:1 slope). Runoff from the outside slopes will discharge as sheet flow and not drain into the reclaimed interior. Drainage from the interior slopes add to the total runoff from the clay settling area.

Table 1. Equipment recommended for chemical treatment of stormwater.

Quantity	Item	Cost
1	Turgidity analyzer—Omega TRCN-96†	$1 995
1	PO_4 analyzer—Isco Helios Phosphate Buoy‡	17 000
1	Flow meter—Isco 4210‡	3 295
1	Sampler—Isco 6712‡	2 795
1	Sample pump—Isco 150‡	995
	Accessories for instruments	NA
1	Fiberglass building 1.2 m × 1.2 m with stainless steel fittings	NA
	Piping and electrical within building	NA
	Labor in building and startup services	NA

†Omega Engineering, Inc., Stamford, CT.
‡Isco, Inc., Lincoln, NE.

For the subject clay settling area the runoff area totaled 148 ha (365 acre). The required ERP retention capacity for 25 mm (1 in) of runoff for a 25-yr design storm was calculated to be 37 498 m^3 (1 324 950 ft^3 [30.4 acre ft]). Rainfall of 20.3 cm d^{-1} (8 in d^{-1}) was derived from a SWFWMD 25-yr rainfall map for west central Florida. A hydrograph (Fig. 1) was computed at the breach exit point with a computed peak flow of 4.2 m^{3}s^{-1} (147.1 ft^3 s^{-1}).

The hydrograph was computed using Hydraflow Hydrographs for Windows (Version 6.0) published by Intellisolve (www.intelisolve.com). Hydraflow utilizes NRCS Unit Hydrograph methodology. A SWFWMD Type II Modified storm distribution and a unit hydrograph shape factor of 256 were utilized. Times of concentration were computed using the TR-55 worksheet method (Cronshey et al., 1986).

A structure at the outflow breach (Fig. 2) with a 6.1-m (20 ft) wide rectangular weir crest at elevation 30 m (98.5 ft) NGVD (Natl. Geodetic Vertical Datum of 1929) met the detention criteria for the on-line treatment system. A temporary-impounded area of 19.4 ha (48 acre) was created at the structure. To bleed down the retained volume after a storm event, a circular orifice was located in the structure below the weir crest. The bottom of the orifice was located at 28.6 m (94.0 ft) NGVD, which established the level of the impoundment area between storm events. Before installation of the structure the peak discharge from the outfall breach for a design storm event was 4.2 m^3 s^{-1} (147.1 ft^3 s^{-1}). After installation of the weir structure, the peak discharge for the same design storm was 3.1 m^3 s^{-1} (110.8 ft^3 s^{-1}) (Fig. 3), which met the ERP quantity criteria since the site was previously designed to accommodate a greater discharge of 4.2 m^3 min^{-1} (147.1 ft^3 s^{-1}).

The on-line treatment system described above meets the ERP criteria for both quantity and quality of

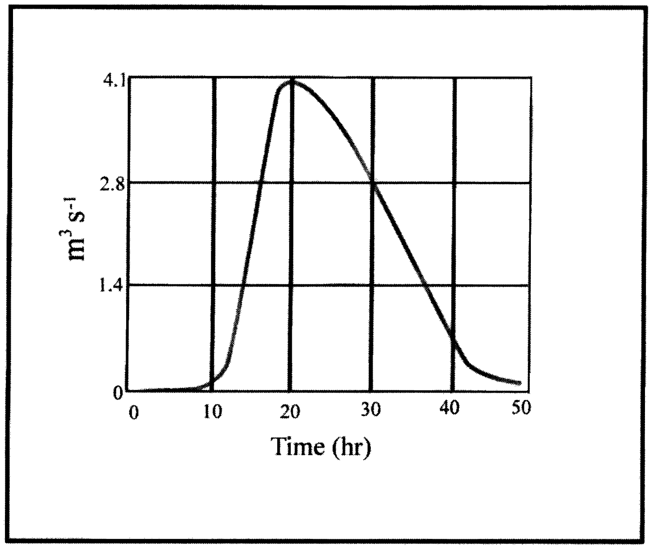

Fig. 1. Hydrographic plot of 25-yr storm event at outfall breach with 4.2 $m^3 s^{-1}$ (147.1 $ft^3 s^{-1}$) peak flow.

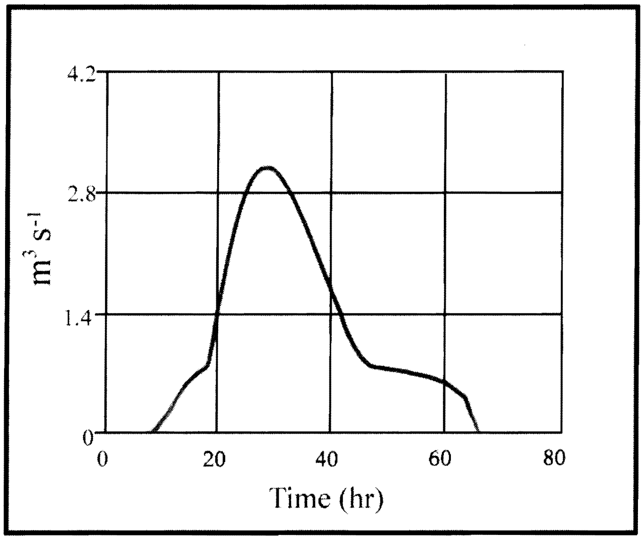

Fig. 3. Hydrographic plot of 25-yr storm event peak flow discharge of 3.1 $m^3 s^{-1}$ (110.8 $ft^3 s^{-1}$) after outfall structure installed.

discharge. The estimated cost of designing and installing the system totaled $27 000. Individual cost items included $13 000 for contour aerial photography, including horizontal and vertical ground control for 30.5 cm (1 ft) intervals, 175 ha (432 acre) @ $74.13 ha^{-1} ($30 $acre^{-1}$). Preparing and submitting the ERP application with hydrologic and hydraulic calculations and revise as required by the agencies, $5500, and construction of control structure in compliance with an approved ERP permit, $8500. Subtracting 19.4 ha (48 acre) used for the retention pond from 147.7 ha (365 acre) within the drainage area of the clay settling area leaves a total of 128.3 ha (317 acre) of useable land. Dividing $27 000 by 128.3 ha (317 acre) provides an average cost of $210 ha^{-1} ($85 $acre^{-1}$) for designing and building the on-line treatment system.

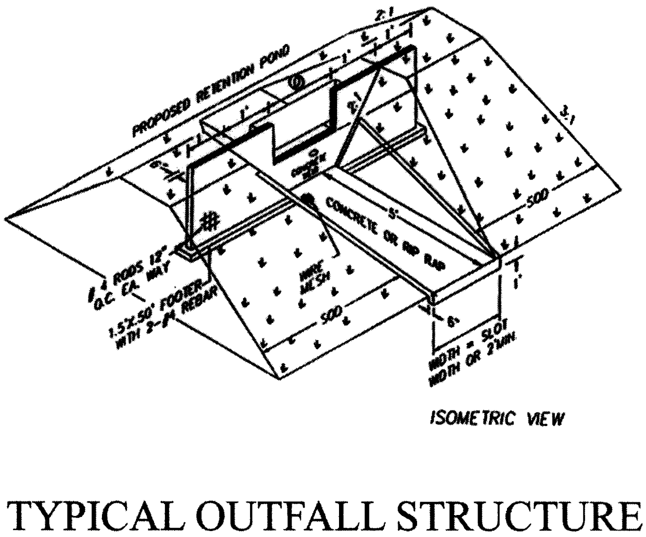

Fig. 2. Typical outfall structure at outfall breach for on-line treatment system.

At the present time, no standard is in place for release of P into the Peace River drainage system. It is likely that such a standard will be in place in the future. If the on-line treatment system alone isn't able to reduce suspended solids and P to a level to meet water quality standards, a chemical treatment system will be needed to remove suspended solids and associated P from stormwater runoff. The estimated cost for the chemical treatment system was $65 000 plus an additional $30 000 for electrical power giving a total cost of $95 000. When these costs are added to the $27 000 cost for design and construction of the on-line treatment system the total comes to $122 000. Dividing $122 000 total cost by 128.3 ha (317 acre) of useable land gives an average cost of $951 ha^{-1} ($385 $acre^{-1}$). This represents the capital cost of installing the systems. Data are not available on the cost of operating the system, especially the chemical treatment system. Although the capital costs are high they may be amortized for a number of years, reducing the cost for a single year.

The additional cost of installing a stormwater treatment system could be a determining factor for a landowner making a decision to develop a clay settling area for intensive agriculture. The cost of the online treatment system alone would be relatively minor when averaged over the entire settling area and amortized. The installation, maintenance and operating expense for the chemical treatment system adds a considerable amount to the cost and could significantly increase the production costs for the operation.

CONCLUSIONS

Phosphatic clay soil has potential for high intensity crop production. Research has shown that stormwater runoff from phosphatic clay soil under cropping with 1.5 to 2% slope contains high levels of suspended solids and associated P. An on-line treatment system built inside a clay settling area will meet ERP requirements. Whether small soil particles associated with a clay soil settle out of the water column in the period of time specified by the ERP is not known. If it does not, treatment with a chemical such as alum will be required to flocculate the soil particles to facilitate settling.

A representative175 ha (432 acre) clay settling area was chosen for this exercise. Costs of installing on-line treatment systems and chemical treatment systems for larger clay settling areas will likely be somewhat higher than for the subject settling area, but not proportionately higher, thus reducing the average cost for larger areas. Conversely, average cost is likely to be higher for smaller settling areas since costs will be averaged over a smaller area.

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The Addition of Clinoptilolite Zeolite to a Simulated Sandy Medium to Reduce Nitrogen Leaching

A. Sutherland, S. H. Daroub*, and I. Ognevich

ABSTRACT

Nitrogen leaching from urban areas including turf and golf courses is a growing concern in south Florida. This study was conducted to determine whether adding a soil amendment, clinoptilolite zeolite (CZ), a mineral group of hydrated aluminosilicates, to typical sandy media of turf and golf courses could affect a change in the amount of N leaching. Leaching columns were set up in the lab containing typical sandy media used for golf courses with CZ added at two particle sizes (0.125-0.5 mm and 0.5-1.5 mm for the fine and coarse particle sizes, respectively) and two rates (100 and 200 ml L^{-1}). The control treatment had no CZ added. The columns were irrigated for three times a week for a period of 4 wk, and leachate collected. Ammonium-N (NH_4-N) and nitrate-N (NO_3-N) were measured in the leachate. All of the amended CZ treatments had an effect on reducing NH_4-N leaching compared to the control. The coarse particle size CZ at both rates exhibited higher NO_3-N leaching compared to the control because a significant amount was already leached out as NH_4-N in the control treatment at the beginning of the experiment. The coarse particle size CZ treatments exhibited no difference in total-N leached compared to the control. Total N leaching was reduced in the fine particle size CZ treatments at both rates compared to the control. Both particle sizes of CZ contained initial NH_4-N and NO_3-N on their surface and it is believed this NH_4-N is more exposed to nitrifying bacteria on the coarse zeolite due to more macropores, which lead to more NO_3-N leaching. The fine CZ could likely be used to effect a reduction in N leached in the field if properly utilized.

INTRODUCTION

A growing concern in urban areas adjacent to agricultural land is that of nutrient leaching from farms into the water supply. It has been established that leaching of N from agricultural land contributes to NO_3 contamination of ground and surface waters (Lichtenberg and Shapiro, 1997). Many times, other point sources of nutrients are present in greater proximity to urban areas in the form of landscapes and turf areas, including golf courses. It is evident that if NO_3 and NH_4 could be retained in the soil or medium, then leaching into the urban water bodies could be reduced. However, in some areas the soil is sandy and naturally holds little nutrients and water, lending itself to more frequent fertilization rates, high irrigation rates and frequencies, and therefore more nutrient leaching. In addition, turf areas subject to heavy traffic, such as golf course putting greens, must be constructed of media resistant to compaction, usually sand (Beard, 1998). Therefore, a soil amendment to increase ion exchange capacity and water holding capacity is needed.

Zeolite, a mineral group of hydrated aluminosilicates, may have some possible candidates for soil amendments for the conditions discussed. Clinoptilolite zeolite

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A. Sutherland, formerly Univ. of Florida, Dep. of Environmental Horticulture and Ft. Lauderdale Res. and Educ. Center, Ft. Lauderdale, FL 33314, currently: Univ. of California, Davis; S. H. Daroub, Soil and Water Science Dep. and Everglades Res. and Educ. Center, Belle Glade, FL 33430; I. Ognevich, Everglades Res. and Educ. Center, Belle Glade, FL 33430. This research was supported by the Florida Agric. Exp. Stn. and is approved for publication as Journal Series No. N-02536.

*Corresponding author (sdaroub@ifas.ufl.edu).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:88-91 (2004).

is the most abundant and most commonly used of the zeolites. Isomorphic substitution of Al^{3+} for Si^{4+} within the mineral structure results in a large cation exchange capacity without expansion or collapse (Perrin, 1998). Clinoptilolite zeolite is interesting in the fact that its many pores and channels yield an immense amount of surface area by mass or volume. This attribute enables CZ to sequester excess materials from the surrounding medium and medium solution, to be released slowly over time as dictated by forces of diffusion and cohesion of water. Natural zeolites exhibit a selective adsorption of soil solution cations, in which monovalent cations with small hydrated radii are favored (Ames, 1967). Since zeolite framework is known to trap soil solution, it is understood that anions in solution can also be somewhat retained as occluded salts (Susic et al., 1971). Commercially available zeolites claim to hold up to 700 g water kg^{-1} dry weight, and up to 300 g kg^{-1} their dry weight in gases (Hoodridge International, 2000). Additionally, since aqueous solutions of NH_3, and anhydrous NH_3 gas show a great affinity for clinoptilolite structures, these zeolites have been used for NH_3 removal in biowastes, such as those resulting from aquaculture or a municipal piggery (Bergero, 1994). Huang and Petrovic (1994) observed a lowered concentration of N compounds in the forms of NO_3 and NH_4 in the leachate collected from lysimeters with CZ amended sand vs. lysimeters with only sand. Theoretically, CZ, with its very small pores and passages, sequesters soil NH_4 within its structure; away from soil solution and nitrifying bacteria. MacKown and Tucker (1978) observed a decreased nitrification rate in coarse soils amended with NH_4-saturated zeolite.

The purpose of this study is to determine whether CZ could be used as a soil amendment in sandy soils and turf areas to reduce leaching of N. There is an additional question regarding the particle size of CZ used and the effects these differences can produce. Studies suggest that the smaller the CZ particle size, the lower the saturated hydraulic conductivity of the media (Huang and Petrovic, 1995), and therefore may reduce N leaching.

MATERIALS AND METHODS

A sandy medium was set up in leaching columns to simulate the root zone of turf in a golf course or landscape plants adjacent to turf in an urban landscape containing sandy soil. The PVC leaching columns were 7.6-cm diam. and 51 cm in depth. The columns were set up vertically with a leachate collection funnel at the base separated by a filter fabric. The bottom 23 cm was comprised of a drainage medium of coarse (0.5-1.0 mm diam.) rounded quartz-sand. This layer was the same for all treatments. Another 23-cm partition located above the drainage media was that of the simulated root zone. Following coastal soils in south Florida and USGA golf green specifications, a fine (0.125-0.25 mm diam.) sand of the same parent material was used. In this section of the columns, treatments were applied. The fine sand was amended with two particle sizes and two concentrations of CZ, placed in the leaching columns and subjected to a series of simulated irrigation events. The CZ particle sizes were designated as fine CZ (0.125-0.5 mm) and coarse CZ (0.5-1.5 mm diam.) (Hoodridge International, Parkland, FL). The two particle sizes were mixed with the fine sand at two concentrations of 100 mL L^{-1} and 200 mL L^{-1} by volume to make a total of five treatments including the control. A control group was established with only fine sand as a root zone. Each treatment was replicated three times as two separate one factorial design (coarse size with two concentration rates and fine size with two concentration rates). The two one-factorial design treatments shared the same control.

Selected properties of CZ are listed in Table 1. The pH was measured in a 1:1.5 zeolite: water ratio (Thomas, 1996), NH_4-N and NO_3-N from zeolite was extracted with 2M KCl (Mulvaney, 1996), cation exchange capacity (CEC) was measured using NH_4 as the saturating cation and Na as the replacing cation (Chapman, 1965). Nitrogen was added to the system via granular turf fertilizer N,P_2O_5, K_2O (16-4-8, Hoodridge International, Parkland, Fl) at a recommended rate for golf course bermudagrass (*Cynodon dactylon* L.) of 97.6 kg/ha/mo (2 lbs N/1000 ft^2/month), or 0.18 g N/column. The N source in the turf fertilizer was ammonium sulfate, urea, and polymer-coated sulfur-coated urea. Since this study took place over four wk, only one application of fertilizer was required. All treatments were kept at field capacity and subjected to simulated irrigation events in which deionized water was added at the top of the column to produce 75 mL of leachate. Irrigation events took place three times a week for four wk. The solution collected was frozen and later analyzed for both NO_3-N and NH_4-N. Nitrate-N was analyzed by the Cd-Cu reduction method by using Flow Injection Analyzer (QuickChem, LACHAT Instruments, Inc., Madison, WI). Ammonium-N was analyzed by a segmented flow analyzer (Alpkem, O.I. Analytical, Inc., College Station, TX). Statistical analyses were performed for NH_4-N, NO_3-N, and total-N (sum of NH_4-N, NO_3-N) leached over the course of the experiment using General Linear Models procedures (SAS, 1999). The two treatments (coarse and fine) were analyzed as separate two one-factorial design, the factor being the rate of application. The F-test was considered significant $\alpha = 0.05$.

RESULTS AND DISCUSSION

Ammonium-N

Throughout this study, the control exhibited significantly higher concentrations of NH_4-N ion in the leachate (Fig. 1). The leaching of NH_4-N in the control was evident from the third irrigation event onward. The amount

Table 1. Selected properties of clinoptilolite zeolite (CZ) used in the study.

Property	Coarse CZ†	Fine CZ
pH	6.1	4.7
NH_4-N (mg kg^{-1})	7.4	23.5
NO_3-N (mg kg^{-1})	25.3	46.0
CEC ($cmol_c$ kg^{-1})	49.9	51.05

†Particle size range for coarse CZ is 0.5-1.5 mm and for fine CZ is 0.125-0.5 mm.

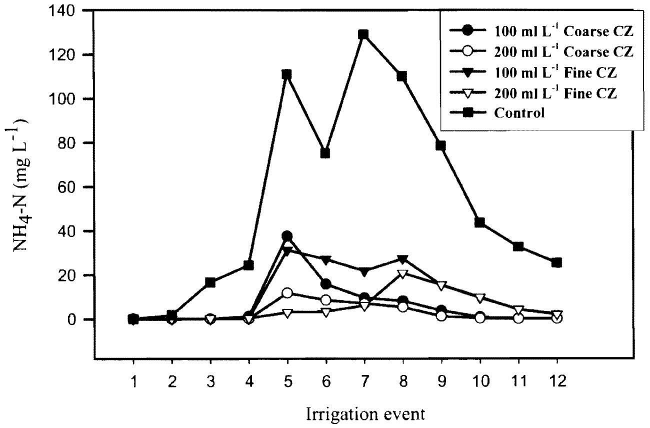

Fig. 1. Ammonium-N (NH_4N) leached with irrigation events. Fine clinoptilolite zeolite (CZ) (0.125-0.5 mm) and coarse CZ (0.5-1.5 mm diam.) were applied each at 0, 100 and 200 ml L^{-1} to typical golf coarse sandy media.

leached increased until the seventh irrigation event, when amounts began to gradually decline. All treatments containing zeolite did not leach NH_4-N until the fifth irrigation event, and then in much smaller concentrations than the control. There was a secondary release peak of NH_4-N recorded in the leachate of all treatments at the seventh and eight irrigation events. This may be due to the breakdown of slower release N compounds, which made a small percentage of the applied fertilizer. Again, the control produced significantly more NH_4-N in the second peak than the zeolite treatments.

Since NH_4 is a cation, it should be adsorbed within the zeolite structures and on the surfaces of the zeolite particles. The results of this trial support this postulate, since much less NH_4-N was observed being leached out of zeolite treatments compared to the control. The leaching of NH_4-N that was observed in the zeolite treatments happened at a later irrigation event than the control, and as mentioned earlier in much lower concentrations. The 100 ml L^{-1} amended CZ seemed to have a little higher concentration of NH_4-N in leachate compared to the 200 ml L^{-1} amended CZ (Fig. 1). It is worthy to note that the CZ treatments had some initial NH_4-N on their sites with the fine CZ having the higher concentrations (Table 1). At the 100 mL L^{-1} incorporation rate, this adds up to 4.6 and 14.6 mg NH_4-N in the coarse and fine CZ, respectively. Concentrations of NH_4-N leached in the zeolite treatments dropped after the eighth irrigation event with no apparent differences among the particle sizes and concentrations.

The CEC of the sand was not measured in this experiment, but typical CEC of sandy soils is less than 3.5 cmol_c kg^{-1} (Brady and Weil, 2002). Therefore, leaching of the NH_4-N in the control at the start of the experiment was not surprising taking into consideration the low CEC and that much of the sand's exchange sites would be already saturated. The CZ amended media reduced NH_4-N leaching at the two particle sizes and two rates applied.

Nitrate-N

All treatments showed an increase in NO_3-N leached as the study progressed, beginning with the fifth irrigation event and gradually declining by the ninth event (Fig. 2). Ammonium-N cations on exposed exchange sites could have been subjected to nitrification and subsequently been leached out as NO_3-N. There was also some NO_3-N occluded in solution inside micropores in the CZ treatments (Table 1). This added up to an additional 15.9 mg and 28.6 mg NO_3-N in the coarse and fine CZ, respectively, at the 100 ml L^{-1} incorporation rate. It makes sense that there was a steady increase in NO_3-N concentration in the collected leachate over time, because occluded salts, including NO_3, should be released as water potentials fluctuate in the media. Coarse CZ exhibited more NO_3-N leaching compared to the control, which may be explained by the fact that large percentage of total N was absent in the control by the fifth irrigation event, having been leached out as NH_4. Coarse sand has few micropores in which to trap NO_3-N in solution and a much lower CEC to begin with and therefore much less exchangeable NH_4 to undergo nitrification.

Ammonium or NH_3 on unprotected exchange sites of the CZ could have eventually undergone nitrification, and have therefore been expressed as NO_3 leached later in the experiment. In addition, the initial loading of NH_4-N and NO_3-N on the coarse CZ added may have contributed to the increase in NO_3-N leaching compared to the control. It is interesting that although the fine CZ had higher initial concentrations of both NH_4-N and NO_3-N, leaching of N was less in that treatment. There did not seem to be any differences regarding the concentration of added materials. The coarse CZ at both rates had similar concentrations and trends of NO_3-N leaching (Fig. 2). The same is true for the fine CZ.

Total-N

Amounts of NH_4-N, NO_3-N, and total N collected over the course of the experiment are presented in Fig. 3 (a&b). The amounts were calculated by multiplying the concentration of the either NH_4-N or NO_3-N in solution by the total volume of leachate collected at each irrigation event. Total-N was calculated as the sum of NH_4-N and NO_3-N. The control leached more NH_4-N

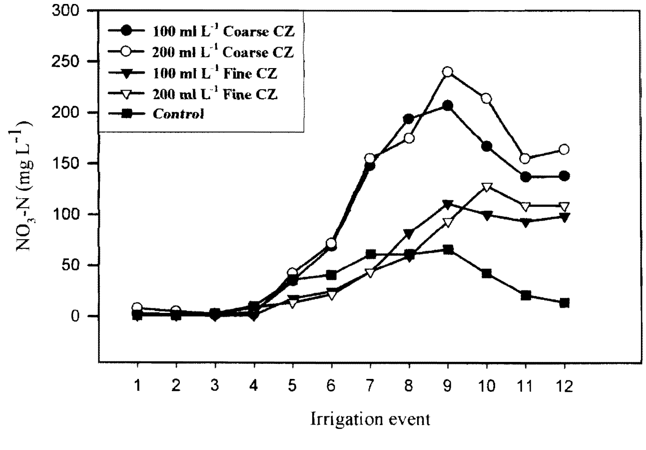

Fig. 2. Nitrate-N (NO_3-N) leached with irrigation events. Fine clinoptilolite zeolite (CZ) (0.125-0.5 mm) and coarse CZ (0.5-1.5 mm diam.) were applied each at 0, 100 and 200 ml L^{-1} to typical golf coarse sandy media.

