

MODELING GROWTH AND COMPOSITION OF  
PERENNIAL TROPICAL FORAGE GRASSES

By

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In addition to their role as feedstuffs, perennial tropical forage grasses such as bahiagrass (*Paspalum notatum* Flüggé) can play a major role in nutrient management on livestock farms; recycling N from fertilizers and manure to produce feed and reduce the importation of other feeds, while lowering potential N leaching. Balancing feed quality, feed quantity, and nutrient recovery can be difficult. A computer model capable of simulating forage growth, composition, and N-dynamics could be a useful management tool. Farmers and consultants could test management practices virtually, then implement those showing the most promise. Our objective was to develop a tool to predict the growth and composition of bahiagrass that responds to environmental and management inputs.

Bahiagrass sod cores were dug weekly for two 8-week regrowth periods (18 July to 12 September, and 12 September to 7 November). Plants were separated into leaf blades, stem, stolon, and roots. Leaf and canopy photosynthesis were measured in each period.

Leaf photosynthetic rate was not different between periods. Leaf and stem growth and rate of development of new leaves was reduced in the second period; however, stolon mass increased dramatically starting in mid-October.

This information aided the development of species-specific parameters required for simulating bahiagrass in the model, CROPGRO. In the process, limitations in the model structure that prevented the prediction of realistic growth patterns were identified. Despite the limitations, prediction of herbage mass was good, having an index of agreement of 0.85, with slightly lower accuracy predicting herbage N concentration.

To address the model's limitations, we modified the CROPGRO source code to include a storage organ (STOR), equivalent to a stolon, and added dormancy functions to increase partitioning of growth to STOR and reduce mobilization from STOR and roots under short daylengths. The freeze-kill function was modified, allowing gradual death of leaves. The Rubisco specificity factor in the leaf-level photosynthesis option was modified for C<sub>4</sub> photosynthesis. Model performance was improved, predicting realistic seasonal growth patterns. Excessive N stress was predicted frequently, but the cause was not identified. The forage version of CROPGRO performs realistically but should be tested under cooler temperatures and finer-textured soils.

## CHAPTER 1 INTRODUCTION

Perennial tropical grasses such as bahiagrass (*Paspalum notatum* Flugge) and bermudagrass [*Cynodon dactylon* (L.) Pers.] have long been the basis of beef production in Florida. As environmental concerns have come to the fore over potential movement of nitrate into Florida groundwater from dairy farms, there is a growing interest in use of these grasses as part of the nutrient management systems on Florida dairies. In both beef and dairy operations, the success of a forage program is measured by several criteria: it must generate enough mass to feed the herd, it may need to utilize a minimum amount of manure nutrients, and the forage produced must meet a significant proportion of the nutritional needs of the animals consuming it. Managing forages to meet all of these goals is a complex trade-off of yield and quality. Emphasizing forage quality generally requires harvesting at young stages of maturity, with shorter regrowth periods and lower yields, whereas managing for forage mass produces forage with reduced concentrations of digestible nutrients.

Current management strategies for perennial tropical forages rely on harvesting at regular intervals with no allowance for changing weather conditions. A 3 to 5 week harvest interval will nearly always produce high quality forage (Staples, 1995) but often the yields are unacceptably low. Delaying harvest when forage growth rates are low increases yield but at what cost to quality? A system that could compensate for changing temperature, rainfall, and soil fertility might allow farmers to harvest forage of more consistent quality in reasonable quantities.

Such a system also could improve N cycling on the farm and reduce N leaching to groundwater. The high growth potential and expansive root system of tropical grasses such as bahiagrass and bermudagrass allow these species to not only uptake large quantities of N from the soil but they may alter the seasonal pattern of N leaching as well (Woodard et al., 2002). Properly managing the timing of fertilizer and manure applications as well as the timing of forage harvests can reduce nutrient losses to the environment while producing additional feed for the herd.

A crop model capable of predicting forage yield and composition along with N leaching dynamics could allow evaluation of management practices (including harvest strategies) before implementing them in the field. To provide output with the desired level of detail, the model must have the ability to respond to a variety of environmental (temperature, rainfall, daylength, soil moisture, etc.) as well as management (fertilizer, irrigation, harvest schedule, etc.) inputs. It would also be advantageous if the model could be easily adapted to simulate other forage species to avoid rewriting the model for each new species to be modeled. The CROPGRO model meets both of these requirements.

CROPGRO is a mechanistic or process-oriented model. That is, it predicts plant growth by simulating many of the underlying biological processes. Some of the plant processes simulated include photosynthesis, transpiration, senescence/mobilization of plant tissue, and root uptake of water and nutrients. In addition several supporting processes such as water infiltration and evaporation in the soil, soil organic matter and N dynamics (mineralization, nitrification, denitrification, and leaching), and biological N



fixation are also simulated. The structure of the model also allows it to be readily adapted to new plant species.

The model code itself is quite generic, including a minimum of crop-specific relationships in the source code. Rather, parameters defining the species-unique responses of the various processes are read from a set of species-specific input files. By providing alternate parameter files, the behavior of the model can be adapted to simulate other plant species. Parameter files have already been created to allow CROPGRO to simulate several crop species including soybean (*Glycine max* L.), peanut (*Arachis hypogaea* L.), dry bean (*Phaseolus vulgaris* L.), faba bean (*Vicia faba* L.), and tomato (*Lycopersicon esculentum* Mill.) (Scholberg et al., 1997; Boote et al., 1998a, 1998b, 2002). Modeling perennial tropical grasses poses challenges not encountered when modeling annual grain or fruit crops. Perennial forages must persist from one year to another, regrow each spring, and go dormant each fall. Additionally, forages are not usually allowed to reach physiological maturity and may be harvested several times in a single growing season. The current CROPGRO structure can accommodate each of these challenges to some degree. However, some code changes are needed to achieve the desired level of model performance for perennial forages.

The goal of this project is to adapt the CROPGRO model code and species file to simulate the growth and composition of bahiagrass over multiple, consecutive growing seasons. Parameter values will be obtained from the existing literature when available, directly measured in experiments when practical, and estimated by calibration when necessary. The Cropping Systems Model or CSM version of CROPGRO which is part of the Decision Support System for Agrotechnology Transfer (DSSAT) version 4 model

will be evaluated to quantify its ability to predict and determine any limitations for modeling perennial grasses. Finally, portions of existing code will be changed and some new code added to create an independent perennial forage version of CSM CROPGRO.

The build date for the code used in our project is 11 July 2003. This is a pre-release version, but the relevant code is substantially the same as the final version released as DSSAT v4 (Hoogenboom et al., 2003). To be compatible with the release version, the PESTCP module was updated, changing the forage cutting code from MOWE to MOW and changing the stubble mass units from g (leaf+stem) DM m<sup>-2</sup> to kg (leaf+stem) ha<sup>-1</sup>. While efforts will be made to maintain compatibility with the existing CROPGRO model and its input-output structure, the perennial forage version will be considered to be a “new” model rather than a new version of the current model.

## CHAPTER 2 LITERATURE REVIEW

### **Bahiagrass**

Native to South America (Ward and Watson, 1973) and northward to Mexico (Scott, 1920), bahiagrass (*Paspalum notatum* Flüggé) is a perennial tropical grass that spreads by seed and vegetative stolons. First planted at the Florida Agricultural Experiment Station in May of 1913 (Scott, 1920), bahiagrass use has spread to over one million hectares (2.5 million acres) in Florida alone (Chambliss, 2002). Initial reports praised the grass for its palatability to cattle and especially for its persistence and capacity to spread and form a sod even under heavy grazing pressure (Scott, 1920). This persistence along with its ability to tolerate a wide variety of management systems has been key to the popularity of this species.

While used primarily for grazing beef cattle, bahiagrass is also harvested as hay. Annual hay yields of near 8000 kg ha<sup>-1</sup> may be expected when harvested every 4 wk (Johnson et al., 2001) and may exceed 11000 kg ha<sup>-1</sup> when harvested every 6 to 8 wk (Blue, 1973). Bahiagrass responds well to N fertilization, yielding 2700 kg ha<sup>-1</sup> yr<sup>-1</sup> with no fertilizer N (Beaty et al., 1964) and increasing to nearly 14000 kg ha<sup>-1</sup> yr<sup>-1</sup> when fertilized with very high levels of N and cut to a low stubble height (Pedreira and Brown, 1996a). The most prolific biomass growth occurs below the common cutting height of 5 to 10 cm. The prostrate growth habit of 'Pensacola' bahiagrass produces a large amount of leaf low in the canopy, with reports of as much as 5600 kg ha<sup>-1</sup> of leaf DM (Beaty et al., 1964) and a leaf area index (LAI) in excess of 1.6 m<sup>2</sup> leaf m<sup>-2</sup> land remaining after

harvest (Pedreira and Brown, 1996b). Beaty et al. (1968) reported that nearly 40% of the total forage produced by Pensacola bahiagrass was present in the bottom 2.5 cm of the canopy. Depending on the fertility and age of the stand, an additional 9800 kg ha<sup>-1</sup> (Beaty et al., 1964) or more of rhizome or stolon (the terms rhizome and stolon are used interchangeably in the literature when referring to bahiagrass) mass were present at the soil surface. Bahiagrass also has an extensive fibrous root system which may produce as much as 19700 kg ha<sup>-1</sup> DM in just the top 15 cm of the soil (Beaty et al., 1964), although a level near 4500 kg ha<sup>-1</sup> root DM (Burton et al., 1954) is more common. Pensacola bahiagrass roots have been reported to extend more than two meters below the soil surface (Burton et al., 1954; Chambliss, 2002). Although other cultivars may exhibit a more erect growth habit or lower stubble mass in the seedling year than Pensacola, even these “improved” cultivars may still have a harvest index of 10% or less (harvested forage as a proportion of total above-ground biomass present at harvest) after the field has been established for more than two years (Pedreira and Brown, 1996b). Such an investment in biomass close to the ground and below-ground encourages the persistence and quick sod formation that the species is noted for. It also can support the crop through periods of stress, allowing it to adapt to a variety of management practices.

The most popular bahiagrass cultivar is Pensacola bahiagrass (Chambliss, 2002), a West Indies-type bahiagrass, thought to have been introduced in ballast offloaded at the Perdido Wharf sometime prior to 1926 and promoted after 1939 by Escambia County Cooperative Extension county agent Ed Finlayson for its aggressive sod formation, persistence, drought tolerance, and palatability to cattle (Finlayson, 1941). Pensacola is distinguished by long, narrow leaves and tall seedheads. Aside from its persistence,

Pensacola bahiagrass is also more cold-tolerant than many other cultivars (Ward and Watson, 1973; Chambliss, 2002).

The productive season for bahiagrass is April to November in North Florida. The season starts in early March in South Florida but growth still slows in October (Chambliss, 2002), suggesting that the decline in growth may not be solely temperature dependent. Indeed, recent work by Sinclair et al. (2001; 2003) and Gates et al. (2001) demonstrate a role of daylength in initiating winter dormancy.

### **Perennating Organs: Rhizomes and Stolons**

While bahiagrass reproduces by seed, the plants spread and form a dense sod through the growth of rhizomes (equivalent to stolons) (Ward and Watson, 1973; Chambliss, 2002). Stolons allow the plants to spread and occupy more land area with nodes on the stolons providing new growing points for additional tiller growth. New tillers form at an axillary bud in response to the flowering of a nearby culm (Sampaio and Beaty, 1976), maintaining tiller density and rejuvenating the stand. New tillers may also form in response to changing light (daylength and light quality) with the onset of spring or after a harvest (and the possible removal of apical dominance). This new growth allows the stand to persist from year to year and under grazing or hay management systems.

The stolons also promote persistence by acting as a storage vessel for C and N reserves, providing nutrients for growth under stressful conditions and promoting rapid regrowth after winter or harvest. As was previously mentioned, the mass of stolons may be several times the mass of leaves, and the reserves may last two to three years (Chambliss, 2002), providing for new growth. Partitioning to, and mobilization from, stolons, may at times account for the majority of the nutrient flows within the plant.

Studies of carbon allocation and movement in bahiagrass using  $^{14}\text{CO}_2$  have shown 50 – 60% of the  $^{14}\text{C}$  partitioned to stolons, with only 10% partitioned to new leaf growth (Beaty et al., 1974). Patterns of mobilization are also affected by harvesting. The same study reported that re-mobilization of  $^{14}\text{C}$  from the surviving tissue ceased within 3 to 6 d after a severe defoliation. No more than 20% of the  $^{14}\text{C}$  assimilated was re-mobilized, of which only 10% moved to the leaves of the main plant while 20 to 40% went to the stolons. Such isotope studies characterizing patterns of mobilization and partitioning to new growth during spring regrowth have not been conducted, but general studies of fall and spring plant growth suggest that there are regulatory roles for two additional factors: daylength and temperature. Late and early season growth can be slowed by the cooler temperatures associated with the fall, winter, and spring months. This is also the period of the year when daylength is near its minimum.

### **Dormancy**

Forage production from tropical grasses like bahiagrass and bermudagrass [*Cynodon dactylon* (L.) Pers.] drops dramatically in the late summer and fall months in the southeastern United States despite continued warm temperatures. Gates et al. (2001) quantified this reduction in yield in bahiagrass by measuring forage growth through two successive fall and winter seasons concurrently at Ona, FL and Tifton, GA. Mean temperatures were 6°C cooler in Tifton where multiple freeze events occurred while there was only one night in the two growing seasons where temperatures dropped below 0°C at Ona. The pattern of seasonal forage production was similar for both sites; however, production at Tifton was lower than for Ona. At Ona daily forage production (leaf and stem mass recovered above the mowing height) decreased from 36 kg DM ha<sup>-1</sup> d<sup>-1</sup> to 8 kg DM ha<sup>-1</sup> d<sup>-1</sup> between 23 September 1993 and 8 November 1993, a 78% decrease in

growth rate. The growth rate remained between 5 and 15 kg DM ha<sup>-1</sup> d<sup>-1</sup> through 7 March, then increased to 35 kg DM ha<sup>-1</sup> d<sup>-1</sup> by 6 April. Cooler temperatures in the second growing season (1994-1995) resulted in a similar pattern of forage growth but lower overall yields and a more rapid increase in growth rate in the spring. Although there was no difference in growth rates between the three cultivars tested (Pensacola, Tifton 9, and RRPS Cycle 18) on dates when minimum growth rates were realized, regrowth of Pensacola in September and April was considerably lower than that of the newer, higher yielding cultivar, RRPS Cycle 18. No information on the cause of the seasonal reduction could be discerned from the study other than the generally lower yields at lower temperatures.

Growers in Georgia have attributed the low productivity of tropical grasses in the fall to a lack of rainfall and fertilizer (Burton et al., 1988). Investigating this hypothesis, Burton et al. (1988) compared the forage yields of well-fertilized, irrigated and non-irrigated Coastal bermudagrass (another C<sub>4</sub> grass that exhibits winter dormancy) harvested every 24 d from 1 April through 27 October for three consecutive years. A seasonal decrease in forage yield was observed in all treatments during the fall and winter. The magnitude of the drop was quite dramatic with yields for the September – October harvest being only slightly more than 1/3 the yield of the May – June harvest period despite slightly higher temperatures in the fall. Correlation analyses of the data showed only a moderate relationship between yield and temperature ( $r=0.46$ ) or growing degree days (GDD) ( $r=0.37$ ), thus, discounting the roles of temperature, rainfall, and fertilizer in the seasonal yield reduction pattern. Two variables that did show a strong correlation with yield were daylength ( $r=0.95$ ) and daily solar radiation ( $r=0.93$ ). It was

not possible to separate these two effects with this dataset. Stepwise regression was also employed using individual growth period data for all years. The single variable model with the best fit was daylength ( $r^2 = 0.64$ ,  $0.69$ , and  $0.61$  for all yields, irrigated yields only, and non-irrigated yields, respectively). When daylength was excluded from the model, the best fit for a single variable was rainfall + irrigation ( $r^2 = 0.45$ ). Adding solar radiation to the rainfall model only increased the  $R^2$  to  $0.57$ , while the daylength + rainfall gave an  $R^2$  of  $0.73$  for all yields and  $0.77$  for irrigated yields only. A model with daylength and water deficit (pan evaporation – rainfall) had an  $R^2$  of  $0.71$  when fit to the non-irrigated yield data. Stepwise regression did not compensate for the confounded effects of daylength and total solar radiation but did lend more weight to the daylength argument.

Marousky et al. (1992) attempted to separate daylength effects from solar radiation effects in a study of daylength effects on turf-type bermudagrass cultivars. Long days were simulated using the same 9-h daytime as the short-day treatment but the dark period was interrupted with 4 hours of light from incandescent lamps. Interruption of the dark period with light causes the reversal of many red/far-red phytochrome reactions; in effect, simulating a much longer day than the total time exposed to light. Long-day plants exhibited a greater degree of leaf extension but no change in plant dry weight or number of stolons produced. The authors' rationale for the apparent conflict with the results of Burton et al. (1988) was that cultivar differences resulted in different responses between the long-leaved, forage-type Coastal bermudagrass and the fine-leaved, turf-type cultivars.



Another possible explanation might be found in work by Britz et al. (1958) who studied short-day (late-season) accumulation of starch in leaves of another tropical grass, *Digitaria decumbens* Stent.. This accumulation of starch was associated with a decrease in translocation of assimilate under short days. The authors used several methods to elicit a long-day response. Gradual extension of the daylength from 7-h (short-day) to 14 h (long-day) with full-spectrum, full-irradiance light ( $400\text{-}600\text{ }\mu\text{mol m}^{-2}\text{ s}^{-1}$  photosynthetic photon flux density) resulted in no decrease in starch accumulation with 9 h daylength but a dramatic drop between 11 and 12 h of light with starch concentrations after 12 h of light equal to levels at 14-h daylength. In contrast, interrupting the dark period with 0.5 h or 2.0 h of full-spectrum light resulted in a partial (~40% and ~60%, respectively) reduction in starch accumulation relative to a 14 h day. The full long-day response was achieved when the 7 h light period was shifted from the first half of the 24 h period to the second half. These results implied that timing of the light periods may be more important than total time of exposure. To separate the effects of daylength and total solar radiation, plants were exposed to 14 h of amber light (589 nm), having a good photosynthetic spectra but lacking photomorphogenetically-active wavelengths. Photosynthate production under long days of amber light was similar to that of the long-day plants under full-spectrum light but starch partitioning was similar to that of the short-day plants. This helped to solidify the conclusion that the starch accumulation was a photoperiodic response but also indicated that it involved a more complex mechanism than a single red/far-red phytochrome response. The different responses of the long day and interrupted night treatments may indicate a similarly complex mechanism in the short-day response of bermudagrass.

Sinclair et al. (2003) avoided these complications by extending the natural daylength over field-grown Pensacola bahiagrass, ‘Florakirk’ bermudagrass, ‘Tifton’ 85 bermudagrass (*Cynodon* spp.), and ‘Florona’ stargrass (*Cynodon nlemfuensis* Vanderyst) to 15 h using halogen lamps during the short daylength months. Light levels under the lamps were equivalent to less than 2% of full sunlight and, thus, not considered to contribute significantly to total daily radiation. While all four species had higher forage production under the extended daylength treatment, bahiagrass showed the greatest response. Extended daylength yields were frequently more than twice those of the natural daylength treatment with yields six times greater on one harvest date. Despite the increases, mid-winter yields under extended daylength were still quite low compared to summer yields. Although forage growth increased, below-ground biomass production was not affected by extending the light period. Another factor potentially related to dormancy, total nonstructural carbohydrate (TNC) concentration in the below-ground biomass (root + stolon), decreased during the short-daylength months in both the natural- and extended-daylength treatments. All this paints a picture of fall dormancy in tropical grasses being triggered, at least in part, by daylength. The exact mechanisms have not been described but the relatively low forage production even under extended daylength as well as the continued loss of TNC during the winter, point to a complex of factors contributing to the response rather than a simple phytochrome-mediated response.

### **Photosynthesis**

The large DM production of bahiagrass can largely be attributed to it being a tropical grass species expressing the C<sub>4</sub> photosynthetic pathway. Temperate grasses express the C<sub>3</sub> photosynthetic pathway wherein CO<sub>2</sub> is fixed by ribulose 1,5-bisphosphate carboxylase/oxygenase (Rubisco) in the chloroplasts to produce 2 molecules of 3-

phosphoglyceric acid (3-PGA; a 3-carbon acid) and, eventually carbohydrate via the Calvin cycle. Rubisco is also an oxygenase, capable of fixing  $O_2$  as well as  $CO_2$ . When  $O_2$  is fixed, one molecule of 2-phosphoglycolate and only one molecule of 3-PGA are produced. Not only is there half as much 3-PGA produced when  $O_2$  is fixed, two molecules of glycolate can be metabolized to release a molecule of  $CO_2$ , hence the term photorespiration referring to oxygenase activity. Both  $CO_2$  and  $O_2$  compete for binding sites on Rubisco, with higher relative concentrations of  $O_2$  in the chloroplast resulting in higher rates of photorespiration and reduced photosynthetic efficiency. In  $C_4$  photosynthesis,  $CO_2$  is fixed in the mesophyll cells (cells near the leaf surface) by phosphoenolpyruvate carboxylase (PEPCase) to form oxaloacetate (OAA; a 4-carbon acid). The OAA is subsequently converted to either malate or aspartate, depending on the type of  $C_4$  pathway expressed in the species, and transported to the bundle sheath cells isolated deep within the leaves. In the bundle sheath cells, the malate or aspartate is decarboxylated near the chloroplast where Rubisco re-fixes the  $CO_2$  to produce 2 molecules of 3-PGA as in  $C_3$  photosynthesis. Energetically,  $C_4$  photosynthesis is more expensive with the additional cost of 2 ATPs to fix  $HCO_3^-$  with PEPCase on top of the cost of 3 ATPs and 2 NADPHs to fix one mole of  $CO_2$  in the  $C_3$  pathway (Kanai and Edwards, 1999). However, PEPCase has no oxygenase activity and, thus, can be more efficient than Rubisco in fixing  $CO_2$  in the presence of  $O_2$ . Also, by isolating Rubisco in the bundle sheath and “shuttling” the  $CO_2$  to it,  $CO_2$  is concentrated around the Rubisco and photorespiration is minimized. Under atmospheric conditions ( $\sim 21\%$   $O_2$  and 370 ppm  $CO_2$ ), photorespiration in  $C_4$  plants may be on the order of 3% of the net rate of  $CO_2$  fixation, compared to rates of 54% observed in the  $C_3$  species wheat (*Triticum aestivum*

L.) (Kanai and Edwards, 1999). Reduced photorespiration not only increases the efficiency of Rubisco carboxylation, it also increases the light level at which light saturated photosynthesis occurs, lowers the CO<sub>2</sub> compensation point, increases quantum efficiency (QE), changes the temperature sensitivity of both QE and photosynthesis, and allows high photosynthetic rates at relatively low concentrations of leaf N or photosynthetic enzymes.

The higher carboxylation rate resulting from CO<sub>2</sub> saturation of Rubisco and the reduced photorespiration enables C<sub>4</sub> plants to potentially attain higher photosynthetic rates at high light. While C<sub>3</sub> photosynthesis becomes light saturated at relatively low light levels, the enhanced capacity of the C<sub>4</sub> system can tolerate very high light levels without becoming light saturated. Ludlow and Wilson (1971) compared leaf net photosynthetic rates of tropical grasses (C<sub>4</sub>) with tropical legumes (C<sub>3</sub>) over a range of illuminances. Consistent with the capacity to respond to higher light levels, the C<sub>4</sub> grasses had net photosynthetic rates ( $37.8 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) that were approximately double those noted for the C<sub>3</sub> legumes ( $17.7 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ). The light response curves of the legumes reached a plateau at around 4000 – 5000 foot-candles of light while the curves for the C<sub>4</sub> grasses were only approaching saturation at the highest illuminance of 10 000 foot-candles. Boote et al. (1999) measured leaf net photosynthesis (P<sub>n</sub>) near  $28 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  in established bahiagrass under atmospheric conditions compared to approximately  $20 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  for the C<sub>3</sub> legume rhizoma peanut (*Arachis glabrata* Benth.). When the CO<sub>2</sub> concentration was doubled from 350  $\mu\text{L L}^{-1}$  to 700  $\mu\text{L L}^{-1}$ , bahiagrass responded with only a 20% increase in P<sub>n</sub>, about half of the 36% increase measured for rhizoma peanut (Boote et al., 1999).

Higher photosynthetic efficiency also allows the CO<sub>2</sub> compensation point (CCMP) (atmospheric CO<sub>2</sub> concentration where the rate of CO<sub>2</sub> uptake by photosynthesis equals the rate of CO<sub>2</sub> efflux) of C<sub>4</sub> plants to be considerably below that of C<sub>3</sub> plants. Bolton and Brown (1980) recorded CO<sub>2</sub> compensation points of 4-14  $\mu\text{L L}^{-1}$  for the C<sub>4</sub> grass *Panicum maximum*, much lower than the values (47-59  $\mu\text{L L}^{-1}$ ) measured in tall fescue (*Festuca arundinacea* Schreb.), a C<sub>3</sub> grass. Several other C<sub>4</sub> grasses have been shown to have CCMPs near 0  $\mu\text{L L}^{-1}$  including *Vetiveria zizanoides* (0 to 5  $\mu\text{L L}^{-1}$ ), and a variety of *Cymbopogon* species (0 to 3  $\mu\text{L L}^{-1}$ ) (Rajendrudu and Das, 1981).

Efficiency of light utilization may also improve with reduced photorespiration. Quantum efficiency or quantum yield is the efficiency of leaf photosynthesis when measured at low light and is generally expressed as  $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  absorbed photons. This describes the initial slope of the photosynthetic response to light (light-limited region). A frequently cited QE value for C<sub>3</sub> species is 0.05241  $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  absorbed photons, the average QE measured at 330  $\mu\text{L CO}_2 \text{L}^{-1}$  for seven C<sub>3</sub> species (Ehleringer and Björkman, 1977). Values for C<sub>4</sub> species are generally higher than those for C<sub>3</sub> species and may range from 0.046 for *Sorghastrum nutans* (Monson et al., 1982) to 0.075 for *Saccharum spontaneum* (Meinzer and Zhu, 1998). Differences in efficiency exist between the three types of C<sub>4</sub> pathways (NAD-ME, NADP-ME, and PCK-type) (Ehleringer and Pearcy, 1983) as well. Ehleringer and Pearcy (1983) found that species expressing the NADP-ME pathway, [e.g. bahiagrass and maize (*Zea mays* L.)] exhibited the highest QE with eight monocot species averaging 0.065  $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  absorbed photons. Reports of QE for other NADP-ME species range from 0.062 to 0.075  $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  absorbed photons for various sugarcane (*Saccharum*) species at 350 ppm

CO<sub>2</sub> (Meinzer and Zhu, 1998). Quantum efficiencies for other C<sub>4</sub> pathway types recorded by Ehleringer and Pearcy (1983) were 0.064  $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  absorbed photons for five monocot species exhibiting the PCK-type pathway, and 0.060  $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  absorbed photons for three NAD-ME species. It should be noted that both the Ehleringer and Pearcy (1983) and Ehleringer and Björkman (1977) studies measured QE at 330 ppm CO<sub>2</sub> rather than the customary 350 ppm CO<sub>2</sub>. The narrow range of values for a given pathway when measured across many species suggests that QE may be a characteristic that is highly conserved across species. This would imply that values for a particular pathway type may be generally applied to other species exhibiting that photosynthetic pathway and that the QE for bahiagrass is near 0.065  $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  absorbed photons.

While the QE of C<sub>4</sub> plants is generally greater than that of C<sub>3</sub> plants at higher temperatures, the QE of C<sub>3</sub> plants may exceed those of C<sub>4</sub> plants at temperatures below 30°C (Ehleringer and Björkman, 1977; Ku and Edwards, 1978; Monson et al., 1982). The QE of C<sub>4</sub> plants is temperature insensitive, decreasing very little as temperatures increase while the QE of C<sub>3</sub> plants falls dramatically as temperature increases (Ehleringer and Björkman, 1977; Ku and Edwards, 1978; Monson et al., 1982; Ehleringer and Pearcy, 1983). The decrease in C<sub>3</sub> QE at higher temperatures is attributed to increased photorespiration (Ehleringer and Björkman, 1977; Monson et al., 1982). The solubility of CO<sub>2</sub> decreases relative to that of O<sub>2</sub> as temperature increases, creating a condition where O<sub>2</sub> concentration around Rubisco may be enhanced, resulting in increased oxygenase activity relative to carboxylation. This effect alone cannot account for the drop in QE of C<sub>3</sub>s at high temperatures (Ehleringer and Björkman, 1977; Ku and

Edwards, 1978), rather it is likely the combined effects of the changing relative gas solubilities and a changing affinity of Rubisco for CO<sub>2</sub> and O<sub>2</sub> (Jordan and Ogren, 1984) that favors O<sub>2</sub> at higher temperatures. The CO<sub>2</sub>-concentrating mechanisms of the C<sub>4</sub> pathways provide a high concentration of CO<sub>2</sub> relative to O<sub>2</sub> in the bundle sheath chloroplast such that photorespiration effects are not evident (Jordan and Ogren, 1984).

Consistent with a higher QE at high temperatures, the temperature optimum for photosynthesis in C<sub>4</sub> plants is generally about 10°C higher than for C<sub>3</sub>s (Long, 1999). Conversely, at lower temperatures, C<sub>4</sub> photosynthetic rates may be below that of comparable C<sub>3</sub> plants. The higher temperature optimum may be explained by the lack of photorespiration in the C<sub>4</sub>s, but the mechanism behind the decreased performance at lower temperatures has been more elusive. In an extensive review of C<sub>4</sub> photosynthesis at low temperatures, Long (1983) explored the effect of low temperatures on several of the steps in the C<sub>4</sub> pathway(s). No single step could be shown to be the limiting factor at low temperatures. Two enzyme steps were identified to be the most likely to limit C<sub>4</sub> photosynthetic rate at low temperatures: pyruvate Pi dikinase (PPDK) activity or Rubisco activity. Pyruvate Pi dikinase was suspected for its relatively low activity at all temperatures and the dramatic increase in its activation time under cold conditions. Rubisco limitation might occur due to the low quantities of the enzyme in C<sub>4</sub> leaves along with a possible inhibition of the CO<sub>2</sub> concentrating mechanism under cold temperatures. In a more recent review of responses of C<sub>4</sub> photosynthesis to various environmental factors, Long (1999) revisits his investigation of low temperature effects, this time refuting the argument for PPDK limitation of photosynthetic rate and concluding that “there is no inherent flaw in C<sub>4</sub> photosynthesis that prevents efficient operation at low

temperatures” (p. 240) and citing *Miscanthus* as an example of a C<sub>4</sub> species capable of persisting at high altitudes/low temperatures. Recent work by Pitterman and Sage (2000) using two ecotypes of *Bouteloua gracilis* Lag., adapted to high or low elevations implicates Rubisco capacity as limiting photosynthesis at temperatures below 17°C. They also identify PPDK activity or ribulose 1,5-bisphosphate (RuBP) regeneration as potentially limiting photosynthesis between 20°C and the optimum temperature (~37°C), and PEPCase capacity as potentially limiting photosynthetic rate at temperatures greater than the optimum. That C<sub>4</sub> photosynthesis could have a rate lower than the C<sub>3</sub> rate at low temperatures if Rubisco was limiting in both pathways was attributed to the low Rubisco content of C<sub>4</sub> leaves coupled with the added cost of carboxylation of PEP in the C<sub>4</sub> pathway.

The low Rubisco content of C<sub>4</sub> leaves (Pittermann and Sage, 2000) contributes to a lower leaf N concentration and smaller proportion of soluble leaf N than is typically found in C<sub>3</sub> plants (Slack and Hatch, 1967; Crespo et al., 1979; Sugiyama and Hirayama, 1983; Usuda et al., 1984). While Rubisco may contribute over 40% of the soluble leaf N in a C<sub>3</sub> leaf, it represents only about 5-28% of soluble N in C<sub>4</sub>s (Slack and Hatch, 1967; Sugiyama and Hirayama, 1983). The added N present in PEPCase (4-10% of soluble leaf N (Slack and Hatch, 1967)) does not match the relative decrease in Rubisco concentrations, resulting in a lower total quantity of photosynthetic enzymes (PEPCase plus Rubisco) and lower total N concentration in C<sub>4</sub> leaves compared to C<sub>3</sub>s (Slack and Hatch, 1967; Brown, 1978; Raghavendra and RamaDas, 1993). Leaf N concentration can be increased by increasing N supply to the plant. Sugiyama and Hirayama (1983) found that Rubisco, PEPCase, and PPDK quantities all increased with increasing N supply.



However, while the concentration of PEPCase and PPDK increased (as a proportion of DM), the concentration of Rubisco decreased relative to C<sub>3</sub> plants even as leaf N concentration increased with N supply. The high photosynthetic rates at low leaf N concentrations result in a high N-use efficiency, a factor critical to the productivity of many tropical grasses in low input systems. Conversely, their low crude protein (CP) concentration coupled with high cell wall concentrations (largely a consequence of the extensive vascular system associated with the Kranz anatomy and bundle sheath) are primary contributors to the relatively low forage quality of most tropical grasses.

### **The CROPGRO Model**

The goal of this section is to familiarize the reader with the major features of CROPGRO pertinent to adapting the model for perennial tropical forages. Discussion will be limited to a review of the pattern of information flow and summaries of some of the plant-related subroutines. More complete descriptions of CROPGRO have been published by Boote et al. (1998a, 1998b) with an extensive review of the hedgerow photosynthesis approach by Boote and Pickering (1994).

One of the primary objectives in developing CROPGRO was to have a model that could easily be adapted to simulate the growth of different plant species. CROPGRO was created as a way to consolidate the existing SOYGRO, PNUTGRO, and BEANGRO models into a single program (Boote et al., 1998a). The three programs shared much of their code, so merging the models primarily involved moving the parameters describing species and cultivar traits from the actual code to external input files. This structure allows other species to be modeled by creating new parameter (input) files.

CROPGRO was developed in the early 1990s as a stand-alone model but could also be run under the Decision Support System for Agrotechnology Transfer (DSSAT) shell

(ICASA, 1998), allowing it to be linked to other crop modeling programs as well as graphics programs to automate presentation of results. After DSSAT version 3.1 was released in 1996, the CROPGRO code was reorganized into a modular structure. Code for simulating different plant and soil processes was organized into individual subroutines for each process. The new subroutines were designed to be executed in four common steps (initialization, rate calculation, integration and final/summary) called by the main model. The modular structure was designed to allow users to add new code or to link code from other programs by inserting new modules into the CROPGRO structure. This approach has been applied to the DSSAT shell such that CROPGRO is an integral component of the Cropping Systems Model (CSM) (Jones et al., 2003). CROPGRO serves as the crop template module (Hoogenboom et al., 2003; Jones et al., 2003); a universal interface for modeling several different species. An overview of DSSAT version 4, which incorporates the CSM version of CROPGRO, can be found in the DSSAT v4 documentation (Hoogenboom et al., 2003) and in Jones et al. (2003).

The modular version of CROPGRO was the first version to include the soil organic matter (SOM) transformation module based on the CENTURY model (Gijssman et al., 2002). The only SOM transformation option available in earlier versions was an adaptation of the PAPRAN model (Godwin and Jones, 1991). Both options address mineralization from SOM as well as immobilization, nitrification, and denitrification of N. The CENTURY option adds the capability of simulating decay of surface residues and the movement of those nutrients into the soil profile. Pasture and other perennial forage systems are often low-input systems relying heavily on recycled nutrients from plant residues for continued productivity. Omission of surface litter nutrient pools from

the PAPRAN option may dramatically reduce the available soil N and C pools, potentially resulting in chronic underprediction of plant growth especially over the multi-year simulation periods typical for perennial forage systems. Thus, the CENTURY option is better suited to modeling perennial forages.

CROPGRO and CSM incorporate several modules for simulating environmental and management responses, soil N transformations, soil water availability, etc. (Figure 2-1). Individual modules depicting different processes are executed once within each of the four steps of the modular structure. This modular structure should enhance the future development of these programs as it allows others to add new features by inserting their own modules. Also, by separating the rate and integration steps, the order of execution of the modules within each step is generally less critical, again, facilitating further development.

In the initialization step, parameter values and simulation control information are read from various input files and initial values set for state variables (variables representing the state of the system at the end of the day, variables that have a quantity such as mass of roots or number of leaves). This step is run once per simulation, although there are provisions to re-run each simulation for multiple years where the initialization step is run once per repetition.

Several input files are used to set the parameters for a species and control the execution of the simulation. Three files contain the plant parameters: a species file, a cultivar file, and an ecotype file. The experiment file, or “X-file” controls the simulation and is supplemented by weather files, a soil information file, and a pest file. Comparison of predicted data to measured experimental results is automated, with the program

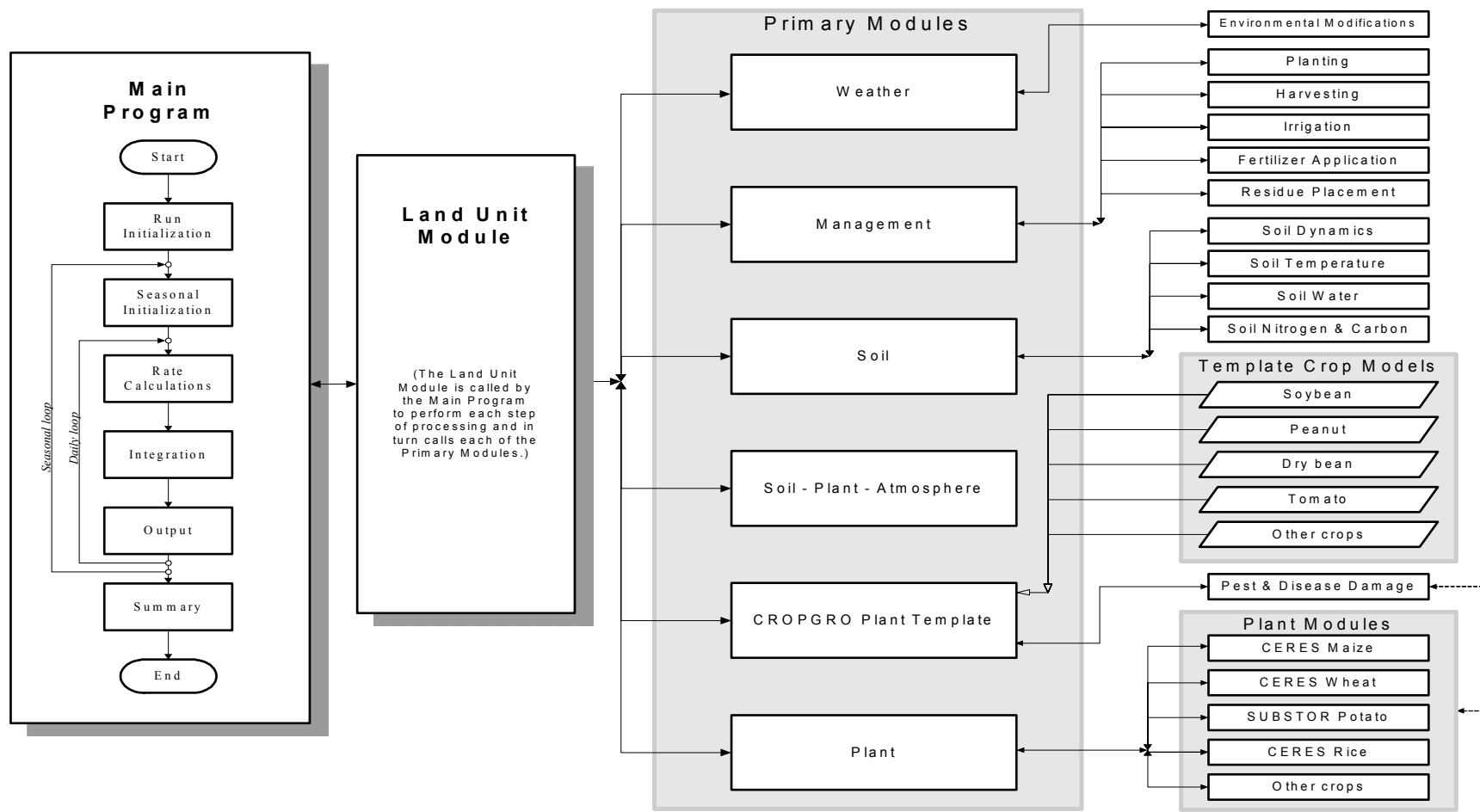


Figure 2-1. Modular structure and summary of model components of the DSSAT-CSM cropping systems model (Jones et al., 2003, p. 239).

reading the measured data from a time-course field data file or “T-file” or a field average observational data file or “file A”.

The species file contains species-specific parameters describing the response of the crop to the environment as well as parameters describing growth and photosynthesis. These parameters are set during model development and are not generally altered by the user. Some parameters may be adjusted to reflect differences in behavior of different cultivars and ecotypes via additional parameters in the cultivar and ecotype files. Parameters in these files include factors such as differences in physiological time between growth stages, relative differences in photosynthetic rate, and leaf size, among others.

Other files, such as the X- and T-files, must be created by the user. A file X contains information describing the simulation, including what weather files to use, what soil type is present (along with site-specific soil profile information), location of the experiment site, management information (planting date, fertilization and irrigation schedules, harvest date, etc.), and simulation controls such as which photosynthesis option to use, whether to predict potential growth (assume no stresses), or water-limited growth, or water- and N-limited growth, and other options that determine modules of the model to be used.

If the simulation results are to be compared to an actual experiment, measured data for each treatment can be listed in a time-course field data file or “T-file” or the field average observational data file (file A). Data from this file can be read by a graphics program to plot the predicted variables against the measured data. The T-file also can be used to list amounts of pest damage and the dates on which the damage is to be imposed.

Based on the pest codes used in the T-file, the Pest file determines what type of damage to impose. The Pest file is generally written during model development, tailoring the codes to the specific crop being modeled. Because the “harvest” date listed in the X-file signals the termination of simulation in CROPGRO, periodic forage harvests must be simulated using the pest code, “MOW” that is entered in the T-file. The user specifies the amount of stubble mass to remain after a harvest or grazing event and CROPGRO reduces the amount of leaf and stem proportionally to leave that amount of stubble at a reduced V-stage. As with any pest damage, the leaf and stem removed by MOW are lost from the simulated system, with the assumption that they were exported from the field. While annual species may be simulated without enabling the Pest option, all forage simulations must use the Pest option to create multiple harvests.

Other site-specific information that must be provided by the user is daily weather information and soil profile information. Daily solar radiation, rainfall, and minimum and maximum temperature data are listed in the weather files which are named according to their location and the year for which they contain data. The soil file (SOIL.SOL) contains soil profile information on the specified soil types. The user must add information to create the soil for the simulation in a specified format. CROPGRO requires all of the above mentioned files except the T-file and A-file to initialize and run a simulation, unless the simulation involves multiple harvest, in which case the T-file is required as well.

Initialization of a simulation begins on the simulation start date, which may be well in advance of the planting date. Planting date can be the day that seed is sown or the day that transplants are placed in the field. The transplant option can be used to initialize the

simulation with an established stand of grass. Sowing date triggers the start of plant growth simulation. Separating the beginning of the simulation from the sowing date allows the model to predict soil conditions on sowing day, which may be helpful if the user has limited information about the actual conditions existing at the site on that day.