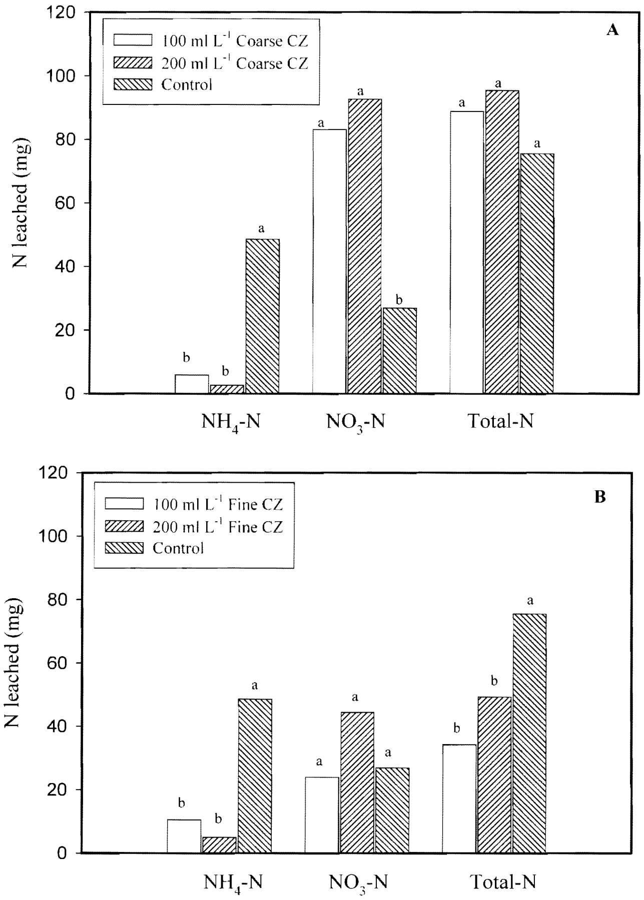

Fig. 3. Ammonium-N, NO_3-N and total-N leached during the course of the experiment. A) Coarse clinoptilolite (CZ). B) Fine CZ. Significant differences $\alpha = 0.05$ between treatments for each analyte are designated by different letters.

compared to the coarse zeolite (Fig. 3a). The coarse CZ at both concentrations, however, leached more NO_3-N compared to the control (Fig. 3a). As mentioned earlier, the control had less NO_3-N to leach since most of the N applied was leached as NH_4-N at the first four irrigation events. In addition, the initial loading of N on the coarse CZ may have contributed to the increased NO_3-N leaching. Total-N leached in the CZ treatments at both concentrations was not statistically different from the control which leads to the conclusion that the incorporation of coarse CZ did not reduce N leaching.

The control again exhibited significantly higher amounts of NH_4-N leaching compared to the fine CZ treatments. There were no differences in the NO_3-N leached between the fine CZ treatments and the control; however the fine zeolite exhibited lower amounts of total-N leaching (Fig. 3b). This suggests that the particle size of the CZ applied plays an important role in reducing NO_3-N and therefore total-N leaching. The initial NH_4-N and NO_3-N concentrations were higher in the fine CZ compared to the coarse CZ (Table 1). The NH_4-N is vulnerable to nitrification, and it is possible that occluded NO_3-N on the coarse CZ was released more readily because it was more exposed due to more macropores and a larger saturated hydraulic conductivity. This exposure would make the occluded solution subject to desiccation and changes in water potential and make the exchange sites more available to nitrifying bacteria.

Related literature suggests that salts occluded by zeolites are somewhat more easily released than cations on exchange sites (Park and Komarneni, 1998). So, even though the fine zeolite may have had more NH_4-N and NO_3-N loaded within it to begin with, the exchange sites and occluded salts are more protected, and N ions are more tightly held. The fine zeolite exhibited a significant decrease in total-N leached compared to the control, and could likely be used for the reduction in N leaching in the field if properly utilized. There were no significant differences in the concentration of zeolite, indicating that 100 mL L^{-1} incorporation rate may be adequate.

In conclusion, although CZ has been shown in the literature to have an effect on reducing N leaching, it is important to look at other factors that may affect the amount of N leaching when these amendments are applied. Particle size was found to be an important factor in this experiment to reduce N leaching. The large particle size CZ amendment reduced NH_4-N leaching, but did not reduce total-N leaching, while fine particle CZ amendment reduced NH_4-N and total-N leaching.

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ENTOMOLOGY AND NEMATOLOGY SECTION

Optimizing Bed Orientation and Number of Plastic Layers for Soil Solarization in Florida

R. J. McGovern, R. McSorley*, and K.-H. Wang

ABSTRACT

Effects of several factors affecting performance of soil solarization against weeds and plant-parasitic nematodes were evaluated in small field tests in Bradenton, FL in 2001. Raised beds solarized with a single layer of clear plastic for 6 wk in May-June were placed in either a north-south (NS) or east-west (EW) orientation. In general, weed coverage was greater ($P \leq 0.05$) on the edges (shoulders) of solarized beds than at the centers of beds. Weed problems were especially severe in beds with EW orientation, which rarely achieved soil temperatures of >45°C in the bed shoulder during the solarization period. Despite being shaded during part of the day, bed shoulders in NS-oriented beds reached temperatures >45°C on many days, and weed pressure, although still higher in the shoulders than in the bed center, was relatively low. A comparison of a single layer vs. a double layer of clear plastic for solarizing beds for 6 wk in Aug.-Sept. revealed similar ($P > 0.10$) performance against nematodes and most weeds, although both clear plastic treatments were usually superior ($P \leq 0.05$) to a control with white plastic. The double layer was more effective ($P \leq 0.05$) than the single layer in reducing density of grasses. Results confirm the favorable performance of NS-oriented beds over EW-oriented, and of a double layer over a single layer of clear plastic in solarization.

INTRODUCTION

Soil solarization offers an opportunity to utilize renewable solar energy directly for pest management. The method has been utilized against soilborne diseases, nematodes, and weeds in many locations throughout the world (McGovern and McSorley, 1997). The efficacy of large-scale solarization has been demonstrated in some Florida vegetable production systems (Chellemi et al., 1993; 1997). It may be particularly useful for organic producers who cannot use traditional soil fumigants (McSorley et al., 1999). However, because solarization depends on weather and other environmental conditions, its performance can be inconsistent at times (McGovern and McSorley, 1997).

Recent work in Florida has provided excellent results when solarization was conducted on a flat surface, without raised beds (McGovern et al., 2000; 2002; McSorley and McGovern, 2000). Using a double-layer, rather than a single layer of clear plastic was shown to increase soil temperatures (Ben-Yephet et al., 1987), and has been effective under Florida conditions (McSorley and McGovern, 2000; McGovern et al., 2002).

We have often observed grasses and other weeds growing from shaded edges or shoulders of raised beds during and following solarization. The overall objective of the current research is to improve the performance of solarization on raised beds. Specific objectives are to directly compare the efficacy of single vs. double layers of clear plastic in solarizing beds, and to evaluate the effect of bed orientation on solarization performance.

MATERIALS AND METHODS

Experiments were conducted at the Univ. of Florida Gulf Coast Res. and Educ. Center in Bradenton, Florida (27.5°N, 82.6°W). Soil type was Eaugallie sand (sandy, siliceous, hyperthermic Alfic Alaquods; 97g sand kg^{-1}, 10 g clay kg^{-1}, 20 g silt kg^{-1}), with 19 g organic matter kg^{-1}. The site had been planted intermittently with solanaceous and cucurbit crops over the previous 20 yr, and contained a number of plant-parasitic nematodes and high populations of nutsedge (*Cyperus rotundus* L. and *C. esculentus* L.) and other weeds.

Bed Orientation Experiments

The site was disked and rotovated in April 2001, and beds were formed in early May. Individual beds were 20 cm (8 in) high and 3.0 m (10 ft) long. Bed width ranged from 81 cm (32 in) across the top tapering to 99 cm (39 in) at the bottom. The distance from center to center of adjacent beds was 1.5 m (5 ft). Two experiments were established, one involving three beds oriented in a north-south (NS) direction, and one with three beds positioned in an east-west (EW) direction. All beds were covered with a single layer of clear, 25-µm-thick, uv-stabilized, low-density polyethylene mulch (ISO Poly Films, Inc., Gray Court, SC) from 11 May to 19 June (6 wk).

Soil temperatures were monitored at a depth of 5 cm from three locations in each bed using WatchDog dataloggers (Spectrum Technologies, Inc., Plainfield, IL). The three locations included the top center of the bed (EW experiment only), and a location on each bed shoulder. The exact location of temperature sensors in the bed shoulders was 10 cm from the top of the bed,

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R. J. McGovern, Dep. Plant Pathology, Univ. of Florida, Gainesville, FL 32611-0680. R. McSorley and K.-H. Wang, Dep. Entomology and Nematology, Univ. of Florida, Gainesville, FL 32611-0620. This research was supported in part by USDA, CSRS grant #00-51102-9571, Integrating pest management alternatives with sustainable crop production, and in part by the Florida Agric.Exp. Sta. and approved for publication as Journal Series No. N-02447.

*Corresponding author (rmcs@mail.ifas.ufl.edu).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:92-95 (2004).

and 5 cm deep perpendicular to the side of the bed. Shading at the edges of the beds was determined on 31 May by measuring the height of the shading on the edge of the bed. In a bed oriented NS for example, the W shoulder of the bed is shaded in the early morning; the height of the shaded area on this bed shoulder decreases as the sun rises further and shading disappears later in the day. On 19 June, the percentage of bed surface covered by weeds was estimated separately for the top and for each edge on all beds. At the same time, three soil samples, each consisting of six soil cores, 2.5-cm (1 inch) diam. × 20 cm (8 in) deep, were collected from each bed using a soil sampling cone (Esser et al., 1965). One sample was collected along the top center line of each bed, and one sample was collected from each shoulder (edge) of the bed. The cores from the edges of the bed were collected by inserting the sampling cone at a 90° angle to the edge of the bed, equidistant (10 cm) from the top and bottom of the bed. The cores comprising a sample were mixed, and a 100-cm^3 (0.2 pt) soil subsample was removed for extraction of nematodes using a modified sieving and centrifugation procedure (Jenkins, 1964). Extracted nematodes were identified and counted under an inverted microscope.

Analysis of variance (ANOVA) (Freed et al., 1991) was used to test for differences in data collected from the top center of the bed and each edge (E and W edges in the NS orientation experiment; N and S edges in the EW orientation experiment). Nematode data were transformed by $\log_{10}$ (x + 1) prior to ANOVA and mean separation using Duncan's multiple-range test, but nontransformed means are presented in all tables.

Single vs. Double Plastic Experiment

The site was disked and rotovated in August 2001, and beds prepared as described previously, except that all beds were oriented in a NS direction, and length of an individual plot was 5 m (16.5 ft). Three treatments were included in a randomized complete block design with three replications: 1) single-layer solarized, 2) double-layer solarized, and 3) nonsolarized control. The single-layer solarization treatment was identical to that described for the previous experiments. For the double-layer treatment, a second layer of clear polyethylene mulch was added and supported ~30 cm (12 in) above the first layer by wire hoops arched over the bed. Beds covered by white plastic (to protect against rainfall) provided the nonsolarized treatment. Treatments were established on 10 August, and the experiment was terminated on 20 September (6 wk).

Soil temperatures were monitored at a depth of 5 cm at the top center of beds. Soil samples for nematode analysis were collected on 20 September from the top centers of every plot, according to protocol described above. Weeds on tops of beds were evaluated by counting all weeds in three 0.28-m^2 (1.0 ft^2) subsamples per bed. Log-transformed count data were compared among single-layer, double-layer, and control treatments by ANOVA followed by mean separation using Duncan's multiple-range test (Freed et al., 1991).

Table 1. Shading on shoulders (edges) on east (E) and west (W) sides of beds in north-south (NS) bed orientation experiment and on north (N) and south (S) sides of beds in east-west (EW) bed orientation experiment, 31 May 2001.

	NS experiment		EW experiment	
Time	E side	W side	N side	S side
-h-	Shading height, cm†			
0800	0	22	0	19
0900	0	22	0	16.5
1000	0	22	0	0
1100	0	21.5	0	0
1200	0	14	0	0
1300	0	0	0	0
1400	0	0	0	0
1500	12	0	0	0
1600	18.5	0	0	0
1700	21.5	0	0	0

†Data are heights of shading on the bed shoulder for each side of the bed. Maximum height = 22 cm, when the entire shoulder is shaded.

RESULTS AND DISCUSSION

Bed Orientation Experiments

In beds with NS orientation, several hours of substantial shading occurred on the W shoulder of the bed in the morning and on the E should of the bed in the afternoon (Table 1). The S edge of beds in the EW orientation experiment also had some shading in the early morning hours. Despite some shading of the E or W side of beds in the NS orientation, high temperatures of >45°C were reached on many days in the bed shoulders of these NS-oriented beds (Table 2). Temperatures >45°C were rarely reached in shoulders of beds that were EW-oriented.

Regardless of bed orientation, weeds were more abundant on the bed shoulders than on the tops of beds (Table 3). In the NS orientation experiment, broadleaf and total weeds were more abundant on the E shoulder, which was shaded in the mid- to late-afternoon, than on the W shoulder, which was shaded in the morning but had more days with temperature >45°C (Tables 1-3). Shading of the bed shoulders was less evident in beds with EW orientation (Table 1), however broadleaf, grasses, and total weeds were more abundant ($P \leq 0.05$) on both bed shoulders than on the top of the beds (Ta-

Table 2. Number of days (11 May to 19 June) with maximum soil temperature >45°C at various positions on solarized beds in north-south (NS) and east-west (EW) bed orientation experiments.

Bed orientation	Position on bed	May	June	Total
		Days		
NS	E shoulder	6	11	17
	W shoulder	14	11	25
EW	Top	20	17	37
	N shoulder	0	6	6
	S shoulder	2	2	4

Table 3. Percentage of bed surface covered by weeds at top of bed and each bed shoulder in north-south (NS) and east-west (EW) bed orientation experiments, 19 June 2001.

Bed orientation	Position on bed	Nutsedge	Broadleaf	Grass	All weeds
		(%)			
NS	Top	5.8 a†	0 b	0 a	5.8 b
	E shoulder	8.6 a	10.3 a	2.7 a	21.7 a
	W shoulder	2.5 a	1.3 b	2.0 a	9.2 b
EW	Top	5.3 a	0 b	0 b	5.3 b
	N shoulder	15.0 a	44.7 a	10.3 a	70.0 a
	S shoulder	20.4 a	43.4 a	12.8 a	76.7 a

†Data are means of three replications. For each experiment, means in columns followed by the same letter do not differ ($P \leq 0.05$) according to Duncan's multiple-range test.

ble 3). The poor weed control in shoulders of beds with EW orientation is likely due to the failure to achieve high temperatures in these bed shoulders (Table 2).

Plant-parasitic nematodes found at this site included stunt (*Tylenchorhynchus* spp.), awl (*Dolichodorus heterocephalus* Cobb), and sting (*Belonolaimus longicaudatus* Rau) nematodes (Table 4), and more rarely, root-knot (*Meloidogyne incognita* (Kofoid & White) Chitwood), ring (*Mesocriconema* spp.), sheath (*Hemicycliophora* spp.), and stubby-root (*Paratrichodorus minor* (Colbran) Siddiqi) nematodes. Although nematode numbers tended to be lower in soil collected from bed centers than from bed shoulders (Table 4), nematode numbers were very low and unevenly distributed, and therefore few effects ($P \leq 0.10$) on nematode levels were evident.

Table 4. Nematode population density at center and shoulders of beds in north-south (NS) and east-west (EW) bed orientation experiments, 19 June 2001.

Bed orientation	Position on bed	Stunt	Awl	Sting	Total
		Nematodes 100 cm^3 soil			
NS	Center	0.33 a†	0 a	0 a	0.67 a
	E side	1.33 a	1.00 a	0.67 a	4.33 a
	W side	0 a	1.67 a	1.00 a	3.00 a
EW	Center	0.33 a	0 b	0 a	1.67 a
	N side	1.67 a	2.33 ab	0.33 a	4.33 a
	S side	1.33 a	4.33 a	0.67 a	6.67 a

†Data are arithmetic means of three replications. For each experiment, means in columns followed by the same letter do not differ ($P \leq 0.10$) according to Duncan's multiple-range test on log-transformed data.

Based on the weed and nematode data, solarization of bed shoulders was more effective when beds were oriented NS than when oriented EW. Comparison of the two bed orientation experiments suggests that high frequency of days with temperatures >45°C is more critical in control of soilborne problems, especially weeds, than temporary shading of bed shoulders during the day. While a shoulder of a bed oriented NS was shaded during part of the day, that shoulder received very direct sunlight during other parts of the day that was evidently sufficient to achieve >45°C on many days. Shoulders of beds oriented in an EW direction never received such direct sun from the E or W side, and failed to achieve >45°C on most days, resulting in poor weed control. Based on the results of these small experiments, a NS orientation of beds appears more effective than an EW orientation of beds for management of weeds and nematodes.

Single vs. Double Plastic Experiment

Soil temperatures tended to be numerically greater under the double layer than under a single layer of plastic (Table 5). Under both clear plastic treatments, temperatures >45°C were reached on >70% of the days during solarization (Table 5). Nutsedge was managed effectively by both solarization treatments, but the double-layer solarization was more effective than the single layer in reducing grass density (Table 6). Plant-parasitic nematodes were greatly reduced ($P \leq 0.10$) by the solarization treatments (Table 6). Although a few nematodes survived the single-layer solarization treatment, numbers were not different ($P > 0.10$) from the zero (non-detectable) levels in the double-layer solarization. Overall, the double-layer solarization was more effective than the single-layer, particularly in

Table 5. Maximum and minimum soil temperatures (1400-1800 h) in early September 2001, and number of days (13 August to 9 September) with maximum soil temperature >45°C in single vs. double layer solarization experiment.

	1 Sept.		2 Sept.		3 Sept.				
Plastic treatment	Min.	Max.	Min.	Max.	Min.	Max.	Aug	Sept	Total
	°C						Days		
White	28.5	40.0	28.5	39.5	28.0	40.0	0	0	0
Single layer†	30.0	49.5	30.0	47.0	29.0	50.5	14	5	19
Double layer†	31.0	52.0	31.0	49.0	31.0	54.5	16	6	22

†Clear plastic.

Table 6. Nematode and weed population densities at center of beds in single vs. double layer solarization experiment. 20 Sept. 2001.

Plastic treatment	Awl	Stunt	Ring	Sting	Nutsedge	Grass
	Nematodes 100 cm^{-3} soil				No. m^{-2}	
White	19.3 a†	26.3 a	2.0 a‡	2.3 a‡	177.0 a	40.7 ab
Clear, single layer	1.3 ab	1.3 b	0 b	0 b	2.4 b	104.1 a
Clear, double layer	0 b	0 b	0 b	0 b	1.2 b	8.3 b

†Data are arithmetic means of three replications. Means in columns followed by the same letter do not differ ($P \leq 0.05$) according to Duncan's multiple-range test on log-transformed data.

‡Mean separation at $P \leq 0.10$.

managing the grasses that have a tendency to encroach from the bed shoulders into the center of the bed.

Further research is needed to continue to improve and optimize solarization for managing soilborne pest problems on crops in Florida. The current work demonstrates the importance of NS bed orientation for maximum solarization effect and confirms the advantage of a double-layer of clear plastic over a single layer. The double layer may be advantageous in managing grasses that may be difficult to control. However, the double-layer solarization has not been mechanized, which will be essential before the method can be utilized in large-scale production systems. Much additional information is also needed to determine the costs and benefits of solarization in various crop production systems.

ACKNOWLEDGMENTS

This research was funded in part by USDA, CSRS grant #00-51102-9571, Integrating pest management alternatives with sustainable crop production. The authors thank Tim Davis, Teresa Seijo, and John Frederick for technical assistance and Nancy Sanders for manuscript preparation.

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Reduction of Fusarium Crown and Root Rot in Tomato by 1,3-Dichloropropene plus Chloropicrin in Southwest Florida

R. J. McGovern* and C. S. Vavrina

ABSTRACT

Two experiments were conducted during 1993-1994 to evaluate the effectiveness of 1,3-dichloropropene plus chloropicrin (1,3-DC) at 200.1 and 327.4 L ha^{-1} for reduction of Fusarium crown and root rot (FCRR) caused by *Fusarium oxysporum* Schlechtend.:Fr. f. sp. *radicis-lycopersici* W. R. Jarvis & Shoemaker in tomato (*Lycopersicon esculentum* Mill.) in southwest Florida. Efficacy of 1,3-DC was compared with methyl bromide plus chloropicrin (336 kg ha^{-1}) in reducing FCRR in fields naturally infested with the causal fungus. Incidence and severity of FCRR in non-treated plots were high (≥95%) and low to moderate (15-25% crown discoloration), respectively. Application of 1, 3-DC resulted in reduction of FCRR incidence and severity in both experiments equivalent to those achieved by methyl bromide plus chloropicrin. Yields did not differ between the treatments and non-treated control.

Fresh market tomato, valued at $474 million during 2001-2002, is the major vegetable crop in Florida, and its southwest region accounted for 42% of state-wide production (Florida Agricultural Statistics Service 2001, 2002). Fusarium crown and root rot in tomato, caused by *F. oxysporum* f.sp. *radicis-lycopersici*, has consistently been the most prevalent soil-borne disease of the crop in southwest Florida during the past 15 yr; up to 70% losses in tomato production have occurred in this region (McGovern et al., 1998). In addition, the disease has been estimated to cause yield losses of 15% and 29% in west-central and southeastern Florida, respectively (Sonoda, 1976; Jones et al., 1990). First detected in Florida during the 1974-1975 tomato cropping season (Sonoda, 1976), FCRR also has been reported in Canada, Israel, Japan, Mexico, many countries in Europe, and other states in the USA including California, New Jersey, New York, New Hampshire, Ohio, Pennsylvania, and Texas (Jarvis, 1988). The disease poses a significant threat to tomato transplant production and to both field and greenhouse fruit production wherever it occurs (Jarvis, 1988; McGovern et al., 1993b).

External symptoms of FCRR in mature plants include brown discoloration and rot at the soil level in the crown and roots. The lower leaves of infected plants turn yellow and the entire plant may wilt around the time of first harvest. The tap root of infected plants often rots entirely. When diseased plants are sectioned lengthwise, extensive brown discoloration and rot are evident in the cortex of crowns and roots.

Fumigation with methyl bromide-chloropicrin (Trichloronitromethane) (MBC) formulations has been the most commonly used preplant practice for control of crown rot and other soil-borne pests in Florida for the past 20 yr. However, methyl bromide has been categorized as a Class I, ozone-depleting substance by the Montreal Protocol (an international treaty promulgated by the United Nations Environmental Program), and it faces removal by the USEPA under the auspices of the Clean Air Act by 2005 (Watson et al., 1992; USEPA, 1993). This situation necessitates development of other management strategies for FCRR and other soil-borne pests including the use of alternative fumigants.

The fumigant 1,3-dichloropropene is one of those under consideration as a methyl bromide alternative because of its good nematicidal properties (Overman and Jones, 1976; Stapleton and Devay, 1983). In the past, 1,3-dichoropropene was combined with methyl isothiocyanate, 1,2-dichloropropane, and related hydrocarbons as DD-MENCS and other trade names, and showed efficacy against *F. oxysporum* in a number of vegetable crops (Hopkins and Elstrom, 1976; Manning and Vardaro, 1977; Jones and Overman, 1978). More recently this fumigant has been formulated with various concentrations of chloropicrin to add disease control. It was our objective to evaluate the effectiveness of 1,3-dichloropropene plus chloropicrin (1,3-DC) in managing FCRR in southwest Florida.

MATERIALS AND METHODS

Experimental Sites

Two tomato fields of Pomello fine sand (sandy, hyperthermic Arenic Alaquods; pH = 7.2 to 7.7, organic matter = 10.5 to 13.1 g kg^{-1}) naturally infested with *F. oxysporum* f.sp. *radicis-lycopersici* on a commercial farm in Immokalee, southwest Florida were chosen for experimentation during 1993-1994 based on previously high crown rot incidences. Methyl bromide-chloropicrin formulations had been used over the preceding 10 yr as the preplant soil sterilant.

Fumigants

Fields were cultivated and irrigated prior to fumigation to ensure adequate soil moisture and tilth for bed formation. Fumigants were injected in beds at a depth of 20 to 23 cm through tubes attached to three chisels spaced 28 cm apart by means of a tractor-drawn super bedder. Beds were 20-cm high, 1-m wide and spaced on 2-m centers. Fumigants were applied on 12 Jan. 1993 in Experiment 1 and 12 Oct. 1993 in Experiment 2. The minimum/maximum soil temperatures as measured at 10 cm at Southwest Florida Research and Education Center (SWFREC) were 27/20.8° C and 31.6/26.2°C on 12 Jan-

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R. J. McGovern, University of Florida-IFAS, Plant Pathology Dep. and Plant Medicine Program, Gainesville, FL 32611 and C. S. Vavrina, Univ. of Florida, Southwest Florida Res. and Educ. Center, Immokalee, FL 34143. This research was supported by the Florida Agric. Exp. Stn. and is approved for publication as Journal Series No. R-1008.

*Corresponding author (rjm@ifas.ufl.edu).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:96-99 (2004).

uary and 12 October, respectively (Reeder, 1993). Methyl bromide (670 mL L^{-1}) plus chloropicrin (330 mL L^{-1}) (Terr-O-Gas 67, Great Lakes Chemical Corp., Indianapolis, IN) was applied at 336 kg ha^{-1} in both experiments (broadcast rate). 1,3-dichloropropene plus chloropicrin (Telone C-17, DowAgriSciences LLC, Indianapolis, IN)] was applied at 200 and 327 Lha^{-1} (broadcast) in Experiments 1 and 2, respectively. Following application of fumigants, beds were immediately covered with 0.0032 mm black or white on gray, low density polyethylene mulch. White mulch is customarily used for tomatoes grown during warm periods (late August through October), and black mulch is used during cooler periods (November through March) in southwest Florida. Both experiments used a randomized complete block design. Five replications consisting of 36-m bed sections were used for each treatment and the non-treated control in Experiment 1, and six replications consisting of 55-m bed sections were used in Experiment 2.

Plants and Harvests

'Sunny' tomato transplants were planted in the beds on 28 Jan. 1993 (Experiment 1) and 3 Nov. 1993 (Experiment 2). Plants were grown using a 45.7-cm in-row spacing. Conventional cultural and pest management practices for commercial staked tomato production in southwest Florida were employed throughout the experiments.

In Experiment 1, marketable fruit (mature green fruit and fruit showing a slight red coloration) were harvested from all the plants in each replication (80 plants) on 20 Apr. 1993. Only one harvest was possible in this experiment because the plants were damaged by a severe rain storm. In Experiment 2, marketable fruit from 32 plants in each replication were harvested on 7 and 24 Feb. and 3 Mar. 1994. Fruit number and weight were recorded in each experiment.

Disease Data

Tomato plants from the center of each replication were uprooted, dissected longitudinally, and rated for FCRR severity (percentage of internal crown and tap root discoloration) on 20 Apr. 2003 and 28 Feb. 2004 in Experiments 1 and 2, respectively. Five plants were sampled in each replication in Experiment 1 and eight in Experiment 2. Crown rot severity was rated using a 1 to7 rating scale, where 1 = 0%, 2 = 1-10%, 3 = 11-20%, 4 = 21-40%, 5 = 41-60%, 6 = 61-90%, 7 = 91-100% discoloration.

Stem tissue from symptomatic control plants from each field was surface-disinfested in 5 mL L^{-1} NaOCl and incubated on Komada's *Fusarium*-selective medium (Komada, 1975). Sunny tomato and the seedling assay of Sanchez et al. (1975) were used to confirm infection by *F. oxysporum* f. sp. *radicis-lycopersici* in 5-6 representative samples from each field.

Data Analysis

Treatment means were separated using Fisher's Protected LSD Test following analysis of variance (Anon., 2002). Arcsin square root or square root transformations were used on percentage data prior to statistical analysis where appropriate (Gomez and Gomez, 1984).

RESULTS AND DISCUSSION

The incidence of FCRR was consistently high in non-treated plots in both fields (95-96%), whereas disease severity, as expressed by the extent of internal crown and tap root discoloration, was low to moderate and ranged from 5.5 to 24.9% (Table 1). Tomato seedling assays consistently confirmed infection of symptomatic plants by *F. oxysporum* f.sp. *radicis-lycopersici* (data not shown). Neither Fusarium wilt [*F. oxysporum* Schlechtend.:Fr. f.sp. *lycopersici* (Sacc.) W. C. Snyder & H. H. Hans.] nor bacterial wilt [*Ralstonia solanacearum* (Smith) Yabuchi et al.] were observed in either field. Root galling caused by *Meloidogyne* spp. and nutsedge (*Cyperus* spp.) were also absent, presumably due to longstanding use of MBC.

MBC and 1,3-DC produced equivalent and statistically significant reductions in FCRR incidence and severity when compared to the non-treated control in both experiments. No significant differences were observed among the treatments and control in terms of total marketable fruit weight or number, although both parameters were numerically increased by each fumigant combination in Experiment 2. Lack of statistical differences in yield between the treatments and non-treated control may have resulted from the low to moderate severity of crown rot observed at the experimental sites.

Our findings are in general agreement with those of other research evaluating suppression of *Fusarium*-induced diseases by 1,3-DC. Researchers in west central Florida observed a significant reduction in the incidence of FCRR by this fumigant combination in fields artificially infested with *F. oxysporum* f.sp. *radicis-lycopersici* (Jones et al., 1996). The effectiveness of 1,3-DC applied by soil injection in suppressing *F. oxysporum* has subsequently been demonstrated in experiments conducted in a number of crops including tomato, strawberry (*Fragaria* spp.), and marigold (*Tagetes* sp.) (Ramirez et al, 1995; Minuto et al., 2000; Cebolla et al., 2002).

However, 1,3-DC does not always reduce *Fusarium* densities to levels achieved by MBC and does not adequately suppress such difficult to control weeds as nutsedge (*Cyperus* spp.) (Webster et al., 2001). Gilreath et al. (2000) demonstrated the effectiveness of combining 1,3-DC with the herbicide pebulate [S-Propyl butyl(ethyl)thiocarbamate] for control of *Fusarium* wilt (*F. oxysporum* f.sp. *lycopersici*), purple nutsedge (*Cyperus rotundus* L.) and root knot nematode [*Meliodogyne incognita* (Kofoid & White) Chitwood] in tomato. Unfortunately, pebulate is not currently labeled for use in tomato. Suitable herbicide companions must likewise be identified for the effective use of 1,3-DC in other crops.

The 1,3-DC label requires the use of personal protective equipment that ensures complete worker coverage including a full face mask for applicators outside of an enclosed cab involved in soil injection of the fumigant. This may make soil injection of 1,3-DC impractical

Table 1. Effect of fumigants on Fusarium crown rot and yield in 'Sunny' tomato.

Treatment	Fusarium crown rot incidence (%)†	Fusarium crown rot severity (%)‡	Fruit weight (kg × 10^3ha^{-1})§	Fruit no. × 10^3ha^{-1}
Experiment 1				
Nontreated control	95.0 a¶	5.5 a	3.85 a	9.98 a
1, 3-dichloro-propene + chloropicrin (200.1 L ha^{-1})	48.0 b	4.4 b	3.26 a	8.98 a
Methyl bromide + chloropicrin (336 kg ha^{-1})	15.0 b	1.6 b	3.56 a	10.30 a
C.V.(%)	32.5	31.7	26.1	27.0
Experiment 2				
Nontreated control	96.0 a	24.9 a	5.98 a	18.78 a
1, 3-dichloro-propene + chloropicrin (327.4 L ha^{-1})	46.0 b	6.6 b	6.77 a	20.78 a
Methyl bromide + chloropicrin (336 kg ha^{-1})	41.0 b	5.0 b	6.47 a	20.38 a
C.V.(%)	14.4	14.6	14.5	12.6

†Arcsin square root transformation was used before data analysis; non-transformed data are presented.

‡Fusarium crown rot severity was based on a 1-7 rating scale where 1 = 0, 2 = 1-10, 3 = 11-20, 4 = 21-40, 5 = 41-60, 6 = 61-90, and 7 = 91-100 percentage of internal crown and taproot discoloration. Square root transformation was used prior to analysis; non-transformed data are presented.

§Yield data based on one harvest of 80 plants/replication or three harvests of 32 plants/replication, in Experiments 1 and 2, respectively.

¶Means (within a column and experiment) followed by the same letter are not significantly different by Fisher's Protected LSD Test ($P \leq 0.05$).

for workers in hot climates due to possible heat stress. An alternative liquid formulation of the fumigant has been developed and was shown to be effective in suppressing soil population of *Pythium* and *Fusarium* spp. when delivered by means of drip irrigation (Seebold et al., 2002).

Fumigation for reduction of soil-borne plant diseases cannot be viewed in a vacuum but must be integrated with other measures to be most effective. Zhou and Everts (2001) found that the greatest reduction of *Fusarium oxysporum* f.sp. *niveum* occurred when 1,3-DC was combined with host plant resistance and the biocontrol *Trichoderma harzianum* Rifai (Zhou and Everts, 2001). Resistance to *F. oxysporum* F.sp. *radicis-lycopersici* in a commercial field-type tomato and reduction of FCRR by biological control agents have been demonstrated (Marois and Mitchell, 1981; Sivan et al., 1987; McGovern et al., 1993a; Datnoff et al., 1995). Pathogen-free transplants and optimal cultural practices are also essential components in an integrated approach to reducing FCRR in tomato (McGovern et al., 1993b; McGovern, 1994).

ACKNOWLEDGMENTS

The authors would like to thank the SWFREC farm staff, K. Armbrester, F. Ligas, L. Richards, J. Kendall, R. McGill, for technical support and Dow AgroSciences for funding.

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Cowpea Cover Crop and Solarization for Managing Root-Knot and Other Plant-Parasitic Nematodes in Herb and Vegetable Crops

K.-H. Wang*, R. J. McGovern, R. McSorley, and R. N. Gallaher

ABSTRACT

Field experiments were conducted to evaluate three non-chemical alternatives to methyl bromide for the management of plant-parasitic nematodes on basil (*Ocimum basilicum* L.) and Chinese cabbage (*Brassica chinensis* L.). Five pre-plant treatments were 1) summer cover crop of cowpea [*Vigna unguiculata* (L.) Walp.], 2) soil solarization during autumn, 3) cowpea + solarization, 4) nontreated control and 5) fumigation with methyl bromide. At planting, each treatment was split with and without application of a commercial rhizobacterial product (PGA$^+$). Cowpea treatment suppressed populations of root-knot [*Meloidogyne incognita* (Kofoid & White) Chitwood] and stubby-root [*Paratrichodorus minor* (Colbran) Siddiqi] nematodes at termination of the cover crop and at basil harvest, but not at Chinese cabbage harvest. Methyl bromide-treated plots had lower ($P \leq 0.01$) numbers of awl (*Dolichodorus heterocephalus* Cobb) and sting (*Belonolaimus longicaudatus* Rau) nematodes and produced higher basil yield than those receiving the cowpea cover crop treatment. However, cowpea resulted in a slight yield benefit on Chinese cabbage, possibly due to a green manure effect from cowpea. Solarization was ineffective due to atypically cloudy weather that resulted in lower than expected soil temperatures and heavy growth of nutsedge (*Cyperus* spp.). Biocontrol with rhizobacteria was largely ineffective, and only suppressed population densities of sting nematode on Chinese cabbage. The cowpea cover crop was the most effective non-chemical alternative, however, the performance of individual non-chemical tactics must be improved before they can be integrated effectively to match fumigation with methyl bromide.

INTRODUCTION

Soil fumigation with methyl bromide is an important method for managing soil-borne pests in winter vegetable production in the United States. However, future use of methyl bromide is not feasible, due to its impending phaseout (Noling and Becker, 1994; Ristaino and Thomas, 1997). A variety of non-chemical practices are available for use against plant-parasitic nematodes and soil-borne plant pathogens (McSorley, 1998), but these methods are not as effective as methyl bromide in achieving rapid short-term reductions in pest population levels (McSorley, 2002). It is possible that results could be improved by combinations of several non-chemical practices (McSorley, 1998).

The use of soil solarization and nematode-suppressive cover crops are practical in regions where summers are not devoted to commercial crop production. Soil solarization has been used effectively against a variety of nematodes, plant pathogens, and weeds (Katan, 1980; Katan and DeVay, 1991; McGovern and McSorley, 1997). In warmer states such as Florida, it can even be used during autumn (McGovern et al., 2002). Tropical crops that are suppressive to nematodes can also be used during the summer in the South (Rodriguez-

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K.-H. Wang and R. McSorley, Dep. Entomology and Nematology, P. O. Box 110620, Univ. Florida, Gainesville, FL 32611-0620. R. J. McGovern, Dep. Plant Pathology, Univ. Florida, Gainesville, FL 32611-0680. R. N. Gallaher, Agronomy Dep., Univ. of Florida, Gainesville, FL 32611-0730. This work was supported in part by USDA, CSREES grant no. 00-51102-9571 and in part by the Florida Agric. Exp. Stn. and approved for publication as Journal Series No. N-02487.

*Corresponding author (koonhui@ufl.edu).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:99-104 (2004).

Kabana et al., 1988; 1989; McSorley, 2001). Although a number of crops may be useful for this purpose, nematode-suppressive legumes are particularly desirable due to soil nitrogen augmentation (McSorley, 1999). Choices of nematode-resistant legumes are more limited, but include cover crops such as velvetbean (*Mucuna* sp.), sunn hemp (*Crotalaria juncea* L.) and some cowpea cultivars such as 'Iron Clay' (Rodriguez-Kabana et al., 1992; Gallaher and McSorley, 1993; McSorley, 1999; Wang et al., 2001). The combination of solarization and cover crop amendment has been another encouraging approach to enhance the suppressive effect of solarization against pests and pathogens. The temperature and time requirements for solarization to control root-knot nematodes can be reduced in soils amended with plant residues (Ploeg and Stapleton, 2001). Similar improvement of solarization was observed for inactivation of chlamydospores of *Phytophthora nicotianae* var. parasitica (Dastur) Waterh. in soil amended with cabbage (*Brassica oleracea* var. *capitata* L.) leaves (Coelho et al., 2001).

A number of rhizosphere-inhabiting bacteria have shown potential for reducing infection by plant-parasitic nematodes (Kluepfel, 1993; Kloepper et al., 1999) and promote plant growth (Kloepper et al., 1980). Kokalis-Burelle et al. (2002) found that some rhizobacteria reduced the numbers of *Pythium* spp. on pepper (*Capsicum annuum* L.) roots and that combination of solarization and a rhizobacterial strain produced pepper yield comparable to methyl bromide fumigation. Commercial rhizobacterial products continue to improve in their consistency and performance for this purpose (McGovern et al., 2002, 2003).

The objectives of the current study are to determine the effect of solarization, a summer cover crop of cowpea, and their combination against nematodes and plant diseases, and to compare the most effective of these non-chemical alternatives with the standard methyl bromide fumigation. The ability of a commercial rhizobacterial product to provide additional protection against plant-pathogenic fungi and nematodes is also evaluated.

MATERIALS AND METHODS

Experiments were conducted at the Univ. of Florida Gulf Coast Res. and Educ. Center in Bradenton, FL (27.5°N, 82.6°W). Soil type was Eau Gallie sand (Sandy, siliceous, thermic Alfic Alaquod) (970 g kg^{-1} sand, 10 g kg^{-1} clay, 20 g kg^{-1} silt), with 19 g kg^{-1} organic matter. The site had been planted intermittently with solanaceous and cucurbit crops during the previous 20 yr, and contained a number of different plant-parasitic nematodes and plant-pathogenic fungi, as well as high levels of yellow nutsedge (*Cyperus esculentus* L.) at 1080 plants m^{-2}. Lower densities of purple nutsedge (*Cyperus rotundus* L.) were also present (McSorley and McGovern, 2000).

The site was disked and rotovated in early summer, 2001, when 30 experimental plots, 18.3-m long by 1.5-m wide, were established. Each of these plots was subjected to one of the following treatments before cash crop planting: 1) summer cover crop of cowpea, 2) soil solarization during autumn, 3) cowpea + solarization, 4) nontreated control or 5) fumigation with methyl bromide. These five treatments were arranged in six randomized complete blocks. After cash crop transplanting, half of each plot received a biocontrol treatment, whereas the other half were untreated.

For treatments involving a summer cover crop, seeds of Iron Clay cowpea were broadcast at 56 kg ha^{-1} on 16 July 2001. Cowpeas were maintained until 20 September when the crop was terminated by rototilling the crop residues. During this period, plots without cowpea treatment were left fallow with weeds. All plots were rotovated again just prior to establishing beds on 3 October. The single bed in each plot was 0.9 m wide by 18.3 m long. The distance from center to center of beds in adjacent rows was 1.5 m; plots in the same row were separated by 6.1-m buffer areas. Soil moisture content prior to bed formation was 160 g water kg^{-1} soil. Immediately after they were formed, beds were covered with clear (solarized treatments) or white (treatments without solarization) plastic mulch. Plots receiving fumigation received an application of 392 kg ha^{-1} of a mixture of 670 g kg^{-1} methyl bromide + 330 g kg^{-1} chloropicrin (Trichloronitromethane) prior to covering the beds with white plastic. The solarization treatments utilized a double layer of clear, 25-μm-thick, uv-stabilized, low-density polyethylene mulch (ISO Poly Films, Inc., Gray Court, SC). Double layers of polyethylene mulch generally achieve higher soil temperatures than a single layer due to increased insulation afforded by heating the intervening air space (Lamberti and Basile, 1991). The first layer was applied on 3 October and the second on 10 October. The second layer was raised 46 to 61 cm above the first, supported by stainless steel hoops. Soil temperatures were monitored at 5, 15, and 23 cm in a single plot mulched with either white or double clear plastic using WatchDog dataloggers (Spectrum Technologies, Inc., Plainfield, IL). Plastic was removed to terminate the solarization on 5 November. All plots were hand-weeded immediately prior to transplanting and as necessary thereafter to remove nutsedge.

Two experiments were set up in these plots, one with 'Genovese' basil and one with 'Sumo F1' Chinese cabbage. Plot size was reduced to 3.0 m in length for each experiment, and all beds were recovered with black plastic. On 16 November, 4-wk-old basil seedlings were transplanted into double rows in each bed with spacings of 45.7 cm between rows and 30.5 cm between plants in rows, for a total of 20 plants per plot. Three-week-old Chinese cabbage seedlings were planted on 30 November using the same spacing.

The biocontrol treatment consisted of Plant Growth Activator Plus (PGA+, Organica, Inc., Norristown, PA), which contains *Bacillus*, *Pseudomonas*, and *Streptomyces* spp. at 1.1 × 1012 colony forming units kg^{-1}, as well as *Trichoderma* sp., growth-promoting bacteria, and other substances including amino acids, vitamins, folic acid, biotin, and natural sugars. PGA+ was initially applied at 1.2 g L^{-1} water as a drench to half of the basil and cabbage seedlings in transplant trays at 18 and 11 d, respectively, after seeding. The biocontrol agent was applied at the same concentration by drenching 200 mL of the mixture to each treated plant at the time of transplanting. Half of each plot selected at random received a biocontrol application and half remained not treated. The same amount of PGA+ was reapplied to those selected plants on 14 and 28 December.

A water soluble fertilizer, Nutricote 15-13.2-12.4 (N-P-K, Agrivert, Inc., New York), was applied weekly at 123 kg N ha^{-1}, 54 kg P ha^{-1} and 103 kg K ha^{-1} throughout the season. The experiments were scouted at least once a week for above-ground insect and plant pathogen pests, and sprayed with insecticides on three (Chinese cabbage) or four (basil) occasions for control of lepidopterous pests. A ditch/seep irrigation system was used to maintain the water table and soil moisture in the bed at the site.

Marketable basil leaves were harvested on 6 and 19 Dec. 2001 and on 3 Jan. 2002. Chinese cabbage was harvested on 9 January. At the final harvest of each crop, the root systems of three plants per subplot were removed for determination of fresh-root weight. Root discoloration from fungi was evaluated on the root systems following a water wash, by estimating the percentage of the root system discolored and by rating on a 1 to 5 scale, where 1 = 0%, 2 = 1-10%, 3 = 11-25%, 4 = 26-50%, and 5 = 51-100% discoloration (McGovern et al., 2003).

Soil samples for analysis of plant-parasitic nematodes were collected on 20 September (before solarization), 14 November (at planting), and 9 January (after final harvest). Each soil sample consisted of four (January) or six (September, November) cores per plot, with each core 2.5-cm diam. by 20-cm deep. The cores comprising a sample were mixed, and a 100-cm^3 subsample was removed for extraction of nematodes using a modified sieving and centrifugation procedure (Jenkins, 1964). Extracted nematodes were identified and counted under an inverted microscope.

Data collected before the biocontrol treatments were imposed were analyzed as a 2 × 2 factorial, to determine the effects of solarization (+ or -), cowpea cover crop (+ or -), and their interaction. The methyl bromide fumigation treatment was compared with selected nonchemical treatment combinations (Table 1) by means of orthogonal contrasts (Freed et al., 1991; Freund and Littell, 1981). Data collected after the biocontrol (+ or -) treatments were imposed were analyzed as a 2 × 2 × 2 factorial. Prior to analysis, arcsine transformation was applied to percentage data and $\log_{10}(x + 1)$ transformation was applied to nematode data, but non-transformed data are presented in all tables.

RESULTS

Insufficient soil heating was achieved for pest management due to very cloudy weather during the solarization period (data not shown). Mean soil temperatures at depths of 5, 15, and 23 cm were 38.2, 30.9, and 30°C, respectively, in the solarized beds. These temperatures were similar to the 31.8, 29.0, and 27.6°C in the control beds.

A variety of different plant-parasitic nematodes were found at this site, however on 20 Sept. 2001, no differences ($P > 0.10$) in population levels of any nematode were found between plots that received a summer cover crop of cowpea and those that did not (data not shown). Nematode population levels on 20 September (before solarization), averaged across all treatments, were: 10.8 awl nematode (*Dolichodorus heterocephalus* Cobb) 100 cm^{-3} soil; 6.4 ring nematodes (*Mesocriconema* spp.) 100 cm^{-3} soil, 8.3 root-knot nematodes 100 cm^{-3} soil; 2.9 sheath nematodes (*Hemicycliophora* spp.) 100 cm^{-3} soil; 5.7 sting nematodes (*Belonolaimus longicaudatus* Rau) 100 cm^{-3} soil; 3.6 stubby-root nematodes [*Paratrichodorus minor* (Colbran) Siddiqi] 100 cm^{-3} soil; 33.7 stunt nematodes (*Tylenchorhynchus* spp.), 100 cm^{-3} soil; 1.5 cyst nem-

Table 1. Effect of cowpea cover crop (C), soil solarization (S), and methyl bromide fumigation (MB) on plant-parasitic nematodes at the end of pre-plant treatment (early stage of crop planting), 14 Nov. 2001.

Treatment	Awl	Cyst	Ring	Root-knot	Sheath	Sting	Stubby-root	Stunt
				Nematodes 100 cm^{-3} soil				
Cowpea	4.7†	2.2	3.7	0	0.2	1.7	0.7	14.3
Solarization (S)	8.5	3.0	1.7	0.8	1.8	3.5	1.0	50.8
Cowpea + S	3.3	5.0	0.5	0	2.3	1.3	0.2	59.7
Control	4.5	0.3	2.5	4.2	1.5	3.3	1.5	19.5
Methyl bromide	0	0	0.8	0	0.7	0	0	6.5
ANOVA effects:‡				F values				
Cowpea	0.97	0.12	0.69	14.09**	2.20	1.81	6.94*	0.21
Solarization	0.35	0.41	0.82	3.14¶	5.34*	0.11	2.09	11.76**
Cowpea × S	3.80¶	0.32	1.20	3.14¶	2.96	0.21	0.26	0.42
Contrasts: §								
Cowpea vs MB	8.00**	1.59	0.54	0	0.30	3.78¶	0.89	10.92**
S vs MB	12.55**	1.93	0.50	0.76	4.11	5.75*	2.01	20.13**
C+S vs. MB	8.90**	1.13	1.93	0	0.78	2.66	1.30	2.12

†Data are means of six replications.

‡F values from analysis of variance (ANOVA) based on log (x + 1) transformation; *, ** indicate significant effects at $P \leq 0.05$ and $P \leq 0.01$, respectively.

§F values from contrasts indicated; *, ** indicate significant effects at $P \leq 0.05$ and $P \leq 0.01$, respectively.

¶Significant at $P \leq 0.1$.

atodes (*Heterodera* spp.) 100 cm^{-3} soil. A few lance (*Hoplolaimus* spp.) and sheathoid nematodes (*Hemicriconemoides* spp.) were also recovered.

By 14 November, the previous cowpea cover crop had suppressed ($P \leq 0.05$) root-knot and stubby-root nematodes (Table 1). Stunt and sheath nematode numbers were increased ($P \leq 0.05$) in plots that had been solarized. Nematodes were at very low levels following methyl bromide fumigation. Fumigation was more effective than cowpea ($P \leq 0.10$) in suppressing awl, sting, and stunt nematodes (Table 1). In a few instances, significant effects from the cowpea cover crop or solarization persisted until the end of the basil (Table 2) and Chinese cabbage (Table 3) crops. However, strong suppression of nematodes by methyl bromide fumigation was evident at the end of the season in both crops (Tables 2, 3). Methyl bromide was more ($P \leq 0.10$) effective than cowpea in suppressing five of seven common plant-parasitic nematodes present in both tests.

The biocontrol treatment was largely ineffective against most nematodes. The only nematode affected by this treatment was the sting nematode in the cabbage experiment ($P \leq 0.05$). Sting nematode densities in plots receiving biocontrol averaged 14.4 nematodes 100 cm^{-3} soil, less ($P \leq 0.05$) than the 23.9 nematodes 100 cm^{-3} soil present in plots without the biocontrol.

The previous summer cover crop of cowpea was beneficial for basil production (Table 4). The cowpea cover crop resulted in increased marketable yield and root weight of basil, while reducing discoloration of roots attributed to fungi. *Fusarium* sp. *Rhizoctonia solani* Kühn, and *Sclerotium rolfsii* Sacc. were the fungi that were frequently isolated from discolored tissue collected during the weekly scouting. Despite these favorable results, the cowpea cover crop treatment was still inferior to methyl bromide fumigation, which resulted in highest ($P \leq 0.05$) yield and root weight (Table 4).

Yield of Chinese cabbage was hindered by solarization (Table 5). On this crop, results from the cowpea cover crop and methyl bromide treatments were similar, except for higher percentage of the root surface discolored ($P \leq 0.1$; Table 5) with cowpea treatment. Although ineffective on basil, the biocontrol treatment resulted in increased ($P \leq 0.05$) root weight in Chinese cabbage, averaging 34.7 g plant^{-1} in biocontrol-treated and 32.4 g^{-1} plant in untreated plots.

DISCUSSION

Plant-parasitic nematodes were suppressed by methyl bromide throughout the growing season on both crops. It is interesting that yield of basil was improved by methyl bromide fumigation while yield of Chinese cabbage was not. The results suggest that the nematodes present were more pathogenic to basil than to Chinese cabbage. Damage to basil by root-knot nematodes is known to be relatively severe (Haseeb et al., 1988; Moreno et al., 1992), but Chinese cabbage is less susceptible (McSorley and Frederick, 1995). Our current studies supported the observation that 'Iron Clay' cowpea suppressed root-knot nematodes (Gallaher and McSorley, 1993), although suppression was maintained through crop harvest on basil, the more susceptible crop, but not on the less susceptible Chinese cabbage.