The rate step is run once on each day of the simulation and calculates the rate variables (variables representing the amount of change in a state variable occurring over a specified period of time – usually one day or less) for the current day of the simulation. For each simulated day, prior to running the CROPGRO plant template, the date, daily minimum and maximum temperatures, daily rainfall, and total daily solar radiation are read from the weather file, and the X- and T-files are checked for any management operations (e.g. planting, irrigation, harvest, or pest damage) for the day. The weather and management information is fed into the soil processes module, predicting the rates of change of available soil water,  $\text{NH}_4^+$ , and  $\text{NO}_3^-$ . The weather data along with plant and soil information from the end of the previous day is used to calculate daily evapotranspiration.

Predicting plant phenology or stage of maturity is a key component of CROPGRO. Several parameters such as partitioning of new growth between plant organs (leaf, stem, roots), and daylength sensitivity of development are dependent on or may vary with the stage of maturity. Stage of maturity is a function of accumulated physiological time which is a combination of time and temperature. Cardinal temperatures (minimum, optimal, and maximum) for various stages of development of each crop are described in the SPE file. Generally, there is no development at temperatures below the minimum or above the maximum cardinal temperatures whereas plants mature at a faster rate as air

temperature nears the optimal range. This rate of change/progression towards the next stage can be altered by daylength and water stress. Progress during vegetative growth is typified by progressive increase in the number of leaves per plant (V-stage) and, beginning with floral induction, by progression through a series of reproductive stages (R-stage).

The daily rate of pest damage is also calculated in the rate step. Information on the extent of damage is listed by the user in the “T-file” and CROPGRO uses the previous day’s plant mass and leaf area to calculate “actual” damage. Codes in the Pest file allow the user to specify the amount ( $\text{kg DM ha}^{-1}$ ) or proportion of leaf and stem to be removed or the reduction in assimilate production due to disease or pest damage. As with all other rate variables, the pest damage rates are not deducted from the existing plant mass until the integration step which signals the end of the current day. This ensures that all new rates are based on the same conditions – the plant mass at the end of the previous day.

The calculation of photosynthetic rate presents an interesting contrast with animal-based models. Many animal nutrition models are sink-driven, predicting nutrient intake as a function of body weight and animal performance while, in CROPGRO, the supply of assimilate, a function of absorbed solar radiation and photosynthesis, determines plant weight and performance (source-driven). One exception is that some plant species may exhibit a “juvenile” period where limited seedling demand can feed back on photosynthate production. CROPGRO offers two options for predicting photosynthesis: a daily canopy photosynthesis option and an hourly leaf-level photosynthesis option.

The daily canopy photosynthesis option is the simpler of the methods and uses an asymptotic exponential response to daily solar radiation to calculate the potential daily



photosynthetic rate. This pattern of daily photosynthetic response to light is defined by two parameters from the species file; the maximum canopy photosynthesis rate and the amount of PAR at which photosynthesis is 63% of maximum. Estimated light interception of the canopy is a function of the predicted LAI on the previous day and the canopy light extinction coefficient specified in the SPE file. The hourly leaf-level photosynthesis option is more mechanistic (based on processes and stoichiometry) but more mathematically complex.

The leaf-level option uses the hedgerow approach described in Boote and Pickering (1994) to estimate potential hourly photosynthetic rates for sunlit and also shaded leaf area portions of the canopy. The hedgerow approach uses parameters describing canopy shape, height and width, leaf angle, row width and direction, latitude of the site, day of year and time of day along with the predicted LAI to estimate light absorption by sunlit versus shaded leaves. Hourly distribution of solar radiation and temperature are estimated from the daily values provided in the weather file and further divided into direct and diffuse components. Potential hourly leaf photosynthetic rate is calculated using an asymptotic exponential equation where quantum efficiency (initial photosynthetic response at low light) sets the initial slope of the response and the maximum potential leaf photosynthetic rate is the asymptote. The photosynthetic rates for the sunlit and shaded leaves are multiplied by their respective LAIs and summed each hour to calculate the hourly canopy photosynthetic rate. The 24 hourly rates are integrated to yield the daily photosynthetic rate. In both the daily canopy and hourly leaf photosynthesis options, the potential photosynthetic rate may be adjusted for cultivar

differences, temperature, leaf N concentration, leaf thickness (specific leaf weight, SLW), atmospheric CO<sub>2</sub> concentration, and an incomplete canopy (light absorption).

In the integration step, updated maturity stages are calculated by computing the daily rate of change for each day and adding this to the previous day's stage rating. All other rates are processed similarly to calculate the new day's state variables. Much of the mechanics of the integration step is an exercise in carbohydrate (CH<sub>2</sub>O) accounting and allocation.

Potentially available CH<sub>2</sub>O from stored reserves is calculated and added to the daily photosynthate production to determine the maximum amount of CH<sub>2</sub>O available for the day. The day's maintenance respiration costs and any assimilate loss due to pest damage are subtracted from the total, the remainder being the amount of CH<sub>2</sub>O available for nutrient uptake and growth. Potential CH<sub>2</sub>O demand for seed and shell growth, CH<sub>2</sub>O cost per g of new vegetative growth (based on proportions of leaf and stem predicted by the new V-stage), as well as potential N demand to "refill" N that has been mobilized from old tissue are calculated and subtracted from the remaining available CH<sub>2</sub>O.

The amount of new growth that can be produced from the available CH<sub>2</sub>O depends on the cost of that new growth which is a function of its composition. Composition of total new growth is, in turn, determined by the partitioning of new growth between the different plant organs (leaf, stem, roots, seeds, etc.) and the protein, carbohydrate (comprised of cell wall and starch), lipid, lignin, organic acid, and ash concentration of each organ's new growth. Parameters describing partitioning to organs and organ composition are listed in the species file. Coefficients developed by Penning deVries et al. (1974) describing the cost to assemble each of these components (both direct cost of C

for C-skeletons as well as the energy used in the biochemical pathways to form them) expressed in glucose equivalents are used along with the composition parameters to calculate the glucose cost of new tissues. Crude protein or N concentrations of new leaf, stem, and root growth can vary within a range of values set by three parameters; a maximum concentration for new growth, a “normal” growth concentration and a residual concentration left after senescence. If there is adequate  $\text{CH}_2\text{O}$  available but available N is limiting, new growth can occur at reduced N concentrations.

Nitrogen demand can be met by two different sources; “Actual” N uptake by the plant, and if this uptake cannot meet the N demand for new growth, N mobilized from vegetative tissues. Once the balance of N uptake and mobilization are calculated, the  $\text{CH}_2\text{O}$  cost of N uptake and any N mobilization is subtracted from the remaining available  $\text{CH}_2\text{O}$  to update the energy budget. If the crop is a legume, N-fixation is estimated, the N added to the available N pool, and the  $\text{CH}_2\text{O}$  cost subtracted from the available  $\text{CH}_2\text{O}$ . The remaining  $\text{CH}_2\text{O}$  is allocated to new growth; first to seed and shell, then to vegetative growth.

The increased root length associated with the day’s predicted new root growth is calculated. The total root length and its distribution are used in determining nutrient and water uptake on the succeeding day. Losses are also calculated; the day’s predicted senescence of leaves, stems, and roots are estimated as well as any damage due to freezing temperatures.

Finally, all of the gains in new growth and losses due to senescence, pest damage, and frost are added to the previous day’s pools of tissue mass and a new total is calculated representing the plant mass present at the end of the current day. This ends the

“day” and after outputs are printed to their respective files, the integration step ends and the rate step is repeated the next day.

The rate and integration steps are repeated daily until the simulation is terminated on the harvest date specified in the X-file or when a killing freeze occurs. At this time the final step is executed to finish printing the output files. These are the basic mechanics and information flow within CROPGRO. The structure has been shown to work well with annual grain crops and legumes as well as tomato. In adapting the model to simulate the growth of perennial tropical grasses, accurate parameters must be developed for the species file. Any plant processes unique to these plants that are not already included in the model may require re-definition of some of the parameters or even changes and additions to the model code.

### **Model Evaluation**

The ultimate measure of a model’s performance is the user’s satisfaction with both the accuracy of predictions and overall utility of the model. Understandably, such a measure is difficult to quantify and is relevant only to the user that generated the rating. Statistical approaches to quantify the accuracy of model predictions provide standardized measures of model performance. Unfortunately, even these methods do not provide completely clear-cut conclusions about the accuracy of model predictions. Use of vague terms like “fairly close” in instructions for interpreting various measures impart an air of skepticism around the use of some of these methods. Given these caveats, the use of several different measures of performance to evaluate a model may present a more complete picture of model performance than any single measure and allow the user to weight individual results according to their priorities.

Two measures that are commonly reported in the literature are the sample correlation coefficient  $r$  and coefficient of determination  $r^2$ . The correlation coefficient provides a measure of the linear relationship or closeness between predicted and observed values. Interpretation of  $r$  is quite general. An  $r$  of 1.0 indicates perfect prediction by the model with positive values of  $r$  indicating some level of a positive correlation between the predicted values ( $P_i$ ) and observed values ( $O_i$ ). Conversely, an  $r$  of 0.0 indicates no correlation of the model to reality whatsoever and negative values indicate an inverse relationship. The coefficient of determination is informally described as the proportion of the variance of the observed values that can be accounted for by the model. This measure has more utility in that it presents an idea of how thoroughly the model represents the system. Statistical analyses demonstrating the level of significance of  $r$  only proves that a linear relationship with a non-zero slope exists between  $P_i$  and  $O_i$  (Snedecor and Cochran, 1989). The validity of this conclusion can come into question if  $P_i$  and  $O_i$  do not meet the underlying assumptions required for the particular analysis used (Willmott, 1981). In spite of their popularity, these measures provide little detail to characterize the relationship between  $P_i$  and  $O_i$ .

A simple method of visualizing the relationship between  $P_i$  and  $O_i$  is plotting a scatterplot of  $P_i$  (Y-axis) and  $O_i$  (X-axis), relative to a line designating a 1:1 relationship. While not quantifiable, some relationships (e.g. consistent underprediction) become apparent. Scatterplots also provide a common sense check for more sophisticated methods of evaluation. If results of a test do not appear consistent with the results of the scatterplot, the test should be re-evaluated. The relationship between  $P_i$  and  $O_i$  presented in the scatterplot can be quantified using linear regression. The slope of the regression

line ( $a$ ) and its Y-intercept ( $b$ ) may provide evidence of systematic error in the model, providing quantities that can be compared across models. A slope of 1.0 with a Y-intercept equal to 0.0 indicates perfect fit of the model predictions. These results along with the means ( $\bar{P}$  and  $\bar{O}$ ) and standard deviations of the predicted values and observed values should be considered for their own merit as well as their use in calculating other measures when evaluating model performance.

Difference measures, derived from the fundamental quantity  $(P_i - O_i)$  (Willmott, 1982), build on the statistical measures listed above to quantify bias and average error. Root mean squared error (RMSE) describes the average difference between  $P_i$  and  $O_i$ .

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \quad (\text{Eq. 2-1})$$

Also, RMSE can be readily compared against the mean of the observed values for comparison of relative error. Both RMSE and its square (mean square error or MSE) can be subdivided into systematic ( $\text{RMSE}_s$  and  $\text{MSE}_s$ ) and unsystematic ( $\text{RMSE}_u$  and  $\text{MSE}_u$ ) components (Willmott, 1981):

$$\text{MSE} = \frac{\sum_{i=1}^n (P_i - O_i)^2}{n} \quad \text{MSE}_s = \frac{\sum_{i=1}^n (\hat{P}_i - O_i)^2}{n} \quad \text{MSE}_u = \frac{\sum_{i=1}^n (P_i - \hat{P}_i)^2}{n} \quad (\text{Eq. 2-2})$$

where  $n$  = the number of pairs of predicted and observed data, and  $\hat{P}_i = aO_i + b$ . When the systematic component is minimized, the model is predicting at its maximum possible accuracy and the primary source of error is not model-related. An alternative presentation is offered by Roseler et al. (1997) where mean square prediction error (MSPE), which has the same mathematical definition as MSE (Neter et al., 1990; Roseler

et al., 1997), is considered as the sum of three components: mean bias  $(\bar{O}-\bar{P})^2$ , line bias  $[S_p^2(1-b)^2]$ , and random variation around the regression line  $[S_o^2(1-r^2)^2]$ , where  $S_p^2$  and  $S_o^2$  are the variances of the predicted and observed values. These measures provide insight not just on the magnitude of error but also hint at the potential sources of error.

Willmott (1981; 1982) proposed another measure of model performance that he called an “index of agreement”. This is referred to elsewhere as the d-index. The d-index describes the degree to which the observed data are accurately estimated by the predicted data. More formally, it specifies the degree to which the deviation of the observed data around  $\bar{O}$  corresponds with the deviation of the predicted data around  $\bar{O}$ , both in magnitude and sign.

$$d = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P'_i| + |O'_i|)^2} \quad (\text{Eq. 2-3})$$

where  $P'_i = P_i - \bar{O}$  and  $O'_i = O_i - \bar{O}$ . Potential values of d range from 0 to 1, with 1.0 indicating perfect agreement between predicted and observed data and 0.0 indicating complete disagreement. The sole assumption is that  $\bar{O}$  is free of error so that all error is contained in  $P'_i$  and  $O'_i$ . The equation can be rewritten as

$$d = 1 - \frac{n \cdot \text{MSE}}{\sum_{i=1}^n (|P'_i| + |O'_i|)^2} \quad (\text{Eq. 2-4})$$

for simplified calculation when MSE is known. The innovation of the d-index is that it responds to both differences between predicted and observed data as well as some

changes in proportionality (Willmott, 1981). The d-index is an improvement on the simple “r”; still, it is not an absolute measure of performance. As with the aforementioned methods, the d-index should be evaluated in the context of knowledge of natural variations in the system being modeled, the capabilities of the model, and an awareness of the amount of potential error in the observed values used in the comparison.

No one of these approaches will be best in all situations, reviewing several of these measures together will provide a more complete description of model performance. The results should also be viewed in the context of the intended use of the model. If the model is to be used to demonstrate the response to a change in the environment to a class of students, a model that predicts a response of the correct direction but severely under- or over-predicts the magnitude may be preferable to a more accurate model if the latter is more difficult for the students to use. Users must decide for themselves what level of performance is acceptable. Likewise, individuals will have their own views of which approach is most appropriate to their interests.



## CHAPTER 3 BAHIAGRASS GROWTH STUDY

### **Introduction**

There has been a resurgence of interest in the cause of winter dormancy in tropical perennial grasses, particularly bahiagrass (Mislevy, 1998; Gates et al., 2001; Sinclair et al., 2003). To date, the primary emphasis of the research has been to identify the conditions triggering dormancy. Traditionally, dormancy was thought to be related to the cooler temperatures of fall and winter; however, daylength has recently been implicated as the triggering condition (Gates et al., 2001; Sinclair et al., 2003). Along with identifying the cause, quantifying the effects of dormancy may help us identify specific characteristics associated with dormancy to both aid in identifying non-dormant individuals as well as help develop management strategies to promote higher yield and longevity of both current and new, non-dormant bahiagrass varieties that may be developed.

Sinclair et al. (2003) presented growth and composition data at the organ level (leaf, stem, and below-ground material) characterizing relative differences in growth and composition between plants grown under normal or extended photoperiods. Their data were quantified for each harvest, at 4 to 5 week intervals. Information quantifying changes within a regrowth period, however, is scarce. More detailed growth analyses conducted during the transition into dormancy may help identify some of the mechanisms involved in the reduction of herbage growth associated with dormancy. Our objective for this study was to document, in detail, weekly patterns of plant growth in late summer and

fall regrowth periods with concurrent measurements of leaf and canopy photosynthesis. The purpose of this information is to help “fill in” some of the detail missed in other studies, and needed for perennial forage crop model development.

### **Materials and Methods**

This research was conducted at the Plant and Soil Science Field Teaching Laboratory at the campus of the University of Florida, Gainesville (29° 38' N, 82° 22' W) on an established bahiagrass sod during the summer and fall of 2001. Based on the age of the stand, fine leaf texture and abundant seedhead production in June, the variety of bahiagrass was assumed to be Pensacola. The soil was an Arredondo fine sand (loamy, siliceous, hyperthermic Grossarenic Paleudult). The experimental design was a randomized complete block four replications each being 190-m<sup>2</sup> plots (PLOT). Treatments were two 8-wk regrowth periods (PER) (18 July – 12 September or 12 September – 7 November). The crop was harvested to a stubble height of 10 cm every 8 wk starting 21 May. The 18 July harvest served as the staging harvest, establishing the initial conditions and base stubble mass for the first growth period. A single sod core sample was taken weekly (WEEK) from each of the four plots beginning on 20 July (Table 3-1). Plant height (distance from the soil surface to the point where the leaves curved over and began to hang down) was measured at six locations within each plot on the same days that the sod cores were sampled.

While the bahiagrass had been established for several years, it had not been fertilized or irrigated regularly in recent years. During our study all plots were fertilized with a commercial blended 16-4-8 fertilizer including trace nutrients and slow-release N at 78 kg N ha<sup>-1</sup>, 10 kg P ha<sup>-1</sup>, and 37 kg K ha<sup>-1</sup> every 8 wk beginning on 13 April. Irrigation was provided as needed to prevent water limitation of plant growth via portable

impact sprinklers (see Table 3-2 for combined rainfall + irrigation). Weather data (total daily PAR, minimum, maximum, and average air temperature and total daily rainfall) were recorded on an automatic datalogger (CR10, Campbell Scientific, Inc. Logan, UT) and are summarized in Table 3-2.

The sod cores measured 20 cm by 35 cm by 15 cm deep and were dug by hand using a pair of narrow-bladed shovels (Figure 3-1). Loose soil was shaken by hand from the sod core and any loose bits of roots and other plant material were recovered. All material was placed in a plastic bag and immediately placed in a cooler for transport to the laboratory. At the laboratory, each sample was thoroughly washed with a garden hose over a 2-mm sieve to dislodge soil. Rinsed samples were placed in sealed plastic bags and refrigerated until processed.

Roots were trimmed from the stolons using hand clippers, placed in a paper bag and transferred to a 55°C forced-air oven. A subsample of the remaining plant material was set aside for detailed analyses. Both the remaining sample and subsample were separated into live leaf, stem, stolon, and dead leaf components. Live leaves were separated from stems at the ligule (if there was one) or where the leaf emerged from the stem (if the leaf had no ligule). Using this separation methodology, the leaf sheath is included in the stem fraction (Figure 3-2). Stems were separated from stolons at a point where they naturally broke by hand. Dead leaves were peeled from the tillers and, thus, included dead sheath material.

Material in the subsample was analyzed for leaf and stem areas (one sided only) using a LI-COR model 3100 leaf area meter (LI-COR Inc., Lincoln, NE). Stems were scanned intact (Figure 3-2), and not dissected into individual immature leaves. The

number of stems (tillers) per stolon was counted and the number of leaves per tiller was recorded as the vegetative stage (V-stage) of each tiller. The presence of seedheads in the subsamples were noted but as there were very few, no additional measures of reproductive stage were recorded.

Upon completion of separation and measurements, the plant components were dried until reaching a constant weight in a 55°C forced-air oven. Care was taken to remove loose sand before weighing. Leaf, stem, stolon, and root dry matter (DM) mass (kg DM ha<sup>-1</sup>) was calculated from the combined sample and subsample masses of leaf, stem, stolon, and root, respectively, and the land area of each core. Specific leaf area (SLA) (m<sup>2</sup> leaf kg<sup>-1</sup> leaf) was calculated from the measured leaf area and leaf mass for each subsample. Leaf area index (LAI) (m<sup>2</sup> leaf m<sup>-2</sup> land) was then calculated by multiplying the SLA by the total leaf mass m<sup>-2</sup> from each core. A “green area index” (GrAI) representing the total photosynthetic area per area of soil surface was calculated using the sum of the leaf and stem area indices. The V-stage was calculated for each plot by averaging the V-stage of all of the tillers in the subsample for each plot. The net accumulation of each component as well as net change in V-stage ( $\Delta$  Leaf, Stem, Stolon, and Root mass,  $\Delta$  V-stage) was calculated for each period by subtracting the WEEK 0 (stubble) mass from the WEEK 8 (final) mass.

Statistical analyses of the growth data were performed using the Mixed procedure of SAS (SAS Institute Inc., 1987) with the model:

$$Y_{ijk} = \mu + A_i + B_j + A_iB_j + C_k + A_iC_k + B_jC_k + e_{ijk}$$

where  $\mu$  was the population mean, A was PLOT, B was PER, C was WEEK, and  $e$  was the residual error for  $i=4$ ,  $j=2$ ,  $k=8$ . The net accumulation data were analyzed using a

simplified form of the same model;  $Y_{ij} = \mu + A_i + B_j + e_{ij}$ . PLOT, and all of its interactions were assumed to be random effects and therefore appeared in the SAS random statement in the order presented above. Growth period (PER), WEEK, and their interaction (PER  $\times$  WEEK) were fixed effects. Means separation for PER was directly from the ANOVA. Orthogonal contrasts were used to qualify significant responses to WEEK and PER  $\times$  WEEK. The  $\alpha=0.10$  level was selected as the threshold for determining the significance of all effects and contrasts.

Concurrent with the growth measurements, leaf and canopy photosynthesis measurements were recorded four times during each growth period. Due to weather constraints, these measurements were not evenly allocated throughout each growth period, nor did they occur at the same time during each period. Leaf and canopy photosynthesis measurements were made at midday using a LI-COR LI-6200 portable photosynthesis system (LI-COR Inc., Lincoln, NE). Leaf photosynthetic (or carbon exchange rate - CER) measurements were made on fully expanded, healthy leaves under full sun conditions (PAR  $>1600 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) using a 0.25-L chamber. Photosynthesis was measured for three leaves per plot on each sampling date. Two 15-sec measurements of carbon exchange rate (CER) ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ leaf s}^{-1}$ ), stomatal conductance ( $\text{mol m}^{-2} \text{ leaf s}^{-1}$ ), and internal  $\text{CO}_2$  concentration ( $\mu\text{L L}^{-1}$ ) were recorded for each leaf. For canopy photosynthesis measurements, the leaf chamber was placed “open” inside an aluminum-frame, clear plastic enclosure. The frame enclosed a land area of  $0.56 \text{ m}^2$ , with a total volume of  $0.49 \text{ m}^3$ . Canopy CER ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ land s}^{-1}$ ) measurements were made under four levels of light varying from full sun to dark. The light level in the chamber was regulated by placing cloths of varying opaqueness over the chamber. Approximate

light levels were: PAR > 1500  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (full sun), 600-800  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , 200-400  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , and 0  $\mu\text{mol m}^{-2} \text{s}^{-1}$  (dark). Three 16-second measurements of carbon exchange rate (CER) ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ land s}^{-1}$ ) were recorded at each light level. The canopy enclosure was opened between each light level measurement to let the humidity and  $[\text{CO}_2]$  in the enclosure equilibrate with the atmosphere. Net CER in full darkness was considered to represent canopy + root + soil (dark) respiration. Gross canopy photosynthesis ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ land s}^{-1}$ ) for each light level was calculated by adding the absolute value of the dark respiration to the measured net photosynthesis for each light level.

We fit the canopy light response data to the asymptotic exponential model (Boote et al., 1985):

$$P = P_{\max} * [1 - e^{(-QE*PAR/P_{\max})}], \quad (\text{Eq. 3-1})$$

using TableCurve 2D v4 software (Jandel Scientific Software, 1996), where  $P$  = canopy gross photosynthetic rate ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{s}^{-1}$ ),  $P_{\max}$  = maximum photosynthetic rate in saturating light ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{s}^{-1}$ ),  $QE$  = quantum efficiency or initial slope of the  $\text{CO}_2$  assimilation : incident PAR response ( $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  absorbed photons), and  $PAR$  = photosynthetically active radiation ( $\mu\text{mol photons m}^{-2} \text{s}^{-1}$ ). We solved for  $P_{\max}$  and  $QE$  and used the resulting values to estimate gross canopy photosynthetic rate at a light intensity of 1500  $\mu\text{mol photons PAR m}^{-2} \text{s}^{-1}$ . By expressing photosynthetic rate for a common light intensity we could compare the different treatments and days without the variation due to changing light levels as the days and seasons progressed.

We also attempted to predict a light-saturated leaf photosynthetic rate ( $Asat$ ) from the canopy gross photosynthesis data. The measured leaf and stem areas as well as

canopy gross photosynthesis and corresponding PAR measurements from the canopy light response measurements were input into the hedgerow photosynthesis model of Boote and Pickering (1994), programmed in SAS, then PROC NLIN in SAS (SAS Institute Inc., 1987) was used to solve for *Asat* using an asymptotic exponential function and outputs from the hedgerow model.

Statistical analyses of the leaf photosynthesis data were performed using the Mixed procedure of SAS (SAS Institute Inc., 1987) with the model:

$$Y_{ijk} = \mu + A_i + B_j + A_iB_j + C + A_iC + B_jC + A_iB_jC + D_k + A_iD_k + B_jD_k + A_iB_jD_k + CD_k + A_iCD_k + B_jCD_k + e_{ijk}$$

where  $\mu$  was the population mean, A was PLOT, B was PER, C was day of period or regrowth (DAY), D was leaf number (LEAF) - three leaves were measured in each plot, and  $e$  was the residual error for  $i=4$ ,  $j=2$ , and  $k=3$ . PLOT and all PLOT interactions were assumed to be random effects and therefore appeared in the SAS random statement, in the order presented above. Growth period (PER), LEAF, DAY, and their interactions were considered to be fixed effects. Since measurements were not taken every week or even on the same day of the week, DAY was treated as a continuous variable and entered as a covariate. Because there was only a single value for *Asat*, canopy P1500, and canopy respiration for each plot on each sampling day, LEAF was not included in the analysis of these variables and a reduced version of the model was used for these variables:

$$Y_{ijk} = \mu + A_i + B_j + A_iB_j + C + A_iC + B_jC + e_{ij}$$

Least squares means were calculated for PER. Means separation for PER was directly

from the ANOVA. The  $\alpha=0.10$  level was selected as the threshold for determining the significance of all effects and contrasts.

## **Results and Discussion**

### **Plant Growth**

Statistically, total plant growth ( $\Delta$  Total Plant Mass) was greater for PER 2 than PER 1 (Table 3-3). The dramatic loss of total plant mass in PER 1 masked a net increase in leaf mass, overshadowing the fact that canopy growth was greater in PER 1 than PER 2. The loss of total plant mass was driven almost entirely by a decrease in root mass in PER 1. In PER 2 root mass stabilized (Table 3-3) and a net gain of total plant mass was realized (Figure 3-3).

Initial root mass for PER 1 was high at 11 500 kg DM ha<sup>-1</sup> but dropped to less than 1/3 of the original mass by WEEK 7 of PER 1 (Figure 3-4). The consistent decline during PER 1 and the relatively constant root mass from the end of PER 1 through PER 2 tends to dismiss random sampling error as the cause of this loss. Alternatively, the Spartan maintenance of the site in past years may have played a role in this behavior. There had been no fertilizer or irrigation applications over several years and the extensive root system may have developed to more thoroughly mine the soil for water and nutrients. At the time we started measuring plant growth, irrigation had been available for three months and a second fertilizer application had just been applied. As PER 1 progressed, nutrients may have become available in sufficient concentrations that plant needs could be met with a less extensive root system. Excess root mass may have been mobilized for new shoot growth or merely allowed to die, resulting in the pattern of loss observed. In contrast to this loss in PER 1, root mass remained relatively constant in PER 2. There was a slight increase in root mass in WEEK 6 (Figure 3-4) which



coincided with a period of increasing stolon mass and, thus, could be related to a dormancy–induced change in priority of assimilate partitioning.

A more obvious signal of approaching dormancy may be seen in the pattern of stolon growth. Throughout PER 1 stolon mass remained unchanged at approximately 4700 kg DM ha<sup>-1</sup> (Figure 3-5). Stolon mass increased in PER2, peaking at 8980 kg DM ha<sup>-1</sup> on WEEK 7 (Figure 3-5). This change in growth pattern, as evidenced by the significant WEEK and PER × WEEK interaction effects, resulted in greater  $\Delta$  stolon mass in PER 2 (Table 3-3). This late-season shift in partitioning of growth towards storage tissue may be part of a dormancy response to shorter daylengths. Increased allocation of growth to stolons may have contributed to the lower increment of leaf and stem mass observed in PER 2 (Table 3-3). The combination of increasing stolon mass and stable-to-increasing root mass in PER 2 is in contrast to the observations of Sinclair et al. (2003) who reported steady or decreasing below-ground plant mass for Pensacola bahiagrass between 22 Sep. 1999 and 1 Dec. 1999 sampling dates at Ona, FL. Our longer, 8-wk, harvest interval may have allowed greater accumulation of stolon mass between harvests than the 4 to 5-week interval of Sinclair et al. (2003). The management history of the two sites could also have had an influence, as judged by the exceptional pattern of root growth observed at our site.

Changes not only in leaf and stem mass (Table 3-3), but also changes in the “character” of the canopy were observed. Shoot growth during the fall season (PER 2) was slower than in summer (PER 1) resulting in less stem and leaf dry weight accumulation (Table 3-3, Figures 3-6 & 3-7) as well as fewer new mature leaves (Figure 3-8) at the end of PER 2. Stem weights were lower for all weeks in PER 2 compared to

PER 1 but the decrease in stem mass was not different between periods (Table 3-3). The linear decline in stem mass in both periods and even the “bump” in stem mass in PER 1 (Figure 3-6) was, at least in part, an artifact of the partitioning scheme employed. Our partitioning strategy grouped developing leaves, still encased in the sheath, with stems. Once the leaves began elongating and emerged from the sheath, the leaves became part of the leaf mass and the fraction of their mass that had previously been developing in the sheath was lost from the stem mass. Very little stem elongation was observed except for the few tillers that developed seedheads, leaving little opportunity to increase stem mass as the plant matured.

Development of leaves in the fall regrowth period (PER 2) was quite different from that in PER 1. Leaf mass increased in a quadratic manner (Table 3-3) to peak on WEEK 6 of both periods (Figure 3-7), with average leaf mass and  $\Delta$  leaf mass slightly lower in PER 2. In contrast, the  $\Delta$  V-stage in PER 2 was only 3.41 leaves, less than half of the 7.65 leaves added in PER 1 (Table 3-3, Figure 3-8). Average LAI followed leaf mass more closely than V-stage, and a quadratic progression in LAI development was observed in both periods. The LAI in PER 1 was higher than that in PER 2 (Table 3-3). Despite the slower development, the initial and final LAI were the same for both periods (Figure 3-9). Thus, the same final LAI was achieved in PER 2 with only half as many mature leaves as were observed in PER 1. It should be noted that only leaves with ligules were included in the V-stage count but all leaf blade material extending from the leaf sheath was included in the LAI measurements.

Accordingly, the SLA (leaf area per g of leaf mass) was slightly larger, indicating thinner leaves, in PER 2, although a quadratic decrease in SLA was observed in both

regrowth periods (Table 3-3, Figure 3-10). Ghannoum et al. (2001a) also observed seasonal effects on SLA in a variety of perennial C<sub>4</sub> grasses grown in summer and winter; however, the response was species-dependent, positive in some cases and negative in others. Although peak daily solar radiation was not recorded, total daily solar radiation was lower in PER 2 (Table 3-2). Our SLA values are in accord with the range of values reported by Boote et al. (1999) (88 to 108 cm<sup>2</sup> g<sup>-1</sup>) for greenhouse-grown bahiagrass at this location. One might expect these levels to be lower (thicker leaves) as high SLAs are generally associated with shaded leaves and leaves grown under reduced light levels such as in greenhouses while our plants were grown outdoors in full sun. Our values are quite low compared to SLAs reported for other perennial C<sub>4</sub> grasses (Ghannoum et al., 2001a, 2001b) and even C<sub>3</sub> grasses (Ryser and Wahl, 2001).

The mean SLA reported for 11 NADP-ME-type C<sub>4</sub> grasses grown inside a glasshouse in summer, with midday PAR levels averaging 860  $\mu\text{mol m}^{-2} \text{s}^{-1}$ , was 314 cm<sup>2</sup> g<sup>-1</sup>, almost five times the level observed in our study (Ghannoum et al., 2001a). However, their plants were harvested only 46 d (approx 6.5 wk) after planting, much younger than the average age of the leaves on our plants. In contrast, the harvest interval employed by Boote et al. (1999) was longer than the current 8 wk. The fine-leaf structure of Pensacola bahiagrass may predispose this cultivar to have a lower than average SLA; however, the low SLA values merit further measurements on this species and its cultivars grown in other locations.

Similarly, the LAI values that we are reporting are lower than those observed by others. At the extreme are LAI values above 8.0 reported for bahiagrass by Agata (1985a; 1985b), which are considerably higher than our values of 1.75 and 1.67 for

8-week regrowth in PER 1 and PER 2, respectively (Figure 3-9), or even our GrAI values which include stem area as well as leaf area (Figure 3-11). Unfortunately, the methodology used by Agata (1985a, 1985b) to determine LAI was not clear, hindering any further comparisons. Other reports give considerably lower LAI values. Pedreira and Brown (1996b) reported LAI for stubble and 13-d regrowth for three populations of bahiagrass grown in the field near Athens, GA. Reported values were averages for two cutting heights (3.5 and 10 cm). This stubble LAI (comparable to our WEEK 0 values) ranged from 0.42 for selection T14 in August to 1.68 for Pensacola bahiagrass in July while regrowth LAI values ranged from 1.67 for selection T14 in August to 2.30 for Tifton 9 in July. These values compare very favorably to our values of 0.19 for WEEK 0 (stubble) and 1.16 for WEEK 2 in PER 1 (Figure 3-9). Methodology for the Athens study was similar to ours in that leaf area measurements were based on leaf lamina only; however, their sample size was much smaller (20 leaves vs. 100-500 leaves per replication in our study).

As the stem tissue is also green, leaf + stem or “green” area index (GrAI) may present a more accurate measure of photosynthetically active plant area than LAI alone. As with LAI, GrAI was higher for PER 1 than PER 2 at 2.49 and 1.85, respectively (Table 3-3). Orthogonal contrasts showed the relationship between GrAI and WEEK to be cubic (Table 3-3), this is likely an artifact of the variation in stem mass resulting from our partitioning scheme and may not be a biologically relevant pattern. The time-series change in GrAI (Figure 3-11) clearly illustrates, more so than LAI, a considerably slower increase and overall lower photosynthetic area throughout most of PER 2. Like LAI,

though, initial GrAI was the same for both periods and final GrAI were also much closer than for the middle of the regrowth periods.

The slower leaf growth rate cannot be attributed to differences in initial leaf mass and initial leaf area as neither differed between periods, although the slower growth rate would reinforce itself through lower leaf mass and LAI once regrowth began. The slower development of LAI and GrAI may have decreased potential photosynthesis during much of PER 2; however, final LAI values were similar or identical for both periods (Figure 3-9). Cooler temperatures and lower solar radiation levels (Table 3-2) likely were major factors reducing fall growth rates. The increased partitioning of growth to stolon tissue could also have reduced leaf growth in the second half of PER 2.

### **Photosynthesis**

Some caveats apply to the photosynthesis results. First, due to a combination of equipment repair and availability issues, photosynthesis measurements for PER 1 were made with a different LI-COR LI-6200 than was used in PER 2. However, both instruments were calibrated using the same reference gas and procedures. Second, the complete set of leaf photosynthetic measurements (two 15-s values for 3 leaves per plot) included a few values that were not physiologically realistic. The leaf data were analyzed to identify and remove outlying data points. Of the 197 photosynthesis measurements, one was more than 1.5 interquartile ranges from the 75<sup>th</sup> percentile and one was more than 1.5 interquartile ranges below the 25<sup>th</sup> percentile; both data points were removed from the analysis. These were the only data points removed from the analysis. The values removed were quite extreme (gross photosynthesis levels of 70.35 and -20.47  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) and may have been the result of air leaking into the leaf chamber during measurement, beginning measurements before  $\text{CO}_2$  concentration in the chamber

had begun to drop, or simply due to high sensitivity to the very small leaf area in the leaf chamber (approximately 1 cm<sup>2</sup>) and a correspondingly small drop in [CO<sub>2</sub>] over the measurement period causing excessive variation on measurements. Under the reduced dataset (n=195), the covariate, DAY, was significant (Table 3-3) with leaf photosynthetic rate being highest during early regrowth (Figure 3-12). Despite lower temperatures in PER 2 and a positive leaf temperature to leaf photosynthesis correlation coefficient of  $r=0.45$ , PER did not have a significant effect on leaf photosynthesis. Our measured leaf photosynthesis values of 31.0 and 26.6  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  for PER 1 and PER 2, respectively, fall well within the range reported by Boote et al. (1999) (24.8 – 35.2  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) and Fritschi et al. (1999) (19.0 – 35.4  $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ) for greenhouse-grown bahiagrass at 350  $\mu\text{L L}^{-1}$  CO<sub>2</sub> concentration at this site.

As expected, predicted leaf *Asat* was considerably higher than the measured leaf photosynthesis values (Table 3-3). Like measured leaf photosynthesis, the predicted *Asat* values were not different between periods, however, unlike the measured data, DAY did not affect *Asat*. This would indicate that the maximum potential leaf photosynthetic rate remained the same over the temperature range experienced in this study. There is precedent for this. *Asat* has been shown frequently to decrease rapidly below 20°C (reviewed by Long [1983]); however, the lowest temperature recorded in the canopy chamber during photosynthesis measurements was 27°C, considerably higher, where the impact may be slight and difficult to discern. This might also help explain why temperature accounted for such a small proportion of the variation in leaf photosynthetic rate. Although there is no way to verify the accuracy of our predicted *Asat* using the data

we collected, the values seem within reason as a handful of measured values were at or above the predicted rates.

To allow us to compare photosynthetic performance across sampling dates and periods despite the varying light conditions, the canopy photosynthesis data were fit to an asymptotic exponential function and the results used to predict canopy photosynthesis at 1500  $\mu\text{mol PAR m}^{-2} \text{s}^{-1}$  (P1500). Model fit was good with an  $r^2 > 0.99$  for most plots and sample days and the lowest  $r^2$  for a plot/day was 0.89. Analysis of the adjusted canopy data showed a higher canopy gross photosynthetic rate in PER 1 than PER 2 (Table 3-3, Figure 3-13). This is consistent with the greater plant mass (particularly leaf and stem) observed in PER 1. Interestingly, when we fitted a regression model using daily maximum temperature ( $T_{\text{max}}$ ), leaf + stem mass (Greenkg), GrAI, and SLA to the P1500 data,  $T_{\text{max}}$  had the best fit ( $r^2 = 0.48$ ) and the addition of either Greenkg or GrAI did not significantly improve the fit of the model. The PER 2 average of 43.0  $\mu\text{mol CO}_2 \text{m}^{-2} \text{land s}^{-1}$  was within the range of 31.6 to 47.1  $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$  reported by Boote et al. (1999) for P1500 in greenhouse-grown bahiagrass canopy gross photosynthesis at 350  $\mu\text{L CO}_2 \text{L}^{-1} \text{CO}_2$ , whereas our PER 1 rate of 55.9  $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$  was outside this range but below the highest rate of 60.7  $\mu\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$  reported by Fritschi et al. (1999) for P1500 of greenhouse-grown bahiagrass in the establishment year. As our plants were grown under full sun, a higher photosynthetic rate than for greenhouse-grown plants would be expected. That Fritschi observed higher rates may be related to the differences in the age of the stands, if the rates are different at all.

Concurrent with the higher photosynthetic rate in PER 1 were higher canopy + root + soil respiration levels. This measurement was based on the  $\text{CO}_2$  exchange rate

measured in total darkness. Respiration rate is dependent on both the amount of tissue respiring as well as the temperature. In regression analysis using the “Backwards” option in PROC REG of SAS (SAS Institute Inc., 1987), both Tair (air temperature) and Greenkg contributed significantly to the model and, combined, they could account for 87% of the variation observed in respiration. Canopy + root + soil respiration rates were  $24.0 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ land s}^{-1}$  in PER 1 and  $13.9 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$  in PER 2 (Table 3-3), slightly higher than the levels reported by Boote et al. (1999) but within the range of values reported by Fritschi et al. (1999) for bahiagrass grown at  $350 \mu\text{L L}^{-1} \text{ CO}_2$ . Respiration rates also varied by day of regrowth (Table 3-3) but since DAY was a covariate, orthogonal contrasts could not be used to discern a pattern of response.

### **Conclusions**

Winter dormancy, the seasonal depression of canopy growth, in bahiagrass often has been attributed to a decrease in temperature. More recently, daylength has been identified as having a role in triggering dormancy (Mislevy, 1998; Gates et al., 2001; Sinclair et al., 2003). The objective of our study was not to identify the cause of dormancy but rather to quantify growth and photosynthesis during the late summer and fall in more detail than previous studies. Our study points out several changes in the pattern of plant growth and photosynthetic rate that may illuminate parts of the underlying mechanism of dormancy. Two key observations were the sudden increase in stolon growth half-way through PER 2 and that the leaf photosynthetic rate was not different between PER 1 and PER 2. The effect of air temperature could explain most of the variation observed in canopy – root – soil respiration, but could explain only 25% of daily variation in leaf photosynthesis or 50% of the variation in canopy photosynthesis (data not shown). The rate of V-stage progression was dramatically lower in the fall



(PER 2), much more so than the reduction in leaf mass. Despite having fewer mature leaves per tiller, initial and final LAI were nearly the same for both 8-wk regrowth periods. Consistent with the lower leaf mass and similar LAI, SLA was higher in PER 2. In the case of shaded leaves, the resulting higher SLA is associated with lower concentrations of photosynthetic apparatus and lower potential photosynthetic rates, however, our predicted *Asat* was not different between periods.

Likely, growth reduction during winter dormancy is the culmination of a number of factors; reduction in growth rate due to lower temperatures, change in partitioning of assimilate favoring storage tissue over leaf growth, and changes in leaf characteristics related to lower light levels. Use of the results of this study to develop parameters for modeling bahiagrass growth testing would allow exploration of “what-if” scenarios and possibly help us better understand how these factors interact to reduce forage production during winter dormancy.

Table 3-1. Schedule of sampling and harvest activities.

Week	Per 1 Date	Per 2 Date	Activity
0	7/18/01	9/12/01	Mow to 10-cm stubble height
0	7/19/01	9/13/03	Fertilize plots
0	7/20/01	9/14/01	Sample stubble
1	7/25/01	9/19/01	Sample growth
2	8/1/01	9/26/01	Sample growth
3	8/8/01	10/3/01	Sample growth
4	8/15/01	10/10/01	Sample growth
5	8/22/01	10/17/01	Sample growth
6	8/29/01	10/24/01	Sample growth
7	9/5/01	10/31/01	Sample growth
8	9/12/01	11/7/01	Sample growth - Final

Table 3-2. Weekly averages of daily temperatures and daily solar radiation and total weekly rainfall + irrigation water applied to bahiagrass grown at the Irrigation Park, Gainesville, FL - 2001

Week	Daily Temperature			Rainfall + Irrigation Total (mm)	Solar Radiation Daily Average (MJ m <sup>-2</sup> day <sup>-1</sup> )
	Average °C	Maximum °C	Minimum °C		
Period 1					
1	25.9	31.8	22.7	94.8	17.9
2	26.0	32.8	22.2	72.4	16.6
3	25.6	31.3	22.2	38.9	16.4
4	27.6	33.8	23.2	4.3	20.0
5	28.1	34.2	23.4	56.7	21.0
6	27.4	34.1	22.1	30.5	19.1
7	25.9	33.1	22.4	50.3	15.5
8	25.4	31.3	22.7	16.8	13.9
Period 2					
1	22.9	27.9	19.1	77.9	13.3
2	24.0	30.1	20.0	63.3	14.7
3	19.8	25.9	14.5	15.0	17.0
4	22.6	28.5	18.5	1.5	12.9
5	21.1	27.8	16.4	27.5	14.0
6	23.6	29.3	20.2	32.0	11.8
7	16.8	24.7	11.3	26.5	14.4
8	19.1	26.1	13.8	0.0	12.1

Table 3-3. Results of statistical comparison of treatment effects on plant growth and photosynthesis. Period means are least squares means. Significance determined by ANOVA for Period and orthogonal contrast for Week and Per X Week interaction.