The sting nematode is very damaging to cabbage, but nematode numbers in tests where cabbage yield was affected (Rhoades, 1971; 1977) were much greater than the numbers encountered here. In the present study, the reduction of sting nematode numbers by the biocontrol treatment and corresponding increase in root weight but not yield of Chinese cabbage suggests that the sting nematode numbers present approached but did not exceed the damage threshold for yield on this crop. The pathogenicity of the awl nematode to basil and Chinese

Table 2. Effect of cowpea cover crop (C), soil solarization (S), and methyl bromide fumigation (MB) on plant-parasitic nematodes in basil experiment at harvest, 9 Jan. 2002.

Treatment	Awl	Ring	Root-knot	Sheath	Sting	Stubby-root	Stunt
	Nematodes 100 cm^{-3} soil						
Cowpea	21.4†	3.4	0.2	1.1	7.6	8.5	8.5
Solarization	21.8	0.8	1.3	4.6	7.7	7.2	55.1
Cowpea + S	19.1	0.7	0.7	3.0	2.2	12.5	37.8
Control	33.2	1.5	1.8	1.2	10.8	9.5	17.2
Methyl bromide	4.6	0.1	0	0.3	0.1	3.9	0.4
ANOVA effects:‡	F values						
Cowpea	1.10	0.15	4.72*	0.02	4.93*	1.82	0.89
Solarization	1.13	1.68	0.04	2.18	13.74**	0.84	14.81**
Cowpea × S	0.01	0.15	2.39	0.34	0.04	1.95	0.17
Contrasts:§							
Cowpea vs MB	19.16**	4.04**	0.16	0.58	16.65**	3.82¶	17.30**
C+S vs. MB	13.74**	1.26	2.64	1.78	4.75*	4.70*	56.38**

†Data are means of 12 replications.

‡F values from analysis of variance (ANOVA) based on log (x + 1) transformation; *, ** indicate significant effect at $P \leq 0.05$ and $P \leq 0.01$, respectively.

§ F values from contrasts indicated; *, ** indicate significant effect at $P \leq 0.05$ and $P \leq 0.01$, respectively.

¶ Significant at $P \leq 0.1$.

Table 3. Effect of cowpea cover crop (C), soil solarization (S), and methyl bromide fumigation (MB) on plant-parasitic nematodes in Chinese cabbage experiment at harvest, 9 Jan. 2002.

Treatment	Awl	Ring	Root-knot	Sheath	Sting	Stubby-root	Stunt
	Nematodes 100 cm^{-3} soil						
Cowpea	8.8†	0.8	0.2	1.2	18.2	14.0	14.2
Solarization (S)	11.2	0.9	0.4	2.8	26.2	8.0	46.2
Cowpea + S	8.6	0.5	1.4	1.8	6.1	6.8	46.3
Control	15.1	0.5	0.5	2.2	26.0	12.2	26.4
Methyl bromide	0.5	0	0	0.2	0.6	0.4	0.8
ANOVA effects:‡	F values						
Cowpea	3.51¶	0.57	0.05	2.81	3.85¶	0.94	0.78
Solarization	0.98	0.31	0.59	0.05	9.56**	1.04	10.34**
Cowpea × S	0.14	1.68	0.59	0.01	1.48	0.57	0.38
Contrasts:§							
Cowpea vs MB	37.37**	3.50¶	0.35	1.48	25.04**	10.13**	22.86**
C + S vs MB	32.75**	1.93	3.15¶	1.62	7.92**	6.36*	60.29**

†Data are means of 12 replications.

‡F values from analysis of variance (ANOVA) based on log (x + 1) transformation; *, ** indicates significant effect at $P \le$ 0. 05 and $P \le 0.01$.

§F values from contrasts indicated; *, ** indicate significant effect at $P \le 0.05$ and $P \le 0.01$, respectively.

¶Significant at $P \le 0.1$.

cabbage is unknown, but the nematode has recently been associated with severe damage to several ornamental crops in Florida (McGovern et al., 2000; 2002). Awl nematode numbers were higher on basil than on Chinese cabbage in the current test and may have been at least partially responsible for the difference in yield response of the two crops to methyl bromide treatment.

Since nematodes and soilborne plant pathogens did not appear to affect yield of Chinese cabbage in this study, the slight yield benefit to this crop following the cowpea cover crop treatment is attributed to a green manure effect. Cowpea is a useful cover crop for fixing and supplying nitrogen to cropping systems in the Southeast (Powers and McSorley, 2000). Solarization was ineffective in the current study, although solarization during the autumn has performed well in Florida in other instances (McGovern et al., 2002). The rainy and cloudy conditions encountered during the current test were atypical for October in Florida, and heavy growth of nutsedge occurred under the clear plastic as a result of the failure to achieve lethal temperatures.

Table 4. Effect of cowpea cover crop (C), soil solarization (S), biocontrol, and methyl bromide fumigation (MB) on basil at harvest, 3 Jan. 2002.

Treatment	Marketable yield	Fresh root wt	Root rating†	Root discoloration
	g pot^{-1}	g $plant^{-1}$		%
Cowpea	809‡	23.1	2.75	14.2
Solarization (S)	706	20.8	3.20	21.5
Cowpea + S	784	23.5	2.67	13.3
Control	720	19.5	3.11	20.0
Methyl bromide	1008	28.1	2.60	12.2
ANOVA effects:§	F values			
Cowpea	5.30*	8.84**	32.49**	28.52**
Solarization	0.30	0.65	0	0.07
Biocontrol	0.44	1.61	1.02	1.02
Contrasts:¶				
Cowpea vs MB	11.60**	5.51*	1.20	0.97
C + S vs MB	9.78**	3.81#	0.34	0.40

†Roots rated on 1-5 scale, where 1 = 0%, 2 = 1-10%, 3 = 11-25%, 4 = 26-50%, and 5 = 51-100% of root surface discolored.

‡Data are means of 12 replications.

§F values from analysis of variance (ANOVA); *, ** indicate significant main effects at $P \le 0.05$ and $P \le 0.01$, respectively. No interactions were significant at $P \le 0.10$.

¶F values from contrasts indicated; *, ** indicate significant contrast at $P \le 0.05$ and $P \le 0.01$, respectively.

#Significant at $P \le 0.1$.

Table 5. Effect of cowpea cover crop (C), soil solarization (S), biocontrol, and methyl bromide fumigation (MB) on Chinese cabbage at harvest, 9 Jan. 2002.

Treatment	Marketable yield	Fresh root weight	Root rating†	Root discoloration
	g pot^{-1}	g $plant^{-1}$		%
Cowpea	5.51‡	35.2	2.45	10.4
Solarization (S)	4.18	31.5	2.57	10.5
Cowpea + S	4.28	32.6	2.41	10.1
Control	4.48	33.2	2.47	11.2
Methyl bromide	4.39	35.2	2.33	9.0
ANOVA effects:§	F values			
Cowpea	3.34v	1.85	0.54	0.24
Solarization	6.29*	3.48*	0.17	0.32
Biocontrol	0.11	5.89*	0.33	0.41
Contrasts:¶				
Cowpea vs MB	1.56	0.45	2.44	3.57#
C + S vs MB	0.06	1.41	1.12	2.01

†Roots rated on 1-5 scale, where 1 = 0%, 2 = 1-10%, 3 = 11-25%, 4 = 26-50%, and 5 = 51-100% of root surface discolored.

‡Data are means of 12 replications (means across biocontrol treatments).

§F values from analysis of variance (ANOVA); * indicates significant effect at $P \le 0.05$. No interactions were significant at $P \le 0.10$.

¶F values from contrasts indicated; no contrasts significant at $P \le 0.05$.

#Significant at $P \le 0.1$.

While the nutsedge was removed in order to better assess effects of treatments on nematodes and soil-borne diseases, some indirect effects of nutsedge on nematode populations may have resulted, such as stimulation of stunt nematode populations in solarized plots. Biocontrol treatments with rhizobacteria, while ineffective against nematodes in previous experiments (McSorley and McGovern, 2001), showed some activities against sting nematode in the current test.

The results of the Chinese cabbage experiment indicate that no yield advantage of methyl bromide over the nonchemical alternatives could be obtained with a tolerant host and when pest and disease pressure is low and nonpathogenic. However, even when low populations of damaging pathogens are present, methyl bromide fumigation was beneficial and superior to the alternatives on a highly nematode susceptible crop such as basil. The use of a cowpea cover crop was encouraging in that it outperformed the other nonchemical treatments and resulted in a basil yield equivalent to 80% of that provided by methyl bromide fumigation. It was hoped that combining soil solarization with the cover crop could recover some of the 20% shortfall in yield, but the solarization was completely ineffective during this unusually wet and cool fall season. The combination of solarization and cowpea cover crop should be reevaluated under more favorable conditions to assess their performance relative to methyl bromide. If the performance of rhizobacterial products in biological control or enhancement of plant growth continues to improve in the future, this may offer an additional option for integration with other nonchemical practices.

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Relationships of Nematode Communities and Soil Nutrients in Cultivated Soils

K.-H. Wang*, R. McSorley, and R. N. Gallaher

ABSTRACT

Nematodes play an important role in soil nutrient cycling, but information on their relationships with soil nutrients is limited. In this study, correlations of nematode abundance and other indices of nematode community structure with soil nutrient concentrations, pH, cation-exchange capacity (CEC), and organic matter (OM) were examined in two greenhouse experiments. In both experiments, soils collected were amended or not amended with 'Tropic Sun' sunn hemp (*Crotalaria juncea* L.) hay, then planted with 'Yellow Crookneck' squash (*Cucurbita pepo* L.) for 2 mo. For the first experiment, soil was from a site with a long-term (LT) agricultural history (>8 yr). In the second experiment, soil was from a site with a shorter-term (ST) agricultural history (4 yr). In the LT experiment, most of the significant ($P \leq 0.10$) correlations between abundance of individual nematode taxa and soil properties were negative, whereas those in the ST experiment were positive. In terms of nematode trophic group abundance, only total fungivore numbers correlated negatively with soil nutrient concentrations in the LT experiment ($P \leq 0.10$), but total abundance of bacterivores, herbivores, omnivores, and predators, but not fungivores, were correlated positively with soil nutrient concentrations in the ST experiment ($P \leq 0.10$). Maturity index, an index to measure nematode communities in response to soil disturbance, correlated positively, whereas diversity correlated negatively with several nutrient concentrations in both experiments. Correlations of other nematode community indices with nutrient concentrations depended on the presence of a broad range of levels of indices and nutrient concentrations in the samples. More frequent observations over time in combination with plant tissue nutrient analysis are needed to clarify the dynamics of nematode communities and nutrient availability in cultivated soil ecosystems.

INTRODUCTION

Nematodes play an important role in soil nutrient cycling. Grazing on microbes by nematodes releases and mineralizes nutrients immobilized by microbes during the initial stages of OM decomposition (Ingham et al., 1985), converting N from organic to inorganic forms, which then can be taken up by plants (Troyfymow and Coleman, 1982; Seastedt et al., 1988; Sohlenius et al., 1988). Nematodes contribute 4 to 22% of total net N mineralization in the soil (Griffiths and Caul, 1993). Most of the studies on the relationship between nematodes and soil nutrients focused on N and P (Ingham et al., 1985; Ferris et al., 1998). Previously, Wang et al. (2004) had determined that in an undisturbed soil (fallow for >1.5 yr), abundance of many genera of bacterivorous nematodes was positively correlated with concentrations of most soil nutrients (except Cu and Fe) as well as OM content. While abundance of fungivorous nematodes correlated with nutrient concentrations, they were always negatively correlated with OM content (Wang et al., 2004). Overall, there is a scarcity of information on the relationships of nematodes with soil nutrients in recently cultivated soil. One of the top research priorities proposed by the Scientific Congress on Organic Agriculture Research is to functionally identify soil microbial communities and to find ways to manage microbial dynamics in order to enhance nutrient cycling and disease suppression (Koenig and Baker, 2002). As reviewed by Neher (2000), the relationship between nematode community structure and nutrient availability is unclear.

Therefore, in the current study, we explored the relationships of the nematode community with nutrient availability in a recently cultivated soil. To generate diverse regimes of nematode communities, we used soils with different agricultural histories and organic amendments. The specific objectives of this research are to: 1) determine the relationship between free-living nematodes and soil nutrient concentrations, CEC, and OM under cultivated soils; and 2) examine whether agricultural histories affect the relationship between nematode communities and soil nutrient concentrations.

MATERIALS AND METHODS

Two greenhouse experiments were conducted on the Univ. of Florida in Gainesville, FL. Using soils receiving or not receiving sunn hemp hay to create different ranges of nematode communities, the relationships between soil properties and nematodes were tested in soils collected from sites with long-term (>8 yr) and short-term (4 yr) agricultural history, thus were referred to as LT and ST experiments, respectively.

LT Experiment

The first experiment was conducted in spring, 2001. Soils were from two field sites previously used for yard-waste compost studies at the former Univ. of Florida Green Acres Agronomy Farm in Alachua Co. Soils were Arredondo loamy sand (loamy, siliceous, hyperthermic, Grossarenic Paleudult) (Thomas and Wittstruck, 1985), with 940 g sand kg^{-1}, 20 g silt kg^{-1}, and 40 g clay kg^{-1}. These soils are characterized as having a long-term history of yard-waste compost (YWC+) or no yard-waste compost (YWC-). Approximately 25 to 30 kg of the YWC+ soil was collected from field plots amended with 269 Mg $ha^{-1}yr^{-1}$ of composted yard-waste plant materials, including sticks, clippings, and wood fragments, each year from 1993 to 1998. The composting process and application is described in detail (McSorley and Gallaher, 1996). By 2001, when significant decomposition had occurred, the main impact from these past treatments was an accumulation of a great amount of soil OM. The site was planted with two successive cycles of corn (*Zea mays* L.)

K.-H. Wang and R. McSorley, Dep. of Entomology and Nematology, Univ. of Florida, Gainesville, FL 32611-0620; and R. N. Gallaher, Dep. of Agronomy, Univ. of Florida, Gainesville, FL 32611-0730. This research was supported in part by Univ. of Florida and is approved for publication as Florida Agric. Exp. Stn. Journal Series No. N-02451.

*Corresponding author (koonhui@ufl.edu).

Contribution published in
Soil Crop Sci. Soc. Florida Proc. 63:105-113 (2004).

with cowpea [*Vigna unguiculata* (L.) Walp.] as an intercycle cover crop during 1998 and 1999, then fallowed with weeds, remaining undisturbed until soil collection in March 2001. Soil OM content of this site was 84.4 g kg^{-1}. A similar amount of YWC- soil was collected from the same experimental sites as the YWC+ (McSorley and Gallaher, 1996) but from field plots not amended with yard-waste compost. Organic matter content of this soil was 24.2 g kg^{-1}. Soil from each site was sieved through a mesh (2 mm) to remove coarse plant debris but still allow smaller flora and fauna to pass through, and the soil was then homogenized for use in a greenhouse experiment.

Soil Amendment

On 7 Mar. 2001, the two soils were either amended or not amended with sunn hemp hay at 10 g kg^{-1} based on soil dry weight. The hay was harvested from a cover crop grown during 2000. The hay was air-dried, and stored for >3 mo. Soil with dry weight of 454 g (adjusted according to soil moisture of each soil) was placed into a 12.7-cm diam. × 7.5-cm-deep plastic pot. The experiment was a 2 × 2 factorial (soil history × sunn hemp amendment), arranged in four randomized complete blocks.

On 18 Mar. 2001, a 3-d old squash seedling was planted into each pot. Five days after planting, 200 *Meloidogyne incognita* (Kofoid & White) Chitwood second-stage juveniles (J2) in 3 mL of water were injected by pipette into three holes made around each seedling. These nematodes had been cultured previously in a greenhouse on 'California Wonder' pepper (*Capsicum annum* L.). Eggs were extracted from root systems in 3.5 g kg^{-1} NaOCl (Hussey and Barker, 1973) and incubated on Baermann trays for 7 d to obtain hatched J2 nematodes (Barker, 1985).

Plants were watered daily and fertilized weekly with 50 mL of a solution of 0.54 g L^{-1} of 15-13.2-12.4 (N: P: K) of Miracle-Gro (Scotts Miracle-Gro Product, Inc., Marysville, OH) fertilizer, using an equal amount of water and fertilizer for each plant. Squash flowers were picked as soon as they appeared to prevent fruiting and uneven growth among the plants. Safer Brand Insecticidal Soap (Safer, Inc., Bloomington, MN) was sprayed on the foliage to manage populations of silverleaf whiteflies (*Bemisia tabaci* Gennadius), but all plants showed some silver leaf symptoms by the end of the experiment. The experiment was terminated on 15 May 2001, 8 wk after *M. incognita* inoculation.

ST Experiment

The experiment was repeated in fall 2001, however, only one soil was tested. Due to the closing of Green Acres Agronomy Farm, Millhopper sand (loamy, siliceous, hyperthermic, Grossarenic Paleudult) (Thomas and Wittstruck, 1985) with 920 g sand kg^{-1}, 30 g silt kg^{-1}, and 50 g clay kg^{-1}, and 1.95 organic matter kg^{-1} from the Univ. of Florida, Experimental Designs Field Teaching Laboratory, was used in the second experiment. In contrast to the LT experiment, this site is considered to have a short-term agricultural history because it was first planted to vegetable crops rather recently (1997). The field site was cropped with various vegetable crops, and was continuously disrupted by rototilling after each short-lived vegetable crop. A cover crop of rye (*Secale cereale* L.) was intercropped with lupine (*Lupinus angustifolius* L.) in the season prior to soil sampling. Soil for the greenhouse test was either amended or not amended with sunn hemp hay as described in the LT experiment. The two treatments were replicated in four randomized complete blocks. Squash seeds were planted on 24 Sept. 2001, and inoculated 1wk after germination. Due to the low recovery of *M. incognita* at the termination of LT experiment, 800 J2 of *M. incognita* were inoculated for each pot in ST experiment. The experiment was terminated on 26 Nov. 2001, 8 wk after nematode inoculation.

Nematode Assay

At the termination of each experiment, soil from each pot was placed in a plastic bag, mixed well, and 100 cm^3 of soil was subsampled to extract nematodes by a sieving and centrifugal flotation method (Jenkins, 1964). The extracted nematodes were heat-killed (2.5 min at 60°C), preserved with 10 mL formalin L^{-1} and 0.5 mL streptomycin sulfate L^{-1}, and stored at 4°C until counted. All nematodes from the subsample were identified by genus, or by family or order if genus was not clear, and counted using an inverted microscope.

Nematode Community Analysis

Nematodes were assigned to five trophic groups: bacterivores, fungivores, herbivores, omnivores, and predators (Yeates et al., 1993). Although feeding habits of some Tylenchidae (mostly *Filenchus* and *Tylenchus* spp.) and *Ecphyadophora* spp. are considered unclear (Yeates et al., 1993), they were classified as fungivores (McSorley and Frederick, 1999; Okada *et al.*, 2002) in this experiment. *Monhystera* spp. was grouped as a bacterivore rather than a substrate ingestor (Yeates et al., 1993). The total number of nematodes in every trophic group and the percentage of every trophic group in the nematode community were calculated.

On the basis of nematode data, several indices of the nematode community were computed. Nematode richness was determined as the total number of different taxa recorded per sample. Simpson's index of dominance (Simpson, 1949) was calculated as $\lambda = \Sigma(p_i)^2$, where p_i is the proportion of each genus i present (those identified to the family or order level were excluded). Simpson's index of diversity was calculated as λ^{-1} (Freckman and Ettema, 1993). Fungivore (F) to bacterivore (B) ratios was calculated to characterize decomposition and mineralization pathways, using the F/B ratio of Freckman and Ettema (1993) and the F(F+B)$^{-1}$ ratio of Neher (1999). Total maturity index (MI) as defined by Yeates and Bird (1994) was calculated as $\Sigma(p_i c_i)$, a weighted mean of the colonizer-persister (*c-p*) values of nematodes in all trophic groups including herbivores, where c_i is the *c-p* rating for taxon *i* according to the 1 to 5 *c-p* scale (Bongers and Bongers, 1998). Nematode fauna were further analyzed by a weighting system for the nematode functional guilds in relation to enrichment and structure of the food web as suggested by Ferris et al. (2001). These indices include the enrichment index (EI), structure index (SI), and channel index (CI). The EI and SI are proposed to describe the enrichment and the structure condition of the soil food web respectively (Ferris et al., 2001). They are calculated as $EI = 100 \times [e(e+b)^{-1}]$ and $SI = 100 \times [s(s+b)^{-1}]$ where e, s, and b are the abundance of nematodes in guilds representing enrichment (guilds Ba_1, Fu_2), structure (guilds Ba_3-Ba_5, Fu_3-Fu_5, Om_3-Om_5, Ca_2-Ca_5) and basal (guilds Ba_2, Fu_2) food web components, respectively (Ferris et al., 2001). The CI represents the predominant decomposition pathway in the soil food web, and is calculated as $CI = 100 \times [0.8Fu_2(3.2Ba_1 + 0.8Fu_2)^{-1}]$ where Fu_2 and Ba_1 are the abundance of fungivorous nematodes in the guild with a *c-p* value of 2, and bacterivorous nematodes in the guild with *c-p* value of 1, respectively.

Soil Properties and Nutrient Analyses

Soils from all the experimental units were analyzed for soil nutrients and properties. Nitrogen was analyzed by a modified micro-Kjedahl procedure (Gallaher et al., 1975). For other soil mineral analysis, a double acid, or Mehlich I (Mehlich, 1953), extraction procedure was used. Phosphorous was analyzed by colorimetry, K and Na by flame emission spectrophotometry, and Ca, Mg, Cu, Fe, Mn, and Zn by atomic absorption spectrophotometry (Gallaher et al., 1975). Soil pH was measured by mixing soil and water on a 1: 2 (v: v) ratio, using a glass electrode pH meter (Peech, 1965). Cation exchange capacity was measured by summation (Jackson, 1958), OM by the Walkley (1947) method, and mechanical analysis by the hydrometer method (Bouyoucos, 1936).

Statistical Analysis

Soil nutrient data were subjected to a 2 × 2 (soil history × amendment) factorial analysis of variance (ANOVA) for the LT experiment, and a one-way ANOVA for the ST experiment. Data for nematode abundance and community indices were also subjected to ANOVA, but results were presented elsewhere (Wang et al., 2003). Simple correlation coefficients (*r*) between population levels of each nematode genus and levels of each soil property, and between nematode community indices and soil properties were calculated (SAS Institute, 2000) for each experiment individually. Correlation analysis in the LT experiment was based on n = 16 and in the ST experiment was based on n = 8, where n = number of experimental units.

RESULTS

Sunn Hemp Effects on Soil Properties

In the LT experiment, soil nutrient analysis indicated that sunn hemp amendment generated different levels of nutrient concentrations for Mg, Na, Fe, and Mn ($P \leq 0.05$), but did not affect levels of pH, CEC, and OM ($P > 0.05$) (Table 1). On the other hand, most of the nutrient concentrations tested except K, and pH, CEC, and OM were different between YWC+ and YWC- soil ($P \leq 0.05$) (Table 1). In the ST experiment, sunn hemp amendment only affected K and Fe concentrations, and OM content ($P \leq 0.05$) (Table 2). In general, soil nutrient concentrations were higher in soils in the LT experiment than the ST experiment (Tables 1 and 2).

Table 1. Effect of sunn hemp (Cj) amendment on soil nutrients and other properties in soil with and without yard-waste compost (YWC+, YWC-) collected from a long-term agricultural site (LT experiment).

	YWC+		YWC-		ANOVA†		
	Cj+	Cj-	Cj+	Cj-	Cj	Soil	Soil × Cj
Nutrient concentration (mg kg^{-1})							
Ca	2512.0	2554.0	620.0	673.0	NS	*	NS
Mg	176.2	204.0*	82.5	91.0	**	***	NS
K	27.9	33.0	20.3	31.2	NS	NS	NS
P	145.2	153.0	121.5	114.5	NS	***	*
Na	61.5	75.3	35.4	57.8	***	***	NS
N	2273.2	2488.0	630.8	800.5	NS	***	NS
Cu	0.31	0.3	0.6	0.6	NS	***	NS
Fe	7.6	8.1	8.0	11.9**	***	***	***
Mn	12.4	14.1	7.0	11.0**	***	***	*
Zn	27.1	26.5	6.5	6.5	NS	***	NS
Soil properties							
pH	6.1	6.3*	5.9	5.8	NS	***	NS
CEC (cmol kg^{-1})‡	17.5	17.8	6.7	7.2	NS	***	NS
OM (g kg^{-1})‡	57	54	18	19	NS	***	NS

†Data are analyzed in a 2 × 2 (Compost × Cj) factorial Analysis of Variance (ANOVA), followed by one-way ANOVA for each compost treatment.

‡CEC = cation exchange capacity; OM = organic matter content.

*,**,***Significant difference between Cj+ and Cj-, and significant difference of ANOVA effect or interaction at $P \leq 0.05$, 0.01, or 0.001, respectively. NS = non-significant at $P > 0.05$.

Table 2. Effect of sunn hemp (Cj) amendment on soil nutrients concentration and other properties in soil collected from a short-term agricultural site (ST experiment).

	Cj+	Cj-
Nutrient concentrations (mg kg^{-1})		
Ca	592.0†	598.67
Mg	76.67	80.20
K	35.13	25.80*
P	80.60	79.20
N	501.50	465.17
Na	38.80	34.33
Cu	0.33	0.55
Fe	4.60	4.13***
Mn	4.10	3.75
Zn	3.49	3.83
Soil properties		
pH	5.93	6.10
CEC (cmol kg^{-1})	4.68	4.55
OM (%)	1.73	1.43 **

†Means (average of 4 replications) followed by *, **, and *** indicating difference between Cj + and Cj- are significant at $P \leq 0.05$, 0.01, and 0.001, respectively, according to analysis of variance.

Soil Properties and Nematode Abundance

The relationship between nematode abundance and soil properties, including soil nutrient concentrations, OM, CEC and pH, behaved differently in soils with different histories. In the LT experiment, most of the correlations ($P \leq 0.10$) between nematode abundance and soil properties were negative (Table 3), whereas most of those in the ST experiment were positive ($P \leq 0.10$) (Table 4). Correlations ($P \leq 0.10$) between nematode abundance and soil properties in the LT experiment involved only bacterivores, fungivores, and herbivores, but not omnivores and predators (Table 3). However, correlations ($P \leq 0.10$) between nematode abundance and soil properties in ST Experiment involved all five nematode trophic groups (Table 4). In the LT experiment, nematode abundance correlated most frequently with pH, CEC, and OM, but these correlations were often weak ($P \leq 0.10$) (Table 3). In the ST experiment, no nematode taxa correlated with OM (Table 4). A wider range of nutrient elements were involved in the correlations in the LT experiment than the ST experiment, but no particular elements correlated with more than two nematode genera at $P \leq 0.05$ (Table 3). On the other hand, in the ST experiment, although fewer nutrient elements were involved in the correlations ($P \leq 0.10$) between nutrient concentrations and nematode abundance, more nematode genera were involved and a higher frequency of nematode genera correlated ($P \leq 0.05$) with concentration of Ca and Mn (Table 4). In the LT experiment, *Eucephalobus*, *Aphelenchoides*, and *Mesocriconema* spp. contributed to most of the correlations ($P \leq 0.10$) (Table 3), whereas *Acrobeles* and *Paratrichodorus* spp. were the nematodes correlated with most nutrient concentrations in the ST experiment (Table 4). Previously in a soil fallow for 1.5 yr, the abundance of many nematode taxa correlated negatively with Cu concentration (Wang et al., 2004), but in this study (Tables 3 and 4) several nematodes correlated positively with Cu concentration except for *Paratrichodorus* in ST experiment (Table 4).

Table 3. Significant correlations between abundance of nematode genera and soil properties in greenhouse squash-planted pots with soil collected from a long-term agricultural site (LT experiment).

Nematode	Soil property	r‡	Nematode	Soil property	r
Bacterivores			Fungivores		
Acrobeles	pH	-0.5171*§	Aphelenchoides	N	-0.4665
Acrobeloides	OM†	0.4303		Ca	-0.4652
Eucephalobus	N	-0.5733*		Mg	-0.5088*
	P	-0.5300*		Cu	0.4856
	Ca	-0.5947*		Zn	-0.4586
	Mg	-0.6334**		pH	-0.4531
	Cu	0.5840*		CEC	-0.4605
	Mn	-0.6824**		OM	0.4303
	Zn	-0.5863*	Herbivores		
	Na	-0.6667**	Meloidogyne	K	-0.4658
	pH	-0.4727	Mesocriconema	Ca	-0.4542
	CEC†	-0.5921*		Cu	0.4489
	OM	-0.5621*		Mn	-0.4811
Rhabditidae	K	-0.6049**		Zn	-0.4460
	Na	-0.5744*		pH	-0.4497
	Mn	-0.4859		CEC	-0.4428
Zeldia	K	0.4582		OM	-0.4789
	Fe	0.5654*	Pratylenchus	N	0.5746*
	pH	-0.4275		CEC	0.4458

†Cation-exchange capacity (CEC), organic matter (OM).

‡Correlation coefficient (*r*) based on N = 16.

§Only correlation significant at $P \leq 0.10$ were reported; * and ** significant at $P \leq 0.05$ and 0.01, respectively.

Table 4. Significant correlations between abundance of nematode genera and soil properties in greenhouse squash-planted pots with soil collected from a short-term agricultural site (ST experiment).

Nematode	Soil property†	*r*‡	Nematode	Soil property	*r*
Bacterivores			Fungivores		
Acrobeles	P	0.7734*§	Aphelenchoides	Ca	0.8532**
	Cu	0.6544	Filenchus	Ca	0.9551***
	Mn	0.6634		Mn	0.7625*
	Zn	0.6834	Tylenchus	CEC	-0.6546
Acrobeloides	Ca	0.9193**	Herbivores		
	Mn	0.6560	Paratrichodorus	Ca	0.8329*
Cephalobus	Ca	-0.6269		Cu	-0.7433*
	Mn	-0.7026*		Mn	-0.6901
	pH	0.6798		pH	0.9682***
Eucephalobus	P	0.7396*	Omnivores		
	Mn	0.7626*	Eudorylaimus	Mn	0.7305*
Plectus	CEC	0.6250	Predators		
Rhabditidae	Mn	0.6274	Nygolaimus	P	0.6778
Zeldia	Mn	0.7721*	Tobrilus	Ca	0.7493*
				pH	0.7589*

†Nutrient concentrations, cation exchange capacity (CEC), organic matter (OM) or pH.

‡Correlation coefficient (*r*) based on N = 8.

§Only correlation significant at $P \leq 0.10$ were reported; *, **, and *** significant at $P \leq 0.05$, 0.01, and 0.001, respectively.

Soil Properties and Nematode Community Indices

Among the total abundance of nematode trophic groups, only fungivore numbers correlated ($P \leq 0.10$) negatively with soil nutrient concentrations in the LT experiment (Table 5). However, in the ST experiment, all trophic groups except fungivores were correlated positively with concentration of at least one soil nutrient (Table 6). In both experiments, diversity was negatively correlated with many nutrient concentrations and CEC, whereas dominance correlated positively with few soil properties (Tables 5 and 6). Maturity index was positively correlated with Mg and N in both experiments (Tables 5 and 6). There were stronger correlations between SI and nutrient concentrations as compared with MI in the LT experiment (Table 5) but not in the ST experiment (Table 6). Enrichment index and CI also correlated with some nutrient concentrations in LT experiment but not in the ST experiment (Tables 5 and 6).

Table 5. Significant correlations between nematode community indices and soil properties in greenhouse squash-planted pots with soil collected from a long-term agricultural site (LT experiment).

Index	Soil property†	*r*‡	Index	Soil property	*r*
Total herbivores	pH	-0.4404§	Diversity	OM	-0.5669*
Total fungivores	N	-0.5269*	Dominance	pH	0.4422
	Ca	-0.5094*	Maturity	Mg	0.4868
	Mg	-0.5174*		K	0.5756*
	Cu	0.5241*		Na	0.4989
	Zn	-0.5084*		N	0.4535
	Na	-0.4791		Cu	-0.4495
	pH	-0.4400	Enrichment	Na	-0.5662*
	CEC	-0.5022*		Mn	-0.4462
	OM	-0.4289	Channel	Fe	0.5109
Diversity¶	N	-0.5453*	Structure	Ca	0.6422**
	P	-0.4911*		Mg	0.6512**
	Ca	-0.5468*		P	0.7417**
	Mg	-0.5396*		N	0.5975*
	Na	-0.4817		Cu	-0.6359**
	Cu	0.5440*		Fe	-0.5027
	Mn	-0.4326		Mn	0.4518
	Zn	-0.5301*			
	pH	-0.4321			
	CEC	-0.5351*			

†Nutrient concentrations, cation exchange capacity (CEC), organic matter (OM) or pH.

‡Correlation coefficient (r) based on 16 values.

§Only correlation significant at $P \leq 0.10$ were reported; * and ** significant at $P \leq 0.05$ and 0.01, respectively.

¶Diversity is reciprocal transformation of Simpson's index (Freckman and Ettema, 1993).

Table 6. Significant correlations between nematode community indexes and soil properties in greenhouse squash-planted pots with soil collected from a short-term agricultural site (ST experiment).

Indexes	Soil property†	r‡	Indexes	Soil property	r
Total bacterivores	Fe	0.6602§	Diversity	Mg	-0.6763
Total omnivores	Fe	0.7907*		P	-0.6293
	OM	0.6389		N	-0.7185*
Total predators	K	0.7280*		Fe	-0.7483*
	OM	0.8260*		Zn	0.9126**
Total herbivores	N	0.6263		CEC	-0.6389
	Fe	0.8083*	Maturity	Mg	0.6981*
Total nematodes	Fe	0.7245*		N	0.6365
F/B¶	CEC	-0.7024*		CEC	0.7328*
Dominance	Mg	0.7583*	Enrichment	OM	0.7313*
	P	0.6605			
	N	0.6405			
	Fe	0.7319*			
	Zn	-0.7574*			
	CEC	0.7126*			

†Nutrient concentrations, cation exchange capacity (CEC), organic matter (OM) or pH.
‡Correlation coefficient (r) based on 8 values.
§Only correlation significant at $P \leq 0.10$ were reported; * and ** significant at $P \leq 0.05$ and 0.01, respectively.
¶F/B is a ratio of fungivore to bacterivore numbers.

DISCUSSION

Overall, results of these experiments revealed inconsistent relationships between nematode abundance and nutrient concentrations in these soils with different agricultural histories. Many genera showed no or few correlations with nutrients and other soil properties. Only diversity and MI correlated with soil nutrient concentrations in a consistent manner in these experiments. Total abundance of nematodes in each trophic group was partially consistent with our previous studies in a fallow soil (Wang et al., 2004) in which bacterivores, omnivores, and predators correlated positively with most nutrient concentrations whereas fungivores correlated negatively with most nutrient concentrations. In the current experiment, where soil from a cultivated squash ecosystem was used as opposed to the 1.5-yr undisturbed fallow soil studied previously (Wang et al., 2004), negative correlation between fungivores and nutrient concentrations in the LT experiment were observed, and only a few instances of positive correlations between most nematode trophic groups (but not fungivores) and nutrient concentrations occurred in the ST experiment.

Factors Affecting Correlation

Many factors could have resulted in these differences between LT and ST experiments. The soil food-web conditions between these two experiments might have resulted in the vast differences in the correlation results between nematode and nutrient concentrations. Due to the different background in agricultural histories, followed by the differences in soil properties such as OM and other factors, these two soils might have been undergoing different nutrient cycling processes at time of sampling.

At sampling, the nematode community of the soil in the LT experiment had an EI ranging from 10 to 31, whereas its SI ranged from 0 to 6 (due to previous YWC treatments and sunn hemp treatments). When the EI and SI values were placed on the enrichment and structure trajectories as defined by Ferris et al. (2001), soil from LT experiment mapped in Quadrat D (representing a stressed and degraded condition). On the other hand, soil from the ST experiment had an EI ranging from 61 to 70 and a SI ranging from 19 to 22, mapping the soil food web in Quadrat A of the enrichment and structure trajectories (representing a highly disturbed but N-enriched condition). These results suggest that soil in LT experiment might have passed its enrichment stage, with nutrients in the soil in a depleted condition. The higher abundance of nematodes may have resulted in a faster mineralization rate in this soil, providing more nutrients readily available for plant uptake, and consequently resulting in a lower soil nutrient concentrations at 8 wk after squash planting. This is consistent with the negative correlations observed between a number of nematode taxa and soil nutrient concentrations in this soil (Table 3). However, observed N levels (ranging from 631-2488 mg kg^{-1} in the LT experiment and from 465-502 mg kg^{-1} in the ST experiment, Tables 1 and 2) are inconsistent with this explanation. The high N levels in the LT experiment, especially in the YWC+ soils (ranging from 2273-2488 mg kg^{-1} N) do not suggest N-depleted conditions. Clearly, frequent sampling of nematodes and nutrients over time would be needed to better understand the complex and dynamic nature of nematode succession, mineralization, and plant uptake, all of which affect nutrient equilibrium in soil food-webs.

The lower inoculum level of *M. incognita* in the LT experiment than in the ST experiment might have allowed squash plants to acquire nutrients more efficiently in the LT than in the ST experiment. Plants in the LT experiment suffered less damage from *M. incognita* infection, perhaps allowing more herbivorous nematodes to reproduce and deplete more nutrients from the soil, resulting in a negative correlation between soil nutrient concentration and abundance of several nematode taxa, especially those in the herbivorous group. Higher inoculum level of *M. incognita* in ST Experiment caused more damage to the plant, leaving more soil nutrients not taken up by plants. Ritzinger et al. (1998) also reported that soil nutrients were greater where root-knot nematode numbers and damage were higher and plant growth was poorer.

Another point of view on why the correlation between nematodes and soil properties differed between LT and ST experiments is that the ranges of many soil properties differed between these experiments. Ranges of concentrations of Ca, Mg, P, Na, N, Fe, Mn, and Zn were higher in the LT experiment than those in the ST experiment (Tables 1 and 2). Similarly, CEC and OM were also higher in the LT than in the ST experiment.

A significant correlation between nematode abundance and levels of soil properties can only be detectable if 1) the nematode examined is present, and 2) different levels of nutrient concentrations or other soil properties exist within a soil. For example, soil in the LT experiment had high abundance of bacterivores (73%) but very low numbers of omnivores and no predatory nematodes (Wang et al., 2003). Therefore, no correlations between the abundance of omnivores and predators and soil properties could be detected in the LT experiment. However, in soil from the ST experiment, numbers of omnivores and predators were relatively higher than those in LT experiment, and when this soil was amended with sunn hemp, a wide range of counts of omnivores and predators were generated between the amended and unamended soils. Therefore, correlations between some genera of omnivores and predators, and some soil nutrient concentrations were obtained in the ST experiment (Table 4). Lack of correlation between nematode abundance and OM, CEC, and pH in the ST experiment was due to the fact that only a narrow range of OM (14-17 g kg^{-1}) and CEC (4.6-4.7 cmol kg^{-1} soil) levels were generated from the sunn hemp amendment among those soils (Table 2). In contrast, previous YWC applications in conjunction with sunn hemp amendment treatments in the LT experiment had generated a wide range of differences in terms of OM content (18-57 g kg^{-1}) in the sampled pots and CEC (6.7-17.8 cmol kg^{-1} soil) among those soils (Table 1). Thus a correlation ($P \leq 0.10$) can be detected between nematode abundance and OM and CEC in the LT experiment.

Relationship Between Soil Properties and Nematode Communities

Many of the negative correlations between soil properties and nematode abundance in the LT experiment were unexpected. For example, higher abundance of bacterivorous nematodes such as *Eucephalobus* and Rhabditidae was related to lower soil nutrient concentrations. As suggested earlier, soil at the end of the LT experiment was at a later stage of nutrient decomposition (Wang et al., 2003). Higher numbers of bacterivorous nematodes might have mineralized most of the nutrient elements into the soil early in the experiment, but more vigorous growth of squash (Wang et al., 2004b) in the LT than in the ST experiment might also have allowed more nutrients being absorbed by plants, thus resulting in a negative correlation between nematode abundance and nutrient concentrations. In contrast, positive correlations between abundance of many nematode genera and nutrient concentrations in the ST experiment were consistent with our previous study (Wang et al., 2004a). Soil in the ST experiment was still in a nutrient-enriched condition (Wang et al., 2003). Therefore higher abundance of many taxa of free-living nematodes resulted in more nutrients available in the soil. Positive correlation between herbivorous nematodes and soil nutrient concentrations are also anticipated, since feeding of these nematodes on plant tissues will cause nutrients leaching from the roots (Yeates et al., 1999). We found positive correlations ($P \leq 0.05$) between *Pratylenchus* and N concentration, and between *Paratrichodorus* and Ca concentration.

Some nutrient elements might be toxic to nematodes. Previously, in a soil fallow for 1.5 yr, the abundance of many nematode taxa except fungivores correlated negatively ($P \leq 0.05$) with Cu concentration (Wang et al., 2004). Copper may be toxic to many nematodes and is not recommended for making nematode extraction sieves (Pitcher and Flegg, 1968). In this study, *Paratrichodorus* numbers was correlated negatively ($P \leq 0.05$) with Cu concentrations (ST experiment). Copper concentration correlated positively ($P \leq 0.05$) with total fungivore abundance, but correlated negatively ($P \leq 0.05$) with MI and SI in this study, consistent with findings that increasing Cu reduced the total abundance, richness, nematode taxa from *c-p* groups 4 and 5, MI, and percentage of herbivores, omnivores, and carnivores (Korthals *et al.* 1996; 1998). It is also possible that Mn might be toxic to *Eucephalobus* in the LT experiment where Mn concentration was high (Table 1), although Mn was positively correlated with number of *Eucephalobus* in the ST experiment where Mn concentration was low (Table 2). *Cephalobus* had a negative correlation ($P \leq 0.05$) with Mn concentration even in the ST experiment, but these observations require further studies.

While only a few nematode genera were correlated with soil properties in this study, some nematode community indices provided more descriptive relationships between nematode abundance and soil properties. Total abundance of fungivores but not bacterivores was correlated with several soil nutrient concentrations in the LT experiment, whereas total abundance of bacterivores but not fungivores was correlated with nutrient concentrations in ST experiment. Correlations between the abundance of omnivores and predators and nutrient concentrations in the ST experiment are due to an indirect pathway because these trophic groups are known to correlate with the abundance of bacterivores (Wang et al., 2004a).

Among the nematode community indices, only MI consistently correlated positively with soil nutrient (except Cu) concentrations in both experiments (Tables 3 and 4). This suggests that MI is a sensitive indicator of soil nutrient levels. Neher and Olson (1999) reported negative correlation between MI and concentration of nitrate and ammonia, but Neher (2000) found positive correlations between MI and decomposition of cellulose in noncultivated, perennial agricultural systems. In addition, we found SI positively correlated with several nutrient concentrations (especially macronutrients) in the LT experiment (Table 3). Failure to find correlations between SI in the ST experiment was due to the narrow range of SI among the soils. Similarly, no differences in EI and CI between sunn hemp amended and unamended soils or YWC treatments (Wang et al., 2003) resulted in few or no correlations between these community indices and soil nutrients levels. Thus, similar to nematode abundance, nematode communities also correlated differently with levels of soil properties in different soil food-web conditions. Yeates and Coleman (1982) suggested that aspects of primary production in nematode ecology should be studied in a stable ecosystem over a period of years. Contradictory correlations between nematode abundance and primary production had also been reported (Yeates and Coleman, 1982). Total nematode abundance was positively correlated with total annual pasture herbage production ($r = 0.71$, $P = 0.05$) in 5-yr-old grazed pasture (Yeates, 1979). However, net primary production was negatively correlated with nematode abundance (Yeates and Coleman, 1982) in a forest. Current experiments agreed that relationship between soil nutrients and nematode should be examined over time, and should take plant nutrient uptake into consideration.

CONCLUSIONS

Agricultural histories or food web conditions affect the relationship between nematode communities and levels of soil nutrients as well as other properties. Abundance of many individual nematode taxa correlated negatively with nutrient concentrations in soil with high OM and history of long-term compost application and agricultural use (LT experiment), but correlated positively in recently cultivated soils (ST experiment). In terms of trophic group abundance, only total fungivore numbers correlated negatively with soil nutrient concentrations in the LT experiments, but total abundance of all the trophic groups including bacterivores, herbivores, omnivores, and predators but not fungivores was correlated positively with soil nutrient concentrations in the ST experiment. However, MI correlated positively and diversity correlated negatively with several soil nutrient concentrations consistently in both experiments. Further research is needed to address the relationship between the nematode community and levels of soil properties in cultivated soils by incorporating a wide range of nutrient levels and by sampling frequently over time in both soil and plant tissues.

ACKNOWLEDGMENT

This project was partially supported by USDA, CREES grant 00-51102-9571, Integrating pest management alternatives to methyl bromide with sustainable crop production.

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Graduate Student Forum Abstracts

Crops and Pest Management

Turnip and Mustard Yields as Impacted by Plant Population and Nitrogen Fertilizer

B. Y. Bracho* and R. N. Gallaher, *Univ. of Florida*

Brassica crops are important for both home gardeners and commercial producers in Florida. Our objective was to determine optimum plant populations and N fertilizer requirements to maximize yield for turnip (*Brassica rapa* L.) and mustard (*Brassica juncea* L.). Two experiments were conducted at 2, 4, and 6 plants m^{-2} as main treatments and 0, 56, 112, 168, and 224 kg N ha^{-1} as sub treatments in split-plot experimental designs. Data was collected on shoot and root yields and nutrient concentrations in diagnostic leaves. Shoot dry weight increased with increasing plant population (turnip: 73, 124, and 142 g m^{-2} and mustard: 172, 214, and 322 g m^{-2} at 2, 4, and 6 plants m^{-2}, respectively). Shoot dry weight for both crops may have not been achieved even at the 6 plants m^{-2}. However, turnip root dry weight appeared to peak at 4 plants m^{-2}. Root dry weight for both crops also increased with plant populations (turnip: 52, 86, and 79 g m^{-2} and mustard: 22, 26, and 30 g m^{-2} at 2, 4, and 6 plants m^{-2}, respectively). The much lower plant dry weight of shoot for turnip can be explained by the partitioning of a significant portion of photosynthate to the roots as compared to mustard. Generally, yields of both turnip and mustard peaked at about 112 kg N ha^{-1}, which is close to the present University of Florida, Cooperative Extension Service recommendation for these crops.

*Belkys Y. Bracho, 352-392-2325, bbracho@ufl.edu, Journal Series No. A-00501.

Agronomic Evaluation of *Paspalum* in the Brazilian Cerrados

M. A. Carvalho*, *Univ. of Florida*, and E. A. Pizarro, *Univ. Federal do Parana*

Many *Paspalum* spp. produce forage in amounts and quality that meet the standard needs of grazing animals. One of the most important *Paspalum* cultivar is 'Pensacola' bahiagrass (*Paspalum notatum* Flugge), and it serves as the base of the forage system much of the southeastern USA. Dry matter yields (DMY) of 44 accessions of 10 *Paspalum* spp. were evaluated on an Oxisol and Ultisol in the Brasilian Cerrados. Accessions were arranged in two randomized complete blocks in 3.75 m by 4.50-m plots. Yield was assessed by clipping a 1-m^2 quadrat, after 180 d of growth during the rainy season in 2 yr. On the Oxisol, DMY ranged from 230 to 10 800 kg ha^{-1} in year 1 and from 100 to 6300 kg ha^{-1} in year 2. On the Ultisol, DMY ranged from 100 to 5340 kg ha^{-1} in year 1, and from 220 to 9910 kg ha^{-1} in year 2. In general, accessions on the Oxisol had greater DMY than those on the Ultisol. Averages on Oxisol were 3820 kg ha^{-1} and 4710 kg ha^{-1} (Oxisol) in years 1 and 2, and 2510 kg ha^{-1} and 2500 kg ha^{-1} on the Ultisol, respectively. Great yield variability among accessions was observed, with some of them showing good adaptation and potential for utilization under grazing in cultivated pastures. Accessions BRA-001490, 003913, 009415, 009610, 009652, 009661, 010391, 010511, 012416, 012602, 012793, and 014851 showed a superior performance and should be evaluated under grazing. These accessions are representatives of *P. atratum* Swallen, *P. guenoarum* Arech., and *P. plicatulum* Michx.

*M. A. Carvalho, 352-3921823, MACarvalho@ifas.ufl.edu, Journal Series A- 00505.

Seasonal Changes in Herbage Mass and Quality of Legume-Bahiagrass Pastures

María Y. Castelo, Martin B. Adjei*, and Carrol G. Chambliss, *Univ. of Florida*

Low average daily gains by cattle on perennial grass pastures in Florida during summer may be overcome with protein supplementation or by the inclusion of legumes in the pastures. *Aeschynomene evenia* C. Wright is a vigorous, short-lived perennial legume with the ability to re-seed itself annually with proper management. 'Shaw' creeping vigna (*Vigna parkeri* Bak.) is a perennial legume that has shown exceptional persistence in pastures at Ona, FL. The purpose of this work was to evaluate livestock performance on and describe forage attributes of mixtures of these legumes with bahiagrass. Yearling steers were used to graze at a variable stocking rate, allowing for ~5 kg DM (100 kg BW)$^{-1}$ from September to November 2001 and from May to October 2002. In 2001, treatments were bahiagrass-evenia and bahiagrass alone, and in 2002 treatments were bahiagrass-evenia, bahiagrass-vigna, and bahiagrass alone. The legume contribution in 2001 was <100 g kg^{-1} of total herbage mass. Mean herbage mass, in vitro organic matter digestion (IVOMD) and crude protein (CP) of bahiagrass was not different between pasture treatments in 2001, but changed through time, ranging from 4005-3550 kg DM ha^{-1} for herbage mass, 70-65 g kg^{-1} for CP, and 409-307 g kg^{-1} for IVOMD. Evenia leaves had higher nutritive value than stems (545 vs. 240 g kg^{-1} IVOMD, and 180 vs. 68 g kg^{-1} CP). In 2002, the contribution of the legumes to total herbage mass <50 g kg^{-1} for both legumes. Herbage mass and CP of bahiagrass were not different among pastures. IVOMD of bahiagrass was higher for bahiagrass-evenia than for bahiagrass-vigna (420 vs. 381 g kg^{-1}). The CP and IVOMD of vigna were higher than evenia (193 vs. 162 g CP kg^{-1} and 678 vs. 535 g IVOMD kg^{-1}). In 2001, steer gain was 32 and 18 kg ha^{-1} for bahiagrass-evenia and bahiagrass alone, respectively. In 2002, seasonal gain was 4, -2 and 4 kg ha^{-1} for bahiagrass-evenia, bahiagrass-vigna and bahiagrass alone, respectively. The inclusion of legumes in bahiagrass pasture did not improve the overall nutritive value of the system sufficiently to support growth of young steers at 5% BW herbage allowance.