Growth Variable	Period Mean		Period	Statistics	
	1	2		Week	Per X Week
Leaf Mass (kg DM ha <sup>-1</sup> )	2150	1700	**	*** / qdr	ns
Δ Leaf Mass (kg DM ha <sup>-1</sup> ) <sup>a</sup>	3015	2511	*	---	---
Stem Mass (kg DM ha <sup>-1</sup> )	3690	1960	***	*** / lin	ns
Δ Stem Mass (kg DM ha <sup>-1</sup> ) <sup>a</sup>	-456	-1396	ns	---	---
Stolon Mass (kg DM ha <sup>-1</sup> )	4740	6870	***	* / lin	* / lin
Δ Stolon Mass (kg DM ha <sup>-1</sup> ) <sup>a</sup>	612	2350	**	---	---
Root Mass (kg DM ha <sup>-1</sup> )	6270	3800	*	*** / lin	*** / lin
Δ Root Mass (kg DM ha <sup>-1</sup> ) <sup>a</sup>	-8009	-344	***	---	---
Total Plant Mass (kg DM ha <sup>-1</sup> )	16845	14325	*	ns	*** / lin
Δ Total Plant Mass (kg DM ha <sup>-1</sup> ) <sup>a</sup>	-4839	3121	**	---	---
Canopy Height (cm)	29.8	22.5	***	*** / cub	*** / lin
V-stage (number of fully emerged leaves tiller <sup>-1</sup> )	3.52	1.70	***	*** / qdr	*** / qdr
Δ V-stage (number of fully emerged leaves tiller <sup>-1</sup> ) <sup>a</sup>	7.65	3.41	***	---	---
SLA (cm <sup>2</sup> leaf g <sup>-1</sup> leaf)	64.8	73.3	*	*** / qdr	ns
LAI (m <sup>2</sup> leaf m <sup>-2</sup> land)	1.28	1.10	*	*** / qdr	ns
Δ LAI (m <sup>2</sup> leaf m <sup>-2</sup> land)	1.56	1.52	Ns	---	---
GrAI (m <sup>2</sup> leaf + stem m <sup>-2</sup> land)	2.49	1.85	***	*** / cub	ns
Δ GrAI (m <sup>2</sup> leaf + stem m <sup>-2</sup> land)	1.84	1.12	*	---	---
Photosynthesis Variable			Period	Day	Per X Day
Measured Leaf Photosynthesis (μmol CO <sub>2</sub> m <sup>-2</sup> leaf s <sup>-1</sup> )	31.0	26.6	ns	***	ns
Predicted Max Leaf Photosynthesis (μmol CO <sub>2</sub> m <sup>-2</sup> leaf s <sup>-1</sup> )	44.2	39.9	ns	ns	ns
Predicted Canopy Gross Photosynthesis at 1500 μmol photons (μmol CO <sub>2</sub> m <sup>-2</sup> land s <sup>-1</sup> )	55.9	43.0	**	*	ns
Canopy – Root – Soil Respiration (μmol CO <sub>2</sub> m <sup>-2</sup> land s <sup>-1</sup> )	24.0	13.9	**	*	ns

\*P<0.10, \*\*P<0.05, \*\*\*P<0.01, ns=not significant, --- does not apply to this variable.

lin, qdr, cub = linear, quadratic or cubic orthogonal contrasts, respectively, are significant

<sup>a</sup> Δ values are net change over period = Week 8 values – Week 0 values.



Figure 3-1. Sod core as removed from the soil.

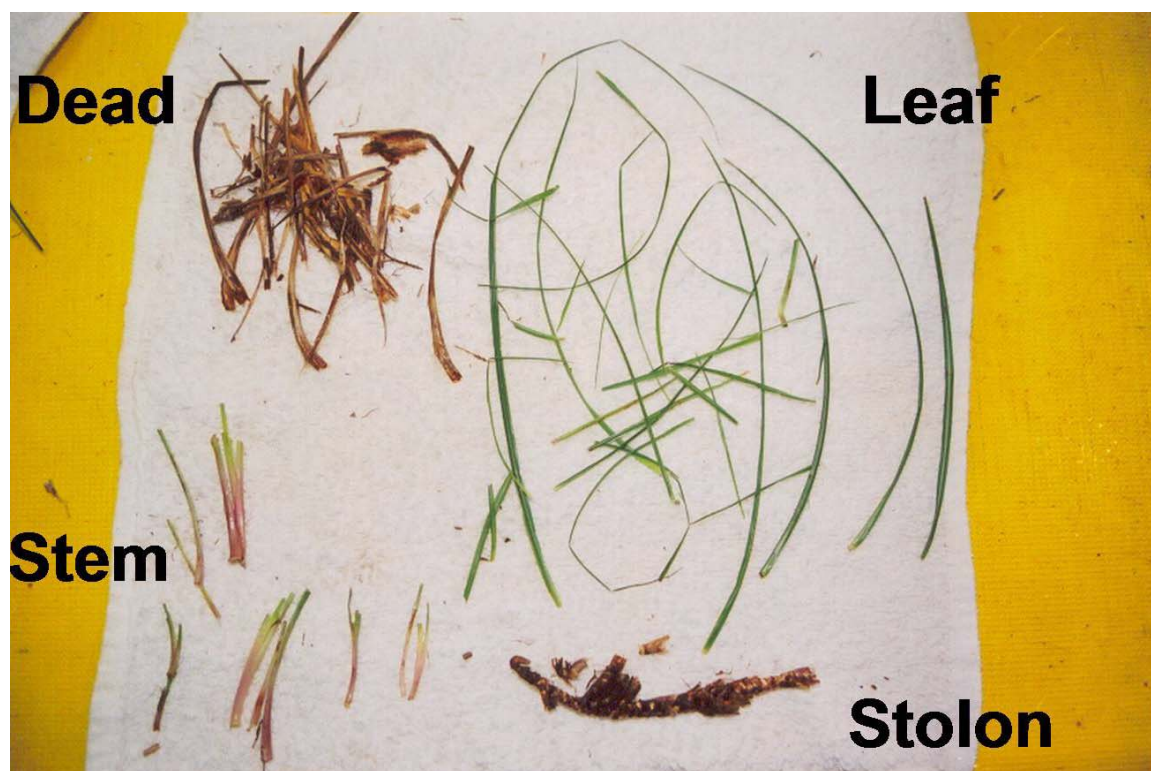


Figure 3-2. Example of a separated subsample of bahiagrass after removing roots.

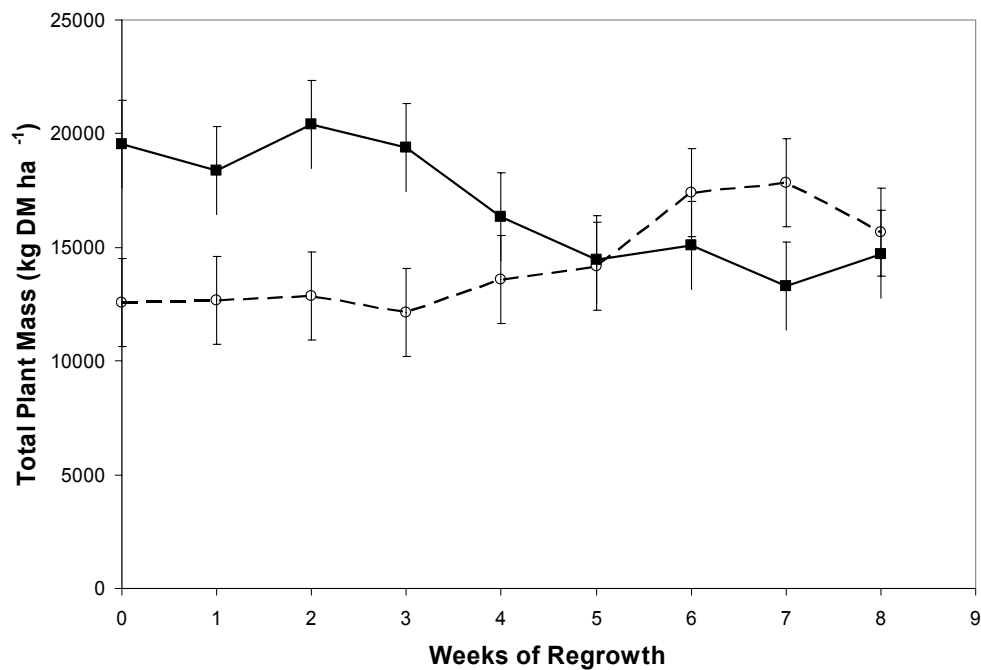


Figure 3-3. Total plant mass for established bahiagrass grown at Gainesville, FL from 18 July to 12 Sept. (—) and 12 Sept. to 7 Nov. (---), 2001.

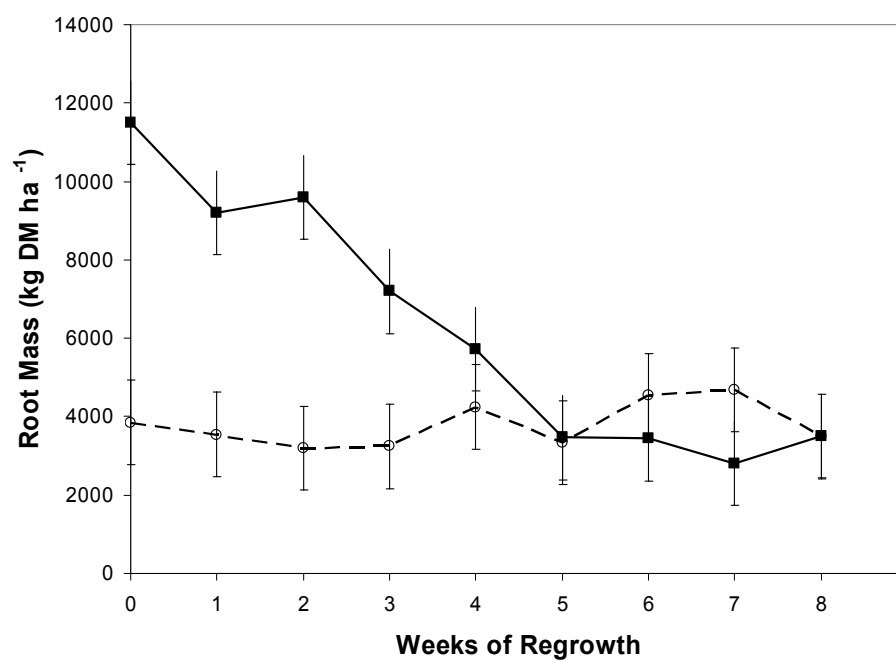


Figure 3-4. Root mass for established bahiagrass grown at Gainesville, FL from 18 July to 12 Sept. (—) and 12 Sept. to 7 Nov. (---), 2001.

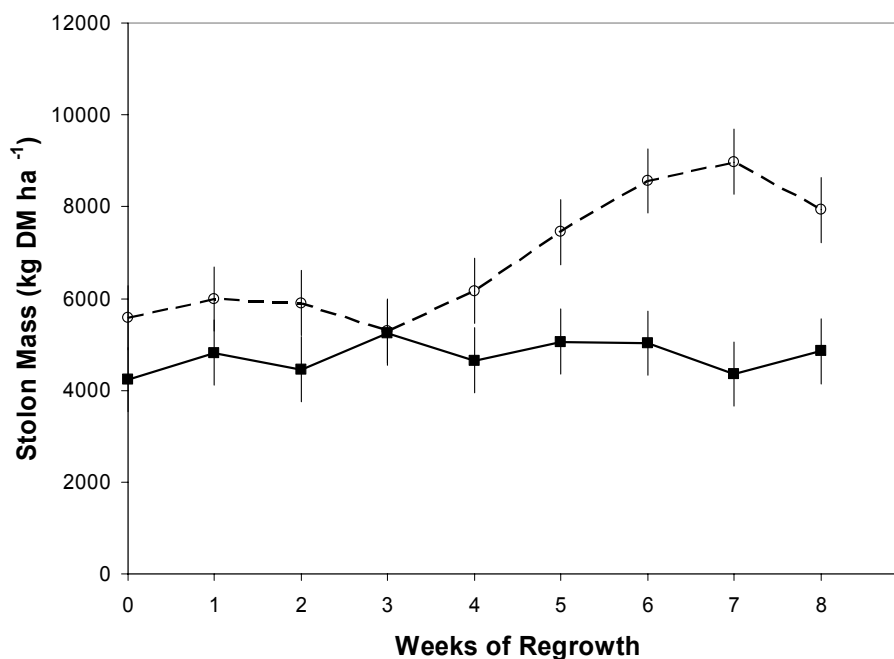


Figure 3-5. Stolon mass for established bahiagrass grown at Gainesville, FL from 18 July to 12 Sept. (—) and 12 Sept. to 7 Nov. (---), 2001.

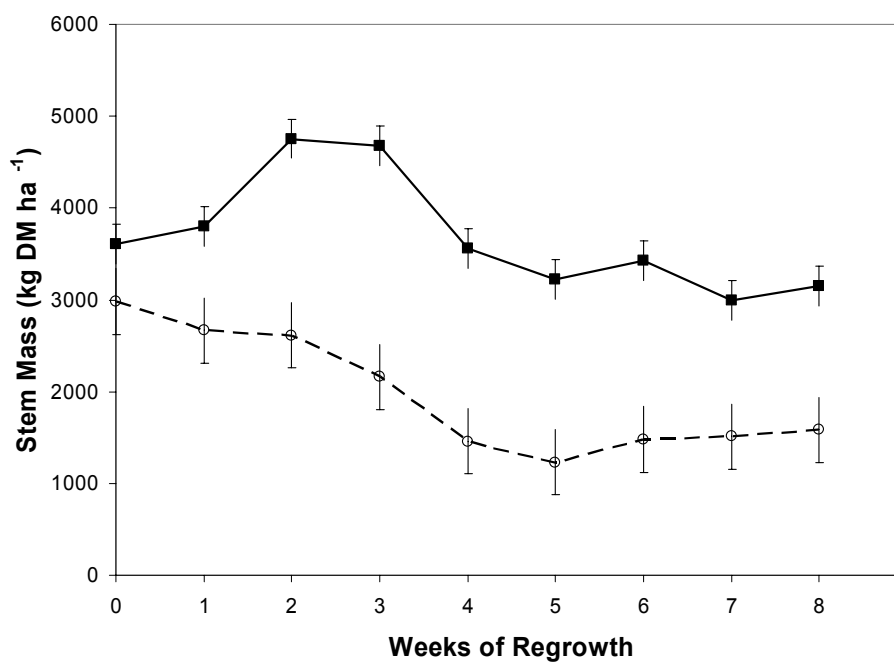


Figure 3-6. Stem mass for established bahiagrass grown at Gainesville, FL from 18 July to 12 Sept. (—) and 12 Sept. to 7 Nov. (---), 2001.

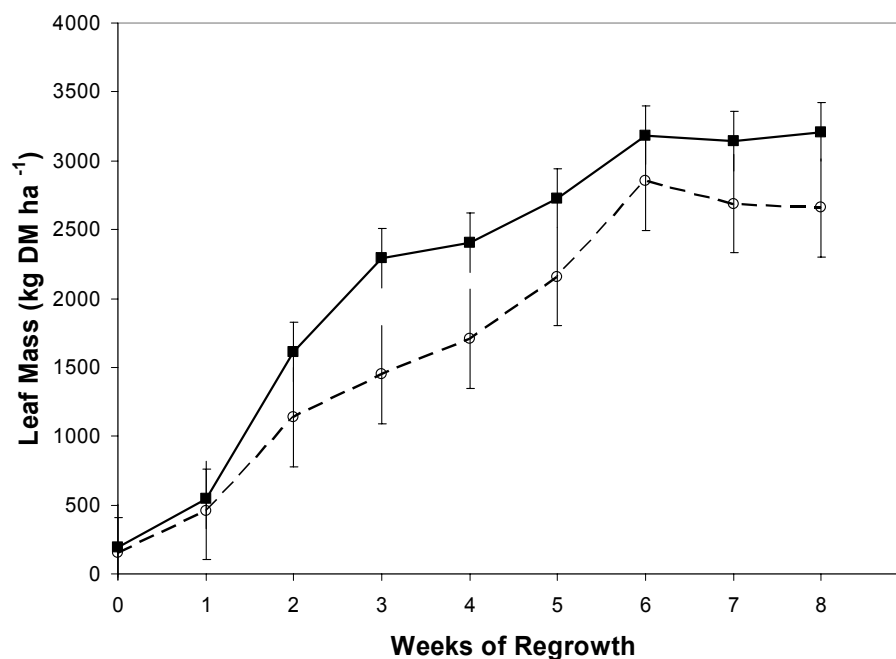


Figure 3-7. Leaf mass for established bahiagrass grown at Gainesville, FL from 18 July to 12 Sept. (—) and 12 Sept. to 7 Nov. (---), 2001.

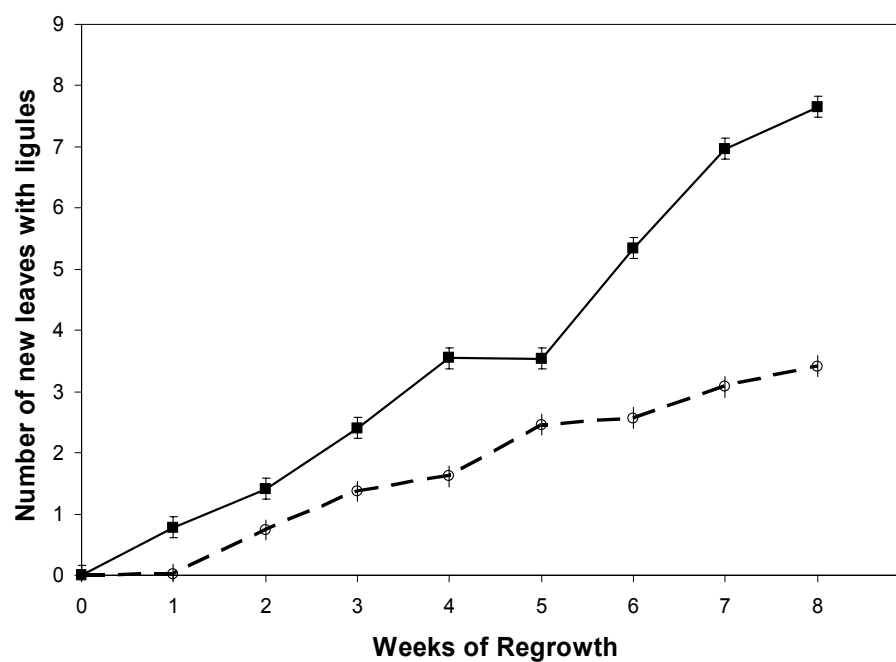


Figure 3-8. V-stage for established bahiagrass grown at Gainesville, FL from 18 July to 12 Sept. (—) and 12 Sept. to 7 Nov. (---), 2001.

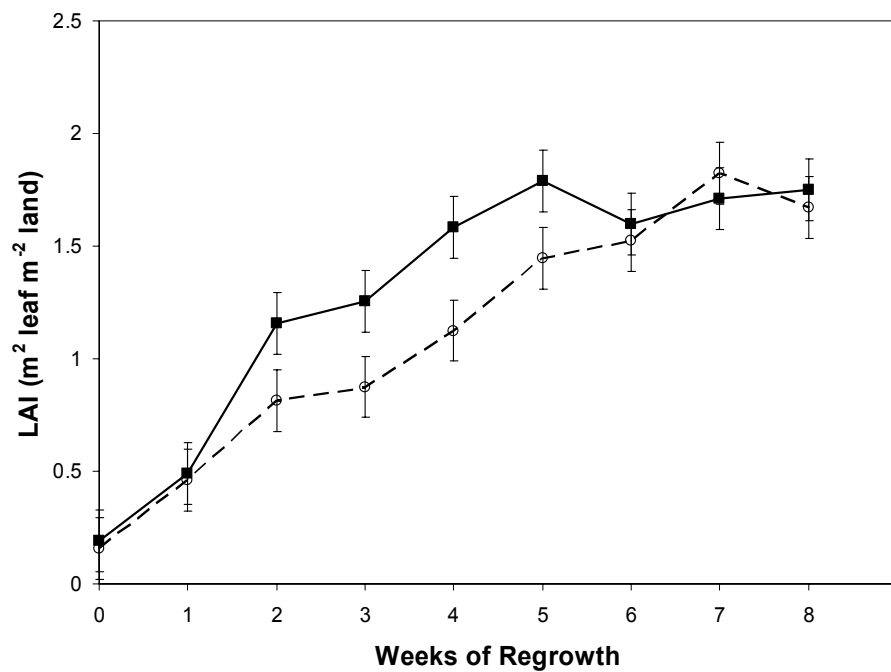


Figure 3-9. Leaf area index (LAI) for established bahiagrass grown at Gainesville, FL from 18 July to 12 Sept. (—) and 12 Sept. to 7 Nov. (---), 2001.

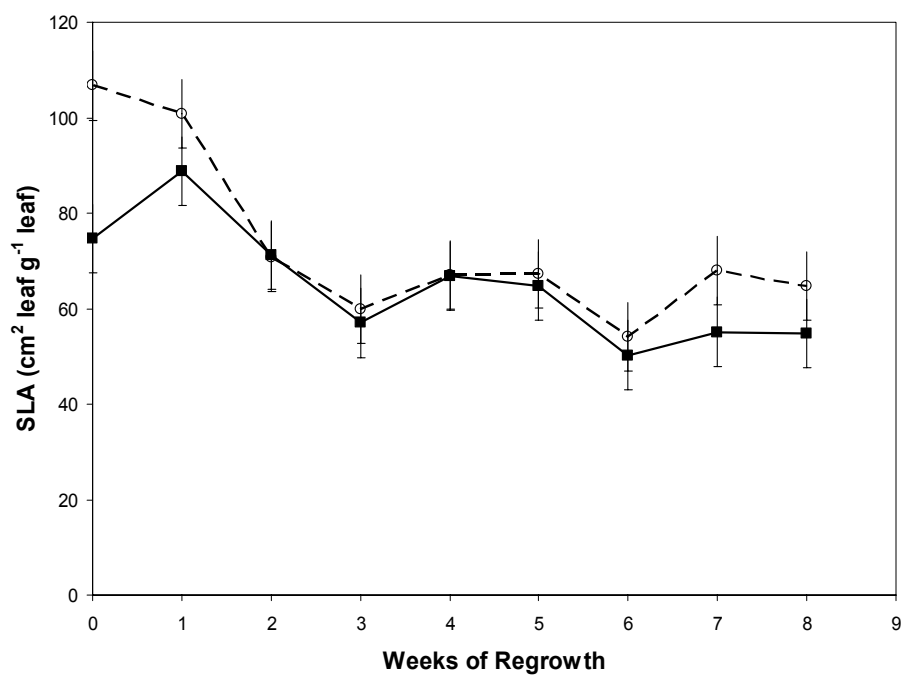


Figure 3-10. Specific leaf area (SLA) for established bahiagrass grown at Gainesville, FL from 18 July to 12 Sept. (—) and 12 Sept. to 7 Nov. (---), 2001.



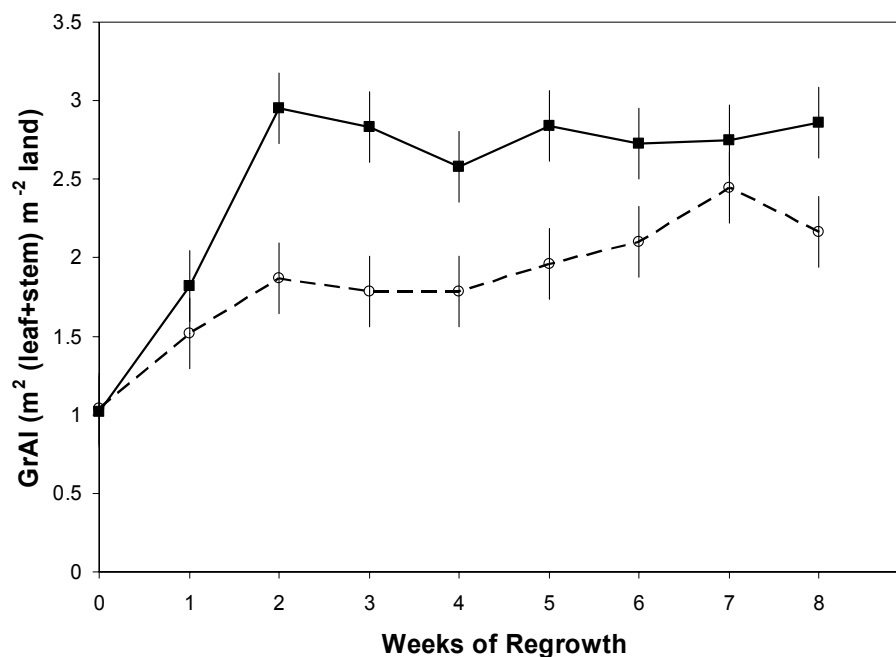


Figure 3-11. Leaf + Stem (green) area index (GrAI) for established bahiagrass grown at Gainesville, FL from 18 July to 12 Sept. (—) and 12 Sept. to 7 Nov. (---), 2001.

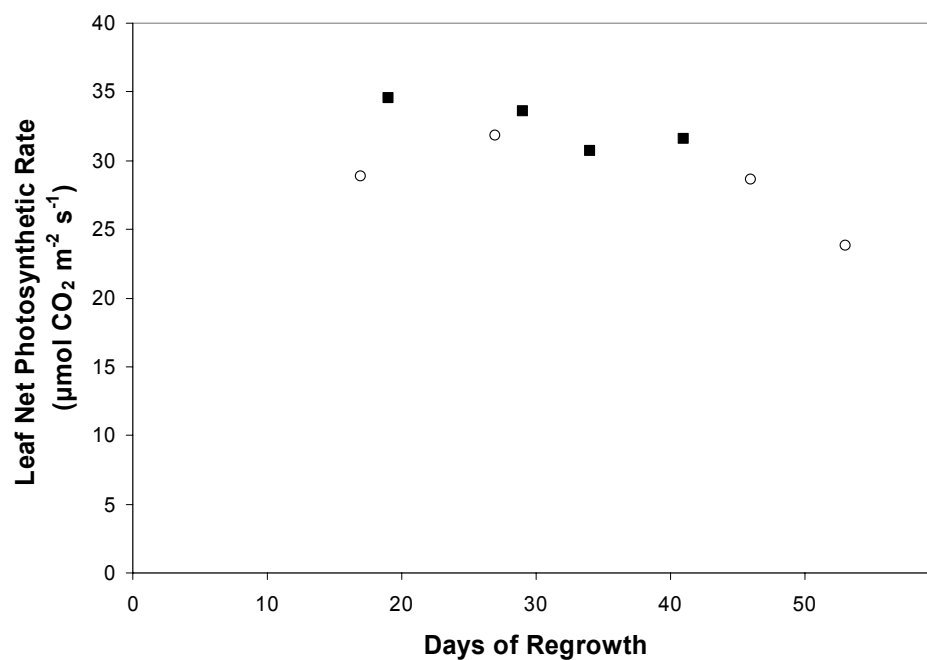


Figure 3-12. Leaf photosynthetic rate for established bahiagrass grown at Gainesville, FL from 18 July to 12 Sept. (■) and 12 Sept. to 7 Nov. (○), 2001.

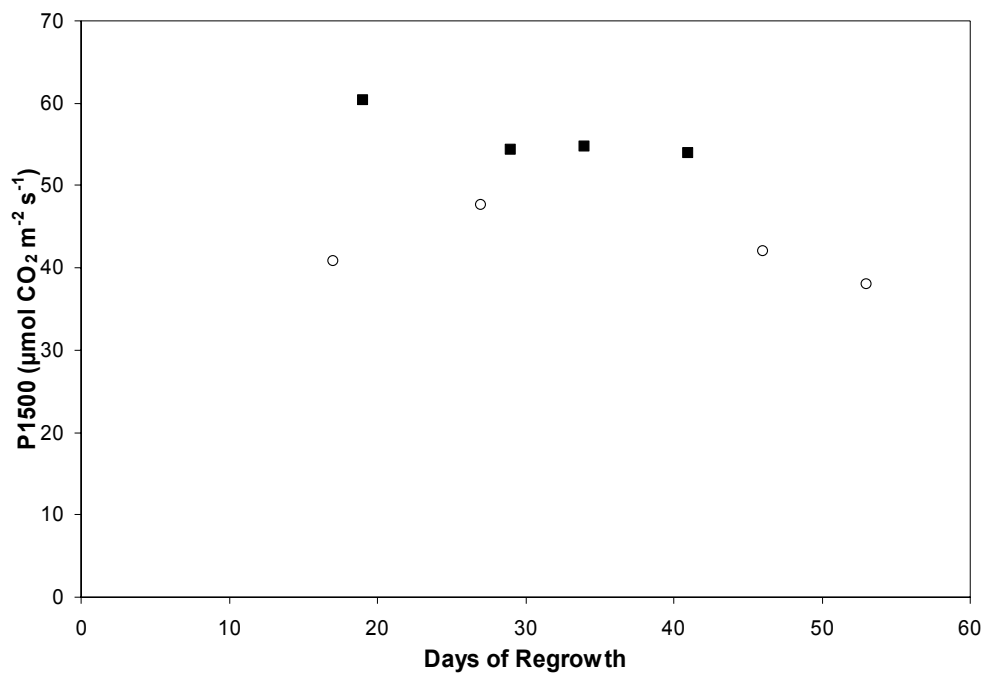


Figure 3-13. Canopy gross photosynthetic rate adjusted to  $1500 \mu\text{mol Par m}^{-2} \text{ s}^{-1}$  (P1500) for established bahiagrass grown at Gainesville, FL from 18 July to 12 Sept. (■) and 12 Sept. to 7 Nov. (○), 2001.

## CHAPTER 4 DEVELOPMENT OF CROPGRO SPECIES FILE PARAMETERS FOR BAHIAGRASS

### **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 to the task of modeling forage growth and nutrient concentration. Additionally, the ability to simulate soil water and N balances, soil organic matter – residue dynamics, and pest/disease damage increase CROPGRO’s utility as a tool for evaluating potential environmental consequences of management changes. Its generic, process-oriented design has allowed it to be adapted to model a variety of different species including soybean (*Glycine max* L.), peanut (*Arachis hypogaea* L.), dry bean (*Phaseolus vulgaris* L.), faba bean (*Vicia faba* L.), and tomato (*Lycopersicon esculentum* Mill.) (Scholberg et al., 1997; Boote et al., 1998a, 1998b, 2002). 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 DM yields, particularly in the cooler months of the year. 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 faithful representation of the seasonal patterns of growth of bahiagrass. The objective of this work was to develop parameters, from searching the literature, experiments, and calibration, to model bahiagrass growth and composition with the CROPGRO CSM model.

### **Materials and Methods**

In deriving model parameters to describe bahiagrass growth and composition, we followed the general adaptation procedure described by Boote et al. (2002). Where possible, parameters describing the basic processes of photosynthesis, respiration, N assimilation, and plant development in bahiagrass were derived from the literature. Parameters describing basic biochemical processes assumed to be conserved, or similar (e.g., growth respiration cost per unit of protein), among species are universal throughout all CROPGRO species files. For some less conserved processes and traits where data were lacking, parameters from the CROPGRO soybean species file were used. Soybean was selected as it is one of the original models used to develop CROPGRO and is arguably the most tested and robust version of the model. Examples of parameters incorporated from the soybean files are lipid, lignin, organic acid, and mineral composition, as well as carbon cost to mobilize N from senesced proteins (Penning de Vries et al., 1974).

Where processes or parameters were believed to be divergent from soybean or thought to be unique to perennial forage species, parameter estimates were interpolated

from literature data from 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 utilizing a “brute-force” optimization strategy. 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 and observed data,  $r^2$ , d-index value (index of agreement [Willmott, 1981]), 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 a spreadsheet, parsed, and sorted from highest (best fit) to lowest d-index rating. The optimized parameter values were selected using a combination of high d-index ranking, low RMSE value, and most logical fit. The optimized parameter set was subsequently tested for fit, using the same procedure as used for testing the literature-based species file.

### **Description of Data Sets Used to Fit Parameters**

Two data sets were selected for use in fitting parameters and testing the optimized model. Only a brief listing of growing conditions will be given here. A more complete description of each data set may be found in the 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 Range Cattle Research and Education Center (REC) at Ona, FL (27° 25'N, 81° 55'W; elevation 27.4 m) on a Pomona fine sand (sandy siliceous, hyperthermic Ultic

Haplaquod) soil. Pensacola bahiagrass received five fertilizer treatments (0, 39, 78, 118, and 157 kg N ha<sup>-1</sup> cutting<sup>-1</sup>), equivalent to annual applications of 0, 234, 468, 708, and 942 kg N ha<sup>-1</sup> supplied as ammonium nitrate. Fertilizer was applied on 5 May and on the day after each cutting except for the October (last) harvests. 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. Forage 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 for October 1996 through September 1997 and 2110 mm from October 1997 through September 1998.

The Eagle Lake, TX (29° 35'N, 96° 20'W, elevation 46 m) experiment was part of a larger study of N contributions of arrowleaf (*Trifolium vesiculosum* Savi) and subterranean (*Trifolium subterraneum* L.) clovers overseeded on bahiagrass and bermudagrass [*Cynodon dactylon* (L.) Pers.] conducted over the 1979-1981 growing seasons (Evers, 1985). The study was located in southeastern Texas at the Texas Agricultural Experiment Station at Eagle Lake on a Crowley fine sandy loam (fine montmorillonitic, thermic, Typic Albaqualfs) soil. The Pensacola bahiagrass treatments included fertilizer applied at annual rates of 0, 84, 168, 252, or 336 kg N ha<sup>-1</sup>. The fertilizer was split into three equal applications made on or about 1 April, 1 June, and 1 August of each year. All plots were harvested monthly from May through October. Forage yield and crude protein data were reported. Daily weather data were acquired from the experiment station's weather station. Freezing temperatures were not uncommon in the winter with minimum temperatures as low as -9°C. Average rainfall

was less than for Ona, with annual precipitation of 1354 mm, 765 mm, and 1223 mm for 1979, 1980, and 1981 seasons, 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 treatment from both data sets was 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 “normal” or the most frequently encountered conditions. The primary objective for the optimization process was to minimize RMSE for the prediction of herbage mass (leaf + stem weight) or herbage N concentration (leaf + stem N concentration), 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. Actual weather data were used for the prior year. The season began with an established plant stand cut to the same stubble height used in the measured years. Fertilization during the prior year was consistent with the medium N fertilization treatment for each site ( $468 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  at Ona, FL, and  $168 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  at Eagle Lake, TX).

To compare simulated and observed growth, the two sets of results had to be expressed on a common basis. The field studies reported yield as herbage (leaf + stem) mass 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, 1996b; 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 approximate total herbage 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<sup>-1</sup>. These values may apply only to Pensacola bahiagrass. Newer bahiagrass varieties with more upright growth habits may have considerably less stubble mass (Pedreira and Brown, 1996b). This tactic basically creates a consistent season-long offset while actual stubble mass may vary with season and N fertilization. This approach represents a compromise between accuracy and simplicity of implementation/utility.

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 of the crop or the entire crop dies (respectively) due to cold. We found that after a FREEZ1 event occurred, there was no regrowth of new leaves, resulting in the plants exhausting all reserves on maintenance respiration and dying. The problem was related to the strategy used to end photosynthesis of grain legumes after a foliage-killing freeze event. Since we could not alter the code, both FREEZ1 and FREEZ2 were set 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.

## **Results and Discussion**

This discussion will be confined to parameters that were unique to perennial tropical grasses or required redefinition or alteration in concept. A complete list of parameter values is provided in Table 4-1.

### **Photosynthesis Parameters**

CROPGRO has two options for predicting daily assimilate production: a daily canopy option and an hourly leaf-level option. The daily canopy option is the more simplistic approach, predicting photosynthate production as an asymptotic light response to total daily solar radiation levels. 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 canopy rate. Both options include adjustments for current temperature, CO<sub>2</sub> concentration, and leaf N concentration conditions.

All previous efforts to adapt CROPGRO involved crops using the C<sub>3</sub> photosynthesis pathway/mechanism. In contrast, bahiagrass expresses the C<sub>4</sub> photosynthetic pathway, more specifically, it is an NADP-ME type species (Hattersley and Watson, 1976), the same pathway that is expressed in maize (*Zea mays* L.).

Concentration of CO<sub>2</sub> in the bundle sheath chloroplasts through the “CO<sub>2</sub> concentrating shuttle” contributes several advantages to C<sub>4</sub> plants. Since CO<sub>2</sub> is concentrated around the CO<sub>2</sub>-fixing Rubisco enzyme in the bundle sheath chloroplasts, the relatively lower solubility of CO<sub>2</sub> at high temperatures is of little consequence, allowing higher rates of carboxylation and suppressing oxygenation activity of Rubisco at higher temperatures

and light levels than is generally possible in C<sub>3</sub> plants. Likewise, the quantum efficiency (QE) is not temperature sensitive, not decreasing at high temperatures as in C<sub>3</sub> plants. As photorespiration is reduced, less Rubisco is required to maintain high carbon exchange rates (CERs), and leaf protein levels are generally lower for C<sub>4</sub> plants. These differences must be reflected in our predicted patterns of photosynthetic response to light intensity, CO<sub>2</sub> concentration, leaf N concentration, and temperature in the model.

The asymptotic light response curve used to predict daily canopy photosynthesis is defined by two parameters; PARMAX, the level of photosynthetically active radiation (PAR) at which photosynthetic rate is 63% of maximum (moles [quanta PAR]m<sup>-2</sup>d<sup>-1</sup>), and PHTMAX, the asymptote (maximum) of daily assimilation rate (g CH<sub>2</sub>O m<sup>-2</sup> d<sup>-1</sup>) occurring at very high light (at least three times as high as PARMAX). These values are not generally presented in the literature so preliminary values (Table 4-1) were estimated as 150% of the corresponding parameter values used for soybean.

The lower rate of photorespiration observed in C<sub>4</sub> species results in a lower CO<sub>2</sub> compensation point (CCMP) (atmospheric CO<sub>2</sub> concentration where the rate of CO<sub>2</sub> uptake by photosynthesis equals the rate of CO<sub>2</sub> evolution by respiration) in C<sub>4</sub> plants. Values of 0 to 14 µL L<sup>-1</sup> have been reported as the CO<sub>2</sub> compensation point for various C<sub>4</sub> species (Bolton and Brown, 1980; Rajendrudu and Das, 1981), most on the order of 0 to 5 µL L<sup>-1</sup> (Rajendrudu and Das, 1981). Based on these results we selected a value of 5 µL L<sup>-1</sup> for CCMP which is used for the daily canopy photosynthesis option.

The leaf-level photosynthesis option is a more complicated system requiring several more parameters than the daily canopy option, but the model at the leaf and chloroplast level 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 broadly defined as the initial slope of the leaf CO<sub>2</sub> assimilation:absorbed PAR response. A value of 0.0541  $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  absorbed photons (Ehleringer and Björkman, 1977) is typically used in CROPGRO for all C<sub>3</sub> species, including soybean. While the same biochemical processes are used in both C<sub>3</sub> and C<sub>4</sub> photosynthesis, the CO<sub>2</sub> concentrating effect of the C<sub>4</sub> systems increases their QE. Differences in efficiency exist between the three variations of the C<sub>4</sub> photosynthetic pathway (NAD-ME, NADP-ME, and PCK-type) with NADP-ME species exhibiting the highest QE with an average QE of 0.065  $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  absorbed photons (Ehleringer and Pearcy, 1983). We selected this value for the bahiagrass species file (Table 4-1). This value appears to be quite robust as it falls well within the range of QE values predicted from bahiagrass canopy photosynthetic light response data (0.054 – 0.081  $\mu\text{mol}^{-1}$  absorbed photons) (Rymph and Boote, 2002), and reported QE values (0.062 to 0.075  $\mu\text{mol CO}_2 \mu\text{mol}^{-1}$  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<sub>3</sub> plants, as temperature increases, the solubility of CO<sub>2</sub> decreases relative to the solubility of O<sub>2</sub>, lowering QE of C<sub>3</sub> species at high temperatures. Because of the high CO<sub>2</sub> concentration surrounding Rubisco in bundle sheath cells of C<sub>4</sub> plants, the effect of temperature on QE is negligible. However, the temperature effect on QE is hard-coded into CROPGRO and currently, there are no user parameters to modify that response.

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 predicted maximum leaf photosynthetic rate developed from bahiagrass canopy light response data (Rymph and Boote, 2002) of approximately  $40.0 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ leaf s}^{-1}$ . Relative differences among 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” cultivar on which the species parameters are based and was the cultivar measured,  $\text{PGREF}=\text{LFMAX}=1.760 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ .

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  $\text{C}_4$  grasses are generally considered to have low concentrations of N in the leaves, yet maintain high photosynthetic rates. Thus, optimal N concentrations for photosynthesis of bahiagrass are 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 [FNPGN(1)] from the lowest reported leaf N concentration  $7.6 \text{ g N kg}^{-1} \text{ leaf}$  (Beaty and Tan, 1972). Sugimoto and Nikki (1979) observed a curvilinear increase in bahiagrass leaf photosynthetic rate as leaf N concentration increased from approximately 20 up to  $30 \text{ g N kg}^{-1}$ . The rate remained constant from  $30 \text{ g N kg}^{-1}$  to almost  $40 \text{ g N kg}^{-1}$ . Hence, we chose a curvilinear (quadratic) shape to define the response of bahiagrass to leaf N concentration, with optimum photosynthetic rates beginning at  $30 \text{ g N kg}^{-1}$  [FNPGN(2)] and no decline in rate at higher N concentration. The  $30 \text{ g N kg}^{-1}$  optimum was also used for LNREF, the N concentration at which PGREF is defined for the species.

The high concentration of CO<sub>2</sub> around Rubisco in the bundle sheath chloroplasts permits high photosynthetic rates at higher temperatures than typically observed in C<sub>3</sub> plants. Although the mechanism is not well understood, C<sub>4</sub> species generally also have a greater sensitivity threshold for low temperature reduction of photosynthetic rate than C<sub>3</sub> 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 C<sub>4</sub> grasses (Ludlow and Wilson, 1971; Wilson, 1975; Unruh et al., 1996); unfortunately none included bahiagrass. Our interpretation of these results are that the optimum range for leaf photosynthesis for a tropical grass species should be between 35 and 45°C, with a base temperature around 7°C and a maximum critical temperature for zero rate near 55°C.

The daily canopy calculations use a daily, rather than hourly, time step. To find daytime temperature thresholds for the daily canopy option, we compared the threshold temperatures for the leaf-level option to daily minimum and/or maximum temperatures for Gainesville, FL and calculated a corresponding average daytime temperature. The corresponding temperatures were: base temperature [FNPGT(1)], 12°C, optimum range [FNPGT(2), FNPGT(3)] from 25°C to 38°C, and maximum temperature of 50°C [FNPGT(4)].