*M. B. Adjei, 863-735-1314, mbadjei@ifas.ufl.edu, Journal Series No. A-00515.

Yield and Disease Ratings of Nine Peanut Varieties Grown Conventional vs. No-Till with a Strip-Till Planter

J. L. McKinney*, R. N. Gallaher, *Univ. of Florida*, J. A. Baldwin, and B. Kermerait, *Univ. of Georgia*

Peanut (*Arachis hypogaea* L.) is one of the leading crops in Florida. The objective of this investigation was to compare newly developed peanut varieties under conventional till vs. no-till management for yield and disease incidence. The two tillage treatments were main treatments and nine varieties were sub treatments in a split-plot experimental design. Peanut varieties, in the order of maximum to the least pod yield were 'C-99-R', 'Hull', 'Georgia Green', 'Norden', 'Carver', 'Southern Runner', 'Andrue II', 'Florunner', and 'Andrue 93', with yields, averaged over tillage, of 5110, 4940, 4580, 3720, 3320, 2830, 2980, 2550, and 1740 kg ha^{-1}, respectively. Yield and diseases (Tomato Spotted Wilt Virus and Southern Leaf Blight) were not affected by tillage. Generally, the high yielding varieties also had the lowest ratings of diseases. From a recent national survey farmers acknowledged an average savings of over $44 ha^{-1} when they converted to conservation tillage management. Our positive results, in favor of conservation tillage management, means Florida peanut farmers should consider converting to no-till to take advantage of the monetary savings and environmental benefits.

*J. L. McKinney, 352-591-2678, jlmckinney@mail.ifas.ufl.edu, Journal Series No. A-00504.

Using the CROPGRO Model to Predict Growth and Composition of Tropical Grasses: Developing Physiological Parameters

S. J. Rymph, K. J. Boote*, A. Irmak, P. Mislevy, *Univ. of Florida*, and G. W. Evers, *Texas A&M Univ.*

Plant growth models can serve a number of purposes, from teaching to planning to exploring hypotheses. The objective of this work is to develop a planning tool for consultants and researchers by adapting CROPGRO to model tropical grass growth and composition. CROPGRO, with its generic, process-oriented design, is adapted to model different species by changing a set of parameters describing the species' response to environmental variables. Information from local experiments and published literature was compiled to develop parameters for bahiagrass. Emphasis was placed on photosynthetic rate response to light, temperature, and N effects on photosynthesis, plant composition, and dry matter partitioning. Yield and composition data were gathered from several experiments conducted in Florida and Texas. Part of this field data was used to develop "optimized" parameters when published data was insufficient. The remainder were used to test the resulting model. Testing revealed limitations related to the model's structure. In CROPGRO, allowing frost-kill of the leaves kills the entire plant. Lowering the temperature threshold to prevent death causes predicted winter growth to greatly exceeded actual growth, resulting in water and nutrient deficiencies in the spring. Addition of a stolon component to the existing leaf, stem and root fractions, would allow an alternative growing point, a sink for assimilate partitioning, and a source for subsequent mobilization. Introduction of a dormancy function would allow control of growth by day length as well as temperature. These changes require modification of the computer code and are the basis of the next phase of model development.

*K. J. Boote, 352-392-1811, kjb@ifas,ufl.edu, Journal Series A-00512.

Maintaining Clipping Heights to Enhance Yield and Nitrogen Content for Sunn Hemp

K. A. Seaman*, R. N. Gallaher, and R. McSorley, *Univ. of Florida*

Sunn hemp (*Crotolaria juncea* L.) is an upright leguminous crop with many beneficial qualities. Our objective was to evaluate its potential as an organic N fertilizer source. Main treatments of this split-plot experiment were three plant populations (90 000, 180 000, and 300 000 plants ha^{-1}). Sub treatments were five plant clipping heights (40, 80, 120, 160, and 200 cm), which corresponded to five, four, three, two and one harvests, respectively. Plants were clipped when they grew 0.6 m above each prescribed height. Final harvest included the remaining stems, branches and leaves, clipped at 5 cm above ground level. Total plant and total clipped dry yields, as well as mineral concentration and content were determined. Total plant dry matter peaked at the 160 cm clipping height (5220 kg ha^{-1}) irrespective of plant population. Peak clipped dry matter occurred at 40-cm clipping height and 30 plants m^{-2} (2120 kg ha^{-1}). Average N concentration for total plant decreased from 30.4 g kg^{-1} for the 40 cm height to 15.2 g kg^{-1} for the 200 cm height. Clipped matter averaged 41 g N kg^{-1} irrespective of plant population and ranged from 42.7 g N kg^{-1}at 80 cm height to 37.8 g N kg^{-1} at 120 cm. Frequent harvest of the top 0.6 m of new growth while maintaining 40 to 80 cm clipping heights for populations of 18 to 30 plants m^{-2} produced an organic fertilizer containing 40 to 42 g N kg^{-1}. This high concentration of N in clipped matter shows that clipped sunn hemp material has great potential as an organic N fertilizer.

*K. A. Seaman, 352-392-2325, kaseaman@ufl.edu, Journal Series No. A-00503.

Cowpea Variety Response to Weed Control with Herbicides

D. C. Yoder*, R. N. Gallaher, and G. E. MacDonald, *Univ. of Florida*

Cowpea (*Vigna unguiculata* (L.) Walp.) is used throughout the world for human food and animal forage. With changing climates, this crop could become important in cropping systems in the southern USA as a multiple or relay crop. Weeds are major economic pests for growing cowpea in Florida. Field trials in 2001 and 2002 in Gainesville tested a nematode susceptible variety vs. a non-susceptible variety ('Iron Clay' and 'White Acre', respectively) as main treatments in a split-plot experimental design. Sub-effects included five weed control treatments as follows: 1) untreated check plot; 2) pendamethalin (N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine) (Prowl)—0.84 kg ai ha^{-1} PRE; 3) pendamethalin—0.84 kg ai ha^{-1} PRE+ flumioxazin (2-[7-fluoro-3,4-dihydro-3-oxo-4-(2-propynyl)-2H-1,4-benzoxazin-6-yl]-4,5,6,7-tetrahydro-1H-isoindole-1,3(2H)-dione) (Valor)—0.02 kg ai ha^{-1} PRE; 4) pendamethalin—0.84 kg ai ha^{-1} PRE+ prometryn (2,4-bis(isopropylamino)-6-(methylthio)-s-triazine) (Caparol)—1.4 kg ai ha^{-1} PRE; 5) metolachlor (2-chloro-N-(2-ethyl-6-methylphenyl)-N-(2-methoxye-1-methyl-ethyl) acetamide) (Dual Magnum)—1.46 kg ai ha^{-1} PRE+ imazethapyr ((±)-2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1-H-imidazol-2-yl]-5-ethyl-3-pryidinecarboxylic acid) (Pursuit)—0.036 kg ai ha^{-1} POST. Plant dry matter yield of Iron Clay was greater than White Acre (3100 kg ha^{-1} vs 2120 kg ha^{-1}). Higher contents of N, P, and K were found in Iron Clay (N = 79.3 kg ha^{-1}; P = 9.9 kg ha^{-1}; K = 63.5 kg ha^{-1}) compared to White Acre (N = 37.6 kg ha^{-1}; P = 4.7 kg ha^{-1}; K = 30.1 kg ha^{-1}). All herbicide treatments effectively controlled weeds compared with the check, which was dominated by *Amaranthus* sp. and *Elusine indicus* (L.) Gaertn. Initial plant stunting occurred from POST application of Pursuit. Although plants appeared to grow out of stunting, dry weight was negatively impacted by the POST application of Pursuit compared with other treatments.

*D. C. Yoder, 863-634-0343, rdyoder@mpinet.net, Journal Series No. A-00502.

Differential Nitrate Leaching and Mass Balance of ^{15}N-Labeled Nitrogen Sources Applied to Turfgrass and Citrus

E. A. Brown and J. B. Sartain*, *Univ. of Florida*

Previous research has raised questions relative to differences in Ca and NO$_3$ leaching potentials of Ca (NO$_3$)$_2$ vs. other sources of soluble N. It was suggested that one mechanism of delineating differences between the leaching and retentive properties of different N sources is through the use of labeled materials. Glasshouse and field studies for grow-in and established turfgrass conditions were evaluated to determine the influence of N source on the N found in leachate, plant, and soil through the use of ^{15}N-labeled Ca(NO$_3$)$_2$ [CN]; NH$_4$NO$_3$ [AN]; KNO$_3$ [KN]; and CO(NH$_2$)$_2$ [urea]. A second objective was to determine the influence of soil properties on the leaching characteristics. Mass balance studies of N using ^{15}N-enriched N were conducted. Field study data indicate that lower leachate pH was correlated with increased dry matter accumulation (DMA). Urea treated plots had a pH 6.6 and DMA of 5.4 g; AN treated plots had pH 6.8 and DMA of 4.8 g; KN treated plots had pH 7.3 and DMA of 2.1 g, and CN treated plots had pH 7.3 and DMA of 1.9 g. These data indicate that, under field conditions, N sources that contain NH$_4$ during the nitrification process resulted in lower soil pH, higher coverage rating, increased DMA, increased N taken up by the turfgrass, and less NO$_3$ and total N leached.

*J. B. Sartain, 352-3921803, jbs@ifas.ufl.edu, Journal Series A-00514.

Soils and Environmental Quality

Effects of High Salinity Irrigation on *Belonolaimus longicaudatus* and *Hoplolaimus galeatus*

A. H. Hixson and W. T. Crow*, *Univ. of Florida*

Seashore paspalum (*Paspalum vaginatum* Sw.) has great potential for use in coastal areas in the southeastern USA where water restrictions are limiting the amount of fresh water available for irrigation of turfgrasses. Plant-parasitic nematodes are damaging pests of turfgrasses in Florida, particularly sting (*Belonolaimus longicaudatus* Rau) and lance (*Hoplolaimus galeatus* Cobb). It is unknown how these plant parasitic nematodes may be impacted by high-salinity irrigation used on seashore paspalum. Experiments were performed to examine the effects of increasing irrigation salinity levels on *B. longicaudatus* and *H. galeatus* using seashore paspalum as a host. Experiments were conducted in clay pots in an environmentally controlled glasshouse. Irrigation treatments were formulated by concentrating deionized water to five salinity levels (5, 10, 25, 40, and 55 dS/M) and deionized water to serve as a control. Soil population densities of *H. galeatus* demonstrated a negative linear regression ($P < 0.0001$) with increasing salinity. Population densities of *B. longicaudatus* declined quadratically ($P < 0.0001$) with increasing salinity from 0 dS/M to 25 dS/M. An increase in population densities of *B. longicaudatus* was observed at 10 dS/M compared to 0 dS/M ($P = 0.0232$). Reproduction and feeding of *B. longicaudatus* and *H. galeatus* decreased at salinity levels of 25 dS/M and above.

W. T. Crow, 352-392-1901, wtcr@ifas.ufl.edu.

Modeling Bioavailable Fraction of Heavy Metals in Contaminated Dredged Sediments and its Implication for Phytoremediation

S. Lamsal*, *Univ. of Florida*, E. Meers, F. Tack and M. Verloo, *Univ. of Ghent, Belgium*

Phytoremediation is the use of vegetation for in situ treatment of contaminated soils, sediments and water. As bioavailability of heavy metals contribute to success of phytoremediation, modeling the bioavailable fraction is important for phytoremediation prospects. The objective of this study was to estimate the bioavailability of heavy metals to willows (*Salix viminalis*) using chemical assays and to determine implications for phytoremediation. Soil and plant samples taken from 100 by 40 m plot of contaminated dredged sediments, planted with willows, were analyzed for contents of six heavy metals (Zn, Cd, Pb, Cr, Ni, and Cu). Total Zn and Cd contents were above the sediment reuse criteria under the Flemish environmental legislation. Heavy metal extraction varied: aqua regia > NH_4OAc-EDTA 4.65 > DTPA > NH_4OAc-7.0 > $CaCl_2.2H_2O$ > H_2O for most of the metals. Aqua regia, NH_4OAc, DTPA and EDTA extractions correlated with Zn, Cd, Pb, and Cr. Concentrations in the plant varied: leaf > bark > root > wood and were correlated to total metal contents in soils. Zinc and Cd showed high bioconcentration factor (BC). DTPA and BC were positively correlated ($P = 0.85$). Assuming phytoremediation was at peak efficiency and all stem biomass were harvested every year, then Cd in the top 30 cm soil could be reduced to below the reuse criteria in 18 yr, while >100 yr is needed for Zn remediation using willows. DTPA extraction gives a good estimate of heavy metal availability to willows. Willows are promising species for use in phytoremediation of contaminated sites.

*S. Lamsal, 352-392-1951, slamsal@ufl.edu, Journal Series A-00507.

Influence of Plant-Parasitic Nematodes on Nitrate Leaching in Turf

J. E. Luc and W. T. Crow* *Univ. of Florida*

In recent years, water quality has been an issue at the forefront of public concern. This experiment determined the relationship between nematode damage to 'Tifdwarf' bermudagrass [*Cynodon dactylon* (*L.*) Pers. var. *dactylon*] roots and N uptake and nitrate leached. Forty lysimeters, 5-cm diam. and 45.8 cm high, were set up with 15 cm of gravel placed in the bottom covered with an additional 30 cm of nematode-free sand. Lysimeters were sprigged with bermudagrass at of 100 kg ha^{-1} and fertilized at 110 kg N ha^{-1} every 3 wk. Turf was irrigated twice a day with 25 mL of water. Twenty lysimeters were inoculated with sting nematodes (*Belonolaimus longicaudatus* Rau), and treatments were in five, randomized complete-blocks. Nematode population densities, root length, tissue N levels, dry matter production, total N uptake, and nitrate leached were assessed 6, 12, and 18 wk after data collection began. No differences were observed ($P \leq 0.05$) for tissue N levels, dry matter production, and total N uptake. Differences were observed ($P \leq 0.05$) for root lengths at 6, 12, and 18 wk and nitrate leached at 18 wk. Nematode feeding reduced root length by 41% and increased the amount of nitrate leaching as much as 114%. This study indicates that nematode damage to turf roots may increase nitrate leaching, thereby adding to water quality concerns.

*W. T. Crow, 352-392-1902, wtcr@ifas,ufl.edu.

Combining Alum with Drinking Water Treatment Residuals to Reduce Phosphorus in Poultry Litter

K. C. Makris, G. A. O'Connor*, W. G. Harris, and T. A. Obreza, *Univ. of Florida*

Alum (aluminum sulfate) has traditionally been applied to poultry manure as a means to reduce soluble P levels. Drinking water treatment residuals (WTRs) can be obtained free of charge and are enriched in Al or Fe hydr(oxides) that make them efficient P sorbents. Combined use of alum and WTRs would be a more cost-effective practice to reduce soluble P in manures than alum-only use. We studied the reductions in soluble P, Al, and total organic carbon (TOC) levels in suspensions prepared by mixing variable WTR and alum rates (0 to 250 g amendment kg^{-1} by weight) with poultry manure. Suspensions were kept at a constant pH of 6.5 during the sorption step, and were left to react up to 50 d, without shaking. On a per mole Al basis, Al-WTR was equally effective as alum in reducing soluble P levels in poultry manure. However, slightly greater WTR mass than alum is needed to reach a target P reduction level. Increasing mixed alum/WTR mass loads resulted in greater soluble P reduction due to increased molar Al/P ratios. Contact time did not significantly influence soluble P reduction by either sorbent. Soluble Al and TOC concentrations were lowest for suspensions with the lowest soluble P levels. We speculated that soluble P was removed from solution as an organo-Al-P mixed precipitate. The amount of P desorbed from the mixtures decreased with increasing alum/WTR mass loads (up to 1.2 Al/P molar ratios). Results suggest that WTR application with or without alum can reduce soluble P in poultry manure; however, field validation is needed.

*G. A. O'Connor, 352-392-1803, gao@ifas.ufl.edu.

Long Term and Seasonal Accumulation of Biomass and Nitrogen by Citrus Grown on Sandy Soils in Central Florida

K. T. Morgan*, T. A. Obreza, and J. M. S. Scholberg, *Univ. of Florida*

Development of improved citrus production methods that minimize the loss of N to groundwater requires accurate information on biomass and N accumulation. This 2-yr study of 'Hamlin' and 'Valencia' sweet orange (*Citrus sinensis* L. Osbeck) quantified i) long term biomass and N accumulation, ii) spatial development of root biomass, iii) seasonal biomass and N content of mature trees, and iv) seasonal biomass and N losses. Citrus tissue biomass and N distribution changed proportionally to increases in canopy volume and average trunk diameter. Dry weight biomass of leaves and twigs <0.7-cm diam. was nearly equal (30.9%) to the sum of dry weights of branches >0.7 cm and trunk (29.5%) in younger trees with canopy volumes of <5 m^3. Whereas, biomass of mature trees with canopy volumes >30 m^3 had significantly smaller amounts of biomass in leaves and twigs (17.5%) compared with branches and trunk (50.9%). Leaves contained more N (37.4%) than twig, branch, and trunk, tissue combined (34.2%) for all canopy volumes. Seasonal leaf N concentrations range from 22 to 27 g kg^{-1}. Minimum values were in May, while maximums were found in February. Seasonal twig N concentrations were in a narrow range from 9 to 10 g kg^{-1}. Root dry weight to total tree biomass ratio was nearly equal for young and mature trees (0.26:1). Root length densities followed a bimodal distribution with depth. Annual leaf biomass loss was 1650 kg ha^{-1}. These relationships can be used in future N-balance studies and the development of an expert system for nutrient management. Such a nutrient management system could lead to reductions in nitrate leaching to groundwater.

K. T. Morgan, 863-956-1151, ktm@lal.ufl.edu, Journal Series No. A-00506.

Water Use Efficiency of Bermudagrass as Influenced by Soil Amendments

T. Shaddox and J. B. Sartain*, *Univ. of Florida*

Droughts from 1997 to 2000 have prompted county agencies to levy water use regulations upon many Florida golf courses. In order to maintain a quality turf while using less water, many superintendents incorporate soil amendments into their greens to increase their moisture retention capacity and, indirectly, increase turf water use efficiency (WUE). This has prompted researchers to investigate not only the moisture retention characteristics of soil amendments, but also how soil amendments influence turfgrass WUE. This study is designed to determine which of eight soil amendments have the greatest influence on WUE of 'Tifdwarf' bermudagrass (*Cynodon dactylon* L.). Pots containing the amendment-sand mixture (85:15 by volume) were weighed weekly and maintained at 90% field capacity. Water required to maintain this moisture was recorded along with harvested turf weight. WUE was calculated: dry matter yield ÷ applied water. While diatomaceous earths and zeolites had the highest plant available water and cation exchange capacity, respectively, calcined clays had the largest WUE at 1.45 mg g^{-1}. In general, the influence of soil amendment class on WUE followed calcined clays > diatomaceous earths > zeolites > peat > sand. Because peat is the most commonly used amendment in USGA greens mixtures, these data indicate that incorporation of calcined clay, diatomaceous earth, or zeolite to existing greens would increase turfgrass WUE and potentially decrease the amount of water necessary to maintain a quality turf.

*J. B. Sartain, 352-392-1803, jbs@ifas.ufl.edu, Journal Series A-00513.

SOCIETY AFFAIRS

2003 PROGRAM
SOIL AND CROP SCIENCE SOCIETY OF FLORIDA
AND
FLORIDA NEMATOLOGY FORUM

SIXTY-THIRD ANNUAL MEETING

21-23 May 2003
Daytona Beach Hilton Oceanfront Resort
Daytona Beach, Florida

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2003 PROGRAM SUMMARY

Wednesday, 21 May 2003

Time	Event	Room
11:00 AM	Registration begins	Bill France Lobby
10:00 AM	SCSSF Board Meeting	Manatee Room
1:00 PM	Symposium I—Issues Associated with Agriculture in the Southern Water-Use Caution Area of the Southwest Florida Water Management District	Bill France Room A
3:00 PM	Symposium II—Biotechnology Update	Bill France Room A
6:30 PM	Welcoming reception	River Room
	Thursday, 22 May 2003	
8:00 AM	Registration continues	Bill France Lobby
8:00 AM	Graduate Student Forum I: Soil, Water and Environmental Quality	Bill France Room B/C
10:15 AM	Graduate Student Forum II: Crops and Crop Management	Bill France Room B/C
1:30 PM	Concurrent paper sessions:	
	Soil, Water, and Environmental Quality	Bill France Room B
	Crops and Crop Management I	Bill France Room C
7:00 PM	SCSSF Banquet—Guest speaker—Dr. Jimmy Cheek, Dean for Academic Programs and the College of Agricultural and Life Sciences: "Honoring the Past, Shaping the Future in CALS"	Bill France Room A
	Friday, 23 May 2003	
8:30 AM	Concurrent paper sessions:	
	Nematology-Plant Pathology	Bill France Room B
	Crops and Crop Management II	Bill France Room C
10:00 AM	Florida Nematology Forum	Bill France Room B

2003 SOCIETY WORKSHOP PAPER SESSIONS

Wednesday PM, 22 May 2002

Symposium I—Issues Associated with Agriculture in the Southern Water-Use Caution Area of the Southwest Florida Water Management District. **Dr. C. D. Stanley, Presiding**

Introductory remarks. C.D. Stanley, Gulf Coast REC, Bradenton.

Water resource allocation and limitation issues: A District perspective. Mark Luchte, Southwest Florida Water Management District, Sarasota.

Environmental issues in the SWUCA : A District perspective. Ross Morton, Southwest Florida Water Management District, Sarasota.

Compliance support for agricultural producers in the SWUCA. Tim Hafner, Assistant State Conservationist, NRCS-Palmetto Service Center.

Life in the SWUCA: An agricultural producer perspective. Gary Bethune, Agricultural Engineer, Pacific Tomato Growers, Palmetto.

Symposium II—Biotechnology Update. **Dr. M. Gallo-Meagher, Presiding**

Introductory remarks. Maria Gallo-Meagher, Agronomy Dep., Gainesville.

Development of transgenic grapevines for Pierce's disease resistance. D. J. Gray and Z. Li, Mid-Florida REC, Apopka.

A genomics approach to the analysis of plant-insect interactions in citrus. R. G. Shatters, Jr. USDA-ARS, Ft. Pierce.

Fall armyworm host strain identification using molecular techniques. R. L. Meagher and R. Nagoshi, USDA-ARS, Gainesville.

Marker-assisted selection in screening peanut for resistance to root-knot nematode. M. Gallo-Meagher, V. Carpentieri-Pipolo, D. W. Dickson, D. W. Gorbet, L. Wunder, and J. C. Seib, Agronomy Dep. and Entomology & Nematology Dep., Gainesville, and North Florida REC, Marianna.

2003 GRADUATE STUDENT FORUM PAPER SESSIONS

Thursday AM, 22 May 2003

Graduate Student Forum I—Soils, Water, and Environmental Quality. **Dr. Lena Ma, Presiding**

Combining alum with drinking water treatment residuals to reduce phosphorus in poultry litter. K. C. Makris*, G. A. O'Connor, W. G. Harris, and T. A. Obreza, Soil & Water Science Dep., Gainesville.

Influence of plant parasitic nematodes on nitrate leaching in turf. J. E. Luc* and W. T. Crow, Dep. Entomology & Nematology, Gainesville.

Modeling bioavailable fraction of heavy metals in contaminated dredged sediments and its implication for phytoremediation. S. Lamsal*, E. Meers, F. Tack, and M. Verloo, Soil & Water Science Dep., Gainesville.

Differential nitrate leaching and mass balance of ^{15}N-labeled nitrogen sources applied to turfgrass. E. A. Brown*, J. B. Sartain, G. H. Snyder, D. A. Graetz, J. L. Cisar, G. L. Miller, and G. W. Easterwood, Soil & Water Science Dep., Gainesville, Everglades REC, Belle Glade, Ft. Lauderdale REC, and Environmental Horticulture Dep., Gainesville.

Long-term and seasonal accumulation of biomass and nitrogen by citrus grown on sandy soils in central Florida. K. T. Morgan*, T. A. Obreza, and J. M. S. Scholberg, Soil & Water Science Dep. and Agronomy Dep., Gainesville.

Effects of high salinity irrigation on *Belonolaimus longicaudatus* and *Hoplolaimus galeatus*. A. H. Hixson* and W. T. Crow, Dep. Entomology & Nematology, Gainesville.

Water use efficiency of bermudagrass as influenced by soil amendments. T. W. Shaddox* and J. B. Sartain, Soil & Water Science Dep., Gainesville.

Yield response of two hot pepper varieties to applied organic and inorganic nutrient sources. D. N. Russell, C. S. Gardner, and G. Queeley*, Florida A&M Univ., Tallahassee.

Graduate Student Forum II—Crops and Crop Management. **Dr. A. R. Blount, Presiding**

Nitrogen and population prediction models for yield of turnip (*Brassica rapa* L.) and mustard (*Brassica juncea* L.). B. Y. Bracho* and R. N. Gallaher, Agronomy Dep., Gainesville.

Tillage response and cultivar selection for yield and disease resistance of peanut (*Arachis hypogaea* L.). J. L. McKinney*, R. N. Gallaher, J. A. Baldwin, and B. Kemerait, Agronomy Dep., Gainesville.

Adapting the CROPGRO model to predict growth and composition of tropical grasses: Developing physiological parameters. S. J. Rymph*, K. J. Boote, A. Irmak, P. Mislevy, and G. W. Evers, Agronomy Dep., and Agricultural & Biological Engineering Dep., Gainesville, Range Cattle REC, Ona, and Statistics Dep., Gainesville.

Seasonal changes in the production and quality of legume-bahiagrass pasture systems. M. Y. Castelo*, M. B. Adjei, and C. G. Chambliss, Range Cattle REC, Ona and Agronomy Dep., Gainesville.

Cowpea (*Vigna unguiculata* L.) variety response to weed control with herbicides. D. C. Yoder*, R. N. Gallaher, and G. E. MacDonald, Agronomy Dep., Gainesville.

Agronomic evaluation of *Paspalum* in the Brazilian Cerrados. M. A. Carvalho, Agronomy Dep., Gainesville.

Maintaining clipping heights to enhance yield and nitrogen content for Sunn Hemp (*Crotalaria juncea* L.). K. A. Seaman*, R. N. Gallaher, and R. McSorley, Agronomy Dep. and Dep. Entomology & Nematology, Gainesville.

2003 CONCURRENT PAPER SESSIONS

Thursday PM, 22 May 2003

Soils, Water, and Environmental Quality. **Dr. G. Sigua, Presiding**

Storm water runoff from a typical clay settling area used for row crop production: Treatment and estimated cost. J. A. Stricker, Univ. of Florida, Cooperative Extension Ser., Bartow.

Using the CROPGRO forage grass model to screen BMPs for N fertilization and minimize leaching for Florida soils and climate. A. Irmak, K. J. Boote, and S. J. Rymph*, Agricultural & Biological Engineering Dep. and Agronomy Dep., Gainesville.

Estimating two-dimensional vertical and horizontal atmospheric dispersion of preplant soil fumigants. L. H. Allen*, J. C. V. Vu, O.-T. Ou, J. E. Thomas, L. A. McCormack, and D. W. Dickson, Agronomy Dep. and Dep. Entomology & Nematology, Gainesville.

The EarthBox™: An international consortium. C. M. Geraldson, Gulf Coast REC, Bradenton.

Fungi associated with coastal tableland soils of Brazil. Q. R. Araujo*, J. L. Bezerra, F. G. Faleiro, N. B. Comerford, A. V. Ogram, A. Al-Ageli, K. M. T. Bezerra, P. V. Menezes, A. S. G. Faleiro, and L. P. Santos Filho, Cocoa Research Center, Bahia, Brazil and Soil & Water Science Dep., Gainesville.

Evaluation of candidate silicon fertilizers. G. H. Snyder, D. W. Rich*, M. P. Barbosa-Filho, and C. L. Elliott, Everglades REC, Belle Glade.

Long-term effect of grazing and haying on the changes of soil phosphorus and other crop nutrients in subtropical pastures. G. C. Sigua*, M. J. Williams, and S. W. Coleman, USDA-ARS, Brooksville.

Development of N-release characterization methods for controlled-release fertilizers. J. B. Sartain*, W. L. Hall, and E. W. Hopwood, Soil & Water Science Dep., Gainesville.

Crops and Crop and Management I. **Dr. M. B. Adjei, Presiding**

Effect of organic biostimulants on the yield of salad amaranth. J. Pablo Morales-Payan* and W. M. Stall, Horticultural Sciences Dep., Gainesville.

Agricultural climate risk information and decision support system. Shrikant Jagtap*, J. W. Jones, and J. O. Brien, Agricultural & Biological Engineering Dep., Gainesville.

Yield response of 'X3R Camelot' bell pepper to soil-applied biostimulants and N and K rates on a sandy soil. A.A. Csizinszky, Gulf Coast REC, Bradenton.

Critical period of pigweed interference with cilantro. J. Pablo Morales-Payan* and W. M. Stall, Horticultural Sciences Dep., Gainesville.

Influence of selected biostimulants on the growth and yield of radish. J. Pablo Morales-Payan* and W. M. Stall, Horticultural Sciences Dep., Gainesville.

Influence of plant maturity changes on biomass production and nutritive value of *Aeschynomene evenia*. P. Mislevy* and F. G. Martin, Range Cattle REC, Ona and Statictics Dep., Gainesville.

The soil seedbank in *Aeschynomene* and *Carpon desmodium* pastures. R. S. Kalmbacher, Range Cattle REC, Ona.

An integrated system of urban food waste recycling for vegetable crop production. C. S. Gardner and G. Queeley*, Florida A&M Univ., Tallahassee.

Friday AM, 23 May 2003

Crops and Crop Management Session II. **Dr. R. N. Gallaher, Presiding**

Evaluating *Leucaena* in three Florida environments. I. V. Ezenwa*, R. S. Kalmbacher, M. J. Williams, D. O. Chellemi, and F. G. Martin, Range Cattle REC, Ona, USDA-ARS Ft. Pierce, USDA-ARS, Brooksville and Statictics Dep., Gainesville.

The distribution and spread of beneficial nematodes on Florida pastures for mole cricket control. M. B. Adjei* and G. C. Smart, Jr., Range Cattle REC, Ona and Dep. Entomology & Nematology, Gainesville.

Recent mole cricket control work in north Florida pastures. A. R. S. Blount* and R. K. Sprenkel, North Florida REC, Quincy.

Pigeonpea: A new crop for Florida. G. M. Prine*, C. S. Gardner, and P. E. Reith, Agronomy Dep., Gainesville.

Bioassays on glyphosate toxicity and photodegradation. J. P. Gilreath and B. M. Santos*, Gulf Coast REC, Bradenton.

Tillage response and hybrid selection for yield and quality of sweet corn. R. N. Gallaher, Agronomy Dep., Gainesville.

Nematology—Plant Pathology. **Dr. G. Smart, Presiding**

Survival of nematodes in Florida peat and composted organic soil mixes formulated for use in ornamental nurseries. P. S. Lehman*, R. N. Inserra, W. L. Robinson, P. Qiao, W. W. Smith, and Z. Smith III, Florida Dep. Agriculture and Consumer Services, Gainesville.

Diagnosis of stubby-root and spiral nematodes from warm-season turfgrasses. W. T. Crow, Dep. Entomology & Nematology, Gainesville.

Observations on some factors affecting solarization in Florida. R. J. McGovern, R. McSorley*, and K. H. Wang, Dep. Entomology & Nematology, Gainesville.

Effect of Sunn Hemp amendment on free-living nematodes and soil nutrients. K.-H. Wang*, R. McSorley, and R. N. Gallaher, Dep. Entomology & Nematology and Agronomy Dep., Gainesville.

Host status and amendment effects of cowpea on root-knot nematode (*Meloidogyne incognita*) in vegetable cropping systems. K.-H. Wang*, R. McSorley, and R. N. Gallaher, Dep. Entomology & Nematology and Agronomy Dep., Gainesville.

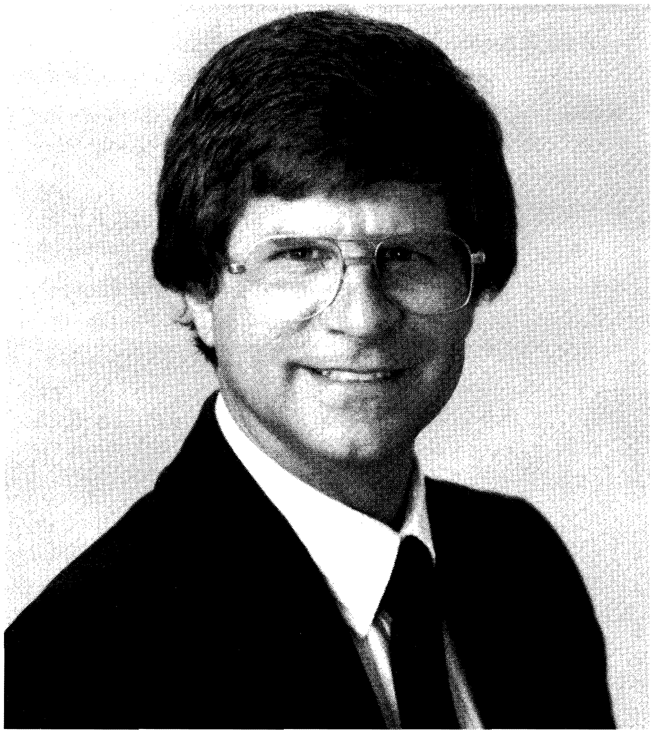
Reduction of *Fusarium* crown rot in tomato in Florida using soil injection of Telone C-17. R. J. McGovern* and C. S. Vavrina, Dep. Entomology & Nematology, Gainesville.

Florida Nematology Forum. **Dr. W. T. Crow, Presiding**

Roundtable discussion

*Indicates the person presenting the paper.

MINUTES
Board of Directors Meeting
4 September 2002



Dr. Craig Stanley

Members present: Craig Stanley, Carroll Chambliss, Anne Blount, Tom Obreza, Paul Pfahler, Grover Smart, Bill Thomas.

The purpose of this meeting was to discuss the outcome of the workshop held at the last SCSSF meeting in May 2002 regarding what should be done to re-energize the Society and improve its relevancy. Craig Stanley handed out a summary of the suggestions that the small groups produced at the workshop.

Craig indicated that we need to somehow stimulate membership and participation, or the society will eventually fall. We need to discuss these issues again and formulate an action plan. Craig said that he needs to appoint a program committee to work with the incoming president to formulate the program for the 2003 meeting, considering the workshop results.

There has been an incredible membership decline during the past 50 yr. There are numerous reasons for this occurrence, such as retirements and lack of grower interest. If the Society is to continue, we need to get department chairs behind it and have them encourage membership of their faculty.

Perhaps the focus of the meeting and the Proceedings should change from scientific research to more of an educational theme. What would the Society be like if we did not have a Proceedings? If this was the case, would the Society be more attractive for people to attend the annual meetings and become a member of the Society? Would there be any advantage to changing over to an electronic publication as opposed to a paper copy? Should we have in-service training scheduled for the meeting that would bring in extension agents? Bill Thomas said that if the SCSSF meeting were just in-service training it would lessen his enthusiasm to attend the meeting.

Should we set up theme sessions where the presenters are invited? Maria Gallo-Meagher had indicated that she would be willing to set up a session with a bio-tech theme. Is there any possibility of forming a consortium of like-minded individuals Florida, Georgia, and Alabama people to increase the scope of the Society? Would there be any benefit to changing our Proceedings to a journal? Regardless of what we might try to do, it will be very difficult if not impossible to change the current perception of the Proceedings. What about having a Southeastern regional journal, but still have state meetings? Should there be statewide faculty meetings held at the SCSSF meeting? The meeting could be used as a vehicle for department chairs to assemble their entire faculty from around the state. If a themed meeting is created, it should be imperative that we get industry and state/federal agencies invited to them. Grover Smart suggested that we continue to have the annual meeting and presentations as usual, but just publish abstracts, not the full papers. The next step that Craig Stanley will take is to have a meeting with some of our department chairs to see what kind of support and suggestions they might generate. One question to ask the administrators is what can the SCSSF do to assist the tenure and promotion process for the younger faculty? The Society will still have a normal meeting in Daytona Beach in May 2003.

MINUTES
Executive Board Meeting
22 November 2002

Members present: Craig Stanley, Anne Blount, Rob Kalmbacher, Carroll Chambliss, Tom Obreza, Paul Pfahler, Bill Thomas, Ken Boote. Other attendees that came in later: Ramesh Reddy, Jerry Bennett.

Craig Stanley opened the meeting at 1010 h. The members read the minutes from the SCSSF Board meetings held at the annual meeting in May 2002 and the special meeting held in September 2002. The minutes were approved as read following a motion, second, and unanimous vote. Tom Obreza made some general comments about the Society's financial situation; no formal report was present. Tom discussed his relocation to Gainesville from Immokalee and how Society affairs would be affected by the transition. He plans to use Greg Means of the Soil & Water Science Dep. to manage day-to-day activities. Greg is a highly technical person and has already moved the financial information and tracking to Quicken software. The 2001-02 financial report will be forthcoming after a little more accounting is done.

Tom Obreza discussed the recently discovered errors in the printing of some of the copies of SCSSF Proceedings, Vol. 61. E. O. Painter Printing has been notified, and they have assured us that they will remedy the situation at their expense.

Rob Kalmbacher indicated that SCSSF Proceedings, Vol. 62 was being prepared, and that he had about ten refereed papers from the 2002 annual meeting. He is still soliciting abstracts from some of the graduate students, and indicated that he had to contact some of their major professors to help expedite the situation.

Craig Stanley discussed the meeting that he had with the Chairs of the Agronomy and Soil & Water Science Dep. At this meeting Craig brought up the question of how SCSSF activities and publications could be altered such that they could aid the tenure and promotion process for young UF faculty. The department chairs indicated that they had a problem recommending that their Assistant and Associate Professors publish in the Proceedings due to its perception at the higher levels of UF administration. After some discussion, there was general agreement that no matter how much time and effort might be put into re-working the Proceedings, the Society will never be able to improve its perception by the IFAS deans and beyond.

The 2003 SCSSF annual meeting will be held at the Daytona Beach Hilton from May 21-23. The meeting planners indicated that they will most likely utilize symposia and workshops to try to attract more attendance. These activities need to be planned soon by the program committee (the past, current, and future presidents, i.e. Don Dickson, Craig Stanley, and Carroll Chambliss). Craig recalled that Maria Gallo-Meagher said she would be willing to put together a workshop on a biotech issue. Craig said he would be able to organize a workshop centering on water issues. He said he would determine who within the university is leading the development of the UF Water Institute and possibly solicit their input or involvement in the workshop. Carroll Chambliss said that he could organize a workshop on row crop management.

Jerry Bennett's opinion was that the Society serves an important role, but it needs to be better defined. He suggested that we stop publishing full papers and change to abstracts or 3-page summaries only. He also indicated that he would not suggest to his young faculty to put their best work in the Proceedings. He felt that our publication serves as good outlet for graduate students to put some of their mid-program work. He pointed out that the Society needs to reach out to a wider audience rather than just those within UF-IFAS departments. He summed up his thoughts by saying that the Society is worth keeping and worth the Board's effort to improve it as opposed to closing the doors.

Ramesh Reddy added a few additional statements indicating that he was in general agreement with Jerry's thoughts. Ramesh also indicated that if the meeting had a broad-based theme, then he would support his faculty's participation.

Other thoughts expressed by the Board and department chairs about how the Society could be modified:

- Put together an issue-oriented meeting every 1 to 2 yr and make it national or international in scope. Assemble a strong program with invited speakers. Use the UF Office of Conferences and Institutes to manage the meeting.
- Publish keynote papers from invited speakers as well as short communications from volunteered papers.
- Presenters give their paper at the SCSSF meeting, publish the abstract in the Proceedings, but then publish the paper in a refereed journal.
- Use the annual meeting as an opportunity for department chairs to call a statewide faculty meeting.
- Center the meeting on broad topics like food security, invasive pests, exotic animals, space biology, and ecological issues beyond water.
- Change paper submission procedure to one where the author submits an abstract plus their PowerPoint presentation, which would then be published on the SCSSF web site.
- Improve the interaction with our clientele (e.g., state and federal agencies, agricultural industries) so we can show them what we are doing.
- Plan symposia far in advance, and offer them as in-service training sessions for county agents. Or, arrange for separate in-service training sessions to be held concurrent with the SCSSF meeting at the same location.

Other comments and questions that were submitted to the group:

- Craig Stanley expressed frustration at the lack of interest in attending the annual meeting, and wondered how we would maintain continuity if we changed our meeting schedule to once every 2 yr.
- Rob Kalmbacher indicated that he has difficulty getting presenters outside of universities (e.g., state agency employees) to submit written material after they participate in a symposium. They tell him that they do not have the time to write a standard article.
- Bill Thomas asked if the material that normally is submitted to the Proceedings does not get published there, then where would it get published? Would this material be turned into EDIS or other web-based documents?
- Even if the Society membership numbers drop, could a smaller core of faculty that has state interest keep the Society going? Is there a major problem with this line of thinking?
- Regarding the location of future annual meetings, it was suggested that we could perhaps have the meeting at an REC that has a big auditorium, like IRREC-Ft. Pierce or MFREC-Apopka.
- Solicit topics for future symposia at the next business meeting.

The group decided that at this point we should present some future possible options or directions for changing the Society and present them to the membership. We will first poll the membership to get an idea of where they want the Society to go. Tom Obreza and Carroll Chambliss will work together to design a simple polling instrument.

The meeting was adjourned at 1200 h.

MINUTES
Executive Board Meeting
Daytona Beach Hilton Hotel
21 May 2003

Members present: Carrol Chambliss, Craig Stanley, Tom Obreza, Bill Thomas.

Craig Stanley called the meeting to order at 1000 h. The group reviewed the minutes from the November 2002 Board meeting, and they were approved as written.

Craig Stanley provided names for the new committee member assignments that he had made: Nominating Committee—Paul Pfahler; Site Selection Committee—Bob Mansell; Membership Committee—Ken Boote and Alex Csizinszky; Audit Committee—Dave Calvert; Necrology Committee—Ken Quesenberry; Dedication of Proceedings and Honorary Lifetime Membership Committee—Craig Stanley.

The 2001-02 financial report was read by Tom Obreza and was approved by the Board.

Carrol Chambliss presented the Necrology Committee report, and indicated that John R. Edwardson, Fred Clark, and O. Charles Ruelke had passed away during the previous year. There were no reports available from the Nominating Committee, the Dedication of Proceedings and Honorary Lifetime Membership committee, or the Membership Committee.

The Audit Committee, chaired by Bob McSorley, submitted a report indicating that the finances as reported were in order. Regarding Graduate Student Committee activities, Carrol Chambliss indicated that all abstracts from graduate students had been submitted to him, and he forwarded them to Lena Ma.

A discussion ensued about the results of the survey that Tom Obreza sent to the membership soliciting opinions on if and how the Society should be revitalized. Craig Stanley said that he wanted to have a specific issue to vote on at the business meeting. It was decided that he will propose that an exploratory committee be set up to investigate the idea of merging with the Florida State Horticultural Society. We will also address the top three vote-getting ideas in the survey.

The meeting was adjourned at 1140 h.

MINUTES
63rd Annual Business Meeting
Daytona Beach Hilton Hotel
22 May 2003

Craig Stanley called the meeting to order at 1610 h.

The minutes of the 2002 business meeting held in Clearwater Beach were reviewed and unanimously accepted by the membership. The financial report was reviewed and discussed by Tom Obreza and the membership accepted it by unanimous vote.

Rob Kalmbacher gave the Editor's report. He has 16 manuscripts for Vol. 62 of the Proceedings. Half are refereed and half are non-refereed. A few in this group are carryover papers from meetings prior to 2002. Rob indicated that he wants to step down as Editor, but he said he will not walk out on the job if there is no one else to take it over. Tom Obreza said he would like to hand off the Secretary/Treasurer's job to someone else as well, but echoed Rob's comments about not walking out either.

The Audit Committee's report was read by Craig Stanley. The committee reported that the finances were in order. The Necrology Report was given by Carrol Chambliss. John Edwardson, Fred Clark, and Dr. O. Charles Ruelke passed away during the previous year. A moment of silence will be taken at the evening banquet.

The Nominating Committee nominated William D. (Bill) Thomas for President-elect and 2004 Program Chairman and Lena Ma for Director-At-Large. Since Bill has one more year left as a Director-At-Large, he will be relieved of this duty by Bob McSorley. After a motion to close the nominations was passed, a vote was taken on the above candidates. All were voted in unanimously and thanked for their willingness to serve.

The Dedication of Proceedings and Honorary Lifetime Member Committee selected Grover Smart as the individual to whom Vol. 63 of the Proceedings will be dedicated. The newest member of the Honorary Lifetime Membership group is Paul Pfahler. The Graduate Student Committee indicated that the winners of the paper contest will be announced during the evening banquet.

Craig Stanley reviewed Tom Obreza's presentation from the previous year regarding membership numbers and their sharp decline during the past 40 yr. The major issues that are affecting the viability of the SCSSF are declining membership, declining participation of the members, and the perception of the Proceedings by upper UF-IFAS administration.

Craig Stanley and Tom Obreza reviewed the results of the survey (attached). Craig recommended to the membership that we form a committee to meet with the Florida State Horticultural Society to see if joining up with them would be in our best interest. If this occurred, the new Society would need to have Agronomic and Soils sections added. Some members offered their opinion that there would be some problems with a merger of this type. It was suggested that a large umbrella organization composed of societies other than just FSHS be formed. Others suggested that we check with the Florida Weed Science Society, the Florida Plant Pathology Society, and the Florida Section of Ag Engineers to see if we could join with them first before approaching FSHS.

It was further suggested that if these other groups view a joint meeting in a favorable light, we should approach the IFAS Office of Conferences and Institutes (OCI) with the idea of arranging a combined meeting. The interest about approaching FSHS is decreasing because of their lack of receptiveness to us when we met jointly in 2001.

Carrol Chambliss said that he is confident that the 2004 SCSSF meeting will be different and not business-as-usual. Jerry Sartain made a motion that the Board of Directors be authorized to contact the Florida Weed Science Society and Florida Ag Engineers to see if they will meet with us next year. Martin Adjei seconded the motion. The vote on this motion was unanimously positive.

Rob Kalmbacher indicated that if we want to go to an electronic format for the SCSSF Proceedings, he will need help. Jerry Sartain made a motion to authorize the treasurer to hire someone to turn the next Proceedings volume to into electronic format. If the electronic Proceedings were placed on our web site, it was unclear if they would be downloadable for free or not. Belinsky Santos from the Gulf Coast REC volunteered to help with the electronic formatting. Martin Adjei seconded Jerry Sartain's motion, and it passed by unanimous vote.

Paul Mislevy indicated that we should not neglect the search for a new Editor and Secretary/Treasurer. Carrol Chambliss said that if we do not have a new Editor in place by February 2003, then the call for papers will be replaced by a call for abstracts.

Jerry Bennett and Ramesh Reddy both said we should use OCI to organize the next meeting. Jean Thomas offered a differing viewpoint by suggesting that a more informal meeting at an REC might be better.

We do not know where we will meet in 2004 because we need to talk to the other groups first. David Calvert indicated that Brian Scully, new Center Director and the IRREC, invited us to have our meeting Ft. Pierce. It was unclear as to how many concurrent sessions could be run using the IRREC facilities.

The meeting was adjourned at 1730 h.

Summary of SCSSF Survey

Surveys sent out: ~ 150. Surveys returned: 38.

Question 1. What should we do with the Soil and Crop Science Society of Florida?

a. Make it survive and hang on, keeping it the same as it always has been.

b. Try to revitalize it by slightly changing it from the way it is now.

c. Try to revitalize it by drastically changing it from the way it is now.

d. The Society should be disbanded.

None answered "A"; 7 answered "B"; 17 answered "C"; 5 answered "B and C"; 3 answered "D"; 7 did not circle any answer, but went on to question 2.

Question 2. What changes would you be in favor of and/or help work towards?

The following numbers indicate the sum of "yes" or "maybe" answers. 11: Stop publishing full papers in the Proceedings; change to abstracts or 3-page summaries only. 12: Go entirely to an electronic format for whatever material is published in the Proceedings. 4: Eliminate the Proceedings entirely, but still have an annual meeting for presentations, symposia, and the graduate student paper contest. 5: Change paper submission procedure to one where the author submits an abstract plus a PowerPoint presentation, which would then be published on the SCSSF web site. 27: Try to reach out to a wider audience than just UF-IFAS. Improve the interaction with our clientele (e.g., state and federal agencies, agricultural industries) so we can show them what we are doing. 3: Limit the annual meeting to only one broad-based theme each year (for example: Water Quality, Forage Production, Food Security, etc.). 7: Put together an issue-oriented meeting once every 2 yr and make it national or international in scope. Assemble a strong program with invited speakers. Use the UF Office of Conferences and Institutes to manage the meeting. 15: Use the annual meeting as an opportunity for Department Chairs to call a statewide faculty meeting. 5: Other then the graduate student competition, have the annual meeting composed of symposia only, which double as in-service training sessions for county agents. 3: Keep the Society going with just a smaller core of interested participants. 20: De-emphasize the formality and cost of annual meetings by holding them at UF-IFAS facilities with a large auditorium like NFREC-Quincy, IRREC-Ft. Pierce or MFREC-Apopka. The banquet would be replaced by a less-formal luncheon and attendees would be on their own for hotel arrangements. 7: Increase income (dues) enough to support a paid, part-time business manager who would handle secretarial, planning, web site, electronic publishing, and marketing duties. 21: Combine the SCSSF with the Florida State Horticultural Society and participate in their annual meetings. (Add additional paper sessions that cover agronomic, soils, and environmental quality topics as needed.)

SOCIETY BANQUET AND AWARDS
Thursday, 22 May 2003

President-Elect Carrol Chambliss presiding. Following an invocation given by Dr. Grover Smart, Dr. Chambliss introduced the honored guests.