Low 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) and TYPPGL, to describe the

effect of minimum night temperature on the subsequent day's light saturated leaf photosynthetic rate. West (1973) observed that *Digitaria decumbens* 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 days photosynthesis -FNPGL(2)] to 18°C, with a quadratic (curvilinear) response between these points (Table 4-1).

### **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, N 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<sup>-1</sup>, 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 or 2% per day. In preliminary simulations this yielded a maximum predicted root mass of approximately 10 000 kg root dry matter (DM) ha<sup>-1</sup>, in the range of the combined stolon and root mass observed by Boote et al. (1999) (10 660 to 15 370 kg ha<sup>-1</sup>) and Rymph and Boote (2002) (7155 to 15 740 kg ha<sup>-1</sup>).

### **Carbon and Nitrogen Mobilization Parameters**

Another area where modeling perennial forages and annual grains differs is N mobilization. The basic concept is the same, but the timing and purpose differ. Nitrogen reserves in annual grain crops are generally mobilized 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 reserves are used primarily to speed vegetative regrowth after a harvest or in the spring. Since perennial forages must be able to do this repeatedly over several growing seasons, the rate and extent of N mobilization may be quite different than 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 N mobilization. On average, 36% of the available N was mobilized within 7 to 10 d of cutting. This translates into approximately 5% d<sup>-1</sup> or a maximum available N mobilization fraction (NMOBMX) of 0.05. 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 TNC data to support changes, the soybean values were used for maximum available CH<sub>2</sub>O mobilization fraction (CMOBMX) (Table 4-1).

### **Vegetative Partitioning Parameters**

During vegetative growth, partitioning of new growth among leaf, stem, and roots is a function of the vegetative stage of the crop (V-stage). This is another area where the concept of V-stage is different between annual crops and 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 (four 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 N, 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 is that, in both cases, if V-stage is low, the priority for partitioning is towards growing leaf mass/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 around observed patterns of regrowth, rather than purely on seedling growth. Parameter values were estimated prior to optimization using growth patterns reported by Rymph (2002) 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 4-1).

### **Leaf Growth and Senescence Parameters**

Complications caused by repeated re-setting of the V-stage of the crop within a growing season mandated some other modifications in addressing 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 mature plant with numerous growing points (stolons). Use of the VSSINK function which allows photosynthesis and leaf expansion to be limited by sink strength rather than assimilate supply, while potentially appropriate for a small seedling, is not likely to fit the conditions of the older plant. To prevent potential limitations to growth in older plants, the VSSINK function was disabled by assigning a value of 0.0 to the VSSINK parameter.

Senescence parameters were modified very little from Kelly's (1995) 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 raw 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  $0.8 \text{ moles photons m}^{-2} \text{ d}^{-1}$ , the same as soybean. In a similar vein, 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**

The actual resetting of V-stage after a harvest is done in the PEST routine, using either the MOW function (remove herbage to a designated residual mass) or a

combination of the HARV and HRVS (remove a designated proportion of existing herbage mass and number of leaves) functions, and no modification of the species file was 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 proportion of canopy mass removed and 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 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 leaves or seeds), optimum (maximum rate of leaf or seed addition), and maximum (upper failure temperature) points (Table 4-1) based on our experiences growing bahiagrass (K.J. Boote, personal communication).

### **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, herbage N concentration and accumulated herbage N mass, respectively, using the leaf-level photosynthesis option and 0.851, 0.531, and 0.907 for the daily canopy photosynthesis option (Table 4-2). Despite the moderate d-index values for predicted herbage N concentration, the  $r^2$  values were quite low at 0.18 and 0.19 for the leaf and canopy models, indicating that the N response was a weak point. The higher d-index value for predicted herbage N mass than for either herbage mass or herbage N concentration represents the effect of offsetting errors (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 (Figure 4-1a). Water and N demand associated with this excessive growth caused elevated water and N stress throughout the spring and early summer (Figure 4-1a), reducing predicted growth rates in May and June. The principle cause of this discrepancy was our failure to simulate winter dormancy. Compounding this was the lack of a working freeze damage routine promoting an artificially high 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.

To reduce winter growth rate we used the PEST routine in CROPGRO to reduce daily photosynthesis production by 70% from 23 October through 30 March. This approach reduces photosynthetic rate but does not concurrently reduce transpiration. Coincident with this change, the periods of water and N stress were shortened considerably (Figure 4-1b). Statistically, however, there were minimal changes in the fit of either leaf or canopy models after this modification (Table 4-2). This approach resulted in slight improvements in d-index values for leaf and canopy model predicted herbage mass, leaf model predicted herbage N mass, and slightly lower (worse) d-index values for canopy model predicted herbage N concentration and herbage N mass (Table 4-2). Late spring regrowth was still considerably reduced compared to the observed growth (Figure 4-1b), possibly because the PEST option reducing photosynthesis does not reduce transpiration except indirectly through the lower LAI resulting from slowed growth.

Further investigation revealed that two mechanisms may have been responsible for the early season water and N stress. In reducing photosynthesis in the PEST routine, the normal photosynthetic rate and transpiration rate were 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 available soil water. The only “reduction” in transpiration was due to the lowered LAI that resulted from the slowed growth. Also, root N was mobilized throughout the winter and into the spring to compensate for the reduced assimilate production, reducing root mass considerably by the end of the winter/early spring period (data not shown). While more water and N may have been available in the soil, the diminished root system had a reduced capacity to exploit them, suppressing early season growth rates. Despite the failure to statistically improve the fit, we used this strategy in all optimization and testing runs as the patterns of N stress were more realistic than before.

Performance of the model using the daily canopy option and winter photosynthetic reduction was quite similar to the leaf-level option performance for predicting herbage mass (Figure 4-2). The d-index values for the fit of the predicted data to herbage mass were identical to those for the leaf-level option. The predicted pattern of growth was also quite similar with slightly reduced winter growth rates but nearly identical summer growth (Figure 4-2). Fit of predicted herbage N concentration was slightly poorer for the canopy option, but fit of predicted herbage N mass was similar for both options (Table 4-2).

Fit of predicted herbage N concentration was not as good as was herbage mass for either option (Table 4-2). Leaf + stem N concentration was consistently overpredicted

for the Ona, FL site (Figure 4-3). During winter regrowth, after the “simulated frost” defoliation, herbage N concentration exceeded  $40 \text{ g N kg}^{-1}$ , equivalent to  $250 \text{ g CP (crude protein) kg}^{-1}$ , higher than the “maximum” leaf N concentration set by PROLFI. This is related to the N allocation problem in the code cited earlier that prohibited leaf regrowth after a FREEZ1 event. As the goal of the present exercise was to calibrate the parameters without changing any source code, this problem could not be addressed.

For the Eagle Lake, TX data, predicted herbage N concentration appeared to follow a more accurate pattern despite greater variation in the observed values (Figure 4-4). 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. Values from the daily canopy photosynthesis option were generally higher than for the leaf-level option (Figures 4-3 and 4-4).

### **Optimization**

Since we were unable to accurately predict the spring growth pattern, some of the early season yield data were excluded from the optimization process. The rationale for “culling” these two data points was that the model was consistently predicting early season N and water stress when there was none; thus 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 datasets used to test the performance of the model. All 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 leaf-level option temperature parameters to establish proper general patterns of growth, then refine the prediction by optimizing parameters that affect the growth response to N. After optimizing the leaf-level option, the temperature parameters for the daily canopy photosynthesis option were optimized followed by simultaneous optimization of PARMAX and PHTMAX.

All temperature parameters (leaf-level and daily canopy options) and PARMAX/PHTMAX optimizations used only the two highest N fertility treatments from each experiment, assuming that N 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 improved the predicted winter growth pattern (Figures 4-5a and 4-5b) but fit of predicted herbage mass during the growing season was generally unaffected (Table 4-2) with similar d-index values for both optimized and literature-based species files. Winter growth pattern was improved most for the daily canopy option where there was almost no regrowth through the winter (Figure 4-5b). A wider range of potential parameter values were offered in the daily canopy option optimization as there was less data available to define the ranges. Winter regrowth was curtailed by increasing FNPGT(1), only allowing growth on days with average temperatures greater than 20°C (Table 4-1). Normally, this would affect growth rates well into the spring and fall growing season, but PARMAX and PHTMAX were also boosted in the optimization (Table 4-1). This combination allowed growth rates to be nearly identical during the

normal growing season (Figures 4-5a and 4-5b). Nitrogen stress was reduced in the optimized simulations (Figures 4-5a and 4-5b); however, water stress was still extensive in the spring, even for the daily canopy option, 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 extreme parameter values to improve the fit of the model.

Overall, both the leaf-level and daily canopy options tended to overpredict herbage mass at lower yields and underpredict at higher yields with this phenomena most evident in the daily canopy option results (Figures 4-6a and 4-6b). Despite the improved fit, the optimized values for these three parameters, FNPGT(1), PARMAX, and PHTMAX, are not realistic and reflect the emphasis on compensating for the excessive winter growth pattern, not improving the relevancy of the parameter value.

Fit of herbage N concentration predictions improved considerably for both the optimized leaf-level and optimized daily canopy photosynthesis options (Table 4-2, Figures 4-7 and 4-8). The d-index rating for both options improved considerably after optimization; however, the  $r^2$  values remained quite low (Table 4-2). Predicted herbage N concentrations were still consistently overpredicted at Ona (Figure 4-7) despite optimization toward lower PROLFI, PROLFG, PROSTI, and PROSTG parameters (Table 4-1). The pattern of predicted herbage N concentration for Eagle Lake remained realistic after optimization (Figure 4-8), however, the optimized parameter values were generally lower than the literature-based parameters (Figure 4-4). The difference between predicted and observed values was also reduced for both the leaf-level (Figure

4-9a) and daily canopy options (Figure 4-9b) indicating a more consistent prediction. Both leaf-level and daily options tended to overpredict herbage N concentration, but this was more pronounced in the daily canopy option predictions (Figures 4-9a and 4-9b). Despite the improvement in herbage N concentration prediction, fit of predicted herbage N mass showed little improvement (Table 4-2) but had been quite high to begin with.

### **Conclusions**

Performance of the literature-based parameters was quite good, especially related to predicting herbage mass and herbage N mass. The prediction of herbage N concentration needed improvement. On review of the results, 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 mass. The absence of a dormancy routine to control vegetative growth during the winter and spring months had a profound effect on early season N and water availability, contributing to low predicted herbage mass throughout the season. The absence of a storage organ such as a rhizome or stolon contributed to this problem by confounding effects of changing proportions of stolon and root mass. 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.

Optimization did improve the fit of both the leaf and canopy models compared to simulations using the literature-based parameters. Winter growth was slow, and excessive levels and variation in leaf N concentration were controlled using the optimized parameters. However, some of the optimized parameters are at the edges of their biological range or beyond as a result of compensating for the missing/problem



components in the model code. The optimization was more an exercise in compensating for the model than in divining more accurate parameter values.

In order to better mimic the biology of perennial, tropical grasses, modifications must be made to the model code itself. Primary among these changes is the addition of a dormancy routine. Evidence for this and the mechanism required is available in the literature. Sinclair et al. (2003), Mislevy et al. (2000), and Gates et al. (2001) clearly demonstrate the role of daylength in controlling dormancy. Hints for the mechanism involved in 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 the same to the stolon would complement the maturity, temperature, and stress mechanisms already present in CROPGRO.

Addition of the storage organ would also allow more realistic prediction of the patterns of accumulation and depletion of roots, avoiding confounding root mass and N 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, it would also supply a source of  $\text{CH}_2\text{O}$  and N 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.

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 to a perennial forage. Situations such as low leaf mass after

a harvest coupled with large amounts of available N from the roots are not generally encountered in the life cycle of maize or soybean 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 was 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.

Table 4-1. Bahiagrass parameter values for the CROPGRO species file. Preliminary values were derived from the literature. Optimized values were derived from optimization runs made based on the preliminary values.

Parameter Name	Preliminary value	Optimized value
PARMAX	60.0	140.0
PHTMAX	90.0	180.0
CCMP	5.0	
FNPGN(1-4)	0.75, 3.0, 10.0, 10.0	1.0, 3.0, 10.0, 10.0
TYPPGN	QDR	
FNPGT(1-4)	12.0, 25.0, 38.0, 50.0	20.0, 25.0, 30.0, 50.0
TYPPGT	LIN	
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
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
FNPGL(1-4)	7.0, 18.0, 45.0, 57.0	7.0, 18.0, 45.0, 57.0
TYPPGL	QDR	
PGEFF	0.065	
SLWREF	0.0035	
LNREF	3.0	
PGREF	1.76	
PROLF I, G, and F	0.22, 0.11, 0.05	0.15, 0.05, 0.04
PROST I, G, and F	0.11, 0.07, 0.033	0.125, 0.04, 0.022
PRORT I, G, and F	0.101, 0.040, 0.022	
PLIP LF, ST, RT	0.025, 0.020, 0.020	
PLIG LF, ST, RT	0.04, 0.06, 0.07	
PCAR LF, ST, RT	0.602, 0.697, 0.702	0.672, 0.682, 0.702
CMOBMX	0.025	
NMOBMX	0.05	
NVSMOB	1.00	
XLEAF	0.0, 1.5, 2.0, 3.0, 5.0, 7.0, 30.0	
YLEAF	0.45, 0.5, 0.6, 0.4, 0.25, 0.2, 0.2	
YSTEM	0.05, 0.05, 0.1, 0.1, 0.05, 0.05, 0.05	
FRSTMF	0.05	
FRLFF	0.20	
FRLFMX	0.60	
FINREF	144	
SLAREF	285	
SIZREF	2.0	
VSSINK	0.0	
SLAMAX	350	
SLAMIN	200	
XVGROW	0.0, 5.0, 10.0, 15.0, 20.0, 25.0	
YVREF	0.0, 10.0, 20.0, 30.0, 40.0, 50.0	
XSLATM	-50.0, 00.0, 10.0, 30.0, 60.0	

Table 4-1. Continued

Parameter Name	Preliminary value	Optimized value
YSLATM	0.25, 0.25, 0.25, 1.00, 1.00	
FREEZ1, FREEZ2	-25.0, -25.0	
ICMP	0.8	
TCMP	25	
XSTAGE	0.0, 5.0, 9.0, 50.0	
XSENMX	3.0, 5.0, 10.0, 50.0	
RTDEPI	20	
RFAC1	5000	
RTSDF	0.02	
RWUEP1	1.5	
Vegetative TB, T1, T2, TMax	9.0, 32.0, 40.0, 45.0	
Early Reproductive TB, T1, T2, TMax	10.0, 28.0, 32.0, 45.0	
Late Reproductive TB, T1, T2, TMax	10.0, 28.0, 32.0, 45.0	
XVSHT (1-10)	0.0, 1.0, 4.0, 6.0, 8.0, 10.0, 14.0, 16.0, 20.0, 40.0	
YVSHT (1-10)	0.0150, 0.0265, 0.0315, 0.0330, 0.0345, 0.0330, 0.0310, 0.0255, 0.0170, 0.0030	
YVSWH (1-10)	0.0150, 0.0255, 0.0310, 0.0320, 0.0330, 0.0315, 0.0295, 0.0230, 0.0125, 0.0005	

Table 4-2. Evaluation of the performance of CROPGRO with literature-based and optimized species files, with and without winter photosynthesis reduction.

Optimized species files, with and without winter photosynthesis reduction						
Observed values						
	Mean					
Herbage Mass	3215	kg DM ha <sup>-1</sup>				
Herbage N Conc.	18.6	g N kg <sup>-1</sup>				
Herbage N Mass	60.1	kg N ha <sup>-1</sup>				
Literature-based species file alone						
Leaf-level photosynthesis option predictions						
	Mean	Slope	Intercept	d-index	r <sup>2</sup>	RMSE
Herbage Mass	3119	0.611	1154	0.843	0.54	557
Herbage N Conc.	20.1	0.603	8.9	0.605	0.18	5.8
Herbage N Mass	65.0	1.005	4.57	0.925	0.77	14.5
Daily canopy photosynthesis option predictions						
Herbage Mass	2944	0.605	999	0.851	0.68	536
Herbage N Conc.	22.8	0.603	11.54	0.531	0.19	6.9
Herbage N Mass	69.21	0.990	9.7	0.907	0.78	16.13
Literature-based species file with winter photosynthesis reduction						
Leaf-level photosynthesis option predictions						
	Mean	Slope	Intercept	d-index	r <sup>2</sup>	RMSE
Herbage Mass	3119	0.624	1113	0.856	0.58	533
Herbage N Conc.	21.1	0.648	9.0	0.582	0.18	6.3
Herbage N Mass	68.2	1.085	3.0	0.926	0.83	14.9
Daily canopy photosynthesis option predictions						
Herbage Mass	2944	0.626	931	0.856	0.68	534
Herbage N Conc.	24.1	0.657	11.9	0.482	0.19	8.0
Herbage N Mass	73.4	1.096	7.6	0.890	0.82	18.6
Optimized species file with winter photosynthesis reduction						
Leaf-level photosynthesis option predictions						
	Mean	Slope	Intercept	d-index	r <sup>2</sup>	RMSE
Herbage Mass	3214	0.649	1129	0.860	0.58	528
Herbage N Conc.	18.2	0.426	10.32	0.676	0.19	4.3
Herbage N Mass	60.0	0.774	13.5	0.935	0.78	11.7
Daily canopy photosynthesis option predictions						
Herbage Mass	2923	0.713	631	0.847	0.62	587
Herbage N Conc.	21.6	0.438	13.4	0.600	0.22	5.1
Herbage N Mass	64.0	0.803	15.8	0.935	0.80	12.0

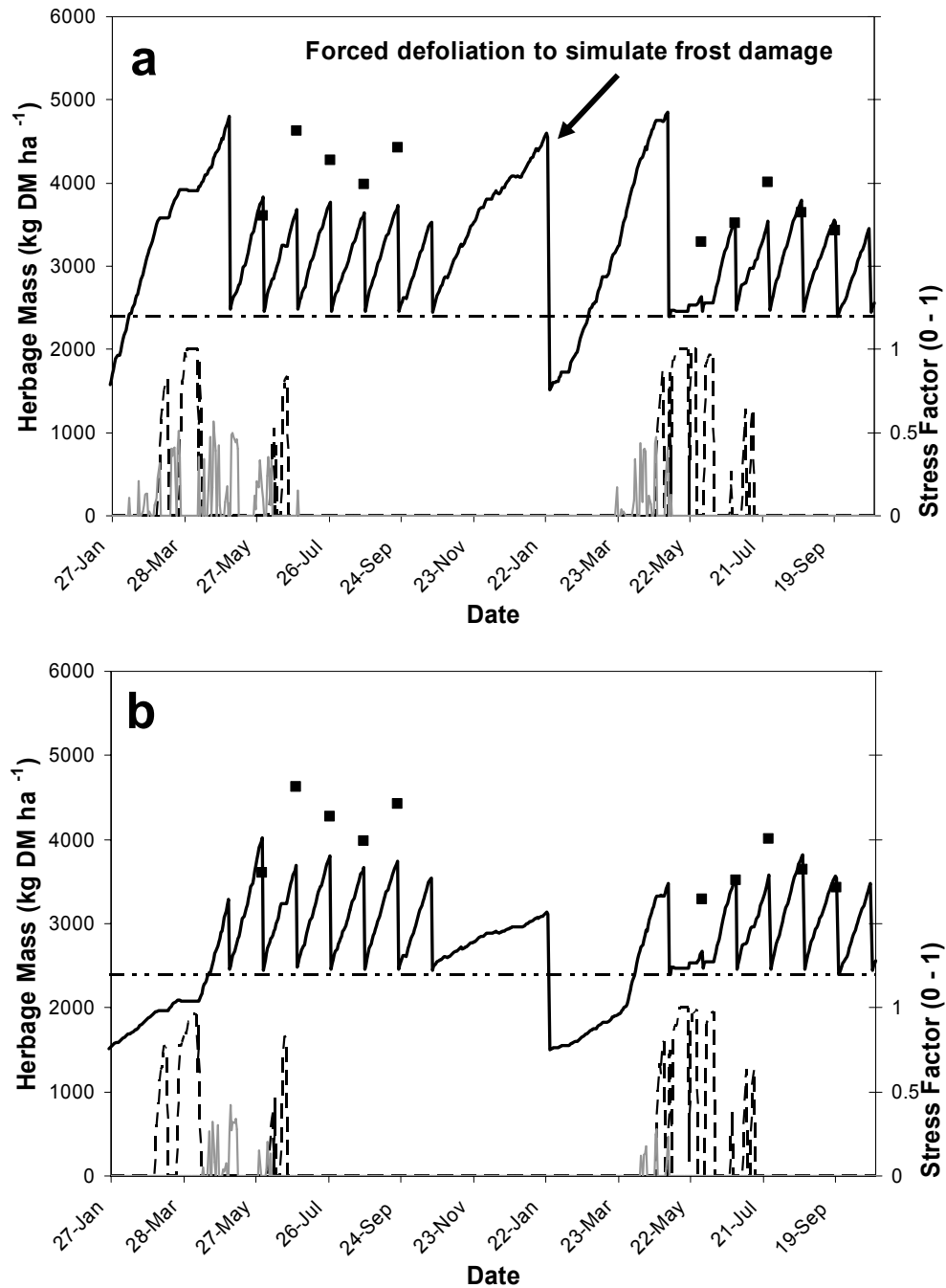


Figure 4-1. Observed herbage mass (■), predicted herbage mass (—), water stress (---), and N stress (—) of bahiagrass grown with 468 kg N ha<sup>-1</sup> yr<sup>-1</sup> at Ona, FL, using the literature-based species file and the leaf-level photosynthesis option, with **a**) No adjustment to winter growth, 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.

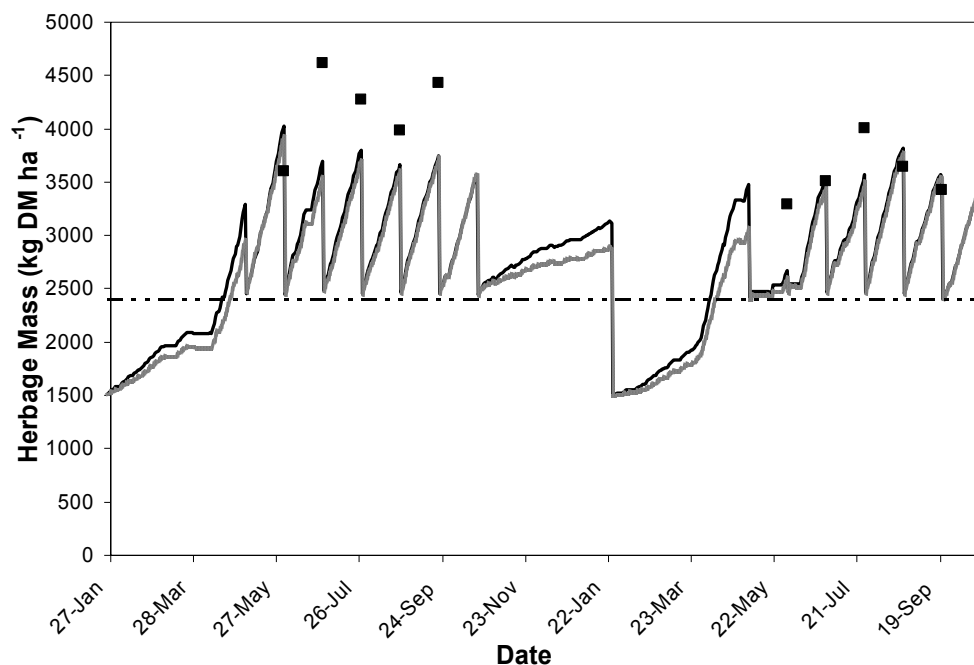


Figure 4-2. Observed bahiagrass herbage mass (■) and predicted bahiagrass herbage mass using the preliminary (literature-based, non-optimized) species file and the leaf-level photosynthesis option (—), or daily canopy photosynthesis option (---). For bahiagrass grown at Ona, FL with 468 kg N ha<sup>-1</sup> yr<sup>-1</sup>. The broken horizontal line (— · · —) denotes the stubble mass left in the field after each harvest.

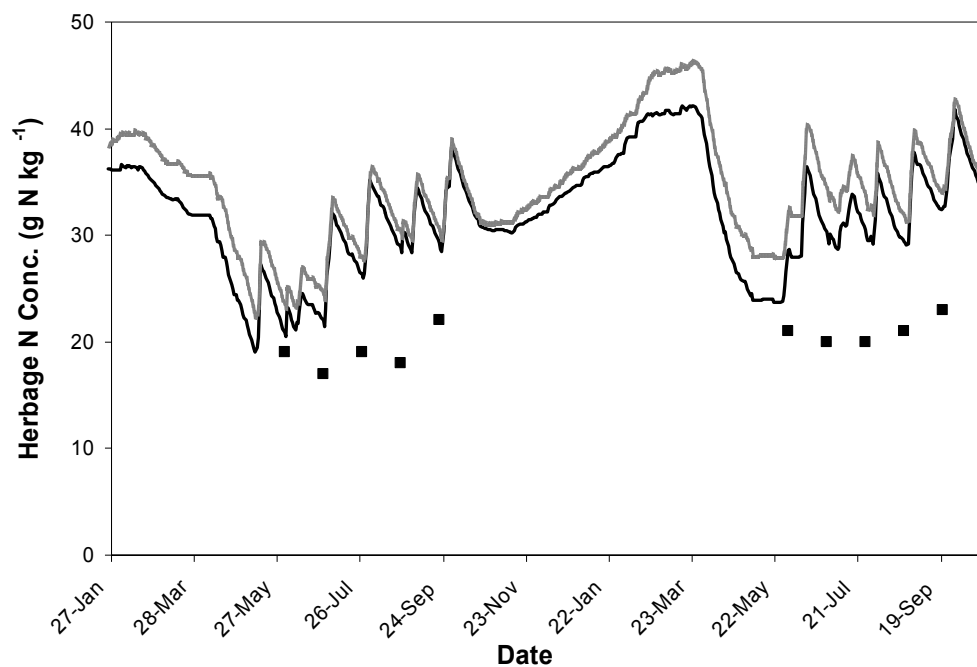


Figure 4-3. Observed bahiagrass herbage N concentration (■) and predicted bahiagrass herbage N concentration using the preliminary (literature-based, non-optimized) species file and the leaf-level option (—), or daily canopy option (—). For bahiagrass grown at Ona, FL with 468 kg N ha<sup>-1</sup> yr<sup>-1</sup>.



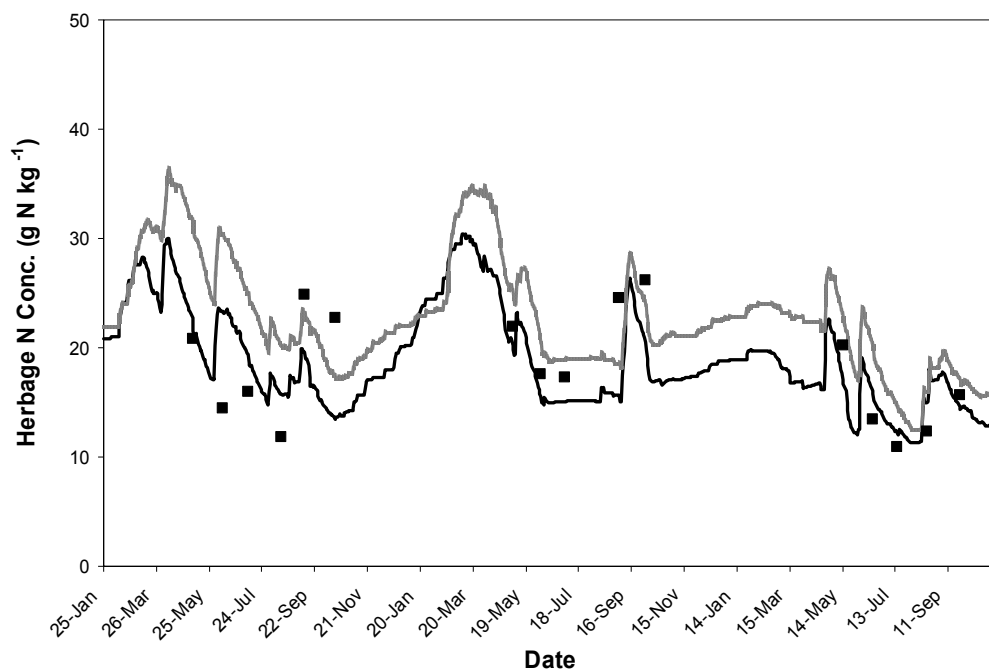


Figure 4-4. Observed bahiagrass herbage N concentration (■) and predicted bahiagrass herbage N concentration using the preliminary (literature-based, non-optimized) species file and the leaf-level option (—), or daily canopy option (—). For bahiagrass grown at Eagle Lake, TX with 168 kg N ha<sup>-1</sup> year<sup>-1</sup>.

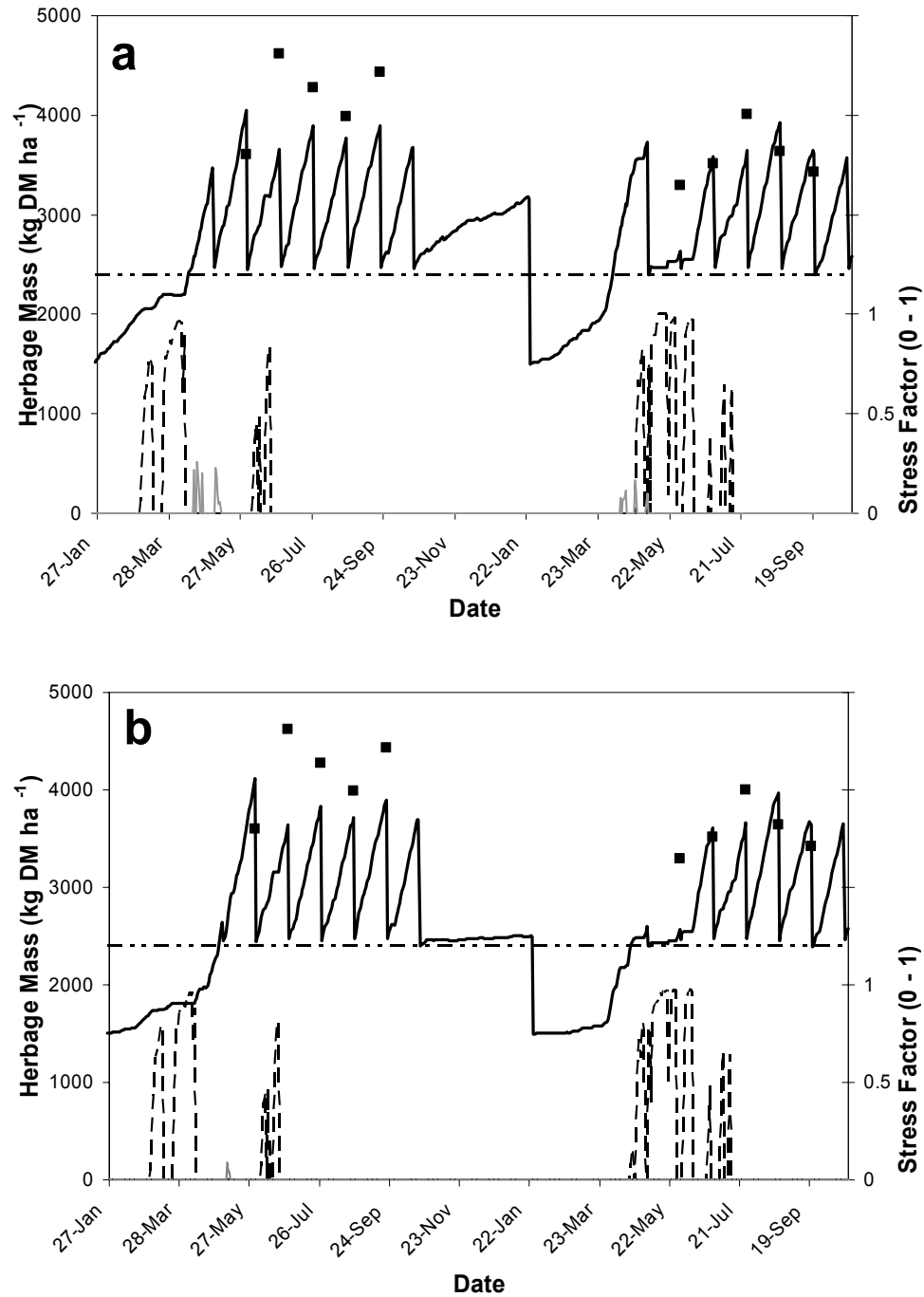


Figure 4-5. Observed herbage mass (■), predicted herbage mass (—), water stress (---), and N stress (—) of bahiagrass grown with 468 kg N ha<sup>-1</sup> yr<sup>-1</sup> at Ona, FL, using the optimized species file with a winter defoliation, 70% reduction in winter photosynthetic rate, and **a**) the leaf-level photosynthesis option or **b**) daily canopy photosynthesis option. Predicted stress factors are 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.

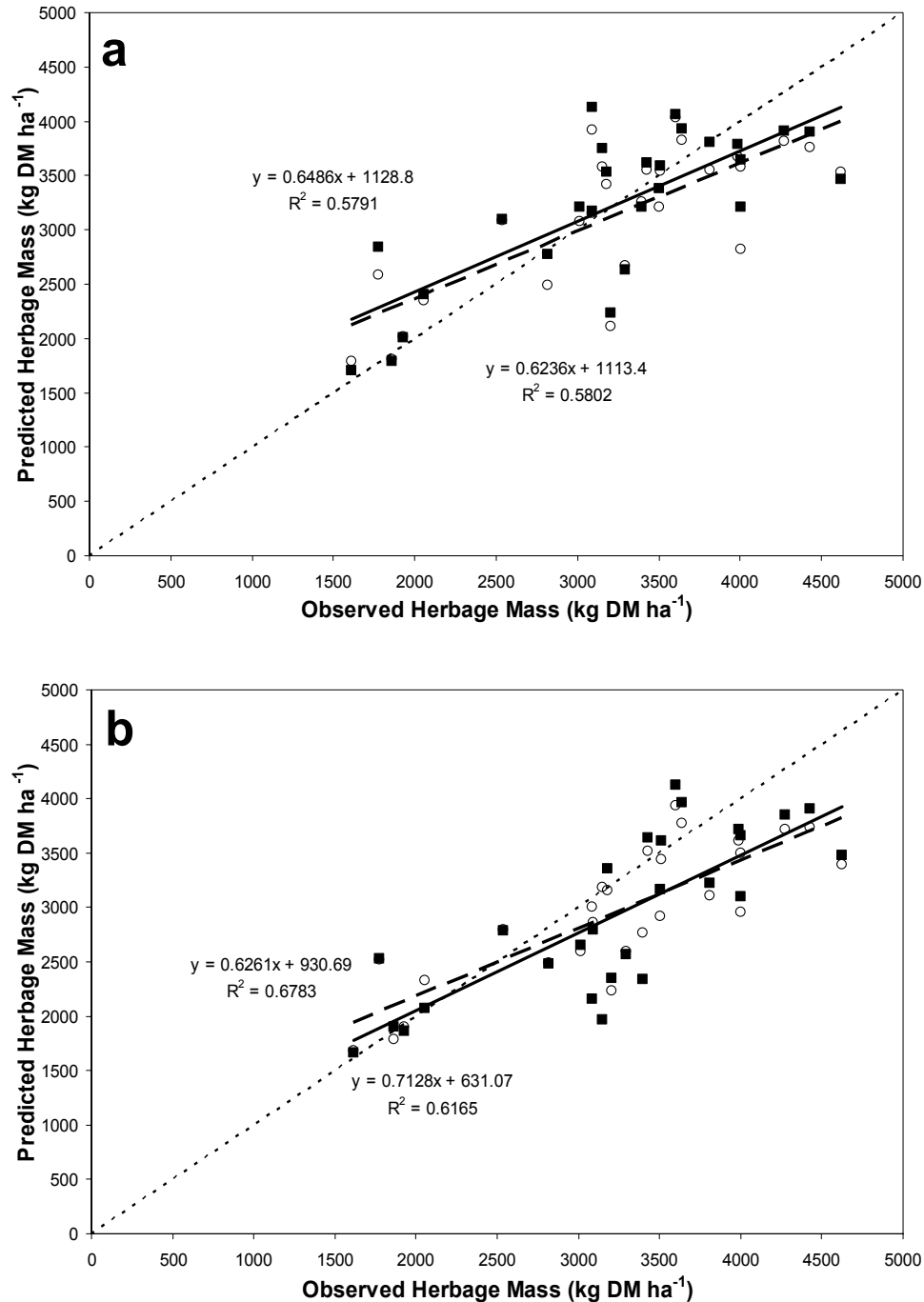


Figure 4-6. Predicted vs. observed herbage mass of bahiagrass grown with 468 kg N ha<sup>-1</sup> yr<sup>-1</sup> at Ona, FL, and 168 kg N ha<sup>-1</sup> yr<sup>-1</sup> at Eagle Lake, TX, using **a**) the leaf-level photosynthesis option, or **b**) daily canopy photosynthesis option. Both options included a 70% reduction of photosynthetic rate over the winter. Plots for both the literature-based (○) and optimized (■) species files are presented. Linear regression lines for preliminary (— —) and optimized (—) species files are presented with their corresponding equations and  $r^2$  values along with a line designating a theoretical 1:1 relationship is (.....).

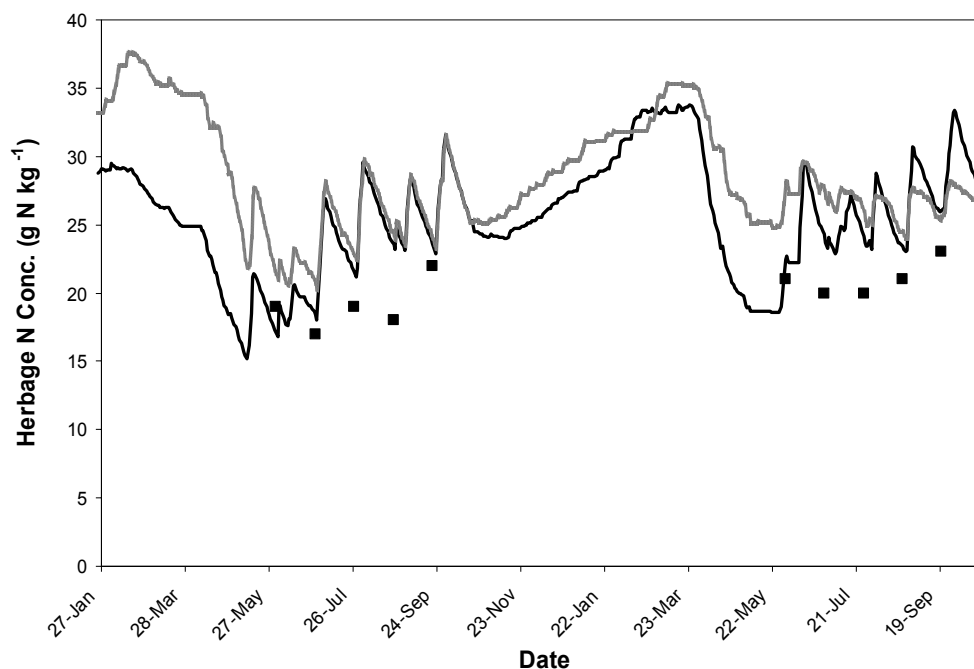


Figure 4-7. Observed herbage N concentration (■) and predicted herbage N concentration of bahiagrass grown with 468 kg N ha<sup>-1</sup> yr<sup>-1</sup> at Ona, FL, using the optimized species file and the leaf-level option (—) or daily canopy photosynthesis option (—).

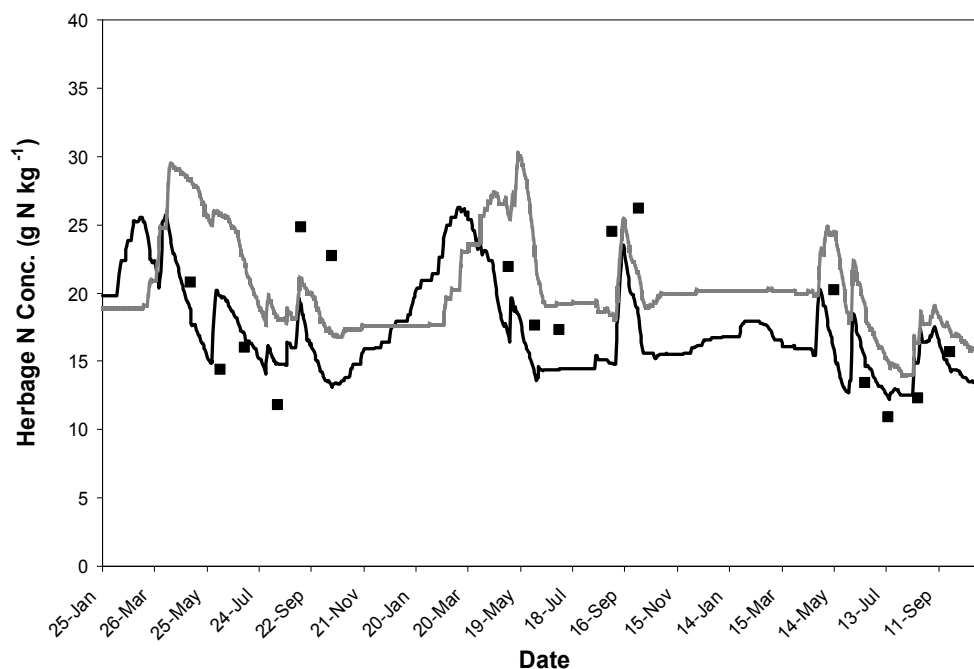


Figure 4-8. Observed herbage N concentration (■) and predicted herbage N concentration of bahiagrass grown with 168 kg N ha<sup>-1</sup> yr<sup>-1</sup> at Eagle Lake, TX, using the optimized species file and the leaf-level option (—) or daily canopy photosynthesis option (—).

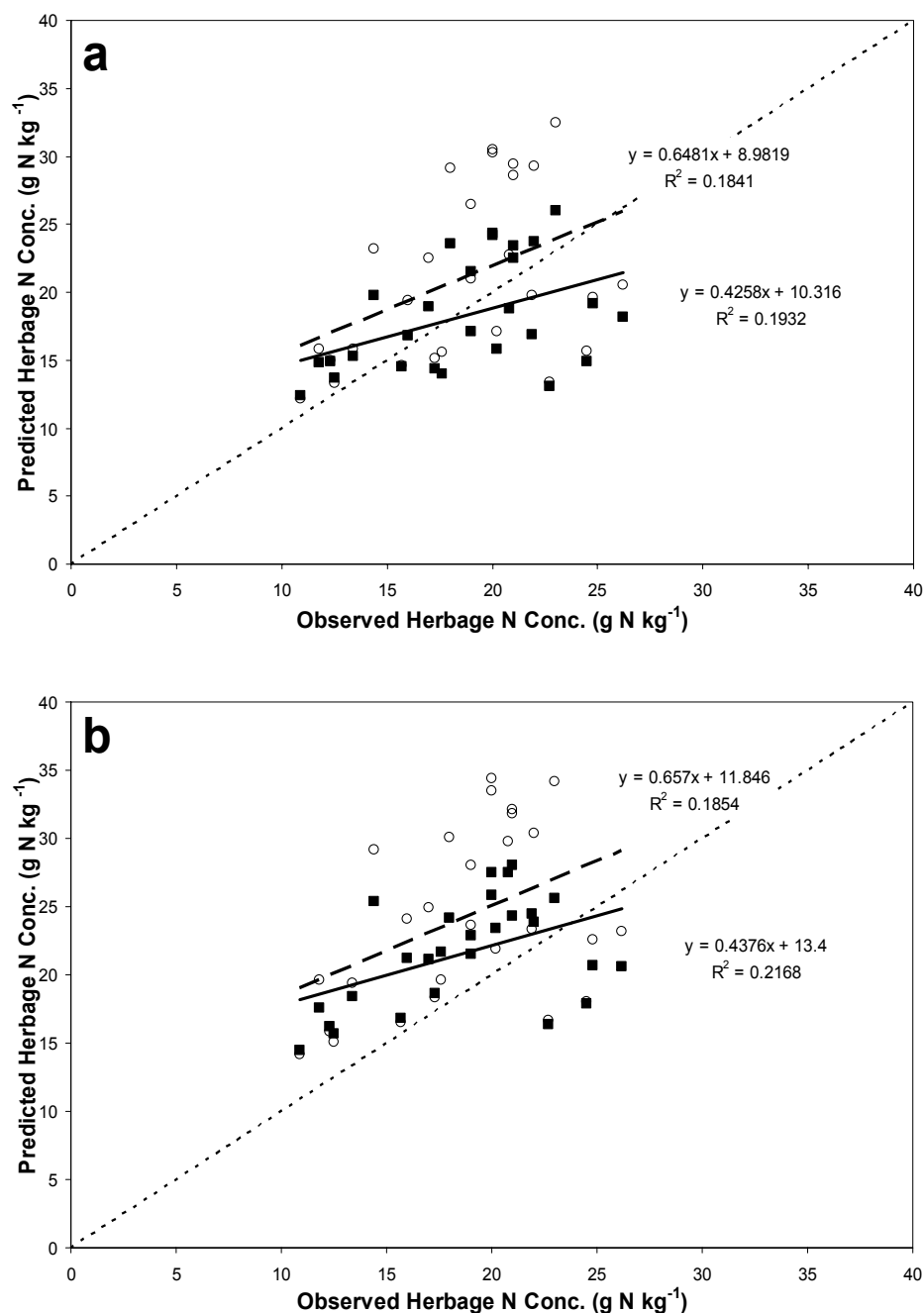


Figure 4-9. Predicted vs. observed herbage N concentration (g kg<sup>-1</sup>) of bahiagrass grown with 468 kg N ha<sup>-1</sup> yr<sup>-1</sup> at Ona, FL, and grown with 168 kg N ha<sup>-1</sup> yr<sup>-1</sup> at Eagle Lake, TX, using **a)** the leaf-level photosynthesis option, or **b)** the daily 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 (---) and optimized (—) species files are presented with their corresponding equations and  $r^2$  values along with a line designating a theoretical 1:1 relationship is (.....).

CHAPTER 5  
ADAPTING CROPGRO TO MODEL PERENNIAL TROPICAL GRASSES:  
STRUCTURAL CHANGES TO THE MODEL

**Introduction**

A model capable of predicting forage yield and composition would be useful in developing harvest management strategies to improve nutrient management on farms and to assist in matching harvested forage composition with animal requirements. The current approach of basing harvest schedules for tropical grasses like bahiagrass (*Paspalum notatum* Flüggé) and bermudagrass [*Cynodon dactylon* (L.) Pers.] on fixed regrowth periods is inflexible and too generalized to be useful in planning or testing new strategies tailored to more specific needs. A crop model that will predict responses of both yield and forage composition to changing environmental conditions and management inputs could be useful for comparing several management systems to determine the best fit for a particular situation. Likewise, such a tool could aid researchers and extension personnel selecting best management practices (BMPs) and developing management recommendations by allowing them to test the practices virtually, and using the knowledge of that experience to design better field experiments. In so doing, the development process may be accelerated and costs reduced. If the model proves accurate and consistent enough, it could be used to support management decisions and nutrient management plans, allowing managers and planners more freedom in responding to conditions and designing plans than being limited to an approved list of BMPs.

The CROPGRO model fits these general qualifications. It is a process-oriented model that uses daily weather and management inputs to predict daily changes in plant composition and growth. Plant composition components that are predicted by the model include CP, carbohydrate (cell wall and starch), lipid, lignin, organic acid, and ash.

Growth and yield components predicted are leaf, stem, seed, and root mass.

Additionally, the model includes soil organic matter, N, and water balance simulation, thus providing information on N cycling, uptake, and losses. CROPGRO has already been adapted to model several different species including soybean (*Glycine max* L.), peanut (*Arachis hypogaea* L.), dry bean (*Phaseolus vulgaris* L.), faba bean (*Vicia faba* L.), and tomato (*Lycopersicon esculentum* Mill.) (Scholberg et al., 1997; Boote et al., 1998a, 1998b, 2002). Generally, CROPGRO can be adapted to model a species by

developing new input files containing species, cultivar, and ecotype parameters appropriate to that species. In a previous chapter we used this approach to adapt CROPGRO to model the C<sub>4</sub> perennial grass, bahiagrass, with some degree of success.

However, in the adaptation process several areas were identified where the CROPGRO model structure either was lacking a critical process or did not adequately describe a process related to perennial tropical or subtropical grass growth (Rymph et al., 2003).

Addressing these processes required modification of the existing CROPGRO code. Our objective in this research was to improve CROPGRO prediction of bahiagrass growth and composition by adding or modifying the code to add a storage organ (e.g., stolon or rhizome) to the model structure, add a dormancy process to alter partitioning of growth and mobilization of N during the winter, alter the freeze damage routine to allow partial loss of leaves and stems to freezing temperatures, and modify the leaf photosynthesis



mechanism to accommodate the effects of the CO<sub>2</sub>-concentrating mechanisms in C<sub>4</sub> photosynthesis. These modifications will be specific to perennial forage crops and warrant a new designation for the model. The modified model will be referred to as the forage version of CROPGRO and treated as a separate entity rather than an incremental improvement of the original model.

### **Materials and Methods**

The CSM version of CROPGRO, distributed as part of DSSATv4 (Hoogenboom et al., 2003) served as the base model for these modifications. Besides being the most recent version of CROPGRO, this version includes a soil organic matter (SOM) decomposition and mineralization option based on the CENTURY SOM model (Gijssman et al., 2002). This option was essential for simulating bahiagrass growth under low input or low N fertilization systems. Previous versions of CROPGRO used an SOM option that did not include decomposition of residue on the soil surface, an important element of the N-cycling dynamics in perennial forage systems. The CSM version is also structured to compartmentalize different plant processes into individual modules. New processes may be added by writing new modules and linking them to the rest of the model. The new dormancy process was added in this way. The freeze damage module was modified for progressive freeze damage as well. However, adding the STOR organ was a more comprehensive change, requiring modification of several of the modules.

Species-specific parameters for bahiagrass developed for the CSM version (Rymph et al., 2003) were used in the forage version as well. Where possible, values for any new parameters were derived from measurements reported in the literature. Where data for a process were not available, parameters were estimated by calibration of model performance to data compiled from several experiments. Primary calibration was done at

the process level. New model functions were written and plotted in MathCad (MathSoft, 1998) and the parameters adjusted to match the response reported in the literature or observed in the test data. The Mathcad equations were rewritten in Fortran and incorporated into CROPGRO. The model was then used to simulate each of the experiments that we had assembled. Parameters that could not be modeled in Mathcad, such as the fraction of new growth partitioned to the new storage organ (STOR) and the senescence rate of STOR, were adjusted to fit the CROPGRO predictions to the observed data or to at least provide realistic patterns of growth. Model performance was evaluated by comparing the predictions from the simulations to the results of actual experiments. Several measures of model fit were calculated to aid in the evaluation. These included the mean of all observations, mean of all corresponding predicted values, slope, intercept, and  $r^2$  of the linear regression of predicted values against observed data, index of agreement (d-index) (Willmott, 1981; 1982), and root mean square error (RMSE).

Data from five experiments conducted at two sites in Florida and one site in Texas were compiled for use in calibrating the new parameters. Combined, these experiments provided 303 measurements of forage mass and 227 measurements of forage CP. Only a brief description of each study will be presented here as more complete descriptions of each study may be found in their original publications (Evers, 1985; Boote et al., 1999; Gates et al., 2001; Johnson et al., 2001; Rymph and Boote, 2002).

**Eagle Lake, TX 1979-1981 (Evers, 1985)** (29° 35'N, Lon 96° 20'W) This experiment reported forage yield from Pensacola bahiagrass pastures fertilized with annual rates of 0, 84, 168, 252, or 336 kg N ha<sup>-1</sup>. All treatments were harvested monthly

from May to October. Forage DM yield and crude protein (CP) concentration were measured at each harvest.

**Gainesville, FL 1995-1998 (Boote et al., 1999)** (29° 38' N, 82° 22' W) Pensacola bahiagrass was grown in temperature/CO<sub>2</sub> gradient greenhouses and in outside plots. Temperature and CO<sub>2</sub> concentration treatments were: baseline temperature (near ambient temperature) and baseline temperature + 1.5°, 3.0°, or 4.5°C under either ambient (360 µL CO<sub>2</sub> L<sup>-1</sup>) or double ambient (700 µL CO<sub>2</sub> L<sup>-1</sup>) CO<sub>2</sub> concentrations. Forage DM yield, forage CP concentration, leaf CP concentration, stem+stolon CP concentration, leaf area index, root mass, and stem+stolon mass were reported for various harvests.

**Gainesville, FL 2001 (Rymph and Boote, 2002)** (29° 38' N, 82° 22' W) This was a bahiagrass growth study. Irrigated Pensacola bahiagrass was fertilized at an annual rate of 312 kg N ha<sup>-1</sup>. There were two 8-wk growth periods, 18 July – 12 September and 12 September – 7 November with weekly digging of sod cores. Sod cores were separated into leaf, stem, root, and stolon. Leaf, stem, stolon, and root mass were reported as well as herbage mass (calculated as the sum of leaf and stem mass).

**Ona, FL 1993-1995 (Gates et al., 2001)** (27° 25'N, 81° 55'W) Pensacola bahiagrass was harvested between September and April for two consecutive growing seasons. Treatments were staggered in time with initial harvests starting on 30 September, 15 October, 30 October, 14 November, 14 December, 13 January, 12 February, 27 February, 14 March, 29 March, and 13 April. The 14 December through 27 February treatments had been staged 30 d prior to harvest while all other harvests were staged 15 d prior to the harvest. The 30 September through 14 November treatments were all harvested a second time on 14 December while all later treatments were

harvested on 13 April. Thus 10 treatments were harvested twice and the regrowth interval between the first and second harvest varied from 0 to 120 d. The 13 April treatment was harvested only once. Forage DM yield was measured for all winter harvests and forage CP concentration was measured for the harvests in the 1994-1995 winter season only.

**Ona, FL 1996-1998 (Johnson et al., 2001).** (27° 25'N, 81° 55'W) Non-irrigated bahiagrass was grown in the field with five N fertilization treatments (0, 39, 78, 118, and 157 kg N ha<sup>-1</sup> cutting<sup>-1</sup>), equivalent to annual applications of 0, 234, 468, 708, and 942 kg N ha<sup>-1</sup>. Forage DM yields and CP concentrations were measured for five harvests each season for two seasons. All treatments were staged by mowing in early May each year and harvested every 28 d until October.

To compare the predicted herbage mass (leaf and stem mass from the surface of the ground to the top of the canopy) values generated by CROPGRO to the forage mass (leaf and stem mass from the cutting height to the top of the canopy) reported in most of these studies, we converted the reported forage mass to herbage mass. Estimates for stubble mass left under 3.5-, 5-, 7.5-, and 10-cm cutting heights were 1500, 1800, 2400, and 3000 kg DM ha<sup>-1</sup> and were determined using data from several studies (Beaty et al., 1968; Pedreira and Brown, 1996b; Rymph and Boote, 2002). The estimated stubble mass was added to the reported forage mass to estimate total above-ground herbage mass and this was used as the observed data for comparison with the model predictions. The following terms will be used in the discussion of the model calibration: herbage mass to indicate the total leaf and stem mass from the soil surface to the top of the canopy, herbage N

concentration indicating the N concentration in the herbage mass, and herbage N mass being the product of herbage mass and herbage N concentration.

## **Results and Discussion**

### **Storage Organ**

In previous attempts to model bahiagrass in CROPGRO, we had grouped stolons with the roots (Rymph et al., 2003) to fit the model structure. Combining the two organs confounded their different patterns of growth and mobilization and required considerable modification of the root length density (cm of roots per g of roots) parameter to control water and N uptake capacity. The prodigious amount of stolon mass produced by bahiagrass made this no small problem. Thus, new code was added to include a storage organ representing stolons, rhizomes, or crowns (STOR) to the model structure. As STOR represents stolons in bahiagrass, we will refer to actual plant storage tissue as stolons in this chapter and the model variable name as STOR. For brevity, this discussion will concentrate on the differences between the existing CROPGRO model and our forage version rather than the overall function of CROPGRO. A more thorough description of the structure of the CROPGRO model can be found in works by Boote et al. (1998a, 1998b) and Boote and Pickering (1994) as well as in the documentation for DSSAT version 4 (Hoogenboom et al., 2003) which includes CROPGRO.

Although stolons may give rise to new tillers, their role as a sink and source of N for regrowth of the plant suggests they be classified as vegetative organs rather than reproductive. The reproductive role of the storage organ is recognized in the revised freeze-damage routine where the simulation is not terminated as long as there is storage organ tissue remaining, recognizing the role of the organ in initiating regrowth. For the most part, the new code for STOR is a duplication of the existing leaf and stem code,

although partitioning of new growth to STOR is regulated somewhat differently and there are some added provisions for the new dormancy process.

The normal rate of partitioning to stolons is defined by the parameter YSTOR, an array containing a series of rates (fractions) corresponding to a progression of V-stage values held in another array (XLEAF). Through use of a lookup function, partitioning will vary with stage of maturity. Once vegetative development ceases, the partitioning fraction to STOR is set to a single value (FRSTRF). All three parameters are read from the species parameter file (species file). This file is one of three external input files containing parameter values used in the model to define plant responses to the environment and management (the other files are the cultivar and ecotype files with cultivar and ecotype-specific parameters). Partitioning to, and mobilization from, STOR are not directly affected by N or water stresses; however, there is an indirect effect as those stresses increase partitioning of growth to root at the expense of leaf, stem, and STOR growth. Dormancy may increase partitioning of new growth to STOR during the short-daylength months. The decision points and information flow for partitioning are depicted in the flowchart in Figure 5-1 which will be discussed in more detail in the dormancy section that follows.

Mobilization of available carbohydrate ( $\text{CH}_2\text{O}$ ) and N from leaves and stems is unchanged in the forage version of CROPGRO. Mobilization of  $\text{CH}_2\text{O}$  and N from STOR relies on a similar approach but is modified to increase mobilization and accelerate regrowth when LAI is low and/or vegetative (leaf, stem, root, and STOR) N-status is high. Rather than sharing a common mobilization parameter with leaves, stems, and roots, the “normal” fraction of available  $\text{CH}_2\text{O}$  and N that can potentially be mobilized

from STOR is set by independent parameters, CMOBSRN and NMOBSRN, in the species file. If LAI is below 3.0 or if vegetative N-status greater than 0.3, the “actual” fraction of  $\text{CH}_2\text{O}$  and N that can potentially be mobilized will be between the “normal” fraction (CMOBSRN, and NMOBSRN) and their maximum fractions (CMOBSRX and NMOBSRX) set in the species file. These fractions can also be decreased if dormancy has been induced. The decision points and information flow controlling mobilization responses are described in Figures 5-2 ( $\text{CH}_2\text{O}$ ) and 5-3 (N), while the calculations are discussed in more detail in the following section on dormancy.

Like leaves and stems, STOR also senesces as the plant ages. The senescence rate is set by the species parameter SENSR and is a function of age/temperature (physiological days/day), the same factors that influence senescence of leaves, stems, and roots. Water and N stress do not affect the senescence rate of STOR. The vegetative stage of maturity (VSTAGE) does not decrease as leaves are senesced.

The fraction of new growth allocated to STOR was estimated to vary from 30% for young plants (VSTAGE 3.0) up to 45% for older plants (VSTAGE >7.0) with a maximum partitioning of 90% of new growth during dormancy. These partitioning rates were derived primarily from data of  $^{14}\text{C}$  experiments conducted by Beaty et al. (1974) showing 33%-63% of  $^{14}\text{C}$  translocated in bahiagrass plants was found in the stolons. The 90% maximum partitioning parameter during peak dormancy was determined by running the model and varying the fraction until leaf and stem growth were reduced to expected levels during the winter. The targeted level of STOR mass was between 8000 and 16 000  $\text{kg DM ha}^{-1}$ . These levels were consistent with data for combined root and stolon mass in Pensacola bahiagrass ranging from 16 500 to 24 000  $\text{kg DM ha}^{-1}$  reported by Impithuksa

and Blue (1985) and 9300 – 15 150 kg DM ha<sup>-1</sup> reported by Beaty et al. (1975). These levels are higher than the measured rhizome weights of 2900 – 9800 kg rhizome DM ha<sup>-1</sup> of Beaty et al. (1964) for Pensacola bahiagrass; however, they also reported an additional 4200 – 10 600kg DM ha<sup>-1</sup> of “miscellaneous” material which likely was primarily senescing and decomposing rhizomes. With the partitioning set as listed above, the STOR senescence rate was set at 1.5% d<sup>-1</sup> to produce the targeted levels of STOR.

There were two experiments in our compilation of experiments that measured stolon mass and, thus, were available for evaluating the model’s prediction of STOR. Of the two experiments, only Rymph and Boote (2002) measured solely stolons. These data were used for evaluating the fit of the predictions (Table 5-1) while the data from Boote et al. (1999) which combined stems with stolons, were used to provide information on the potential range of stolon mass found in the field. Despite having only 19 data pairs in the evaluation, the fit of the predicted values was quite good with a slope of 0.81 and an  $r^2$  of 0.86 for the linear regression of predicted to observed data. The index of agreement or d-index was low in relation to those parameters at 0.615 (a d-index of 1.0 indicates perfect agreement), likely because the model consistently overpredicted stolon mass (Figure 5-4). Increasing the stolon senescence rate or shifting some of the partitioning from stolon to root would have lessened the overprediction and possibly improved the prediction of roots (Table 5-1); however, compared to the stolon + stem data of Boote et al. (1999), the model consistently underpredicted stolon mass. The extent of this underprediction easily exceeded any anticipated level of stem mass that was included in the measurements. Given those opposing results, the parameters were left as described and not optimized further.



## Dormancy

Several studies have reported a seasonal decline in forage yield of bahiagrass and bermudagrass in the fall and winter months despite the relatively mild temperatures of the Southeast (Burton et al., 1988; Gates et al., 2001; Chambliss, 2002; Sinclair et al., 2003). Winter dormancy in *Bouteloua gracilis* has been modeled as a function of low soil temperatures (Detling et al., 1979); however, studies by Sinclair et al. (2003) demonstrated a controlling role of daylength in triggering the dormancy response. Gates et al. (2001) and Sinclair et al. (2003) reported the greatest reductions in yield to occur in mid-winter, indicating that the degree of dormancy may increase with decreasing daylength.

The exact mechanism of dormancy has not been described. There are no reports of significant reductions in photosynthetic rate beyond the expected effects of cooler temperatures. Assuming that herbage growth is reduced to a greater degree than photosynthetic rate, photosynthate must be diverted elsewhere. DiPaola et al. (1982) reported an increase in root mass of turf-type bermudagrass for a short period in the fall after shoot growth had ceased, then root growth ceased as well. Sinclair et al. (2003) found no difference in below-ground biomass growth of bahiagrass between natural daylength and extended daylength treatments but did observe a higher proportion of leaves to total plant mass during the short-daylength months in the natural daylength treatments. Although Sinclair et al. (2003) did not report specifically on stolon growth, Rymph and Boote (2002) observed a sharp increase in bahiagrass stolon mass in October and November in Gainesville, FL. Given this information, the most likely sink for bahiagrass photosynthate production during dormancy is the stolons. Thus, the dormancy process model added to CROPGRO increases partitioning to and decreases mobilization

from the stolon. Increasing partitioning to STOR provides a sink for assimilate that results in decreased apparent above-ground shoot production during the winter and will also serve as a N source after dormancy. Minimizing mobilization of N from STOR during dormancy curbs the regrowth rate of the shoot. Parameters were added to allow a dormancy effect on photosynthesis in the event that evidence is presented supporting that phenomenon. For the present time, that feature has been disabled by assigning a constant value of 1.0 to this factor so it will not modify photosynthetic rate.

The dormancy process in the forage version of CROPGRO has a partitioning component (Fig. 5-1) and mobilization components (Figures 5-2 and 5-3), each of which is modeled independently. These processes have their own daylength thresholds for initiating/ending dormancy and for imposing maximum dormancy, and they have their own parameters defining the pattern of dormancy. These parameters are defined in the species file but another ecotype-specific parameter can scale the degree of dormancy exhibited, to create differential responses of individual ecotypes if needed.

As illustrated in Fig. 5-1, the “normal” fraction of new growth partitioned to STOR (FRSTR) is set through a lookup-table matching the current V-stage to the fraction of new growth to be partitioned to leaf, stem, and STOR. Partitioning to root is then calculated by difference with all fractions summing to 1.0. When daylength is less than 12.5 h, dormancy is progressively induced and partitioning to STOR is increased above the “normal” fraction to reflect a diversion of growth away from leaf and stem to stolon. When daylength is above 12.5 h, the dormancy partitioning factor (PPTFAC) is set to 0.0 and partitioning to STOR is not affected. As daylength drops below 12.5 h and approaches the maximum dormancy threshold of 10.5 h, PPTFAC increases linearly to

1.0 (Figure 5-5), increasing the partitioning of new growth towards the maximum fraction specified in the species file (FRSTRMX) using the equation:

$$\text{FRSTR} = (\text{FRSTRMX} - \text{FRSTR}) * \text{PPTFAC} + \text{FRSTR} \quad (\text{Eq. 5-1})$$

where FRSTR is the fraction of new growth partitioned to STOR (initially set by V-stage), FRSTRMX is the maximum fraction partitioned to STOR under maximum dormancy (0.90), and PPTFAC is the dormancy adjustment factor for partitioning to STOR. Using the current parameters and the scheme in Fig. 5-1, if the crop is at V-stage 7.0, FRSTR is 0.40 or 40% of the new growth would normally be partitioned to the STOR organ, 35% would be allocated to roots, 20% to leaves, and 5% to stems. If the daylength is 11.5 h; however, PPTFAC is 0.5, and the adjusted partitioning to STOR would be  $[(0.90 - 0.40) * 0.5 + 0.40]$  or 0.65 and 65% of all growth would be partitioned to STOR. With this increase in FRSTR, partitioning to the other vegetative organs must be recalculated. The relative proportions of “normal” allocation to leaf, stem, and root are used to calculate the reduced partitioning fractions to non-STOR organs as follows:

$$\text{TFRLF} = \text{FRLF} / (\text{FRLF} + \text{FRSTM} + \text{FRRT}) * (1 - \text{FRSTR}) \quad (\text{Eq. 5-2})$$

where TFRLF is a temporary variable holding the new, reduced fraction of new growth partitioned to leaf, FRLF is the “normal” fraction of new growth partitioned to leaf, FRSTM is the “normal” fraction of new growth partitioned to stem, and FRSTR is the fraction of new growth partitioned to STOR after being adjusted for dormancy. Using

the example listed above, the original 20% fraction of new growth partitioned to leaves becomes  $[0.20/(0.20+0.05+0.35)*(1-0.65)]$  or 12%. Stem partitioning is adjusted using a similar equation and root partitioning is calculated by difference so that all fractions add to 1.0 or 100%. Thus, the new stem partitioning fraction would be  $[0.05 / (0.20+0.05+0.35) * (1-0.65)]$  or 3% and the fraction partitioned to root would be 20%. Once adjusted for dormancy, partitioning among organs is only affected by water-stress and N-stress; both of which increase partitioning of new growth to roots, and, consequently, decrease partitioning to leaves, stems, and STOR (Figure 5-1).

Separate flowcharts depict decision points and the flow of information for  $\text{CH}_2\text{O}$  mobilization (Figure 5-2) and N mobilization (Figure 5-3). Potential mobilization of  $\text{CH}_2\text{O}$  and N is a function of the “normal” fraction mobilized, maximum fraction mobilized, LAI, vegetative N-status, and stage of dormancy or daylength. On each simulation day, mobilization adjustment factors are calculated from the current LAI, vegetative N-status (leaf, stem, root, and STOR), and daylength. These adjustment factors are calculated from separate functions defined in the species file. Depending on the daily values of these factors, the fraction of  $\text{CH}_2\text{O}$  and N that can potentially be mobilized from STOR can range from 10% of the normal potential mobilization rate (CMOBSRN, NMOBSRN) to a maximum rate (CMOBSRX, NMOBSRX) defined in the species file. The calculation of the potential fraction of N mobilized is a three-step process and while the day’s potential fraction of mobilizable  $\text{CH}_2\text{O}$  and N are calculated independently, they both use the same basic equations. The N mobilization calculations will be used as an example for both nutrients. The N-status adjustment factor (VNMOBR) is applied as follows:

$$\text{NMOBSR} = (\text{NMOBSRN} + (\text{NMOBSRX} - \text{NMOBSRN}) * \text{VNMOBR}) \text{ (Eq. 5-3)}$$

where NMOBSR is the fraction of available N that can potentially be mobilized from STOR on the current day, NMOBSRN is the “normal” fraction of available N that can be mobilized from STOR, NMOBSRX is the maximum fraction of available N that is potentially mobilizable, and VNMOBR is the N-status factor (ranging from 0.0 to 1.0). Vegetative N-status is calculated as the current N mass of the leaves, stems, roots, and STOR relative to the maximum potential N mass if all four organs contained their maximum (new growth) N concentrations. This factor may have a value ranging from a minimum of 0.0 (no increase in potential N or CH<sub>2</sub>O mobilization when N-status is 30% of maximum or lower, increasing in a curvilinear pattern to 1.0 (maximum CH<sub>2</sub>O and N mobilization) as N-status approaches 70% of maximum (Figure 5-6a). Thus, potential mobilization of N from STOR may remain at NMOBSRN if VNMOBR is 0.0 and increases towards NMOBSRX as VNMOBR approaches 1.0.

Next, NMOBSR is updated to reflect the LAI and dormancy adjustment factors:

$$\text{NMOBSR} = (\text{NMOBSR} + (\text{NMOBSRX} - \text{NMOBSR}) * \text{LAIMOBR}) * \text{PPMFAC} \text{ (Eq. 5-4)}$$

where LAIMOBR is the LAI adjustment factor (ranging from 0.0 to 1.0) and PPMFAC is the dormancy or daylength factor (ranging from 0.1 to 1.0) controlling mobilization. The LAI adjustment factor (LAIMOBR) has a value of 0.0 (no increase in potential mobilization) when LAI is greater than 3.0 and increases to 1.0 (maximum potential

mobilization) as LAI decreases to 1.0 or below (Figure 5-6b). If VNMOBR is 1.0, or LAIMOBR is 0.0, then LAIMOBR has no effect; however, if VNMOBR is less than 1.0 and LAIMOBR is greater than 0.0, then the fraction of available N potentially mobilized increases from the value of NMOBSR calculated in equation 5-3. For NMOBSR to equal NMOBSRX either VNMOBR or LAIMOBR or both factors must have a value of 1.0.

The dormancy factor, PPMFAC, is applied after all other adjustments are made and acts as a scalar, decreasing potential mobilization from STOR as daylength decreases below a dormancy threshold. If daylength is greater than 12.5 h, PPMFAC is set to 1.0 and there is no effect of dormancy on mobilization (the adjusted fraction is multiplied by 1.0). As daylength decreases from 12.5 h to 10.5 h, PPMFAC decreases linearly from 1.0 to 0.1. This decreases the potential mobilization fraction proportionally (e.g., if daylength is 11.4 h, PPMFAC will be 0.5, and the fraction of available N that is potentially mobilizable will be 50% of what would be mobilized if only adjusted for LAI and N-status). As daylength decreases below 10.5 h, maximum dormancy is achieved and PPMFAC remains at 0.1. The daylength thresholds for initiation of dormancy and maximum dormancy as well as the minimum and maximum value for PPMFAC are defined in the species file and, hence, may be adjusted for other species. There is also an ecotype-specific parameter in the ecotype file that allows for differences in various ecotypes' dormancy responses relative to the species response.

Potential mobilization of  $\text{CH}_2\text{O}$  and N from roots is also reduced by PPMFAC during dormancy to control depletion of root reserves and root mass over the winter. Reducing the fraction of  $\text{CH}_2\text{O}$  and N that can potentially be mobilized preserves STOR and root mass for spring regrowth and, sometimes, reduces leaf and stem growth rates

during dormancy. Mobilization rates of leaf and stem reserves are unaffected by these dormancy factors although the amount of mobilization may increase due to the limitations placed on STOR and root mobilization. It should be stressed that this discussion addresses the fraction of  $\text{CH}_2\text{O}$  and N that can potentially be mobilized in a day. The fraction actually mobilized in the model depends on daily photosynthate production, N uptake, and crop N demand as well as the actual pool of  $\text{CH}_2\text{O}$  and N that can be mobilized.

Running simulations with the forage version, the partitioning and mobilization factor values cycled through the seasons, initiating dormancy on September 1, reaching maximum dormancy on November 22 then lessening the degree dormancy on January 19 until completely breaking dormancy on April 9 (Figure 5-5b). To evaluate the accuracy of herbage mass predictions during dormancy, we simulated the cool season bahiagrass yield experiment from Ona, FL (Gates et al., 2001) and compared model predictions of herbage mass to the measured results. Although the  $r^2$  of the linear regression of the predicted data against the observed was only 0.29 (Figure 5-7), the other measures of model fit were quite positive. The slope of the linear regression was nearly 0.8 and the intercept was  $494 \text{ kg DM ha}^{-1}$ , indicating systematic error was relatively small. The mean of the predicted herbage mass was  $2160 \text{ kg ha}^{-1}$  (data not shown) and was quite low compared to summer harvests at other locations and is also very close to the mean of the observed values of  $2100 \text{ kg ha}^{-1}$ . Other statistical indicators were promising with a d-index of 0.68 and an RMSE of  $291 \text{ kg DM ha}^{-1}$  using 41 data pairs in the analysis.

The dormancy factors were effective in reducing herbage yield during the winter, which reduced the water stress predicted in the spring compared to levels predicted by the

previous CSM model. Despite the reduced winter growth, spring water stress was still predicted in experiments where there should have been none. Modification of the code for modeling evapotranspiration (ET) may be required to correct this. The current ET model uses a daily energy balance approach (Priestley-Taylor) and is linked to photosynthesis only if evaporative demand exceeds potential root water uptake. There is no feedback from low photosynthesis (in winter months) to transpiration as may actually occur via stomatal regulation effects. While photosynthate production was limited by the reduced leaf growth in the forage version, ET still responded to the mild winter temperatures with potentially excessive rates of water loss.

### **Freeze Damage**

Freezing temperatures can cause two types of damage in the unmodified existing CROPGRO. If temperatures drop to a sub-lethal threshold (FREEZ1), all leaves on the plants are killed, if temperatures fall to the lethal threshold (FREEZ2), all plants are killed and the simulation is terminated. Earlier experiences in deriving species parameters for bahiagrass (Rymph et al., 2003) showed that plants would not recover from even a FREEZ1 event. Inspection of the code revealed that while  $\text{CH}_2\text{O}$  and N from the roots could be mobilized, there was no photosynthesis (no leaf area after freeze) and the mobilized  $\text{CH}_2\text{O}$  was expended on maintenance respiration and N uptake. With no assimilate left, N uptake went to refill N depleted tissues and no new growth occurred. Eventually the simulated crop exhausted  $\text{CH}_2\text{O}$  reserves and died. Adding stolon (STOR) with large pools of carbohydrate and N, as well as decreasing maintenance respiration coefficients, helped solve the problem of allowing regrowth. In addition, peripheral changes were made to correct  $\text{CH}_2\text{O}$  and N allocation in the model in general to restrict  $\text{CH}_2\text{O}$  use for N demand and refill of N-depleted tissue when total growth is



low as it is after total leaf area loss. These changes are not directly related to the adaptation of the model for bahiagrass and will be addressed in another venue.

The freeze damage routine in CROPGRO needed to be more flexible for modeling forage crops. While we kept the two freeze threshold parameters, FREEZ1 and FREEZ2, we added a progressive leaf damage process as well as a cold-hardening routine to allow gradual loss of leaves and increased freeze tolerance with exposure to cold temperatures. For these changes we adapted the approach used by Kanneganti et al. (1998) in the ALFACOLD model.

The FREEZ1 parameter was re-defined here as the temperature that triggers the onset of freeze damage to leaves and stems (previously it resulted in killing of all foliage, and thus eliminating photosynthesis). Temperatures below FREEZ1 result in leaf and stem death at a fraction defined by a freezing death-constant parameter (FRZDC) in the species file. The death-constant defines the proportion of leaf and stem killed on a given day for each degree that the minimum daily temperature (TMIN) drops below FREEZ1. Plants will survive for a period with no living leaves if the STOR tissue has not been killed. The FREEZ2 parameter is still the lethal temperature threshold that kills all plants and ends the simulation. With the addition of the STOR tissue, FREEZ2 now reflects the TMIN required to kill the STOR tissue, which may be protected in the top layer of soil. When FREEZ2 is reached, all STOR tissue is killed, currently there is no gradual killing of STOR. However, a cold hardening process for STOR tissue only was added that will allow plant survival below this temperature if the crop exhibits cold-hardening and has been previously exposed to cold temperatures (Fig. 5-8). The degree of tolerance increases with added exposure to cold temperatures and is reversed by warm

temperatures. A dehardening process begins when daylength begins to increase. Dehardening reduces the degree of cold-hardening and operates using temperature thresholds defined in the species file separate of the cold-hardening thresholds. Thus, it is possible for a crop to experience cold hardening and dehardening at the same time. As there is no evidence of a significant cold hardening effect on bahiagrass, the cold hardening process was disabled by setting all related parameter values to  $-25^{\circ}\text{C}$ , a temperature below that experienced in our calibration datasets. As the cold-hardening function was not used for bahiagrass, discussion of its function will be limited to that already presented along with a flowchart (Figure 5-8) depicting decision points and information flow related to calculating the degree of cold hardening and adjustment of FREEZ2.

Establishing accurate values for FREEZ1 and FREEZ2 was not possible given the dataset that we had compiled. There were no datasets with measurements of freeze damage and no sites that experienced lethal freezing temperatures. The coldest site was Eagle Lake, TX with an average of only 18 nights below freezing each winter. Freeze damage parameters were set to start killing leaves at  $\text{FREEZ1} = -5^{\circ}\text{C}$  with a daily death loss of 5% of the leaves and stems for each  $1^{\circ}\text{C}$  that nighttime minimum temperatures drop below  $-5^{\circ}\text{C}$ . Work by Kimball and Salisbury (1973) favor a threshold temperature closer to  $0^{\circ}\text{C}$  as they observed a 90% death loss of bahiagrass plants kept at  $0^{\circ}\text{C}$  for 3 d and 100% loss at  $-5^{\circ}\text{C}$ . However, they used very young plants (2 leaves, no stolons present) grown in pots, whereas established stands grown in the field should tolerate lower temperatures especially for shorter durations. As there were no reports of plant

death due to freezing, an arbitrary value of  $-18^{\circ}\text{C}$  was assigned to FREEZ2 to avoid predicting plant death at any of the test sites.

Applying these parameters predicted freeze damage on 2 to 3 nights per year in Eagle Lake, TX, reduced herbage mass by as much as 22% in a single night yet still allowed for rapid regrowth in the spring. This approach to predicting freeze damage is flexible and easily adjusted for each species, however the parameter values are somewhat arbitrary and calibration of these parameters against measured data on freeze damage is still required for them to be useful at more northern latitudes or at altitude.

### **Photosynthesis**

Bahiagrass is a  $\text{C}_4$  plant, wherein  $\text{CO}_2$  is first fixed in the mesophyll cells by phosphoenolpyruvate carboxylase (PEPCase) then transported to the bundle sheath cells and released near the chloroplasts. This results in much higher concentrations of  $\text{CO}_2$  in the bundle sheath than in the mesophyll, enhancing the carboxylation efficiency of the ribulose 1,5-bisphosphate (Rubisco) in the bundle sheath chloroplasts by reducing the competitive inhibition of Rubisco carboxylase activity by  $\text{O}_2$ . This concentrating of  $\text{CO}_2$  around Rubisco imparts different responses to light,  $\text{CO}_2$  concentration, and temperature. A typical  $\text{C}_4$  plant has a high potential photosynthetic rate which is not light saturated except at high light levels. Also,  $\text{C}_4$  photosynthesis is quite sensitive to low temperatures while tolerant of high temperatures. Additionally,  $\text{C}_4$  photosynthesis is not as responsive to elevated  $\text{CO}_2$  concentrations as the  $\text{C}_3$  photosynthetic pathway exhibited in many temperate grasses and legumes.

CROPGRO offers two options for predicting daily canopy photosynthesis. The simplest is the daily canopy photosynthesis option which estimates daily canopy photosynthetic rate directly from total daily photosynthetically active radiation (PAR).

The leaf-level option predicts hourly leaf photosynthesis for sunlit and shaded leaves and, through hourly iteration, estimates daily canopy photosynthesis (Boote and Pickering, 1994). Modeling of daily canopy and hourly leaf-level photosynthesis is based on asymptotic exponential representations of canopy (for daily canopy option) and leaf (for leaf-level option) photosynthetic responses to light. Photosynthetic responses to environmental factors are imposed through various modifiers which simulate some of the underlying biochemical processes controlling photosynthesis. Most of the CO<sub>2</sub> concentration effects listed above are simulated in the CSM version of CROPGRO, with no modification of the daily canopy photosynthetic option required beyond determining appropriate parameter values defining the CO<sub>2</sub> response. These values were estimated from the canopy photosynthesis measurements of Boote et al. (1999). The leaf-level photosynthesis option, however, does not accurately reflect some of the effects of the CO<sub>2</sub>-concentrating mechanism on the sensitivities of quantum efficiency (QE) and maximum photosynthetic rate to temperature and CO<sub>2</sub> concentration, and thus it required modification.

The asymptotic exponential equation describing leaf photosynthetic response to light (PGLF) is

$$\text{PGLF} = \text{LFMAX} * \left(1.0 - e^{\frac{-\text{QE} * \text{PARLF}}{\text{LFMAX}}}\right) \quad (\text{Eq. 5-5})$$

where LFMAX is the potential light-saturated leaf photosynthetic rate at 30°C and 350 µL L<sup>-1</sup> CO<sub>2</sub>, and 21% O<sub>2</sub>, QE is the quantum efficiency of the species defined at the same conditions, and PARLF is the absorbed PAR µmol quanta m<sup>-2</sup> s<sup>-1</sup>. The leaf QE, which defines the initial slope of the light response curve, is specified in the species parameter file but is modified by factors for hourly temperature and CO<sub>2</sub> concentration and leaf N

concentration. The cultivar-specific maximum leaf photosynthetic rate (LFMAX), describes the asymptote of the response and is also specified in the species parameter file and subsequently multiplied by factors for SLW, hourly air temperature, leaf N concentration, CO<sub>2</sub> concentration, and nighttime chilling. The effects of CO<sub>2</sub> concentration and temperature are estimated separately for QE and LFMAX but both originate in a single equation:

$$\tau = e^{-3.949 + \frac{28990}{8.314(T+273)}}, \quad (\text{Eq. 5-6})$$

where Tau ( $\tau$ ) is the specificity factor of Rubisco for CO<sub>2</sub> relative to O<sub>2</sub> or the relative tendency of Rubisco to fix CO<sub>2</sub> rather than O<sub>2</sub>, T is the temperature in °C, and 8.314 is the universal gas constant. Tau reflects the decreasing solubility of CO<sub>2</sub> relative to O<sub>2</sub> as temperature increases. The effect of  $\tau$  on CO<sub>2</sub> compensation point ( $\Gamma^*$ ) and photosynthetic response (at QE and saturating rate) to CO<sub>2</sub> depend further on intercellular CO<sub>2</sub> concentration as parameterized by the Ribulose 1,5-bisphosphate (RuBP)-limited photosynthesis algorithm of Farquhar and von Caemmerer (1982). To allow adjustment of the  $\tau$  ratio to account for the CO<sub>2</sub> concentrating effect of C<sub>4</sub> photosynthesis, we added a “CO<sub>2</sub>-concentrating” factor (CCNEFF) to the species file. Tau is multiplied by CCNEFF to predict the relative increase in CO<sub>2</sub> concentration at the Rubisco site in the bundle sheath cells. Increasing “ $\tau$  times CCNEFF” in CROPGRO reduced  $\Gamma^*$ , and decreased the sensitivity of both the QE and LFMAX CO<sub>2</sub> concentration adjustment factors to higher temperatures and CO<sub>2</sub> concentrations.

An arbitrarily selected value of 10 for CCNEFF produced a  $\Gamma^*$  of 5  $\mu\text{L CO}_2 \text{ L}^{-1}$  at 30°C (Figure 5-9), consistent with reports of CO<sub>2</sub> compensation points ranging from 0.0 to 5.0 for various C<sub>4</sub> species (Rajendrudu and Das, 1981). When the CO<sub>2</sub> concentration

factors for QE and LFMAX were re-scaled to 1.0 at 30°C (where they are defined to 1.0) to account for the lowered  $\Gamma^*$ , the responsiveness of LFMAX to high CO<sub>2</sub> concentrations decreased. The new system predicted a CO<sub>2</sub> adjustment factor for LFMAX (CO2MAX) for an atmospheric CO<sub>2</sub> concentration of 700  $\mu\text{L CO}_2 \text{ L}^{-1}$  giving only a 6% increase in the predicted light-saturated leaf rate when coupled with a ratio of intercellular to atmospheric CO<sub>2</sub> concentration (Ci:Ca) set to 0.4. In contrast, Boote et al. (1999) measured an 18% increase in photosynthetic rate under high light when atmospheric CO<sub>2</sub> concentration was doubled from ambient (360  $\mu\text{L CO}_2 \text{ L}^{-1}$ ) to 700  $\mu\text{L CO}_2 \text{ L}^{-1}$ . Working backwards from the measured data we arrived at a value of 3.0 for CCNEFF. This produced a CO2MAX which increased from 1.0 at 350  $\mu\text{L CO}_2 \text{ L}^{-1}$  to 1.18 at 700  $\mu\text{L CO}_2 \text{ L}^{-1}$  (Figure 5-10) yet still lowered  $\Gamma^*$  to 18  $\mu\text{L CO}_2 \text{ L}^{-1}$  at 30°C (Figure 5-9). This is near the CO<sub>2</sub> compensation values of 4-14  $\mu\text{L CO}_2 \text{ L}^{-1}$  reported for the C<sub>4</sub> grass *Panicum maximum* by Bolton and Brown (1980) and considerably lower than the 55  $\mu\text{L CO}_2 \text{ L}^{-1}$  predicted by the CSM version of the CROPGRO code for C<sub>3</sub> species.