Following dinner, Dr. Chambliss introduced the guest speaker, Dr. Jimmy Cheek, Dean for Academic Programs and the College of Agriculture and Life Sciences (CALS) at the Univ. of Florida. Dr. Cheek addressed the group on the topic: "Honoring the Past, Shaping the Future in CALS."

Lena Ma presented the Graduate Paper Contest Awards to the 1st, 2nd, and 3rd place finishers in each Graduate Student Forum. In Soils, Water, and Environmental Quality, first place ($250) was awarded to Travis Shaddox (J. B. Sartain, major professor), second ($200) went to Eric Brown (J. B. Sartain, major professors), and third ($150) went to John Eric Luc (W. T. Crow, major professor). In Crops and Crop Management, first place ($250) was awarded to Kim Seaman (R. N. Gallaher, major professor), second ($200) went to Stuart Rymph (K. J. Boote, major professor), and third ($150) went to David Yoder (R. N. Gallaher, major professor). The judges congratulated all graduate student participants for their excellent work.

Volume 63 of the Proceedings was dedicated to Dr. Grover Smart. A statement about Dr. Smart's life and professional career was read by Rob Kalmbacher. The necrology report was given by Carrol Chambliss, followed by a moment of silence to honor John R. Edwardson, Fred Clark, and O. Charles Ruelke, who passed away during the preceding year.

Craig Stanley announced that William D. (Bill) Thomas was named President-Elect and 2004 program chair, and Bob McSorley and Lena Ma were named new members of the Board of Directors. The gavel was then passed from Craig to Carrol Chambliss, who took responsibility as President for the coming year. Carrol presented a plaque to Craig on behalf of the Society that expressed appreciation for his hard work and dedication during his term as President.

SOIL AND CROP SCIENCE SOCIETY OF FLORIDA FINANCIAL REPORT
1 July 2002 through 30 June 2003

ASSETS IN BANK (1 July 2002)		
Checking Account—Bank of America	6678.90	
Certificate of Deposit—Bank of America (300 000 7062 2783)	11992.75	
Certificate of Deposit—Bank of America (300 000 7257 3362)	5632.61	
Total In Bank		**24304.26**
RECEIPTS		
Dues	2070.00	
Sale of Proceedings	2095.00	
Page Charges, Volumes 61	3813.75	
Annual Meetings	5157.50	
Banquet	360.00	
Registration	4797.50	
Interest	217.80	
Certificate of Deposit (300 000 7062 2783)	140.35	
Certificate of Deposit (300 000 7257 3362)	65.84	
Checking Account	11.61	
Gift received	180.00	
Total Receipts		**13534.05**
DISBURSEMENTS		
Printing SCSSF Proceedings Vol 61	5128.13	
Postage	799.76	
Refund	94.00	
Reimbursement (Gas to pick up Proceedings)	27.00	
Annual Meeting Expenses		
Meeting rooms	1409.55	
Breaks	343.36	
Opening reception	1251.38	
Grad student awards	1200.00	
Grad student hotel rooms	662.34	
Guest speaker hotel room	113.03	
Awards banquet	1794.47	
Awards hardware	91.20	
Clerical expenses	94.80	
Office Supplies	76.84	
Service Charge—Checking Account	90.00	
Bank Charge	5.00	
Annual license fee to Florida Dept of State	61.25	
Total disbursements		**13242.11**
ASSETS IN BANK (30 June 2003)		
Checking Account—Bank of America	12463.10	
Certificate of Deposit—Bank of America (300 000 7062 2783)	12133.10	
Total in Bank		**24596.20**

2004 COMMITTEES

(Date in parenthesis indicates year each member rotates off after the annual meeting.)

Audit

Lynn Sollenberger	(2004)
David Calvert	(2005)

Necrology

Ben Whitty	(2004)
Ken Quesenberry	(2005)

Nominating

Dan Gorbet	(2004)
Paul Pfahler	(2005)

Site Selection/Local Arrangements

Johan Scholberg	(2004)
Bob Mansell	(2005)

Dedication of Proceedings & Honorary Lifetime Member Selection

Jack Rechcigl	(2004)
Craig Stanley	(2005)

Membership

Hartwell Allen	(2004)
Samira Daroub	(2004)
Ken Boote	(2005)
Alex Csizinsky	(2005)

Graduate Student Presentation Contest

William Crow	(2004)
TBD Not Determined	(2005)

MEMBERSHIP LISTS

REGULAR MEMBERS 2003

MARTIN B. ADJEI
RANGE CATTLE REC—ONA
3401 EXPERIMENT STATION
ONA, FL 33865-9706

L. H. ALLEN
UNIVERSITY OF FLORIDA
PO BOX 110965
GAINESVILLE, FL 32611-0965

D. D. BALTENSPERGER
UNIVERSITY OF NEBRASKA
4502 AVE. I
SCOTTSBLUFF, NE 69361-4939

RAY BASSETT
AGLIME SALES, INC.
1375 THORNBURG ROAD
BABSON PARK, FL 33827

JERRY M. BENNETT
UNIVERSITY OF FLORIDA
PO BOX 110500
GAINESVILLE, FL 32611-0500

D. A. BERGER
NORTH FLORIDA REC
55 RESEARCH RD
QUINCY, FL 32351-5677

KENNETH J. BOOTE
UNIVERSITY OF FLORIDA
PO BOX 110500
GAINESVILLE, FL 32611-0500

BARRY J. BRECKE
WEST FLORIDA REC
5988 HWY 90, BLDG 4900
MILTON, FL 32583

JACQUE W. BREMAN
ROUTE 3, BOX 299
LAKE BUTLER, FL 32054

ERIC C. BREVIK
VALDOSTA STATE UNIVERSITY
DEPT PHYSICS, ASTRON & GEOSCIENCE
VALDOSTA, GA 31698-0055

J. B. BROLMANN
2914 FOREST TERRACE
FT. PIERCE, FL 34982

ROBIN BRYANT
TROPICANA, INC
1001 13TH AVENUE EAST
BRADENTON, FL 34208

DAVID V. CALVERT
INDIAN RIVER REC
2199 S. ROCK ROAD
FT. PIERCE, FL 34945-3138

KENNETH L. CAMPBELL
UNIVERSITY OF FLORIDA
PO BOX 110570
GAINESVILLE, FL 32611-0570

CARROLL CHAMBLISS
UNIVERSITY OF FLORIDA
PO BOX 110500
GAINESVILLE, FL 32611-0500

MING CHEN
EVERGLADES REC
PO BOX 8003
BELLE GLADE, FL 33430

WILLIAM CROW
UNIVERSITY OF FLORIDA
PO BOX 110620
GAINESVILLE, FL 32611-0620

A. A. CSIZINSKY
GULF COAST REC
5007 60 STREET EAST
BRADENTON, FL 34203-9324

SAMIRA DAROUB
EVERGLADES REC
3200 E. PALM BEACH RD
BELLE GLADE, FL 33430

DONALD W. DICKSON
UNIVERSITY OF FLORIDA
PO BOX 110630
GAINESVILLE, FL 32611-0630

SPENCER G. DOUGLASS
DOUGLASS FERTILIZER
1180 SPRING CENTER BOULEVARD
ALTAMONTE SPRINGS, FL 32714

MICHAEL DUKES
UNIVERSITY OF FLORIDA
PO BOX 110570
GAINESVILLE, FL 32611-0570

LARRY DUNCAN
CITRUS REC
700 EXPERIMENT STATION ROAD
LAKE ALFRED, FL 33850-2299

JOE EGER
DOW AGRO SCIENCES
2606 S. DUNDEE BLVD
TAMPA, FL 33629

IKE EZENWA
RANGE CATTLE REC
3401 EXPERIMENT STATION
ONA, FL 33865-9706

JAMES FERGUSON
UNIVERSITY OF FLORIDA
PO BOX 110690
GAINESVILLE, FL 32611-0690

RAYMOND GALLAHER
UNIVERSITY OF FLORIDA
PO BOX 110730
GAINESVILLE, FL 32611-0730

MARIA GALLO-MEAGHER
UNIVERSITY OF FLORIDA
PO BOX 110300
GAINESVILLE, FL 32611-0300

ROBERT GILBERT
EVERGLADES REC
PO BOX 8003
BELLE GLADE, FL 33430

BARRY GLAZ
USDA-ARS
12990 US HIGHWAY 441
CANAL POINT, FL 33438

D. W. GORBET
NORTH FLORIDA REC
3925 HIGHWAY 71
MARIANNA, FL 32446

HAROLD E. GUILFORD
CITRUS CONSULTANT
521 BONNIE DRIVE
LAKELAND, FL 33803-2005

EDWARD A. HANLON
SOUTHWEST FLORIDA REC
2686 SR 29 NORTH
IMMOKALEE, FL 33438

ZHENLI HE
INDIAN RIVER REC
2199 SOUTH ROCK ROAD
FT. PIERCE, FL 34945

GEORGE J. HOCHMUTH
NORTH FLORIDA REC
155 RESEARCH ROAD
QUINCY, FL 32351-5677

EDWARD W. HOPWOOD, JR.
5200 NW 62ND COURT
GAINESVILLE, FL 32653

CARL S. HOVELAND
UNIVERSITY OF GEORGIA
CROP & SOIL SCIENCE DEPT
ATHENS, GA 30602

R. N. INSERRA
UNIVERSITY OF FLORIDA
PO BOX 147100
GAINESVILLE, FL 32614-7100

JENNIFER M. JACOBS
UNIVERSITY OF FLORIDA
PO BOX 116580
GAINESVILLE, FL 32611-6580

JAY JAYACHANDRAN
FLORIDA INTERNATIONAL UNIV.
ENVIRONMENTAL STUDIES DEPT.
MIAMI, FL 33199

JONATHAN D. JORDAN
UNIVERSITY OF FLORIDA
PO BOX 110570
GAINESVILLE, FL 32611-0570

ROBERT S. KALMBACHER
RANGE CATTLE REC—ONA
3401 EXPERIMENT STATION
ONA, FL 33865-9706

NANCY KOKALIS-BURELLE
USDA-HORT. RES. LAB
2001 S ROCK RD.
FT. PIERCE, FL 34945

THOMAS A. KUCHAREK
UNIVERSITY OF FLORIDA
PO BOX 110680
GAINESVILLE, FL 32611-0680

PAUL S. LEHMAN
DPI/FDACS
PO BOX 147100
GAINEVILLE, FL 32614-7100

YUNCONG LI
TREC
18905 SW 280 STREET
HOMESTEAD, FL 33031

SALVADORE J. LOCASCIO
UNIVERSITY OF FLORIDA
PO BOX 110690
GAINESVILLE, FL 32611-0690

LENA Q. MA
UNIVERSITY OF FLORIDA
PO BOX 110290
SOIL AND WATER SCIENCE
GAINESVILLE, FL 32611-0290

ROBERT MANSELL
UNIVERSITY OF FLORIDA
PO BOX 110290
GAINESVILLE, FL 32611-0290

BRUCE MATHEWS
UNIVERSITY OF HAWAII-HILO
COLLEGE OF AGRICULTURE
200 W. KAWILI ST
HILO, HI 96720-4091

ROBERT MCGOVERN
UNIVERSITY OF FLORIDA
PLANT MEDICINE PROGRAM
PO BOX 110680
GAINESVILLE, FL 32611-0680

ROBERT MCSORLEY
UNIVERSITY OF FLORIDA
PO BOX 110620
GAINESVILLE, FL 32611-0620

J. D. MILLER
SUGARCANE FIELD STATION
STAR ROUTE BOX 8
CANAL POINT, FL 33438

PAUL MISLEVY
RANGE CATTLE REC—ONA
3401 EXPERIMENT STATION
ONA, FL 33865-9706

DOLEN MORRIS
USDA, SUGARCANE FIELD STATION
12990 HWY 441
CANAL POINT, FL 33438

ROSA M. MUCHOVEJ
SWFREC
2686 SR 29 NORTH
IMMOKALEE, FL 34142-9515

KENNETH R. MUZYK
GOWAN CO
408 LARRIE ELLEN WAY
BRANDON, FL 33511

RAO MYLAVARAPU
UNIVERSITY OF FLORIDA
PO BOX 110290
SOIL AND WATER SCIENCE
GAINESVILLE, FL 32611

THOMAS A. OBREZA
UNIVERSITY OF FLORIDA
PO BOX 110290
GAINESVILLE, FL 32611-0290

OGHENEKOME U. ONOKPISE
FLORIDA A & M UNIVERSITY
RM 203, SOUTH PERRY-PAIGE BLDG
TALLAHASSEE, FL 32307

HUGH L. POPENOE
UNIVERSITY OF FLORIDA
PO BOX 110286
GAINESVILLE, FL 32611-0286

KENNETH H. QUESENBERRY
UNIVERSITY OF FLORIDA
PO BOX 110500
GAINESVILLE, FL 32611-0500

JACK RECHCIGL
GULF COAST REC
5007 60 STREET E
BRADENTON, FL 34203-9324

PAUL REITH
UNIVERSITY OF FLORIDA
PO BOX 110500
GAINESVILLE, FL 32611-0500

JERRY B. SARTAIN
UNIVERSITY OF FLORIDA
PO BOX 110510
GAINESVILLE, FL 32611-0510

LIESBETH M. SCHMIDT
ROUTE 3, BOX 224-10
LAKE CITY, FL 32025

ARNOLD SCHUMANN
CITRUS REC
700 EXPERIMENT STATION ROAD
LAKE ALFRED, FL 33850-2299

LARRY SCHWANDES
1805 NW 38 TERRACE
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Historical Record of Society Officers

Year	President	President Elect	Secretary-Treasurer	Board Directors†
2005				M. B. Adjei
2004	C. G. Chambliss	W. D. Thomas	T. A. Obreza	W. D. Thomas (R. McSorley)
2003	C. D. Stanley	C. G. Chambliss	T. A. Obreza	P. Nkedi-Kizza
2002	D. W. Dickson	C. D. Stanley	T. A. Obreza	R. M. Muchovej
2001	R. N. Gallaher	D. W. Dickson	T. A. Obreza	Robert Kinloch
2000	D. V. Calvert	R. N. Gallaher	T. A. Obreza	J. E. Rechcigl
1999	T. A. Kucharek	D. V. Calvert	T. A. Obreza	E. C. French III
1998	K. H. Quesenberry	T. A. Kucharek	T. A. Obreza	S. C. Schank/J. R. Rich
1997	R. S. Mansell	K. H. Quesenberry	T. A. Obreza	E. A. Hanlon
1996	J. W. Noling	R. S. Mansell	C. D. Stanley	M. J. Williams
1995	D. L. Wright	J. W. Noling	C. D. Stanley	L. E. Sollenberger
1994	E. E. Albregts	D. L. Wright	C. D. Stanley	D. A. Graetz
1993	G. H. Snyder	E. E. Albregts	C. G. Chambliss	J. M. Bennett
1992	G. C. Smart, Jr.	G. H. Snyder	C. G. Chambliss	F. M. Rhoads
1991	R. S. Kalmbacher	G. C. Smart, Jr.	C. G. Chambliss	N. R. Usherwood
1990	R. D. Barnett	R. S. Kalmbacher	C. G. Chambliss	G. C. Smart, Jr.
1989	J. B. Sartain	R. D. Barnett	C. G. Chambliss	R. W. Johnson
1988	P. Mislevy	J. B. Sartain	D. D. Baltensperger/C. G. Chambliss	J. W. Prevatt/J. B. Sartain/B. L. McNeal
1987	D. F. Rothwell	P. Mislevy	G. Kidder	E. E. Albregts
1986	E. B. Whitty	D. F. Rothwell	G. Kidder	D. R. Hensel
1985	J. G. A. Fiskell	E. B. Whitty	G. Kidder	P. Mislevy
1984	G. M. Prine	J. G. A. Fiskell	G. Kidder	D. V. Calvert
1983	F. M. Rhoads	G. M. Prine	G. Kidder	G. M. Prine
1982	O. C. Ruelke	F. M. Rhoads	G. Kidder	T. W. Winsberg
1981	A. J. Overman	O. C. Ruelke	J. B. Sartain	F. M. Rhoads
1980	V. W. Carlisle	A. J. Overman	J. B. Sartain	P. H. Everett
1979	D. W. Jones	V. W. Carlisle	J. B. Sartain	O. C. Ruelke
1978	W. L. Pritchett	D. W. Jones	J. B. Sartain	A. J. Overman
1977	K. Hinson	W. L. Pritchett	D. W. Jones	R. L. Smith
1976	H. L. Breland	K. Hinson	D. W. Jones	A. L. Taylor
1975	A. E. Kretschmer, Jr.	H. L. Breland	D. W. Jones	A. E. Kretschmer, Jr./G. L. Gascho
1974	L. C. Hammond	A. E. Kretschmer, Jr.	D. W. Jones	H. L. Breland
1973	F. T. Boyd	L. C. Hammond	D. W. Jones	J. T. Russell
1972	C. E. Hutton	F. T. Boyd	D. F. Rothwell	
1971	E. M. Hodges	C. E. Hutton	D. F. Rothwell	
1970	W. K. Robertson	E. M. Hodges	J. NeSmith	
1969	E. S. Horner	W. K. Robertson	J. NeSmith	
1968	C. M. Geraldson	E. S. Horner	J. NeSmith	
1967	G. B. Killinger	C. M. Geraldson	J. NeSmith	
1966	C. F. Eno	G. B. Killinger	J. NeSmith	
1965	V. E. Green, Jr.	C. F. Eno	R. V. Allison	
1964	D. O. Spinks	V. E. Green, Jr.	R. V. Allison	
1963	H. C. Harris	D. O. Spinks	R. V. Allison	
1962	W. G. Blue	H. C. Harris	R. V. Allison	
1961	W. H. Chapman	W. G. Blue	R. V. Allison	
1960	J. R. Henderson	W. H. Chapman	R. V. Allison	
1959	P. H. Senn	J. R. Henderson	R. V. Allison	
1958	G. D. Thornton	P. H. Senn	R. V. Allison	
1957	D. E. McCloud	G. D. Thornton	R. V. Allison	
1956	R. W. Ruprecht	D. E. McCloud	R. V. Allison	
1955	F. H. Hull	W. Reuther	R. V. Allison	
1954	E. L. Spencer	F. H. Hull	R. V. Allison	
1953	N. Gammon, Jr.	E. L. Spencer	R. V. Allison	
1952	I. W. Wander	N. Gammon, Jr.	R. V. Allison	
1951	R. A. Carrigan	I. W. Wander	R. V. Allison	
1950	W. T. Forsee, Jr.	R. A. Carrigan	R. V. Allison	
1949	W. T. Forsee, Jr.	R. A. Carrigan	R. V. Allison	
1948	H. A. Bestor	L. H. Rogers	R. V. Allison	
1947	H. A. Bestor	L. H. Rogers	R. V. Allison	
1946	H. Gunter	H. A. Bestor	R. V. Allison	
1945	W. E. Stokes	H. Gunter	R. V. Allison	
1944	G. M. Volk	W. E. Stokes	R. V. Allison	
1943	H. I. Mossbarger	G. M. Volk	R. V. Allison	
1942	J. R. Neller	H. I. Mossbarger	R. V. Allison	
1941	F. B. Smith	J. R. Neller	R. V. Allison	
1940	M. Peech	F. B. Smith	R. A. Carrigan	
1939	R. V. Allison	M. Peech	R. A. Carrigan	

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1954	Lyman James Briggs
1956	Hardrada Harold Hume
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1959	Wilson Popenoe
1960	Pettis Holmes Senn
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1961	Joseph R. Neller
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1962	Frank L. Holland
1963	Herman Gunter
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1964	Henry Agard Wallace
1965	Robert Verrill Allison
1966	Richard Bradfield
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1970	William Thomas Forsee, Jr.
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1979	Gordon Beverly Killinger
1980	Roy Albert Bair
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1981	Darell Edison McCloud
1982	Nathan Gammon, Jr.
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1984	Lester T. Kurtz
1986	David Wilson Jones
1988	Paul Harrison Everett
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1990	William Guard Blue
1991	Earl Stewart Horner
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1992	Donald L. Myhre
1993	Carroll M. Geraldson
1995	Donald F. Rothwell
1996	Luther C. Hammond
1997	Amegda J. Overman
1998	Charles F. Eno
	Albert E. Kretschmer, Jr.
1999	Robert P. Esser
2000	Gordon M. Prine
2001	None elected
2002	None elected
2003	Paul Pfahler

Editors*

1953	C. F. Eno
1954	C. F. Eno
1955	I. W. Wander
1956	Walter Reuther
1957-1973	G. D. Thornton
1973	E. S. Horner
1974	E. S. Horner
1975	E. S. Horner
1976	E. S. Horner
1977	E. S. Horner
1978	E. S. Horner
1979	E. S. Horner
1980	E. S. Horner
1981	E. S. Horner
1982	E. S. Horner
1983	W. G. Blue
1984	V. E. Green, Jr.
1985	V. E. Green, Jr.
1986	V. E. Green/E. S. Horner
1987	W. G. Blue
1988	W. G. Blue
1989	W. G. Blue
1990	W. G. Blue
1991	P. L. Pfahler
1992	P. L. Pfahler
1993	P. L. Pfahler
1994	B. L. McNeal
1995	B. L. McNeal
1996	B. L. McNeal
1997	B. L. McNeal
1998	B. L. McNeal/ R. S. Kalmbacher
1999	R. S. Kalmbacher
2000	R. S. Kalmbacher
2001	R. S. Kalmbacher
2002	R. S. Kalmbacher
2003	R. S. Kalmbacher

*Prior to 1953, the minutes printed in the Proceedings do not name the Editor, although a publication report is printed and an Editor is mentioned. The minutes imply, but do not explicitly state, that for the first several years there was an Editorial Committee with the Chairman of the Committee serving as Editor.

The Soil Science Society of Florida was formed on 18 April 1939 under the leadership of Drs. R. V. Allison, R. A. Carrigan, F. B. Smith, Michael Peech, and Mr. W. L. Tait. In 1955 the name was changed to the Soil and Crop Science Society of Florida. The Society was incorporated as a non-profit organization of 6 June 1975. The articles of incorporation were published in Volume 35 of the Proceedings, and the By-Laws in Volume 41.

Volumes 31 and 44 of the Proceedings listed the previous officers of the Society. The information listed above draws heavily upon those two volumes and the minutes of the Society published in each volume. I discovered a few errors, especially in the Board of Directors, and all have been corrected to the best of my knowledge.

Grover C. Smart, Jr., President, SCSSF, 1991-92.

Dedication of Proceedings

Year	Volume	Person
1939	1	Robert M. Barnette
1940	2	H. H. Bennett & Selman A. Waksman
1941	3	Harry R. Leach
1942	4-A	Spessard L. Holland
1942	4-B	H. Harold Hume
1943	5-A	Nathan Mayo
1943	5-B	Wilmon Newell
1944	6	Herman Gunter
1945	7	Lewis Ralph Jones
1946-47	8	Millard F. Caldweld
1948-49	9	Willis E. Teal, Col. USA
1950	10	The First 11 Honorary Lifetime Members
1951	11	Charles R. Short
1952	12	Robert M. Salter
1953	13	J. Hillis Miller
1954	14	Lyman James Briggs
1955	15	Lorenzo A. Richards
1956	16	T. L. Collins & Fla. Water Resource Study Commission
1957	17	Firmin E. Bear
1958	18	Harold Mowry
1959	19	Work & Workers in the Fla. Agr. Ext. Serv. 1939-59
1960	20	Roger W. Bledsoe
1961	21	Doyle Conner
1962	22	R. V. Allison
1963	23	J. G. Tigert
1964	24	J. R. Neller
1965	25	Active Charter Members of the SCSSF
1966	26	Fred Harold Hull
1967	27	Frederick Buren Smith
1968	28	William Thomas Forsee, Jr.
1969	29	Henry Clayton Harris
1970	30	William G. Kirk
1971-72	31	Alvin Thomas Wallace
1973	32	Curtis E. Hutton
1974	33	E. Travis York, Jr.
1975	34	George Daniel Thornton
1976	35	Marshall O. Watkins
1977	36	Frederick T. Boyd
1978	37	Gaylord M. Volk
1979	38	Gordon Beverly Killinger
1980	39	Nathan Gammon, Jr.
1981	40	Fred Clark
1982	41	John W. Sites
1983	42	William K. Robertson
1984	43	Charles F. Eno
1985	44	Theodore (Ted) W. Winsberg
1986	45	Gerald O. Mott
1987	46	J. G. A. Fiskell
1988	47	Francis Aloysius Wood
1989	48	Victor E. Green, Jr.
1990	49	Earl S. Horner
1991	50	Amegda J. Overman
1992	51	William Guard Blue
1993	52	Charles E. Dean
1994	53	Luther C. Hammond
1995	54	Allan J. Norden
1996	55	Kuell Hinson
1997	56	Noble R. Usherwood
1998	57	Earl E. Albregts
1999	58	James M. Davidson
2000	59	William Pritchett
2001	60	E. C. French
		A. Smajstrla
		S. F. Shih
2002	61	Shirlie West
2003	62	Fred M. Rhoads
2004	63	Grover Smart

*In the earlier years, the Proceedings bear a date which coincides with the year of the annual meeting. During the years of World War II, publication was irregular and at least some of the volumes were published after the war. Also, the actual year that a publication is available becomes the "legal" date of a issue, not the year the meeting was held. Thus, volumes 32 and after bear a date one year after the annual meetings.