Prediction of the effect of temperature on QE was also improved using CCNEFF set to 3.0. The predicted temperature/CO<sub>2</sub> concentration factor (CO2QE) varied only 7% from 1.034 at 0°C to 0.967 at 45°C (Figure 5-11), demonstrating the substantial lack of temperature sensitivity of QE in C<sub>4</sub> species. This response is quite small compared to the 46% range predicted by the CSM version over the same temperature range. Using a QE of 0.0541 for a hypothetical C<sub>3</sub> species and 0.065 for the C<sub>4</sub> bahiagrass, and CCNEFF=3.0, the predicted QE of the C<sub>3</sub> species will be higher than that of the C<sub>4</sub> only at temperatures below 5°C. This crossover temperature is considerably lower than the approximate 20° to 23°C crossover temperatures reported by Ku and Edwards (1978) and

Monson et al. (1982). Increasing CCNEFF to 10.0 increases the temperature at which  $C_4$  QE surpasses the  $C_3$  QE to 14°C which presents an argument for a CCNEFF of 10.0. However, as QE has the most influence on leaf photosynthetic rate at low light levels while LFMAX dominates at higher levels, CCNEFF was set to 3.0, favoring the improved CO2MAX predictions.

Evaluation of the performance of the modified  $C_4$  photosynthesis options was somewhat complicated compared to other aspects of the model. Differences in growth resulting from changes in photosynthetic rate are compounded each day, so a simple comparison of changes in plant mass are inadequate. To judge the photosynthetic response to increasing  $CO_2$  concentration, the experiment of Johnson et al. (2001) was simulated using 350 and 700  $\mu L CO_2 L^{-1}$  ambient  $CO_2$  concentrations. This experiment was chosen as it began with an established crop. Gross canopy photosynthesis for the first day of each simulation was compared. Using the daily canopy photosynthesis option, the gross canopy photosynthesis at 700  $\mu L CO_2 L^{-1}$  was 11% greater than at 350  $\mu L CO_2 L^{-1}$  (data not shown), verifying that the  $CO_2$  concentration factor was producing the intended increase in photosynthetic rate. Similarly, when the noontime maximum photosynthetic rates for sunlit leaves predicted in the leaf-level option were compared, the rate predicted for the 700  $\mu L CO_2 L^{-1}$  level was 17% greater than for the 350  $\mu L CO_2 L^{-1}$  level, again, the desired response. Despite the increased photosynthetic rates, predicted herbage mass was not increased at the higher  $CO_2$  concentrations except at the highest N fertilization treatments regardless of the photosynthesis option used.

This lack of a growth response despite an apparent increase in photosynthetic rate is likely due to excessive predicted N-stress limiting growth. For most of the

experiments, N should have been limiting only in the low N fertility treatments, but there was no mention of N deficiency symptoms in the reports. However, even under normal atmospheric CO<sub>2</sub> concentrations (330 to 350  $\mu\text{L CO}_2 \text{ L}^{-1}$ ), predicted N-stress frequently limited growth in the low and mid-level N treatments. Unlike the early-season N-stress predicted using the unmodified CSM version of CROPGRO, this predicted N-stress recurred throughout the growing season. At elevated CO<sub>2</sub> concentrations, photosynthetic rate increased but without extra available N, N stress also increased and the extra CH<sub>2</sub>O produced was stored as mobile carbohydrate in the stems, roots and, primarily, in the STOR organ. Thus there was a sizeable increase in STOR and root mass with no corresponding increase in leaf mass (Figure 5-12).

It is difficult to assess the cause of the predicted N shortage. Potential errors in the prediction of root mass and N uptake capacity are prime candidates. However, there are several other potential contributors outside of the crop model itself. As there were no actual soil analyses available for any of the experiments, the soil profiles used in the simulations were based on soil surveys with soil water retention parameters derived from a database using the k-Nearest Neighbor approach (Jagtap et al., 2004). Similarly, the model's default coefficients were used to set initial proportions of microbial, intermediate, and passive OM fractions for the SOM processes. Other initial soil conditions such as available water and N, amount and composition of residue, and even initial plant mass were estimated by starting the simulation one year before the actual experiment, letting the system predict the initial conditions. Inaccuracies in any and all of these estimates contribute to the problem. The predicted N stress was generally worst



in the spring while the majority of the N leaching occurred in the winter, implying that mineralization rates of SOM may be excessive during the winter.

### **Overall Model Performance – Herbage Mass and N Concentration**

Plots of the predicted growth from the experiments were encouraging as much for the patterns of growth as for the levels of production (Figure 5-13). Predicted stolon mass and root mass were on the order of reports by Blue (1973) and Beaty et al. (1968). Stolon growth increased during the short-daylength months and decreased over the summer while root mass increased over the summer and was partially depleted over the winter. Leaf and stem growth were reduced in the fall and winter but still aggressive in the spring (Figure 5-14), especially when viewed on an annual cycle (Fig. 5-13). The performance of the new CROPGRO-forage version was greatly improved over the CSM model where an artificial defoliation had to be imposed during the winter to slow growth (Figure 5-15).

The modifications implemented in the forage version of CROPGRO improved the performance of the model over the CSM version in almost every measure. Compared to the unmodified CSM version running the bahiagrass parameters developed in an earlier step of the model adaptation (Rymph et al., 2003), the forage version had a slope closer to 1.0, an intercept closer to 0.0, and a larger  $r^2$  of the linear regression of predicted against observed values, a larger d-index and smaller RMSE for predicted herbage mass (Table 5-2). The greatest improvements were a 14% increase in the d-index and a large increase in the  $r^2$ . A 46% increase in the slope of the linear regression indicated that systematic error was reduced, meaning that less of the total error was due to the way the model worked and more was due to random error such as errors in estimating the stubble mass for each experiment.

In absolute terms, the prediction of herbage mass by the forage version was encouraging as well. A d-index value of 0.81 was achieved using the leaf-level photosynthesis option with a nearly identical fit for the daily canopy version (0.82) (Table 5-2). The mean predicted values for the two versions were also nearly identical at 3145 and 3150 kg DM ha<sup>-1</sup> for the leaf-level and daily canopy versions, respectively, both very close to the observed mean of 3066 kg DM ha<sup>-1</sup>. The RMSE with the leaf-level photosynthesis was less at 857 kg DM ha<sup>-1</sup> and when expressed as a coefficient of variation, was 28% of the observed mean. This was slightly better for the daily canopy option. The greater slopes of 0.694 (leaf-level) and 0.62 (daily canopy), indicate that systematic errors may be less than the random errors. However, the scatterplot of predicted against observed herbage mass (Figure 5-16) indicates that there is a tendency to overpredict herbage mass at higher levels and underpredict at lower levels of growth.

A tendency to overpredict at higher levels of herbage mass production may explain the apparent contradiction between the lower predicted mean for all experiments and the overprediction of herbage mass compared to the underprediction of the CSM version for the Ona, FL 1996-1998 experiment (Figure 5-15). The herbage mass production for the Ona 1996-1998 experiment was the highest of any of the experiments in our dataset. If the forage model overpredicts at higher levels of herbage mass production, it would be most apparent in the Ona 1996-1998 simulation. In comparing the predicted herbage mass across different N fertilization treatments, the forage model did not appear to be excessively sensitive to N fertilization, particularly at Ona in the 1996-1998 experiment. In the Ona experiment, increasing annual N fertilization from 0 to 468 kg N ha<sup>-1</sup> resulted in a large increase in forage production but doubling the N application to 942 kg N ha<sup>-1</sup>

yr<sup>-1</sup> had little effect on forage production (Johnson et al., 2001). The forage version of CROPGRO predicted a similar pattern of response of herbage mass to N fertilization (Figure 5-17), with little or no increase in growth at the higher N fertilization levels. At Eagle Lake, TX where lower levels of N fertilization were applied, the magnitude of both the observed and predicted responses to higher levels of N fertilizer was greater than for Ona. This, along with the other improvements noted, suggests that despite the excessive predictions of N stress, the N-response of the new forage model is realistic.

Herbage N concentration prediction was also improved for the forage version although not to as great an extent as herbage mass. While herbage mass predictions using leaf-level and daily canopy photosynthesis options were similar, the two options diverged more in their predictions of herbage N concentration. The mean predicted herbage N concentration using the leaf-level option (14.6 g N kg<sup>-1</sup>) was slightly lower than the mean observed value of 15.6 kg N ha<sup>-1</sup>, while the daily canopy option produced a mean N concentration of 17.6 kg N ha<sup>-1</sup>, greater than the observed mean (Table 5-2). The seasonal dynamics of herbage N concentration was predicted better by the modified model (Figure 5-18), especially for Ona, FL. The slope of the linear regression of predicted herbage N concentration was not any closer to 1:1 for the modified model (0.78 and 0.60 for the daily canopy and leaf-level options, respectively); however, the d-index values for herbage N concentration was improved, as evidenced by the improved N predictions at Ona (Figure 5-18). Scatterplots of predicted against observed herbage N concentration show no clear pattern of over- or underprediction except that the magnitude of overprediction may be greater than for underprediction (Figure 5-19). This is evident when herbage N concentration response is compared across the various N-fertilization

treatments. While observed herbage N concentrations increased as N fertilization increased at Ona, FL, the magnitude of the predicted response was much greater (Figure 5-20). Herbage N concentration was underpredicted by the forage model for the 0 kg N ha<sup>-1</sup> yr<sup>-1</sup> fertilization treatment but overpredicted for the 468 and 942 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatments. While no statistical comparison was made, the magnitude of overprediction for the 942 kg N ha<sup>-1</sup> yr<sup>-1</sup> appears to be greater than for the 468 kg N ha<sup>-1</sup> yr<sup>-1</sup> treatment. Predicted herbage N concentrations for the Eagle Lake, TX experiment did not show clear patterns of overprediction or underprediction (Figure 5-20). The magnitude of the predicted response to increasing the annual fertilization rate from 168 to 336 kg N ha<sup>-1</sup> appeared to be greater than the response to increasing N fertilization from 0 to 168 kg N ha<sup>-1</sup> yr<sup>-1</sup>. This is consistent with the observed pattern of response to N fertilization, particularly for the last two growing seasons. It appears that at high N fertilization levels the forage version of the CROPGRO model is predicting a higher concentration of N than is observed but this is not reflected in increased herbage mass production.

The d-index values for herbage N mass (>0.85 for both leaf-level and daily canopy options) were higher than those for either herbage mass or herbage N concentration, implying a better fit for herbage N mass than for either component used to calculate it (Table 5-2). The other measures of fit also supported this conclusion (Table 5-2, Figure 5-21). The slightly high herbage mass and slightly low herbage N concentration predicted using the leaf-level photosynthesis option likely offset each other to produce the improved fit. Some other offsetting errors could be responsible for the good fit of the predictions produced by the daily canopy photosynthesis option as both herbage mass and N concentration were overpredicted. The one fit parameter that was slightly worse for

the forage model predictions of both herbage N concentration and herbage N mass was their slopes (Table 5-2). Both photosynthesis options produced linear regression results with greater (albeit only slightly) slopes than were seen with the CSM model, indicating that the error likely lies with the model and was not due to random error.

### **Conclusions**

The addition of a storage organ and addition of dormancy regulation of partitioning/mobilization to the CROPGRO structure was an integral part of the new improvements for dormancy and re-growth processes of the forage version of CROPGRO. The two modifications to the model structure allowed seasonal reductions in herbage production by partitioning a greater proportion of new growth to STOR while reducing mobilization from STOR and roots. This produced a more realistic pattern of bahiagrass growth than was possible with the CSM version of the model. The perennial nature of bahiagrass was also better simulated by the modification of the freeze damage process to allow gradual loss of leaves and stems. Damage proportional to the temperature can be imposed without terminating the simulation. The modification to the leaf-level photosynthesis option successfully simulated the lowered response to CO<sub>2</sub> concentration observed in C<sub>4</sub> plants. This response was not reflected in the pattern of herbage mass accumulation as N stress, which was already overpredicted, was heightened by the increased photosynthate production. Thus under CO<sub>2</sub> enrichment, this resulted in most of the additional photosynthate accumulating in STOR and roots as mobile CH<sub>2</sub>O.

Additional testing using sites with finer textured soils may help differentiate the roles of the crop, soil water, and SOM processes in predicting excessive N stress. Modification of the ET process to include a link to photosynthesis may also improve the soil water balance processes. While the freeze damage parameters may be adequate for

the subtropical areas used here, calibration against data from cooler regions may improve the accuracy of the dormancy and freeze damage parameters and broaden the model's utility.

The modifications made to CROPGRO to create the forage version predicted more realistic growth patterns for bahiagrass and improved prediction of herbage mass, herbage N concentration, and herbage N mass. While not ready for general release, the performance of the forage version of CROPGRO was quite good and should progress from this calibration stage on to more vigorous testing.

Table 5-1. Summary of performance of the forage version of CROPGRO in simulating mass of below-ground plant organs (kg DM ha<sup>-1</sup>).

	Mean						
	Observed	Predicted	Slope	Intercept	d-index	r <sup>2</sup>	RMSE
Stolon (kg DM ha <sup>-1</sup> )	6463	4268	0.326	2160	0.382	0.05	2613
Root (kg DM ha <sup>-1</sup> )	5930	8507	0.814	3682	0.615	0.86	2638

Table 5-2. Summary of performance of the CSM (unmodified) and forage version of CROPGRO in simulating five experiments to predict herbage mass, herbage N concentration, and herbage N mass.

Observed values						
	Mean					
Herbage Mass	3066	kg DM ha <sup>-1</sup>				
Herbage N Conc.	15.6	g N kg <sup>-1</sup>				
Herbage N Mass	49.1	kg N ha <sup>-1</sup>				
CSM version						
Leaf-level photosynthesis option predictions						
	Mean	Slope	Intercept	d-index	r <sup>2</sup>	RMSE
Herbage Mass	3165	0.475	1709	0.714	0.24	1003
Herbage N Conc.	18.0	0.671	7.6	0.661	0.24	7.8
Herbage N Mass	59.3	1.133	3.7	0.849	0.66	22.8
Daily canopy photosynthesis option predictions						
Herbage Mass	3092	0.461	1677	0.734	0.28	930
Herbage N Conc.	19.4	0.806	6.8	0.690	0.35	7.8
Herbage N Mass	61.4	1.108	7.0	0.849	0.68	22.5
Forage version						
Leaf-level photosynthesis option predictions						
	Mean	Slope	Intercept	d-index	r <sup>2</sup>	RMSE
Herbage Mass	3145	0.694	1017	0.814	0.44	857
Herbage N Conc.	14.6	0.600	5.3	0.776	0.36	5.5
Herbage N Mass	50.5	1.270	-12.1	0.892	0.75	19.5
Daily canopy photosynthesis option predictions						
Herbage Mass	3150	0.616	1261	0.823	0.46	782
Herbage N Conc.	17.6	0.782	5.4	0.767	0.40	6.2
Herbage N Mass	58.6	1.227	-1.9	0.863	0.71	22.1

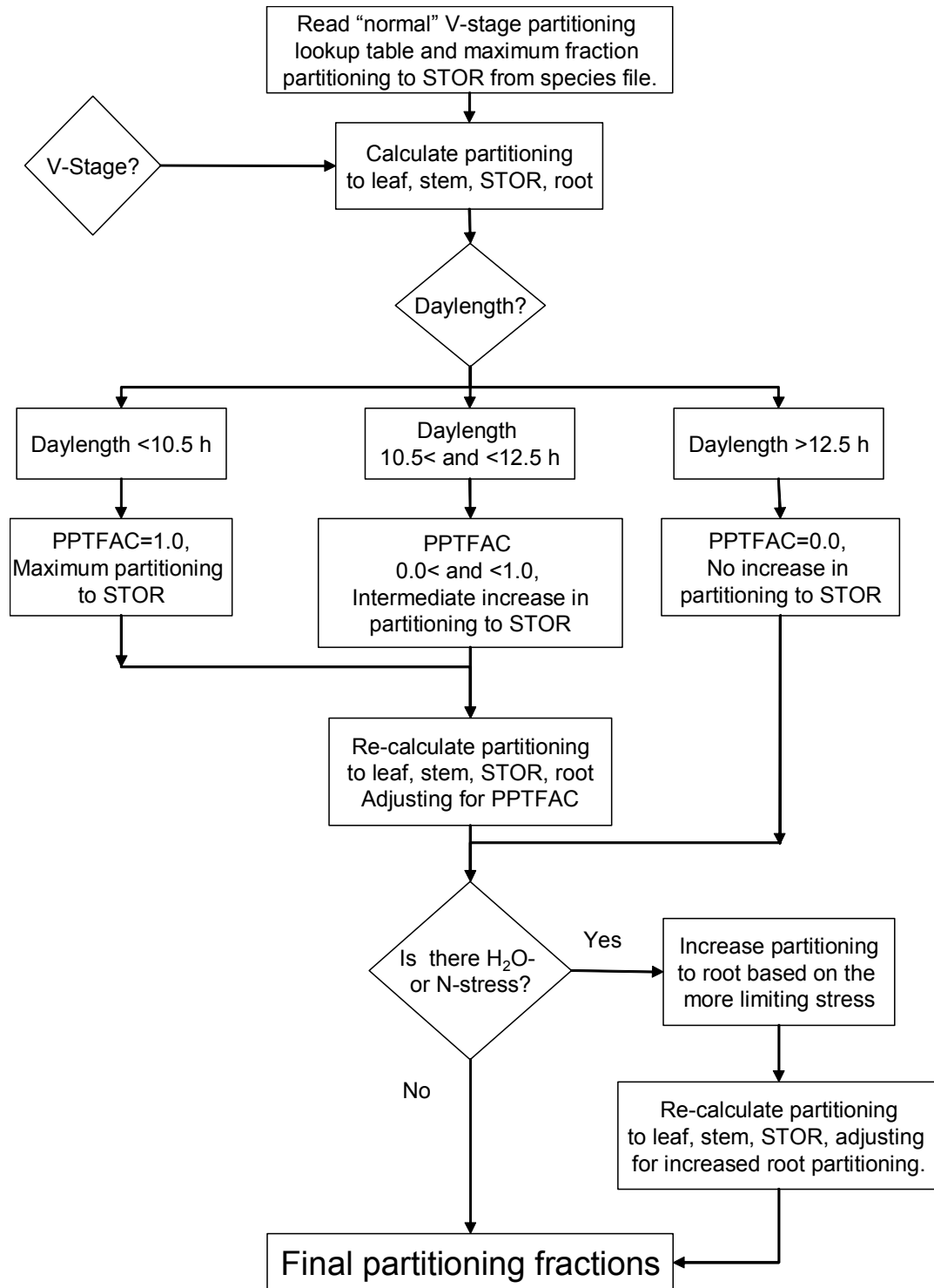


Figure 5-1. Schematic of daily partitioning of new growth among vegetative tissues for the forage version of CROPGRO. Diamond-shaped boxes indicate decision-point variables predicted in the model, rectangle-shaped boxes indicate an action in the model.



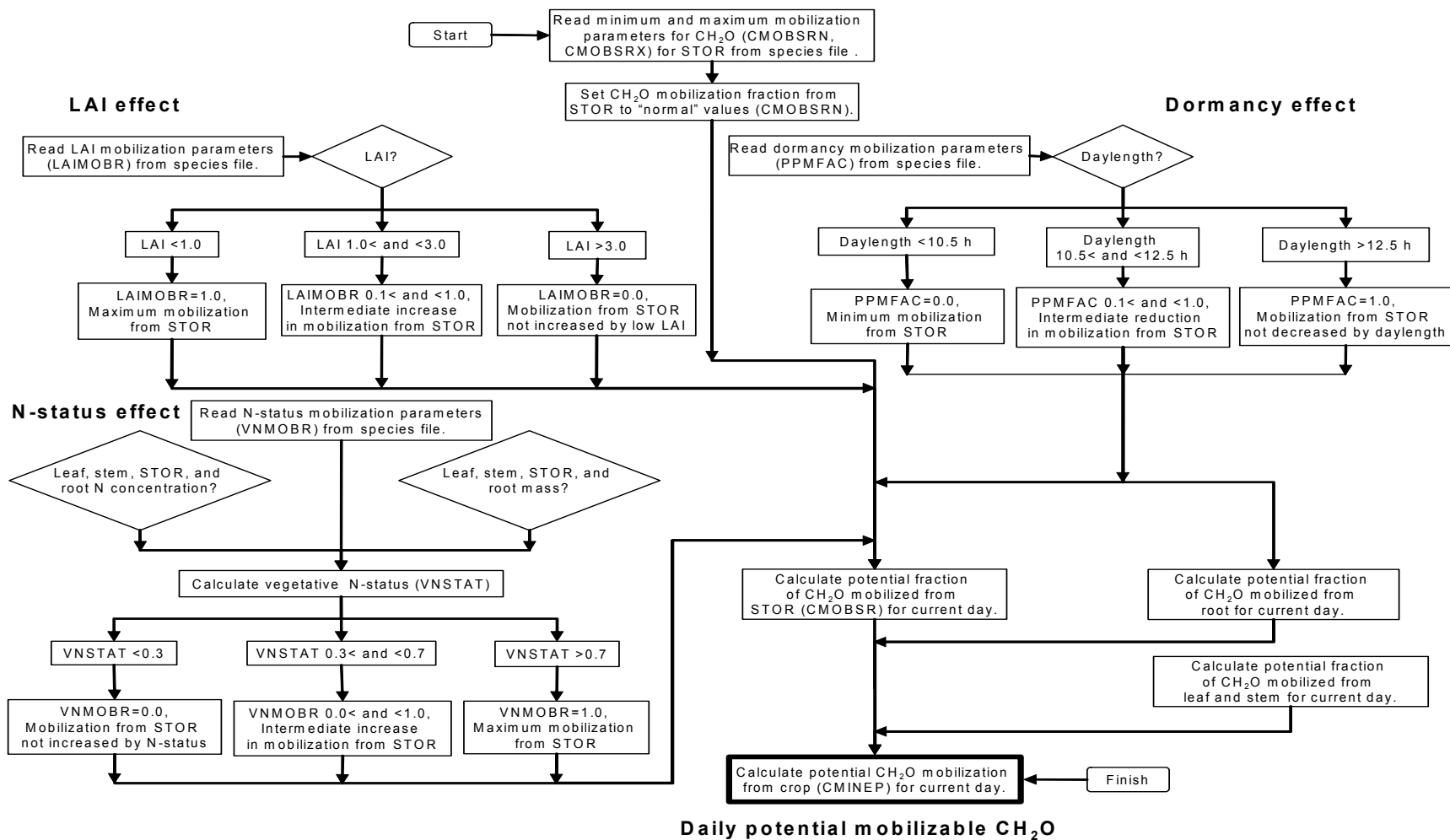


Figure 5-2. Schematic of the calculation of potential mobilization of CH<sub>2</sub>O from leaf, stem, root and STOR in the forage version of CROPGRO. Diamond-shaped boxes indicate decision-point variables predicted in the model, rectangle-shaped boxes indicate an action in the model.

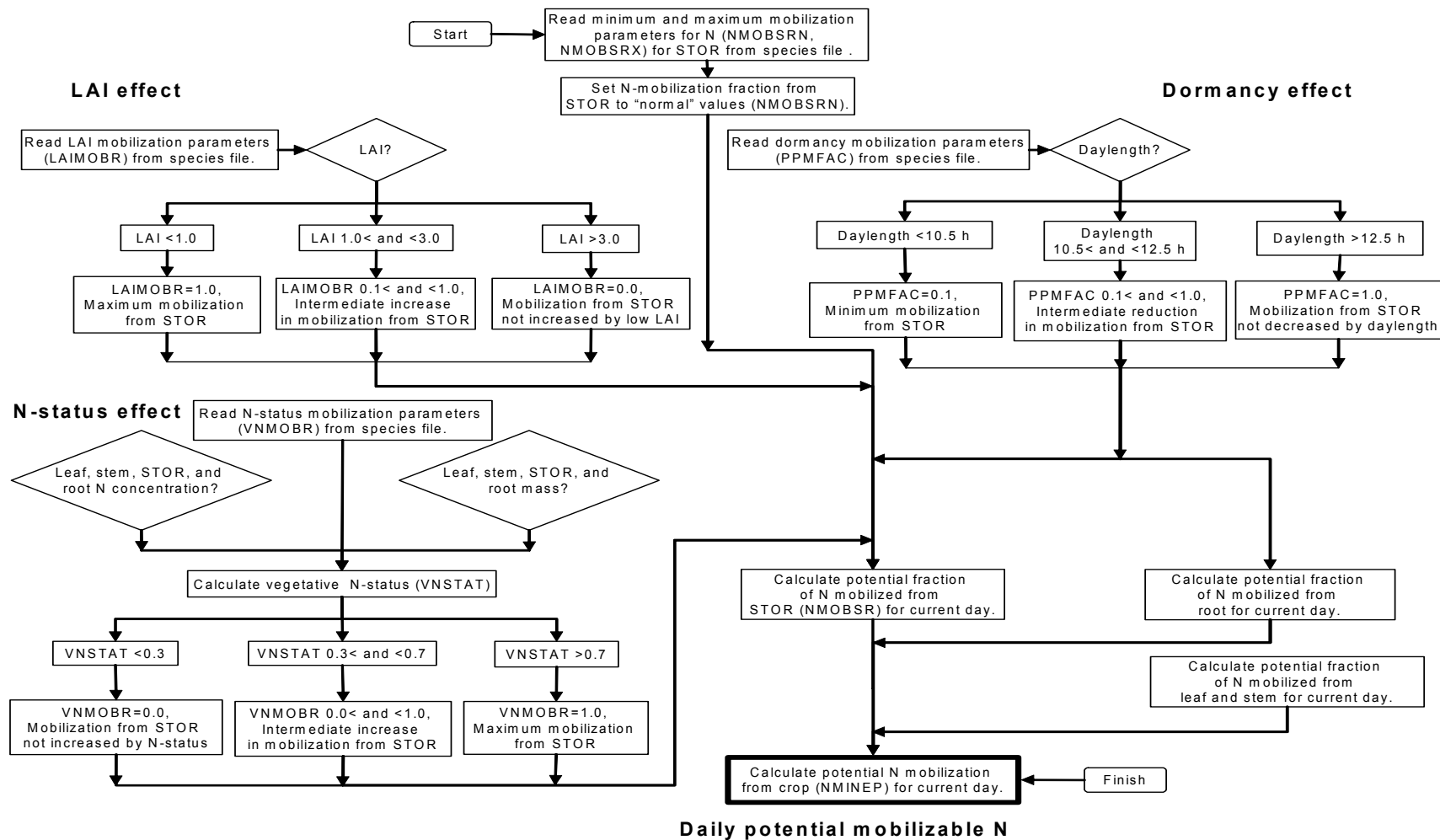


Figure 5-3. Schematic of the calculation of potential mobilization of N from leaf, stem, root and STOR in the forage version of CROPGRO. Diamond-shaped boxes indicate decision-point variables predicted in the model, rectangle-shaped boxes indicate an action in the model.

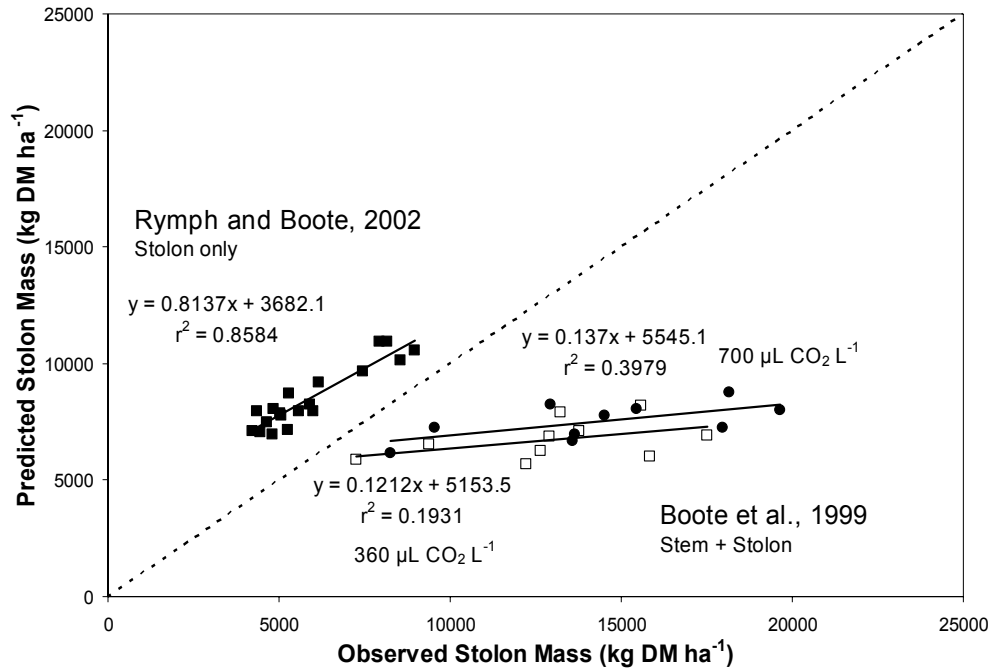


Figure 5-4. Predicted vs. observed stolon mass for bahiagrass grown in the field in Gainesville, FL in 2001 (■), and in temperature and CO<sub>2</sub> gradient greenhouses at 360 µL CO<sub>2</sub> L<sup>-1</sup> (●), and 700 µL CO<sub>2</sub> L<sup>-1</sup> (□). Predicted using the modified leaf-level photosynthesis option in the forage version of CROPGRO. Linear regression lines (—) are presented with their corresponding equations and  $r^2$  values along with a line designating a theoretical 1:1 relationship (---).

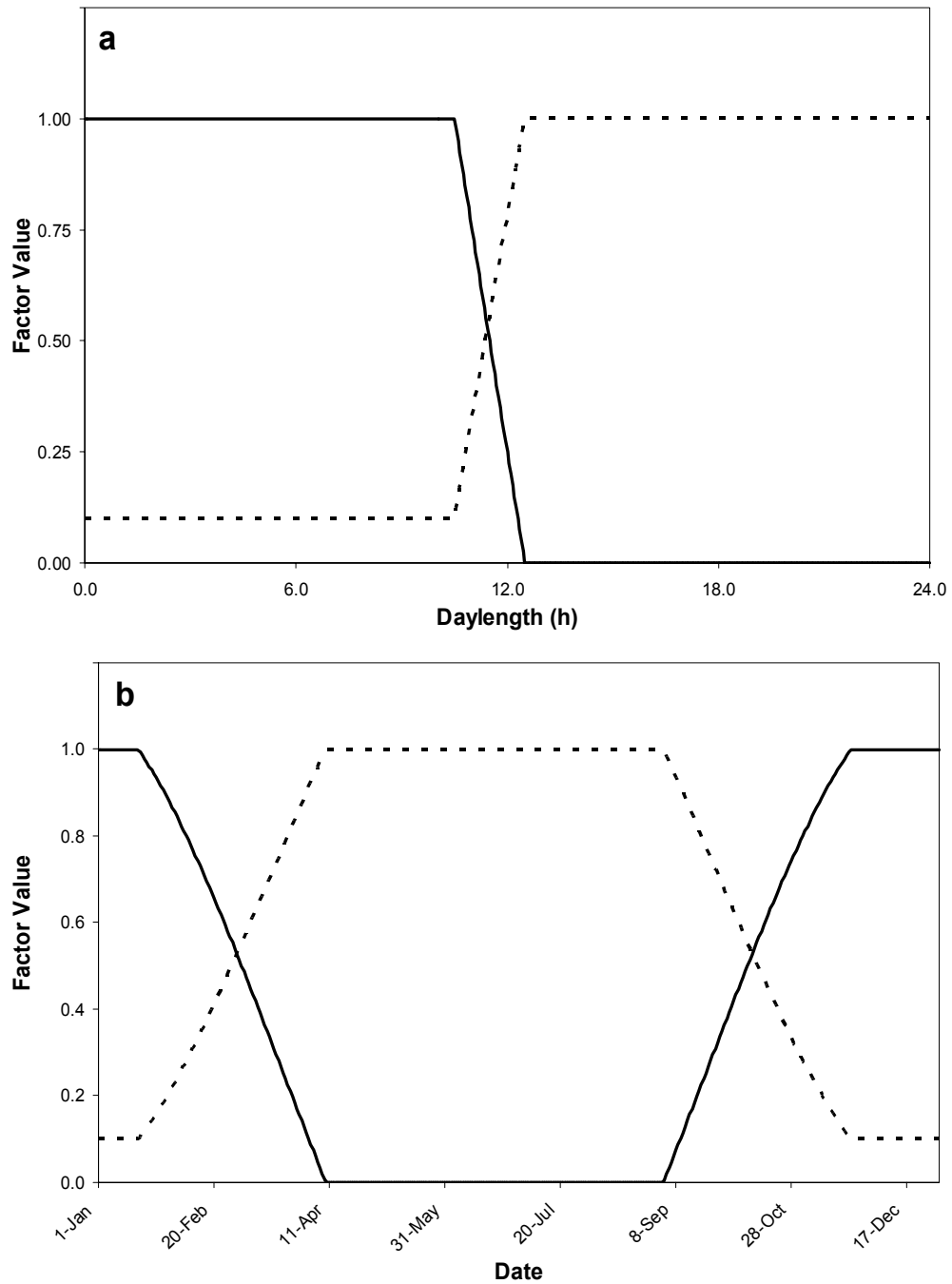


Figure 5-5. The **a)** controlling functions and **b)** seasonal expression of the predicted effect of daylength on incremental (increase above baseline) partitioning to STOR(—) or mobilization from STOR (---) in the forage version of CROPGRO.

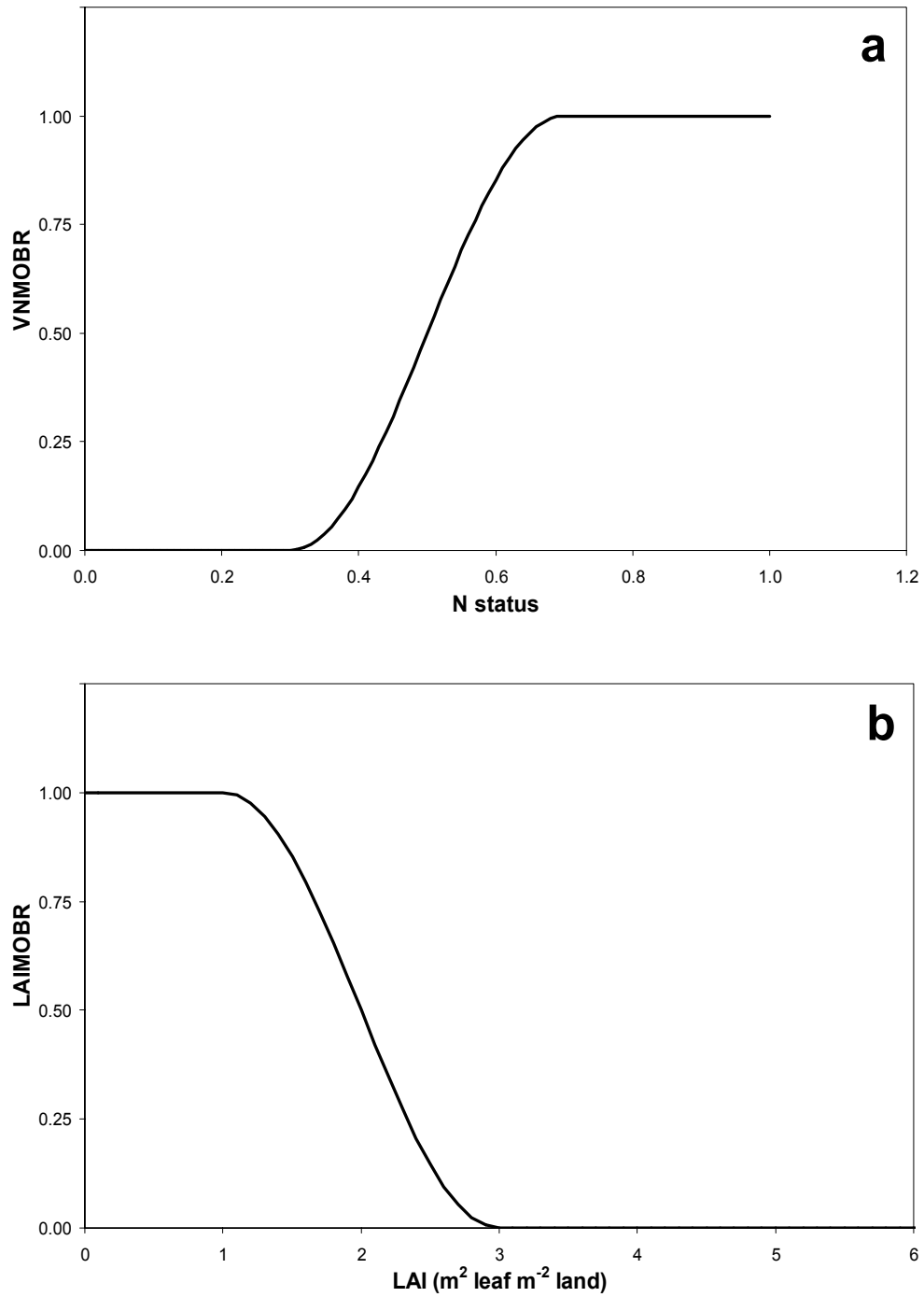


Figure 5-6. Mobilization factors in the forage version of CROPGRO that affect mobilization from STOR as a function of **a)** vegetative N status and **b)** LAI.

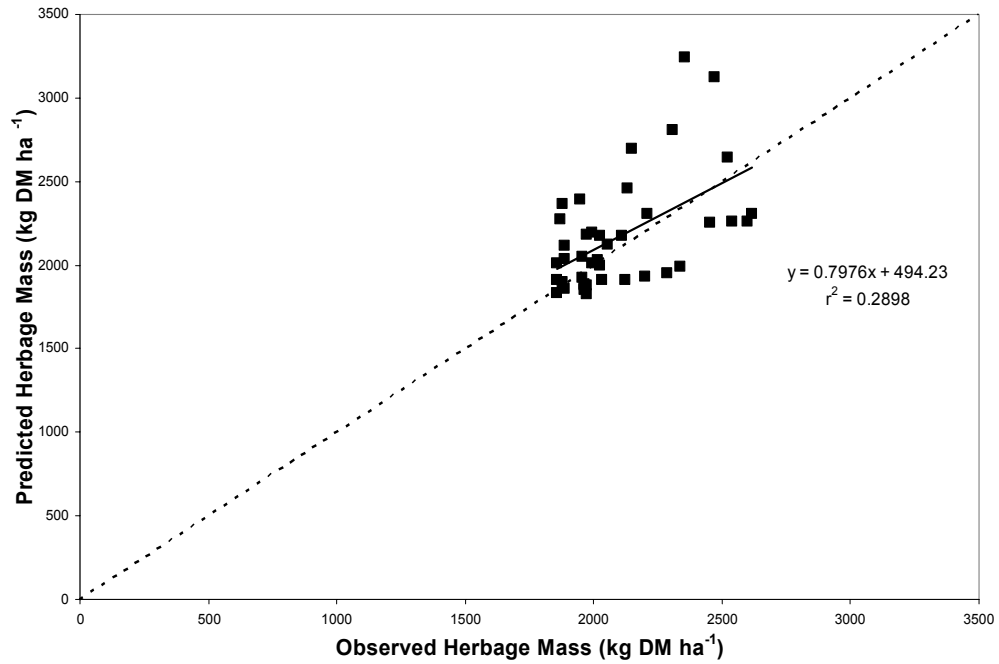


Figure 5-7. Predicted (■) vs. observed bahiagrass herbage mass for late-season harvests at Ona, FL in the 1993-1994 and the 1995-1996 growing seasons - using the modified leaf-level photosynthesis option in the forage version of CROPGRO. The linear regression line (—) is presented with its corresponding equations and  $r^2$  values along with a line designating a theoretical 1:1 relationship (---).

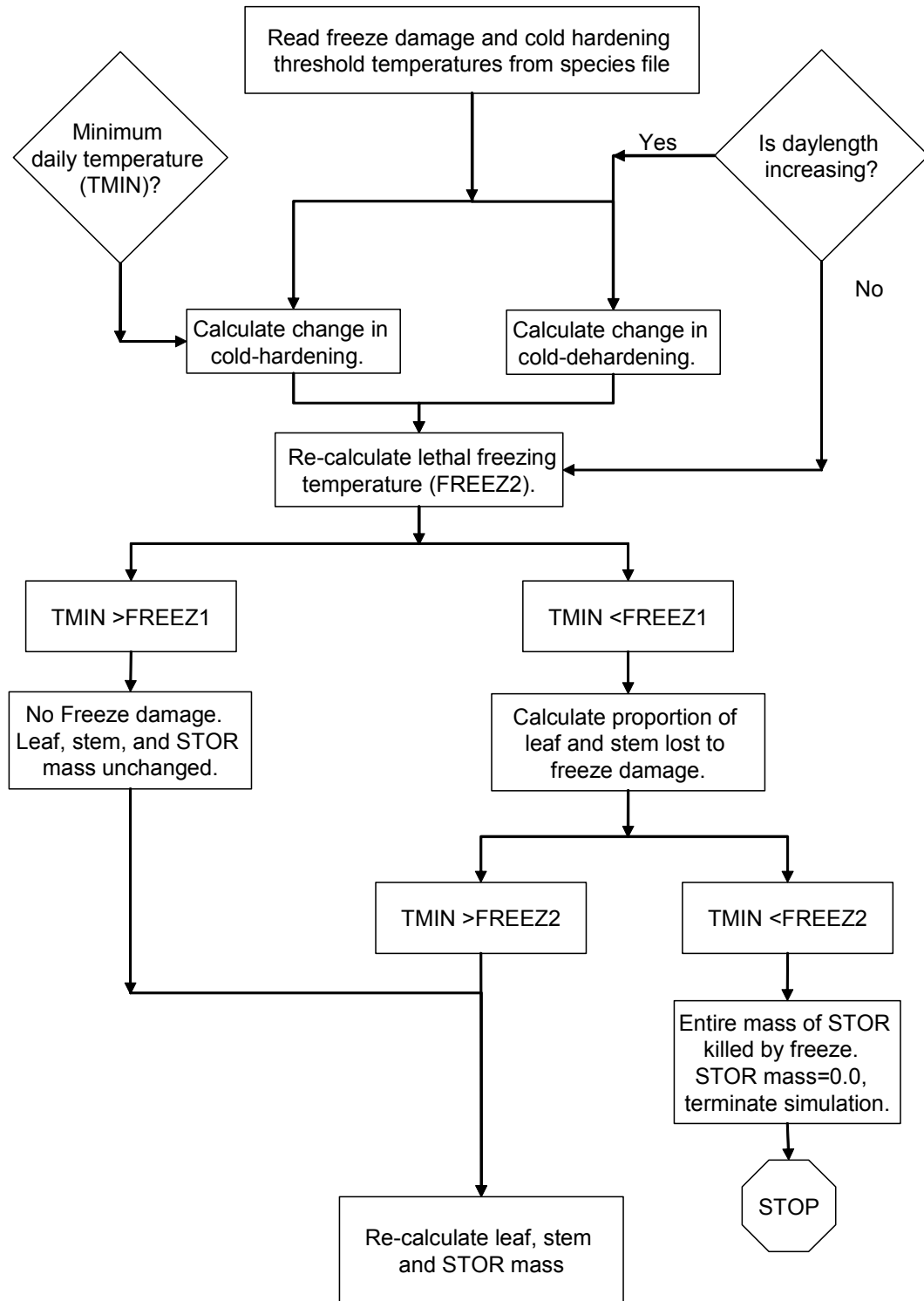


Figure 5-8. Schematic of freeze damage to leaves and stems and cold-hardening of STOR tissues in the forage version of CROPGRO. Diamond-shaped boxes indicate decision-point variables predicted in the model, rectangle-shaped boxes indicate an action in the model.

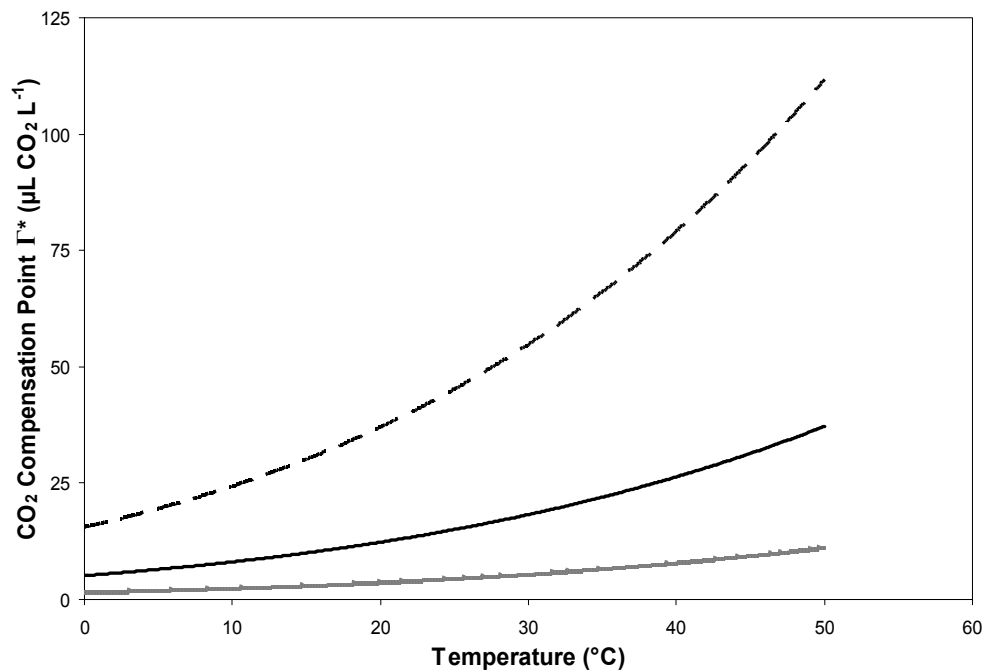


Figure 5-9. Predicted CO<sub>2</sub> compensation point for the CSM version of CROPGRO (— —) and for two hypothetical C<sub>4</sub> species with a  $C_i/C_a$  of 0.4 and a CO<sub>2</sub> concentrating factor of either 3 (—) or 10 (—) predicted using the forage version of CROPGRO.



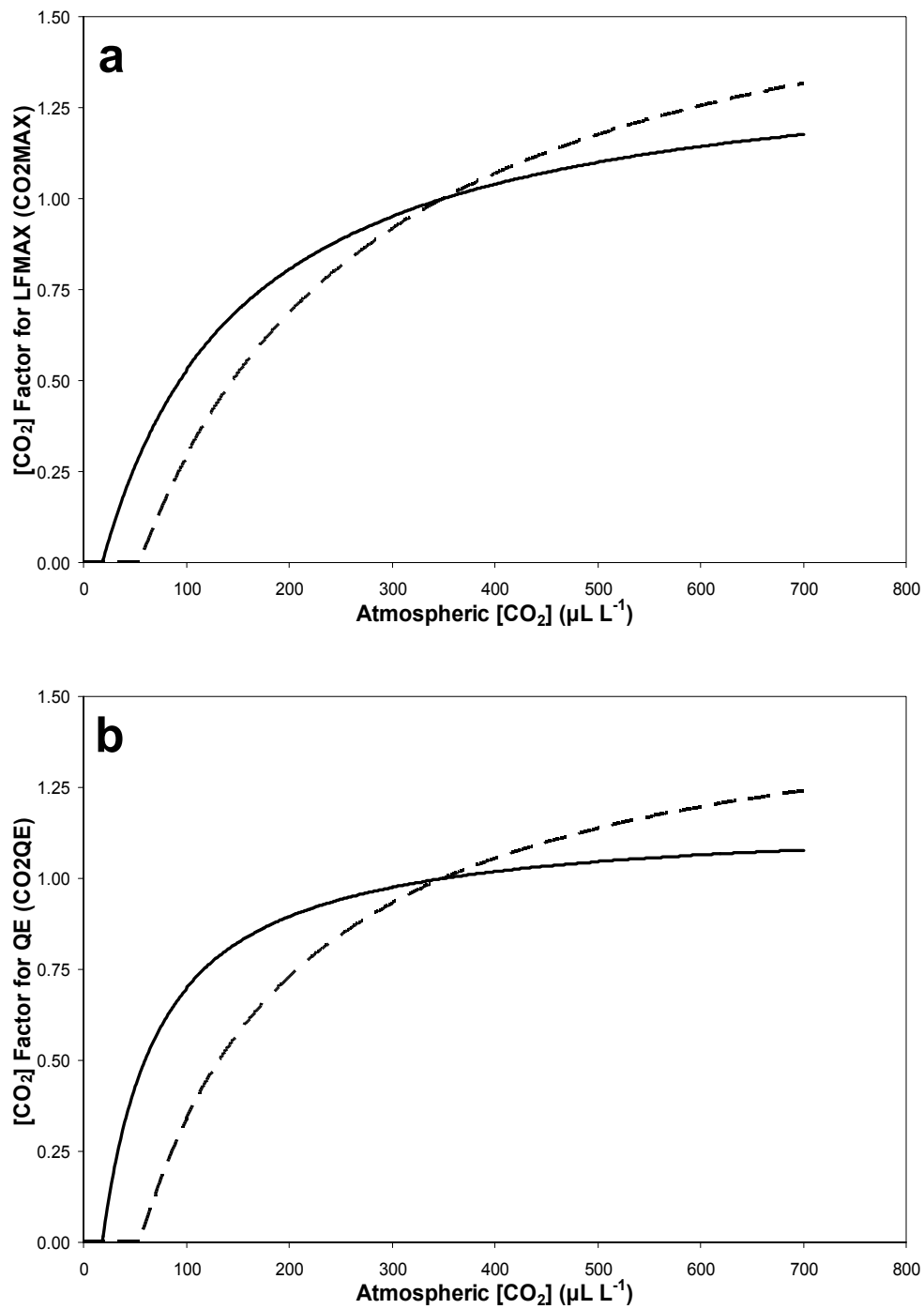


Figure 5-10. Relative CO<sub>2</sub> concentration effect on **a)** CO<sub>2</sub> factor for LFMAX and **b)** QE for a C<sub>3</sub> species in the CSM version (— —) and for a C<sub>4</sub> species in the forage version of CROPGRO using a Ci/Ca of 0.4 and CCNEFF of 3 (—).

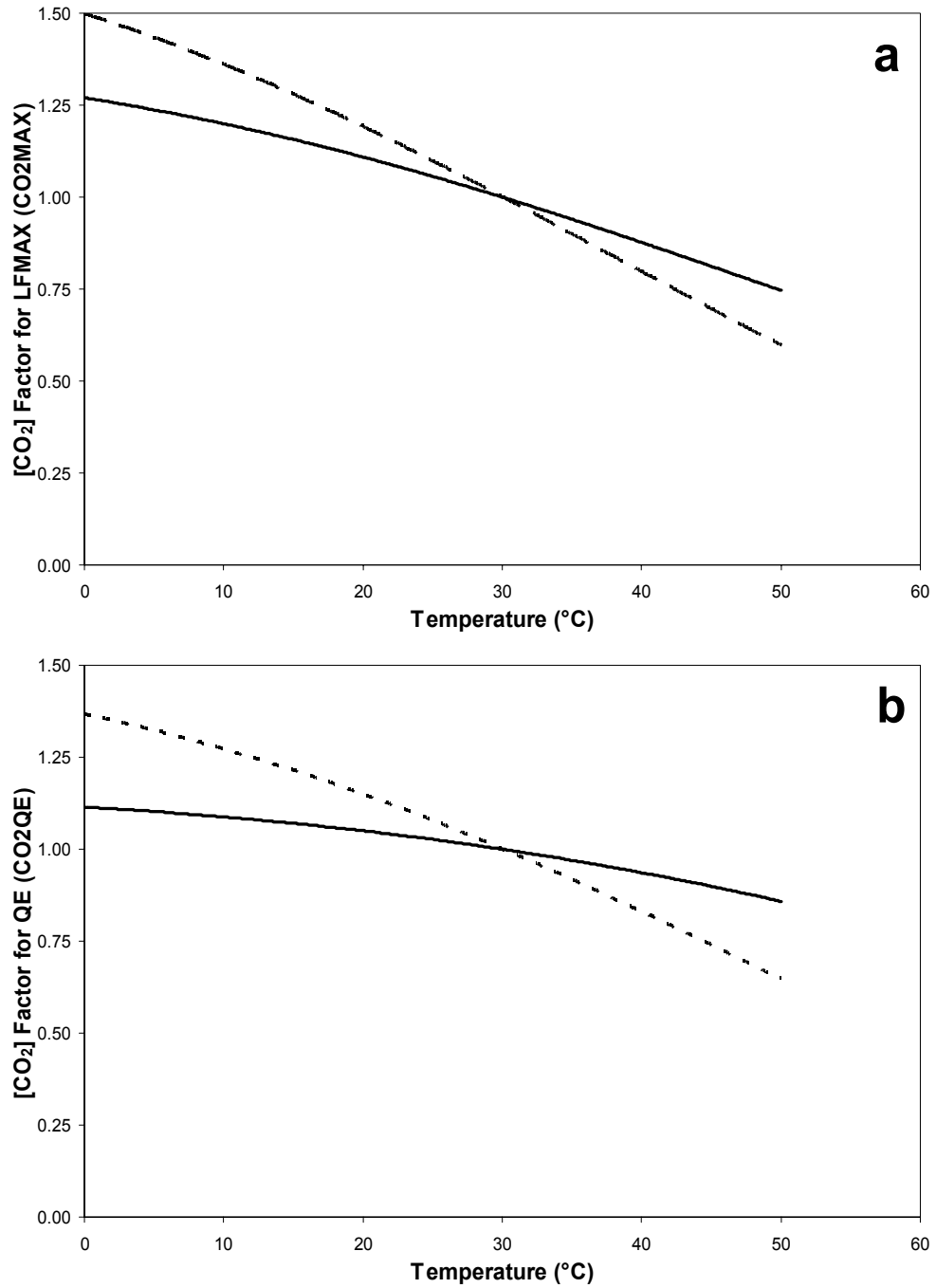


Figure 5-11. Relative temperature effect on **a**) CO<sub>2</sub> factor for LFMAX and **b**) QE for a C<sub>3</sub> species in the CSM version (—) and for a C<sub>4</sub> species in the forage version of CROPGRO using a Ci/Ca of 0.4 and CCNEFF of 3 (---).

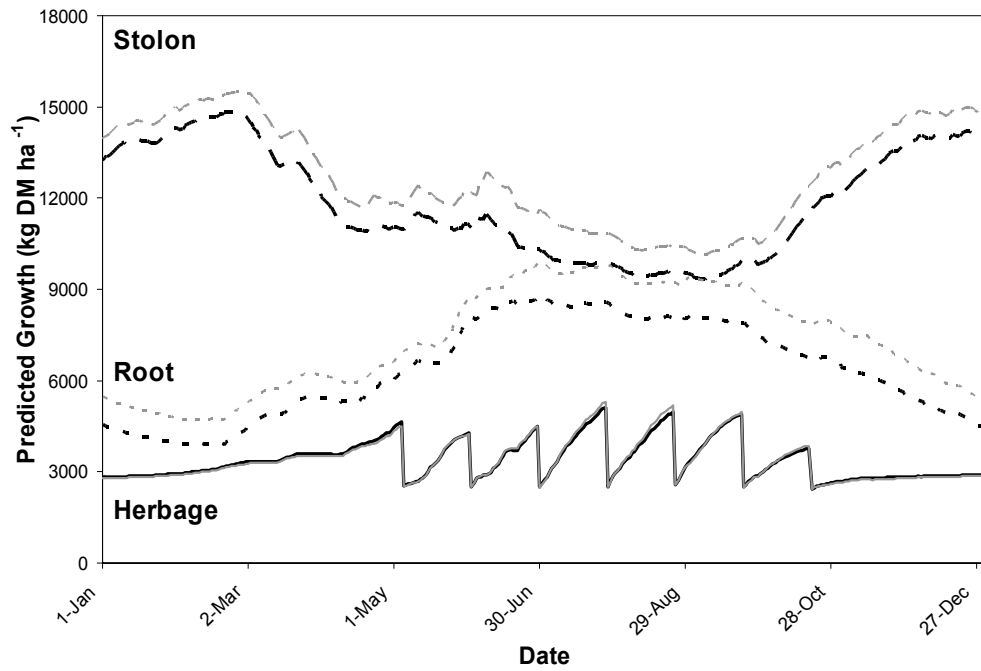


Figure 5-12. Predicted growth of bahiagrass components under 350  $\mu\text{L CO}_2 \text{ L}^{-1}$  atmospheric  $\text{CO}_2$  - stolon (— —), root (.....), and herbage (——) relative to predicted growth under 700  $\mu\text{L CO}_2 \text{ L}^{-1}$  atmospheric  $\text{CO}_2$  - stolon (— —), root (.....), and herbage (——) using the forage version of CROPGRO.

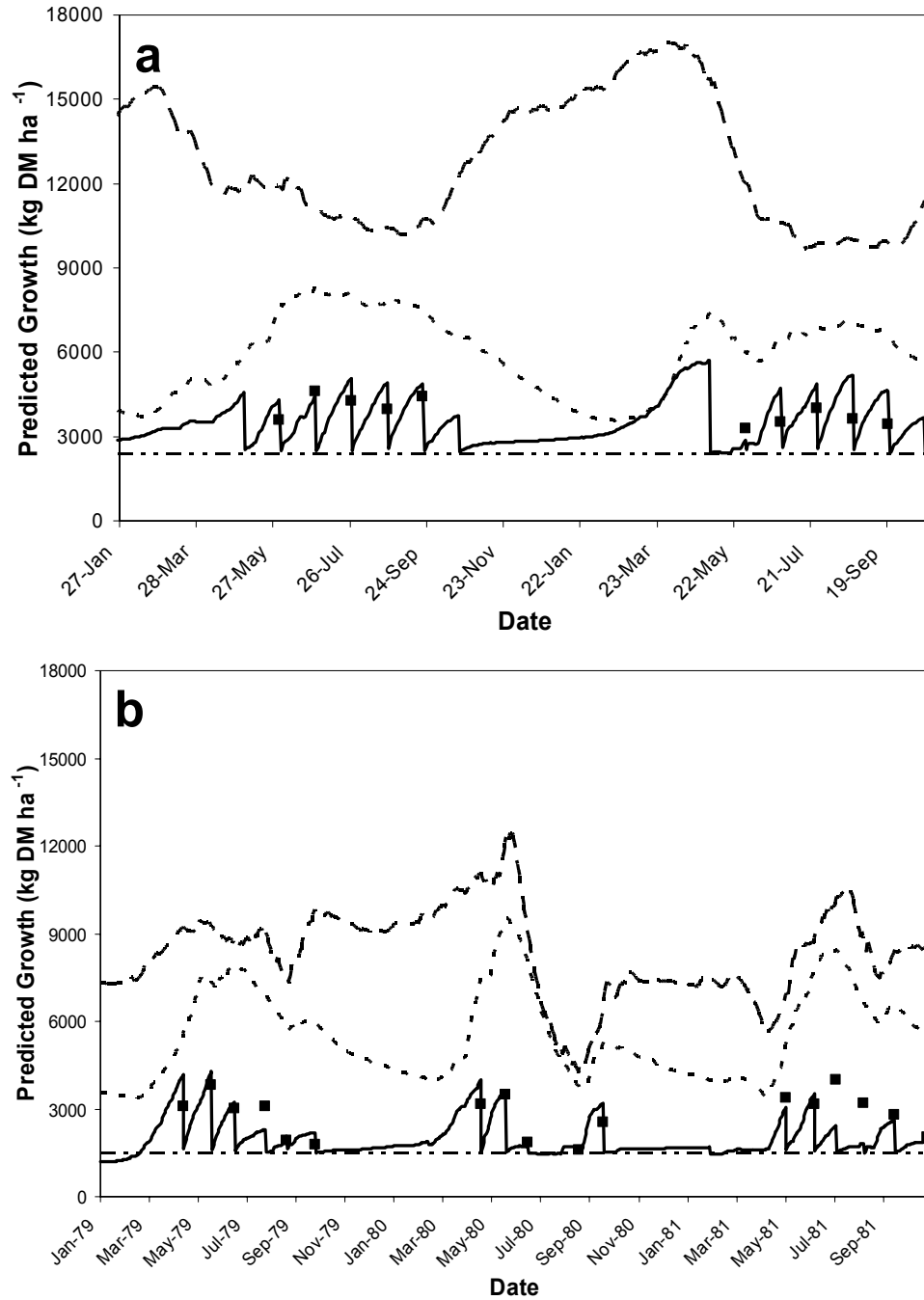


Figure 5-13. Observed bahiagrass herbage mass (■), predicted stolon (— — —), root (.....), and herbage mass (——) for bahiagrass grown in **a**) Ona, FL with 468 kg N ha<sup>-1</sup> yr<sup>-1</sup> or **b**) Eagle Lake, TX with 168 kg N ha<sup>-1</sup> yr<sup>-1</sup>. Predicted values generated by the forage version of CROPGRO.

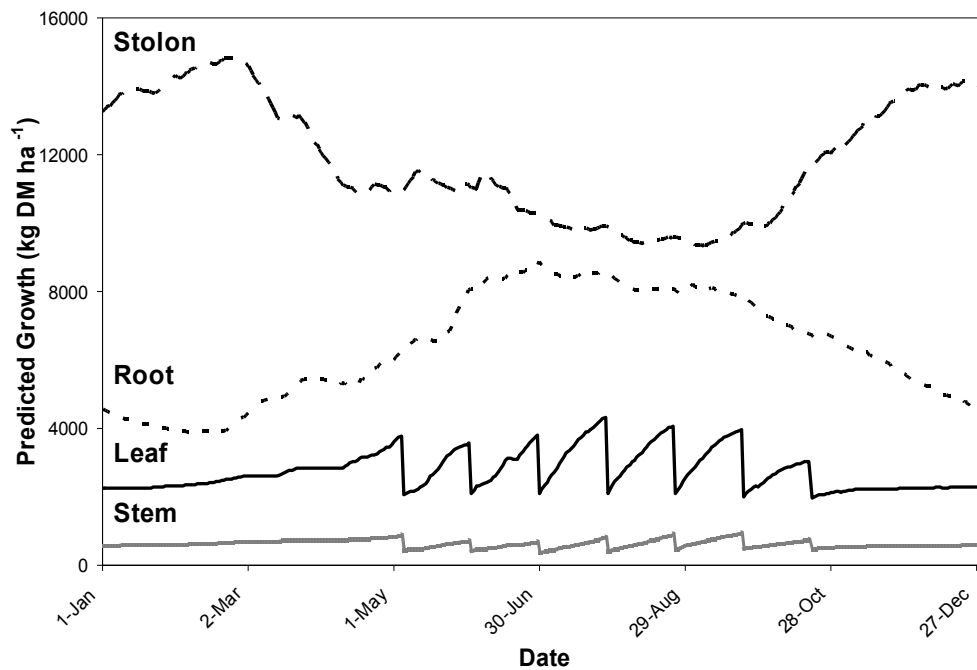


Figure 5-14. Predicted stolon (— —), root (.....), leaf (—), and stem (—) growth for bahiagrass grown with 468 kg N ha<sup>-1</sup> yr<sup>-1</sup> in Ona, FL in 1997 using the forage version of CROPGRO.

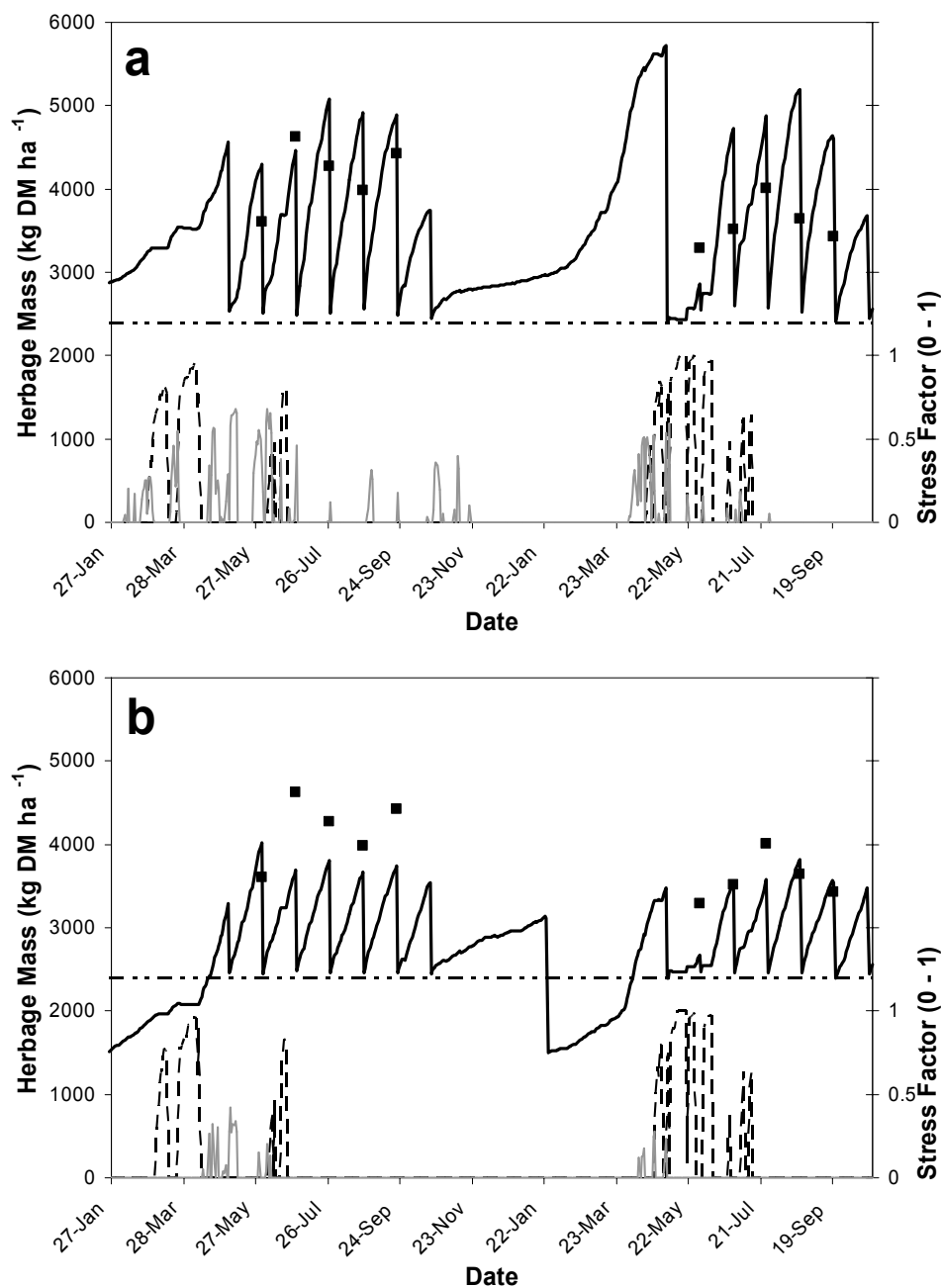


Figure 5-15. Observed herbage mass (■), predicted herbage mass (—), water stress (— —), and N stress (—) of bahiagrass grown with 468 kg N ha<sup>-1</sup> yr<sup>-1</sup> at Ona, FL. Predicted using the leaf-level photosynthesis option in **a**) the forage version of CROPGRO or **b**) the unmodified CSM version of CROPGRO. To simulate dormancy in the CSM simulation, photosynthesis was reduced by 70% and partial defoliation was simulated in the winter. Both 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.



Figure 5-16. Predicted (■) vs. observed bahiagrass herbage mass for five experiments, using the modified leaf-level photosynthesis option in the forage version of CROPGRO. The linear regression line (—) is presented with its corresponding equations and  $r^2$  values along with a line designating a theoretical 1:1 relationship (---).

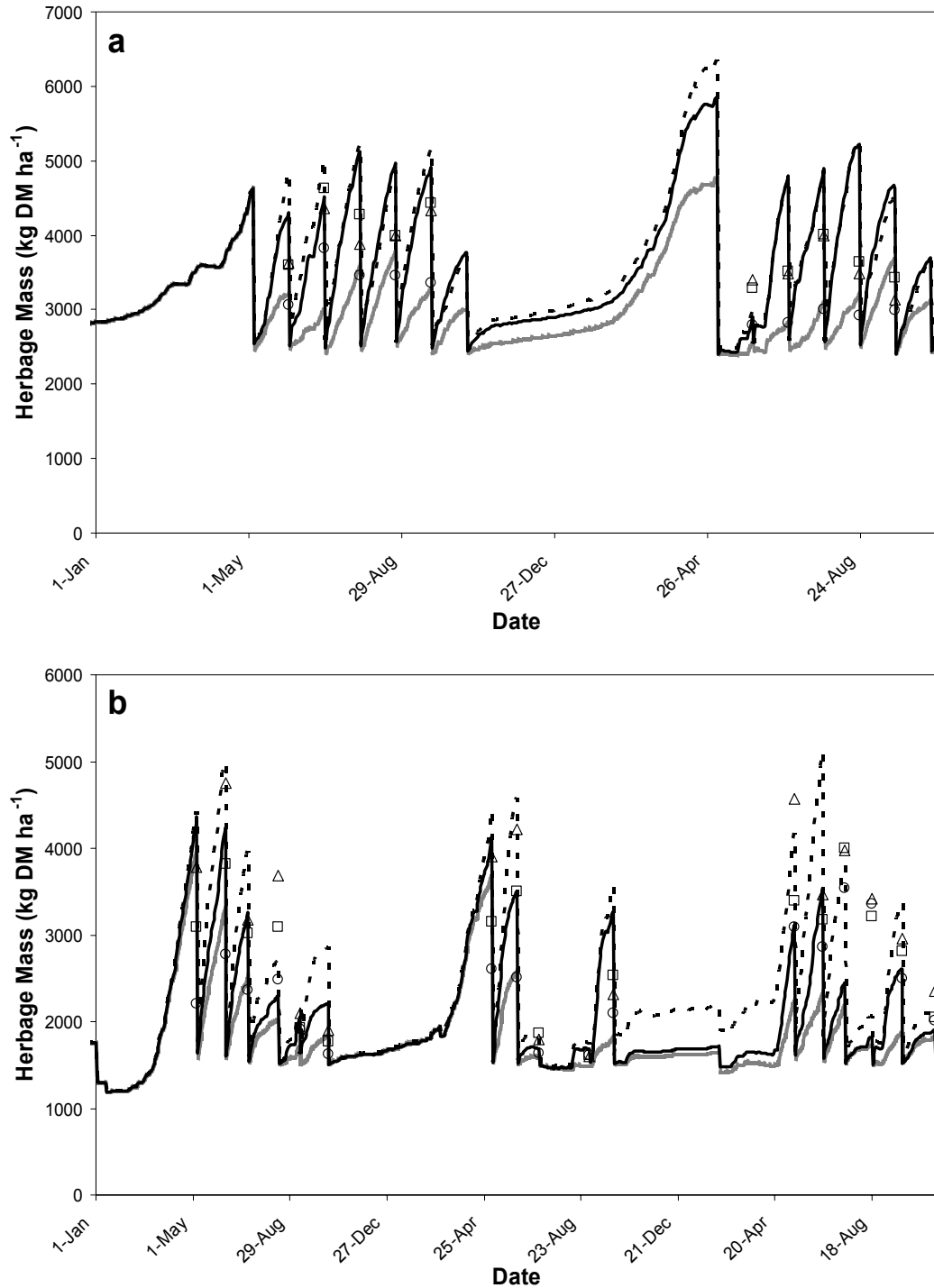


Figure 5-17. Observed/predicted bahiagrass herbage mass for **a)** the 0 kg N ha<sup>-1</sup> yr<sup>-1</sup> (○ and —), 468 kg N ha<sup>-1</sup> yr<sup>-1</sup> (□ and —), and 942 kg N ha<sup>-1</sup> yr<sup>-1</sup> (△ and ..... ) treatments at Ona, FL and **b)** the 0 kg N ha<sup>-1</sup> yr<sup>-1</sup> (○ and —), 168 kg N ha<sup>-1</sup> yr<sup>-1</sup> (□ and —), and 336 kg N ha<sup>-1</sup> yr<sup>-1</sup> (△ and ..... ) treatments at Eagle Lake, TX. Predicted values generated by the forage version of CROPGRO.



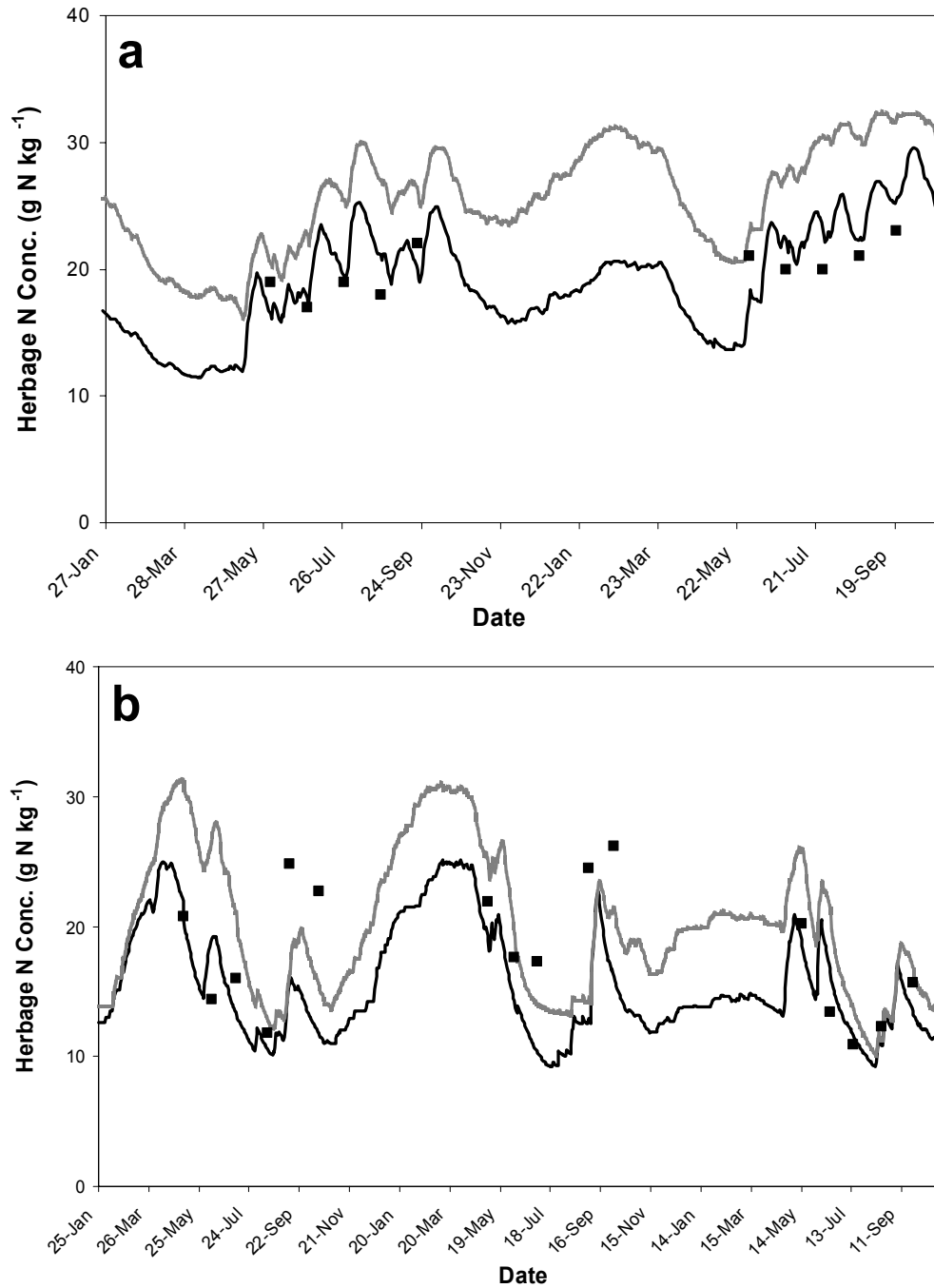


Figure 5-18. Observed bahiagrass herbage N concentration (■) and predicted bahiagrass herbage N concentration using the forage version of CROPGRO and the leaf-level option (—), or daily canopy option (—). For **a**) bahiagrass grown at Ona, FL with 468 kg N ha<sup>-1</sup> yr<sup>-1</sup>, or **b**) bahiagrass grown at Eagle Lake, TX with 168 kg N ha<sup>-1</sup> year<sup>-1</sup>.

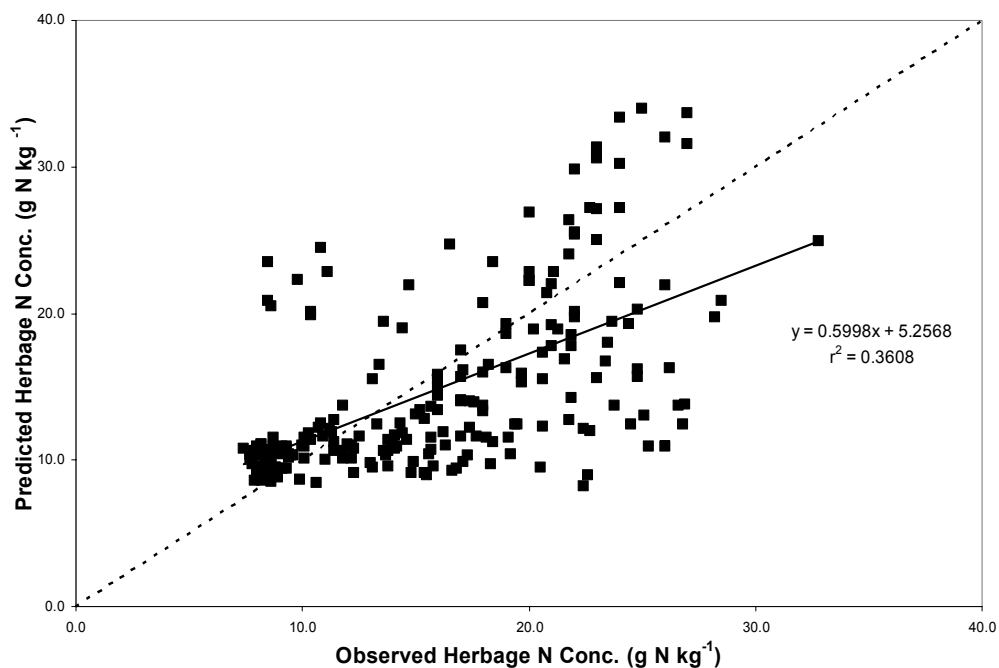


Figure 5-19. Predicted (■) vs. observed bahiagrass herbage N concentration for five experiments, using the modified leaf-level photosynthesis option in the forage version of CROPGRO. The linear regression line (—) is presented with its corresponding equations and  $r^2$  values along with a line designating a theoretical 1:1 relationship (---).

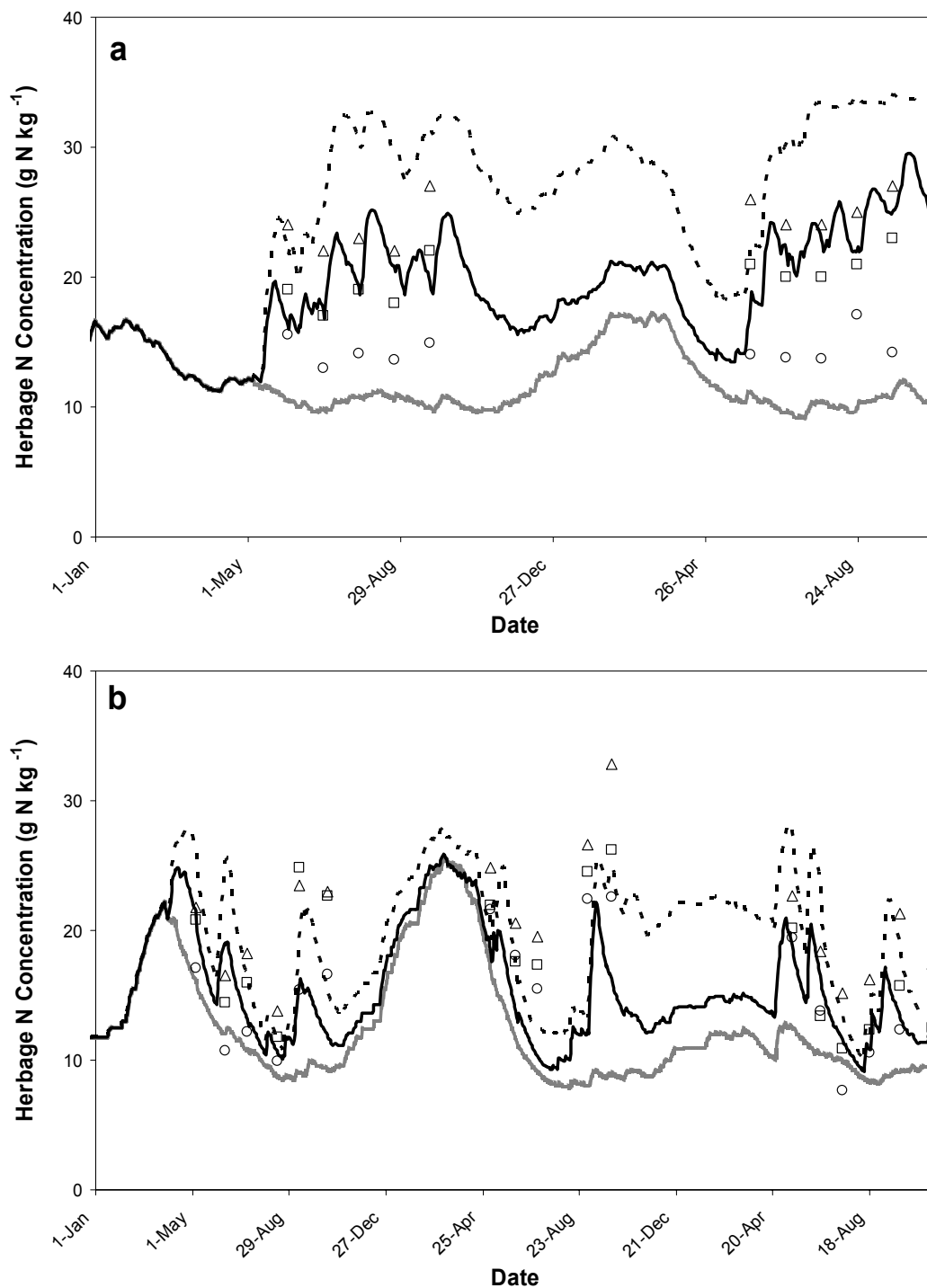


Figure 5-20. Observed/predicted bahiagrass herbage N concentration for **a)** the 0 kg N ha<sup>-1</sup> yr<sup>-1</sup> (○ and —), 468 kg N ha<sup>-1</sup> yr<sup>-1</sup> (□ and —), and 942 kg N ha<sup>-1</sup> yr<sup>-1</sup> (△ and - - -) treatments at Ona, FL and **b)** the 0 kg N ha<sup>-1</sup> yr<sup>-1</sup> (○ and —), 168 kg N ha<sup>-1</sup> yr<sup>-1</sup> (□ and —), and 336 kg N ha<sup>-1</sup> yr<sup>-1</sup> (△ and - - -) treatments at Eagle Lake, TX. Predicted values generated by the forage version of CROPGRO.

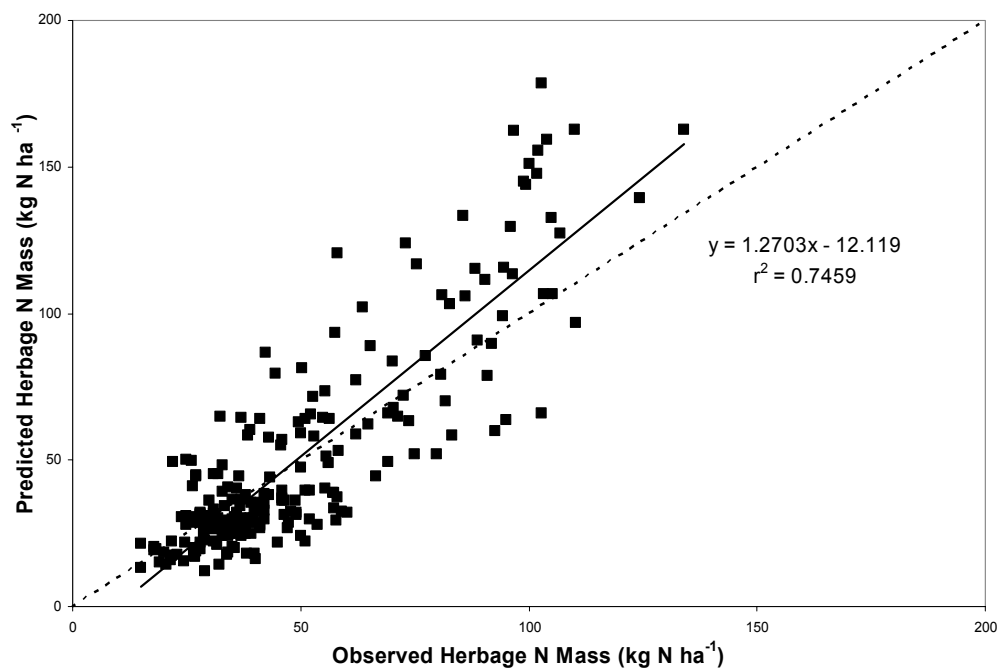


Figure 5-21. Predicted (■) vs. observed bahiagrass herbage N mass for five experiments, using the modified leaf-level photosynthesis option in the forage version of CROPGRO. The linear regression line (—) is presented with its corresponding equations and  $r^2$  values along with a line designating a theoretical 1:1 relationship (---).

## CHAPTER 6

### SUMMARY AND CONCLUSIONS

Perennial tropical forages such as bahiagrass (*Paspalum notatum* Flüggé) fulfill roles as both a feedstuff and a component of nutrient recovery/recycling on livestock farms. These crops may be managed for any combination of yield, feed quality, and nutrient uptake. A crop model that predicts the growth and composition of the forage as well as the N dynamics of the crop-soil system could be a useful tool in finding the proper balance between these objectives.

The objective of this research was to develop a tool to predict the growth and composition of bahiagrass that responds to environmental and management inputs. In this effort, a bahiagrass growth study was conducted in the summer and fall of 2001 to examine, in detail, changes in growth as the plant advances through the regrowth cycle and through the end of the growing season (Chapter 3). We used information from this experiment to supplement the existing literature in an effort to adapt the CSM version of the CROPGRO model to simulate the growth and composition of bahiagrass (Chapter 4). Our initial testing revealed limitations in the model structure preventing realistic simulation of seasonal growth patterns. To address these limitations, the source code was modified to add a storage organ (stolon) and dormancy process, the freeze damage process was modified to allow gradual loss of leaves and stems in winter, and the leaf-level photosynthesis option was modified to better simulate  $C_4$  photosynthesis (Chapter 5).

### **Bahiagrass Growth Study**

An established stand of bahiagrass was monitored weekly to quantify changes in growth patterns and photosynthesis during late summer (18 July – 12 September) and fall (12 September – 7 November) regrowth periods. Sod cores, dug weekly, were washed and plant material separated into leaf blade, stem, stolon, and root components. Leaf and canopy photosynthesis were measured periodically during both regrowth periods.

There was a large decrease in root mass in the first period, thought to be due to previous management of the field. Stem mass decreased during each period, likely due to our reclassification of leaves from stems prior to elongation and reclassification as leaf blade after elongation. Leaf growth was lower in the second period and only half as many leaves emerged per tiller during the second period as in the first. Stolon mass did not change during the first period but increased dramatically during the second. Although canopy photosynthesis was lower in the second period, consistent with the reduced leaf growth, leaf photosynthetic rate did not change. Thus, leaf growth was reduced in the fall as growth of stolons increased.

### **Development of Species File Parameters for Bahiagrass**

New species, cultivar, and ecotype files were created to allow simulation of bahiagrass growth and composition with CROPGRO. A set of files was created from data available in the literature and minimal curve fitting. Two experiments were selected from the literature and simulated in CROPGRO. The measured data from the experiments were split into two sets with the high and low N fertilization treatments used for calibration of the model and the medium N fertilization treatments used to test the model. The fit of the herbage mass predictions from the literature-based species file were good with an index of agreement (d-index) of 0.85, a slope of 0.611 and an  $r^2$  of 0.54

though there was a tendency to underpredict, especially at higher amounts of herbage mass. Fit of herbage N concentration was not as accurate with a d-index of 0.605 and an  $r^2$  of 0.18 and a tendency to overpredict herbage N concentration. Performance using both the leaf-level and daily canopy photosynthesis options of the CSM model was similar. Three limitations posed by the model structure were identified that inhibited simulation of realistic growth patterns. These items were 1) a lack of a storage organ (stolon) in the model structure, 2) the freeze damage routine was not flexible enough as it would either kill all leaves and compromise the simulation or killed none and allowed excessive leaf growth to persist, and 3) lack of a dormancy process to slow herbage growth during the winter. An optimized species file was developed but it performed little better than the literature-based file. It was concluded that the optimization did little more than try to compensate for the limitations of the model and did not represent a better representation of the biology.

### **Adapting CROPGRO to Model Perennial Tropical Grasses: Structural Changes to the Model**

The source code for the CSM version of CROPGRO was modified to address the limitations identified while developing new species parameter files. A new organ (STOR) was added to simulate stolons. Much of the new code was a duplication of that already in use for simulating leaves and stems. Partitioning of new growth and mobilization of N were handled differently for STOR. New functions were added to increase mobilization of both N and carbohydrate ( $\text{CH}_2\text{O}$ ) from STOR when 1) LAI was low ( $<3$ ), and / or when whole-plant N status was adequate to high ( $>30\%$ ). These factors allowed faster regrowth after harvests and in the spring. The STOR organ was an integral component of the dormancy process. Daylength both induces and breaks

dormancy. Once induced by a daylength of  $<12.5$  h, dormancy functions increase partitioning to STOR and decrease mobilization of both N and  $\text{CH}_2\text{O}$  from both STOR and roots. The degree of dormancy and extent of modification of partitioning and mobilization reach a maximum when daylength decreases to 10.5 h. As daylength begins to lengthen above 10.5 h, the degree of dormancy decreases with dormancy breaking when daylength reaches 12.5 h. As partitioning to STOR increases, partitioning to leaves, stems, and roots decreases, resulting in reduced herbage growth over the winter.

The freeze damage process was modified with a “death constant” reducing leaf and stem mass 5% for every degree the daily minimum temperature drops below  $-5^\circ\text{C}$ . Code for a reversible cold-hardening process with dehardening as daylength increases was added for future modeling of more cold-hardy species but was not enabled for bahiagrass.

A “ $\text{CO}_2$ -concentrating factor” was also added to the leaf-level photosynthesis code to allow better simulation of  $\text{C}_4$  photosynthesis. This reduced the sensitivity of quantum efficiency and maximum leaf photosynthetic rate to temperature and  $\text{CO}_2$ , thus reflecting the influence of the high  $\text{CO}_2$  concentrations around the bundle sheath chloroplasts of  $\text{C}_4$  plants.

Three more experiments were added to our collection for calibrating the new forage version of the model. Most of the new parameters were either selected from the literature or calculated to impart the desired response. General parameters such as maximum fraction of new growth partitioned to STOR during dormancy were adjusted while running the model. Performance of the new forage version was better than for the CSM version of the model. Based on the larger dataset, the d-index for predicted herbage mass was 0.81 and 0.82 using the leaf-level and daily canopy options (respectively) in the new



version compared to 0.71 and 0.73 for the CSM version. All other measures of fit improved as well. Prediction of herbage N concentration was not as accurate as prediction of herbage mass, but similarly improved over the CSM version. The predicted CO<sub>2</sub>-induced leaf-level photosynthetic response to elevated CO<sub>2</sub> was of the same magnitude as observed in the field but the higher rate was not reflected in increased herbage mass. Frequent N stress was predicted, resulting in the increased photosynthate production being stored in STOR and roots. This was likely an overprediction of N stress as most treatments simulated were designed so that N would not be limiting growth. The cause of the prediction of excessive N stress was not identified but could be due to errors in estimating soil and soil organic matter parameters or initial conditions.

### **Implications of the Research**

As the first working version, the modified forage version of CROPGRO CSM model marks a significant step in adapting the model to better represent the biology and management of tropical perennial forages. Viable mechanisms have been added to simulate some of the unique aspects of both growth and harvest management of perennial tropical forages. Parameters may be easily adjusted as new knowledge becomes available. Adaptation to other perennial forages should be much simpler with the new version's structure. Given these advances, additional testing and calibration is still needed to improve the robustness of the model for general use.

Beyond the added utility of the model, the performance may be adequate to use under limited conditions. Accurate prediction of single season production may be a ways off, limiting its usefulness to farmers and consultants looking for a tool to make mid-season management changes. However, multi-year simulations comparing relative differences between management strategies may produce useful results regarding herbage

production and even herbage N composition. Thus, there is potential utility for use in research and forecasting. Given the excessive N stress frequently predicted by the model, use to evaluate N management strategies may require extensive calibration of soil parameters or species N parameters for the given location prior to running the evaluation.

### **Future Research**

The most immediate priority to further model development is to identify the cause of the excessive N-stress predictions. Once that is done, other parameters can be recalibrated. The next step beyond that would be to test the temperature parameters over a wider range of conditions. Addressing those two concerns should improve the usefulness of the model considerably. Confidence in shorter-term simulation results should increase. After this, use of the model in long and short-term testing of nutrient management strategies and use of the results in directing research priorities may be quite viable. The adaptation of the forage version to other forages such as alfalfa (*Medicago sativa*) and temperate grasses could follow soon. Looking towards future improvements, two additional modifications that would improve the utility and accuracy of the model are the development of a “true” C<sub>4</sub> photosynthesis option and expansion to include the ability to predict changes in forage quality.

While simulating C<sub>4</sub> photosynthetic processes down to the molecular level may not be necessary, a dual compartment system that simulated mesophyll and bundle sheath processes separately could allow more flexibility and accuracy in simulating the response of C<sub>4</sub> photosynthesis to CO<sub>2</sub> concentration and temperature. The bundle sheath photosynthesis component would essentially be an extension of the current leaf-level photosynthesis option, hence useful for both C<sub>3</sub> and C<sub>4</sub> species.

Looking in new directions for improving the model, we should look to the potential users. As cattle are the ultimate consumers of forage, the priorities of the model should extend in that direction. The forage version of CROPGRO already predicts leaf and stem crude protein, lignin, and carbohydrate composition, and tracks mobile carbohydrate content and physiological age. From these variables, a new output file could be created to provide information targeted to livestock feeding and performance. Neutral detergent fiber (cell wall, an indicator of energy content and “fill” value) concentration might be predicted by subtracting mobile carbohydrate concentration from total carbohydrate concentration. Forage digestibility might be predicted by correlation with predicted lignin and cell wall concentration, physiological age, and, possibly, crude protein concentration. These additions are natural extensions of this adaptation process, initiating new directions for model development.

## APPENDIX A

### CROPGRO CSM PARAMETER CODE DEFINITIONS

Variable definitions listed in order of their appearance in the species file, followed by those in the ecotype file.

PARMAX - PAR at which photosynthesis is 63% of the maximum value (PHTMAX).  
Used in daily canopy photosynthesis calculations ( $\text{moles[quanta] m}^{-2} \text{ d}^{-1}$ ). Used to define asymptotic response of daily canopy assimilation to daily photosynthetic photon flux.

PHTMAX - Maximum amount of  $\text{CH}_2\text{O}$  which can be produced if photosynthetically active radiation (PAR) is very high (3 times PARMAX) and all other factors are optimal ( $\text{g[CH}_2\text{O]m}^{-2} \text{ d}^{-1}$ ). Used to define asymptotic response of daily canopy assimilation to daily photosynthetic photon flux.

CCMP - Canopy  $\text{CO}_2$  compensation point ( $\text{CO}_2$  at which daily photosynthesis is 0.0).

FNPGN(4) - Critical leaf N concentration for function to reduce photosynthesis due to low leaf N levels (4 values for function CURV). This is a two-sided generic curve using only the two leftmost points to describe both canopy and leaf photosynthesis response to leaf N concentration. Same leaf-derived function is used for leaf and canopy options; however, subroutine PHOTO modifies it for DAILY option with a square root change.

TYPPGN - Character variable specifying the type of function to use for the relationship between leaf N concentration and photosynthesis (for use in function subroutine CURV). QDR defines a quadratic curve as photosynthesis increases from zero at the minimum leaf N concentration to its maximum at the maximum leaf N concentration.

FNPGT(4) - Critical values of temperature for the functions to reduce canopy PG under non-optimal temperatures (in function CURV). A two-sided generic curve that describes daily canopy assimilation in response to average daytime temperature

TYPPGT - Character variable specifying the type of function to use for the relationship between temperature and photosynthesis (for use in function subroutine CURV). LIN means linear 4-point lookup.

XLMAXT (6 VALUES) and YLMAXT (6 VALUES) - This is a 6-point lookup function, that describes relative rate of photosynthetic electron-transport (YLMAXT) in response to temperature (XLMAXT). Used only for Leaf option and affects computed light-saturated leaf photosynthesis.

- FNPGL(4), - Describes relative effect of minimum night temperature (TMIN) on next day's single leaf light-saturated photosynthesis rate. Use only the two leftmost values,
- TYPGGL - Character variable specifying the type of function to use for the relationship between TMIN and next day's single leaf light-saturated photosynthesis rate. QDR quadratic/parabolic response from 0.0 to 1.0 (no effect) on leaf photosynthesis.
- PGEFF - Quantum efficiency of leaf photosynthesis, defined at 350 ppm CO<sub>2</sub>, 21% oxygen, and 30 C. Set from published values in literature, Ehleringer and Björkman (1977).
- SLWREF - Specific leaf weight at which LFMAX is defined.
- LNREF - Value of leaf N above which canopy PG is maximum (for standard cultivar). Leaf N concentration at which LFMAX is defined.
- PGREF - Reference value for leaf level photosynthesis used in canopy light response curve ( $\mu\text{mol}[\text{CO}_2] \text{ m}^{-2} \text{ s}^{-1}$ ). Used only for the "Daily" canopy assimilation option. Allows cultivar variation in LFMAX to change daily canopy assimilation. Not used for the leaf-level, hedgerow photosynthesis option.
- PROLFI, PROLFG, PROLFF - "Maximum", "normal growth", and "final" protein concentrations of leaf tissue.
- PROSTI, PROSTG, PROSTF - "Maximum", "normal growth", and "final" protein concentrations of stem tissue.
- PRORTI, PRORTG, PRORTF - "Maximum", "normal growth", and "final" protein concentrations of root tissue.
- PLIPLF, PLIPST, PLIPRT, PLIPSH, PLIPNO - Lipid concentration of leaf, stem, root, shell, and nodule tissues, respectively.
- PLIGLF, PLIGST, PLIGRT, PLIGSH, PLIGSD, PLIGNO - Lignin concentration of leaf, stem, root, shell, seed, and nodule tissue, respectively.
- PCARLF, PCARST, PCARRT, PCARSH, PCARSD, PCARNO - Carbohydrate-cellulose concentration of leaf, stem, root, shell, seed, and nodule tissues, respectively.
- CMOBMX - Maximum rate of mobilization of carbohydrate from vegetative tissues, fraction of available carbohydrate pool per day.
- NMOBMX - Maximum rate of mobilization of protein from vegetative tissues, during reproductive growth, fraction of available protein pool per day.
- NVSMOB - Maximum rate of mobilization of carbohydrate from vegetative tissues, during vegetative growth, fraction of available protein pool per day.
- XLEAF(8) - V-stage at which partitioning to leaves is YLEAF(I) (leaf nodes).
- YLEAF(8) - Partitioning fraction to leaf growth at V-stage XLEAF(I) ( $\text{g}[\text{leaf}] \text{ g}[\text{veg. plant}]^{-1}$ ).

- YSTEM(8) - Partitioning fraction to stem growth at V-stage XLEAF(I) ( $\text{g}[\text{stem}] \text{g}[\text{veg. plant}]^{-1}$ )
- FRSTMF - Fraction of daily dry weight increase in vegetative plant parts which goes to stems after the day on which the maximum number of V-stages occurs (NDVSTG). ( $\text{g}[\text{stem}] \text{g}[\text{veg}]^{-1}$ ).
- FRLFF - Fraction of daily increase in vegetative dry weight which goes to leaves after the day on which the maximum number of V-stages occurs (NDVSTG). ( $\text{g}[\text{leaf}] \text{g}[\text{veg}]^{-1}$ ).
- FRLFMX - Maximum leaf partitioning ( $\text{g}[\text{leaf}] \text{g}[\text{veg}]^{-1}$ ).
- FINREF - Specific leaf area (SLA) of leaves of standard crop cultivar when plants emerge ( $\text{cm}^2[\text{leaf}] \text{g}[\text{leaf}]^{-1}$ ).
- SLAREF - Specific leaf area (SLA) for new leaves during peak vegetative growth for the standard cultivar. ( $\text{cm}^2 \text{g}^{-1}$ ).
- SIZREF - The size of a normal upper node leaf (nodes 8 – 10) of standard cultivar. ( $\text{cm}^2 \text{leaf}^{-1}$ ).
- VSSINK - Vegetative stage beyond which sink-limited leaf area expansion can no longer limit photosynthesis or leaf area growth.
- SLAMAX - Maximum specific leaf area for new leaves when grown under low radiation, but optimum water and temperature conditions ( $\text{cm}^2 \text{g}^{-1}$ ). The (thinnest) leaves can be under low light.
- SLAMIN - Minimum specific leaf area for new leaves when grown under high radiation and optimum water and temperature conditions ( $\text{cm}^2 \text{g}^{-1}$ ). The (thickest) leaves can be under high light.
- XVGROW(6) - V-stage at which maximum leaf area growth per plant since emergence is YVGROW(I). (number of leaf nodes).
- YVREF(6) - Maximum leaf area grown per plant at V-stage XVGROW(I), for reference cultivar. ( $\text{cm}^2 \text{plant}^{-1}$ ).
- XSLATM(5) - Temperature values for function that reduces specific leaf area (SLA) ( $^{\circ}\text{C}$ ).
- YSLATM(5) - Array which describes the effect of temperature on specific leaf area. Relative temperature effect on specific leaf area of newly-formed leaves.
- FREEZ1 - Temperature below which all leaves are killed, but stems, pods, and seeds remain alive, development to maturity proceeds, and seeds can grow on mobilized reserves ( $^{\circ}\text{C}$ ).
- FREEZ2 - Temperature below which plant growth stops completely, development and crop growth simulation stops ( $^{\circ}\text{C}$ ).
- ICMP - Light compensation point for senescence of lower leaves because of excessive self-shading by crop canopy ( $\text{moles m}^{-2} \text{d}^{-1}$ ).

TCMP - Time constant for senescence of lower leaves because of excessive self-shading by crop canopy (thermal days).

XSTAGE(4) - V-stage at which SENPOR(I) fraction of cumulative leaf growth will have been senesced if no water stress occurred (number of leaf nodes).

SENPOR(4) - The fraction leaf abscission that normally occurs by a given V stage. Proportion of leaf weight grown which will have been senesced by a given V-stage (XSTAGE(I)) if no water stress has occurred prior to this V-stage (XSTAGE(I)) -- normal vegetative senescence does not occur if prior water stress has already reduced leaf mass.

XSENMX(4) - V-stage at which maximum fraction of cumulative leaf growth vulnerable to loss due to water stress is SENMAX(I) (number of leaf nodes).

SENMAX(4) - Maximum proportion of total leaf weight as a function of V-stage (XSENMX(I)) which can be senesced due to water stress. The maximum allowable leaf abscission due to water stress that is allowed to occur by a given V stage.

RTDEPI - Depth of roots on day of plant emergence. (cm).

RFAC1 - Root length per unit root mass ( $\text{cm g}^{-1}$ ).

RTSDF - Maximum fraction of root length senesced in a given layer per physiological day when water content in a given layer falls below 25 % of extractable soil water.

RWUEP1 - The ratio of evaporative demand:root water uptake at which the water stress factor, TURFAC, is 1.00 (maximum stress), and declines below that ratio.

TB, T1, T2, TMAX - Base temperature (TB), first optimum (TO1), second optimum (TO2), and maximum temperature (TM). Relative rate of phenological development is zero at TB and TM, and optimum (1.0) at TO1 and TO2. Possible to use linear (LIN) or parabolic (QDR) between these points.

XVSHT(10) - Node number on main stem for use in computing height and width growth rates.

YVSHT(10) - Length of internode (m) vs. position on the main stem defined by XVSHT ( $\text{m node}^{-1}$ ).

YVSWH(10) - Increase in canopy width per node developed on the main stem ( $\text{m node}^{-1}$ ).

APPENDIX B  
SPECIES, CULTIVAR, AND ECOTYPE FILES FOR THE UNMODIFIED CSM  
VERSION OF CROPGRO

Literature-Based Species file:



\*BAHIA SPECIES COEFICIENTS

!\*PHOTOSYNTHESIS PARAMETERS

60.0	90.0	0.55									PARMAX,PHTMAX,KCAN
20.0	1.30	.0090									CCMP,CCMAX,CCEFF; CO2 EFFECT ON PGCAN
0.75	3.0	10.0	10.0	QDR							FNPGR(4),TYPPGR-LF N EFFECT ON PG
12.0	25.0	38.0	50.0	LIN							FNPGR(4),TYPPGR-TEMP EFFECT-CANOPY PG
-5.0	7.0	35.0	45.0	55.0	60.0						XLMAXT (6 VALUES)
0.0	0.0	1.0	1.0	0.0	0.0						YLMAXT (6 VALUES)
7.0	18.0	45.0	57.0	QDR							FNPGL(4),TYPPGL-TMIN EFFECT-LEAF PG
.0650	0.20	0.80	2.0								PGEFF SCV KDIF, LFANGB 11/5/02
.0035	.0002	.2000	3.00	1.760							SLWREF,SLWSLO,NSLOPE,LNREF,PGREF
0.0	.001	.002	.003	.0035	.004	.005	.006	.008	.010		XPGSLW(1-10)
.162	.679	.867	.966	1.000	1.027	1.069	1.100	1.141	1.167		YPGSLW(1-10)

!\*RESPIRATION PARAMETERS

0.35E-04	.0029										RES30C,R30C2
2.556	2.556	.360	2.830								RN03C,RNH4C,RPRO,RFIXN
1.242	3.106	2.174	.929	0.05	1.13						RCH20,RLIP,RLIG,ROA,RMIN,PCH20

!\*PLANT COMPOSITION VALUES

.220	.110	.050	.110	.070	.033		PROLFI,PROLFG,PROLFF,PROSTI,PROSTG,PROSTF
.101	.040	.022	.039	.039	.038		PRORTI,PRORTG,PRORTF,PROSHI,PROSHG,PROSHF
.115	.115	.300	.015	.019	.800		SDPROS,SDPROG,PRONOD,PROMIN,PROMAX,THETA

.602	.697	.702	.251	.750	.480	PCARLF,PCARST,PCARRT,PCARSH,PCARSD,PCARNO
.025	.020	.020	.011	.050		PLIPLF,PLIPST,PLIPRT,PLIPSH,PLIPNO
.040	.060	.070	.100	.030	.070	PLIGLF,PLIGST,PLIGRT,PLIGSH,PLIGSD,PLIGNO
.050	.050	.050	.040	.040	.050	POALF,POAST,POART,POASH,POASD,POANO
.063	.063	.057	.100	.030	.050	PMINLF,PMINST,PMINRT,PMINSH,PMINSD,PMINNO

!\*SEED COMPOSITION VALUES

7.168	23.65	0.908	0.430			LIPTB,LIPOPT,SLOSUM*100,CARMIN
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!\*CARBON AND NITROGEN MINING PARAMETERS

0.025	0.75	.280	0.050	1.00	0.15	CMOBMX,CADSTF,CADPR1,NMOBMX,NVSMOB,NRCVR
	PD					XPODF
0.04	0.08	0.04	0.08			ALPHL,ALPHS,ALPHR,ALPHSH

!\*NITROGEN FIXATION PARAMETERS

.050	.160	0.01	0.0	0.04	0.05	SNACTM,NODRGM,DWNODI,TTFIX,NDTHMX,CNODCR
7.00	28.0	35.0	44.0	LIN		FNNGT(4),TYPNGT-TEMP EFF ON NOD GROWTH
5.00	23.0	35.0	44.0	LIN		FNFX(4),TYPFX-TEMP EFF ON N FIX
-.15	0.20	1.00	10.0	LIN		FNFXD(4),TYPFXD-REL SW-DRY EFF ON N FIX
-.02	.001	1.00	2.00	LIN		FNFXW(4),TYPFXW-REL SW-WET EFF ON N FIX
0.00	0.10	1.00	0.00	INL		FNFXA(4),TYPFXA-AGE EFF ON N FIX

!\*VEGETATIVE PARTITIONING PARAMETERS

0.0	1.5	2.0	3.0	5.0	7.0	30.0	40.0	XLEAF VALUES
0.60	0.60	0.60	0.40	0.25	0.20	0.20	0.20	YLEAF VALUES

0.10	0.10	0.10	0.10	0.05	0.05	0.05	0.05	YSTEM VALUES
0.55	0.00	0.05	0.20	1.00				WTFSD,PORPT,FRSTMF,FRLFF,ATOP
0.60								FRLFMX

!\*LEAF GROWTH PARAMETERS

144.	285.	2.0	0.0	00.0				FINREF,SLAREF,SIZREF,VSSINK,EVMODC
350.	200.	-.048	1.20					SLAMAX,SLAMIN,SLAPAR,TURSLA
0.0	5.0	10.0	15.0	20.0	25.0			XVGROW(1-6), VSTAGE VALUES
0.0	10.0	20.0	30.0	40.0	50.0			YVREF(1-6), LEAF AREA VALUES,CM2
-50.0	00.0	10.0	30.0	60.0				XSLATM(1-5),TEMP VALUES
0.25	0.25	0.25	1.00	1.0				YSLATM(1-5),EFFECT ON SLA

!\*LEAF SENESCENCE FACTORS

0.80	0.00	0.05	-25.0	-25.0				SEN RTE,SENRT2,SENDAY,FREEZ1,FREEZ2
0.80	25.0							ICMP,TCMP(Light comp, time constant-senes)

!	.....	XSTAGE.....	.....	XSENMX.....				
	0.0	5.0	9.0	50.0	3.0	5.0	10.0	50.0
!	.....	SENPOR.....	.....	SENMAX.....				
	0.0	0.0	0.12	0.12	0.0	0.2	0.6	0.6

!\*ROOT PARAMETERS

20.0	5000.	0.010	0.1	0.02	1.50	0.04		RTDEPI,RFAC1,RTSEN,RLDSM,RTSDF,RWUEP1,RWUMX
0.0	2.50	3.0	2.50	6.0	2.50	30.0	2.50	XRTFAC,YRTFAC

0.006 0.006 0.02 0.10

RTN03,RTNH4,PORMIN,RTEXF

!\*SEED AND SHELL GROWTH PARAMETERS

0.60 0.3 0.00 100.

SETMAX,SRMAX,RFLWAB,XMPAGE

15.0 0.0 0.0

DSWBAR,XFRMAX,SHLAG

14.0 21.5 26.5 40.0 QDR

FNPDT(1-4),TYP PDT-TEMP EFFECT ON POD SET

6.0 21.0 23.5 41.0 QDR

FNSDT(1-4),TYP SDT-TEMP EFFECT ON SD GRWTH

0.00 10.00 20.00 26.00 32.00 60.00

XXFTEM(1-6),TEMPERATURES

1.00 1.00 1.00 1.00 1.00 1.00

YXFTEM(1-6),REL CHG IN PARTIT

0.00 0.50 1.00 1.00

XSWFAC(1-4)

0.00 1.00 1.00 1.00

YSWFAC(1-4)

0.00 0.01 0.25 1.00 1.00

XSWBAR(1-5),REL WATER TOPSOIL

1.00 1.00 1.00 1.00 1.00

YSWBAR(1-5),EFFECT ON SEED ADDITION

0.00 0.50 0.75 1.00

XTRFAC(1-4),TURFAC

0.00 0.00 0.00 0.00

YTRFAC(1-4),ENHANCE REPROD. GROWTH

!\*POD LOSS PARAMETERS

N 6.0 .3961 -.865 1.00 0.00

DETACH,DWC,PR1DET,PR2DET,XP1DET,XP2DET

!\*PHENOLOGY PARAMETERS

! TB T01 T02 TM

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9.0 32.0 40.0 45.0

1 VEGETATIVE DEVELOPMENT

10.0 28.0 32.0 45.0

2 EARLY REPRODUCTIVE DEVELOPMENT

10.0 28.0 32.0 45.0

3 LATE REPRODUCTIVE DEVELOPMENT

!FOLLOWING LINE: STAGE; REF STAGE; PHOTOPERIOD FUNCTION; TEMPERATURE FUNCT;  
 !POINTER TO VEGD(1) OR REPDA(2) OR REPDB(3) TEMP SENS; SENS TO WATER;N; AND P

1	1	NON	LIN	1	-0.50	0.00	0.00	PLANT(STG 1) TO EMERG(STG 2) PHASE
2	2	NON	LIN	1	-0.50	0.00	0.00	EMERG(STG 2) TO V1(STG 3) PHASE
3	2	NON	LIN	1	-0.50	0.00	0.00	EMERG(STG 2) TO END JV(STG 4) PHASE
4	4	INL	LIN	1	-0.40	0.00	0.00	END JV(STG 4) TO FL IND(STG 5) PHASE
5	5	INL	LIN	1	-0.40	0.00	0.00	FL IND(STG 5) TO 1ST FL(STG 6) PHASE
6	6	INL	LIN	1	-0.50	0.00	0.00	1ST FL(STG 6) TO 1ST PEG(STG 7) PHASE
7	6	INL	LIN	2	-0.50	0.00	0.00	1ST FL(STG 6) TO 1ST POD(STG 8) PHASE
8	6	INL	LIN	2	-0.50	0.00	0.00	1ST FL(STG 6) TO 1ST SD(STG 9) PHASE
9	9	INL	LIN	3	0.30	0.00	0.00	1ST SD(STG 9) TO LST SD(STG 10) PHASE
10	9	INL	LIN	3	0.30	0.00	0.00	1ST SD(STG 9) TO PH MAT(STG 11) PHASE
11	11	NON	NON	1	0.00	0.00	0.00	PH MAT(STG 11) TO H-MAT(STG 12) PHASE
12	6	INL	LIN	2	-0.70	0.00	0.00	1ST FL(STG 6) TO LST VST(STG 13) PHASE
13	6	INL	LIN	2	-0.70	0.00	0.00	1ST FL(STG 6) TO LST LF(STG 14) PHASE

!\*CANOPY HEIGHT AND WIDTH GROWTH PARAMETERS

! VSTAGE, FOLLOWED BY INTERNODE LENGTH PER NODE, THEN CANOPY WIDTH PER NODE

0.00	1.00	4.00	6.00	8.00	10.00	14.00	16.00	20.00	40.00	XVSHT(1-10)
.0150	.0265	.0315	.0330	.0345	.0330	.0310	.0255	.0170	.0030	YVSHT(1-10)
.0150	.0255	.0310	.0320	.0330	.0315	.0295	.0230	.0125	.0005	YVSWH(1-10)

-50.0	00.0	15.0	30.0	60.0
0.55	0.55	0.55	1.00	1.00

XHWTEM(1-5),TEMPERATURES
YHWTEM(1-5),RELATIVE EXPAN

0.00	5.00	7.50	10.00	15.00	20.00	30.00	80.00
4.00	2.00	1.50	1.25	1.05	1.00	1.00	1.00

XHWPAR(1-8),PAR VALUES

YHWPAR(1-8),RELATIVE EXPAN

!\*EVAPOTRANSPIRATION

0.70	1.0	KEP, EORATIO
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Cultivar File:

\*BAHIA GENOTYPE COEFFICIENTS

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!
! COEFF  DEFINITIONS
! =====
! ECO#    Code for the ecotype to which this cultivar belongs (see *.eco file)
! CSDL    Critical Short Day Length below which reproductive development
!          progresses with no daylength effect (for shortday plants) (hour)
! PPSEN   Slope of the relative response of development to photoperiod with time
!          (positive for shortday plants) (1/hour)
! EM-FL   Time between plant emergence and flower appearance (R1)
!          (photothermal days)
! FL-SH   Time between first flower and first pod (R3) (photothermal days)
! FL-SD   Time between first flower and first seed (R5) (photothermal days)
! SD-PM   Time between first seed (R5) and physiological maturity (R7)
!          (photothermal days)
! FL-LF   Time between first flower (R1) and end of leaf expansion
!          (photothermal days)
! LFMAX   Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high light
!          (mg CO2/m2-s)
! SLAVR   Specific leaf area of cultivar under standard growth conditions
!          (cm2/g)
! SIZLF   Maximum size of full leaf (three leaflets) (cm2)
! XFRT    Maximum fraction of daily growth that is partitioned to seed + shell
! WTPSD   Maximum weight per seed (g)
! SFDUR   Seed filling duration for pod cohort at standard growth conditions

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!          (photothermal days)
! SDPDV    Average seed per pod under standard growing conditions (#/pod)
! PODUR    Time required for cultivar to reach final pod load under optimal
!           conditions (photothermal days)
!
@VAR#  VRNAME..... ECO#  CSDL PPSEN EM-FL FL-SH FL-SD SD-PM FL-LF LFMAX SLAVR
SIZLF  XFRT WTPSD SFDUR SDPDV PODUR
!
10     11     12     13     14     15
UF0001 PENSACOLA BAHIA  G00001 12.00 0.200 99.0 10.0 18.0 33.00 25.00 1.76 285.
2.0 0.01 0.020 15.0 2.05 20.0

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Ecotype File:

\*BAHIA ECOTYPE COEFFICIENTS

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!
! COEFF  DEFINITIONS
! =====
! ECO#    Code for the ecotype to which a cultivar belongs (see *.cul
!          file)
! ECONAME Name of the ecotype, which is referenced from *.CUL file
! MG      Maturity group number for this ecotype, such as maturity
!          group in soybean
! TM      Indicator of temperature adaptation
! THVAR   Minimum rate of reproductive development under short days
!          and optimal temperature
! PL-EM   Time between planting and emergence (V0) (thermal days)
! EM-V1   Time required from emergence to first true leaf (V1), thermal
!          days
! V1-JU   Time required from first true leaf to end of juvenile phase,
!          thermal days
! JU-R0   Time required for floral induction, equal to the minimum
!          number of days for floral induction under optimal temperature and
!          daylengths, photothermal days
! PM06    Proportion of time between first flower and first pod for
!          first peg (peanut only)
! PM09    Proportion of time between first seed and physiological
!          maturity that the last seed can be formed
! LNGSH   Time required for growth of individual shells (photothermal

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! days)  
 ! R7-R8 Time between physiological (R7) and harvest maturity (R8) (days)  
 ! FL-VS Time from first flower to last leaf on main stem (photothermal  
 ! days)  
 ! TRIFL Rate of appearance of leaves on the mainstem (leaves per  
 ! thermal day) default was 0.10, not getting enough leaves, changed to 0.15  
 2/21/03  
 ! RWDTH Relative width of this ecotype in comparison to the standard  
 ! width per node (YVSWH) defined in the species file (\*.SPE)  
 ! RHGHT Relative height of this ecotype in comparison to the  
 ! standard height per node (YVSHT) defined in the species file  
 ! (\*.SPE)  
 ! THRSH The maximum ratio of (seed/(seed+shell)) at maturity.  
 ! Causes seed to stop growing as their dry weights  
 ! increase until shells are filled in a cohort.  
 ! (Threshing percentage).  
 ! SDPRO Fraction protein in seeds (g(protein)/g(seed))  
 ! SDLIP Fraction oil in seeds (g(oil)/g(seed))  
 ! R1PPO Increase in daylength sensitivity after R1 (CSDVAR and CLDVAR  
 ! both decrease with the same amount) (h)  
 ! OPTBI Minimum daily temperature above which there is no effect on  
 ! slowing normal development toward flowering (oC)  
 ! SLOBI Slope of relationship reducing progress toward flowering if  
 ! TMIN for the day is less than OPTBI  
 !

@ECO#	ECONAME.....	MG	TM	THVAR	PL-EM	EM-V1	V1-JU	JU-R0	PM06	PM09	LNGSH	R7-R8	FL-
VS	TRIFL	RWDTH	RHGHT	THRSH	SDPRO	SDLIP	R1PPO	OPTBI	SLOBI				
!						1	2	3	4	5	6	7	8
10	11	12	13	14	15	16	17	18	19				
G00001	PENSACOLA	BAHIA	00	01	1.00	0.0	0.0	9999.	9999.	0.0	0.75	10.0	9999.
9999.	0.15	1.0	1.0	78.0	.115	.035	.000	0.0	.000				

Optimized Species File:

\*BAHIA SPECIES COEFICIENTS

!\*PHOTOSYNTHESIS PARAMETERS

106.0	185.0	0.55									PARMAX,PHTMAX,KCAN
5.0	1.40	.0105									CCMP,CCMAX,CCEFF; CO2 EFFECT ON PGCAN
1.00	3.0	10.0	10.0	QDR							FNPGR(4),TYPPGR-LF N EFFECT ON PG
23.0	25.0	25.5	50.0	LIN							FNPGR(4),TYPPGR-TEMP EFFECT-CANOPY PG
-5.0	7.0	35.0	45.0	55.0	60.0						XLMAXT (6 VALUES)
0.0	0.0	1.0	1.0	0.0	0.0						YLMAXT (6 VALUES)
7.0	18.0	45.0	57.0	QDR							FNPGL(4),TYPPGL-TMIN EFFECT-LEAF PG
.0650	0.20	0.80	2.0								PGEFF SCV KDIF, LFANGB 11/5/02
.0035	.0002	.2000	3.00	1.760							SLWREF,SLWSLO,NSLOPE,LNREF,PGREF
0.0	.001	.002	.003	.0035	.004	.005	.006	.008	.010		XPGSLW(1-10)
.162	.679	.867	.966	1.000	1.027	1.069	1.100	1.141	1.167		YPGSLW(1-10)

!\*RESPIRATION PARAMETERS

3.5E-04	.0029										RES30C,R30C2
2.556	2.556	.360	2.830								RNO3C,RNH4C,RPRO,RFIXN
1.242	3.106	2.174	.929	0.05	1.13						RCH20,RLIP,RLIG,ROA,RMIN,PCH20

!\*PLANT COMPOSITION VALUES

.170	.080	.050	.090	.060	.033		PROLFI,PROLFG,PROLFF,PROSTI,PROSTG,PROSTF
.101	.040	.022	.039	.039	.038		PRORTI,PRORTG,PRORTF,PROSHI,PROSHG,PROSHF
.115	.115	.300	.015	.019	.800		SDPROS,SDPROG,PRONOD,PROMIN,PROMAX,THETA

.652	.717	.702	.251	.750	.480	PCARLF,PCARST,PCARRT,PCARSH,PCARSD,PCARNO
.025	.020	.020	.011	.050		PLIPLF,PLIPST,PLIPRT,PLIPSH,PLIPNO
.040	.060	.070	.100	.030	.070	PLIGLF,PLIGST,PLIGRT,PLIGSH,PLIGSD,PLIGNO
.050	.050	.050	.040	.040	.050	POALF,POAST,POART,POASH,POASD,POANO
.063	.063	.057	.100	.030	.050	PMINLF,PMINST,PMINRT,PMINSH,PMINSD,PMINNO

!\*SEED COMPOSITION VALUES

7.168	23.65	0.908	0.430			LIPTB,LIPOPT,SLOSUM*100,CARMIN
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!\*CARBON AND NITROGEN MINING PARAMETERS

0.025	0.75	.280	0.050	1.00	0.15	CMOBMX,CADSTF,CADPR1,NMOBMX,NVSMOB,NRCVR
	PD					XPODF
0.04	0.08	0.04	0.08			ALPHL,ALPHS,ALPHR,ALPHSH

!\*NITROGEN FIXATION PARAMETERS

.050	.160	0.01	0.0	0.04	0.05	SNACTM,NODRGM,DWNODI,TTFIX,NDTHMX,CNODCR
7.00	28.0	35.0	44.0	LIN		FNNGT(4),TYPNGT-TEMP EFF ON NOD GROWTH
5.00	23.0	35.0	44.0	LIN		FNFX(4),TYPFXT-TEMP EFF ON N FIX
-.15	0.20	1.00	10.0	LIN		FNFXD(4),TYPFXD-REL SW-DRY EFF ON N FIX
-.02	.001	1.00	2.00	LIN		FNFXW(4),TYPFXW-REL SW-WET EFF ON N FIX
0.00	0.10	1.00	0.00	INL		FNFXA(4),TYPFXA-AGE EFF ON N FIX

!\*VEGETATIVE PARTITIONING PARAMETERS

0.0	1.5	2.0	3.0	5.0	7.0	30.0	40.0	XLEAF VALUES
0.60	0.60	0.60	0.40	0.25	0.20	0.20	0.20	YLEAF VALUES



0.10	0.10	0.10	0.10	0.05	0.05	0.05	0.05	YSTEM VALUES
0.55	0.00	0.05	0.20	1.00				WTFSD,PORPT,FRSTMF,FRLFF,ATOP
0.60								FRLFMX

!\*LEAF GROWTH PARAMETERS

144.	285.	2.0	0.0	00.0				FINREF,SLAREF,SIZREF,VSSINK,EVMODC
350.	200.	-.048	1.20					SLAMAX,SLAMIN,SLAPAR,TURSLA
0.0	5.0	10.0	15.0	20.0	25.0			XVGROW(1-6), VSTAGE VALUES
0.0	10.0	20.0	30.0	40.0	50.0			YVREF(1-6), LEAF AREA VALUES,CM2
-50.0	00.0	10.0	30.0	60.0				XSLATM(1-5),TEMP VALUES
0.25	0.25	0.25	1.00	1.0				YSLATM(1-5),EFFECT ON SLA

!\*LEAF SENESCENCE FACTORS

0.80	0.00	0.05	-25.0	-25.0				SEN RTE,SENRT2,SENDAY,FREEZ1,FREEZ2
0.80	25.0							ICMP,TCMP(Light comp, time constant-senes)

!	.....	XSTAGE.....	.....	XSENMX.....				
	0.0	5.0	9.0	50.0	3.0	5.0	10.0	50.0
!	.....	SENPOR.....	.....	SENMAX.....				
	0.0	0.0	0.12	0.12	0.0	0.2	0.6	0.6

!\*ROOT PARAMETERS

20.0	5000.	0.010	0.1	0.02	1.50	0.04		RTDEPI,RFAC1,RTSEN,RLDSM,RTSDF,RWUEP1,RWUMX
0.0	2.50	3.0	2.50	6.0	2.50	30.0	2.50	XRTFAC,YRTFAC

0.006 0.006 0.02 0.10

RTN03,RTNH4,PORMIN,RTEXF

!\*SEED AND SHELL GROWTH PARAMETERS

0.60 0.3 0.00 100.

SETMAX,SRMAX,RFLWAB,XMPAGE

15.0 0.0 0.0

DSWBAR,XFRMAX,SHLAG

14.0 21.5 26.5 40.0 QDR

FNPDT(1-4),TYP PDT-TEMP EFFECT ON POD SET

6.0 21.0 23.5 41.0 QDR

FNSDT(1-4),TYP SDT-TEMP EFFECT ON SD GRWTH

0.00 10.00 20.00 26.00 32.00 60.00

XXFTEM(1-6),TEMPERATURES

1.00 1.00 1.00 1.00 1.00 1.00

YXFTEM(1-6),REL CHG IN PARTIT

0.00 0.50 1.00 1.00

XSWFAC(1-4)

0.00 1.00 1.00 1.00

YSWFAC(1-4)

0.00 0.01 0.25 1.00 1.00

XSWBAR(1-5),REL WATER TOPSOIL

1.00 1.00 1.00 1.00 1.00

YSWBAR(1-5),EFFECT ON SEED ADDITION

0.00 0.50 0.75 1.00

XTRFAC(1-4),TURFAC

0.00 0.00 0.00 0.00

YTRFAC(1-4),ENHANCE REPROD. GROWTH

!\*POD LOSS PARAMETERS

N 6.0 .3961 -.865 1.00 0.00

DETACH,DWC,PR1DET,PR2DET,XP1DET,XP2DET

!\*PHENOLOGY PARAMETERS

! TB T01 T02 TM

I

9.0 32.0 40.0 45.0

1 VEGETATIVE DEVELOPMENT

10.0 28.0 32.0 45.0

2 EARLY REPRODUCTIVE DEVELOPMENT

10.0 28.0 32.0 45.0

3 LATE REPRODUCTIVE DEVELOPMENT

!FOLLOWING LINE: STAGE; REF STAGE; PHOTOPERIOD FUNCTION; TEMPERATURE FUNCT;  
 !POINTER TO VEGD(1) OR REPDA(2) OR REPDB(3) TEMP SENS; SENS TO WATER;N; AND P

1	1	NON	LIN	1	-0.50	0.00	0.00	PLANT(STG 1) TO EMERG(STG 2) PHASE
2	2	NON	LIN	1	-0.50	0.00	0.00	EMERG(STG 2) TO V1(STG 3) PHASE
3	2	NON	LIN	1	-0.50	0.00	0.00	EMERG(STG 2) TO END JV(STG 4) PHASE
4	4	INL	LIN	1	-0.40	0.00	0.00	END JV(STG 4) TO FL IND(STG 5) PHASE
5	5	INL	LIN	1	-0.40	0.00	0.00	FL IND(STG 5) TO 1ST FL(STG 6) PHASE
6	6	INL	LIN	1	-0.50	0.00	0.00	1ST FL(STG 6) TO 1ST PEG(STG 7) PHASE
7	6	INL	LIN	2	-0.50	0.00	0.00	1ST FL(STG 6) TO 1ST POD(STG 8) PHASE
8	6	INL	LIN	2	-0.50	0.00	0.00	1ST FL(STG 6) TO 1ST SD(STG 9) PHASE
9	9	INL	LIN	3	0.30	0.00	0.00	1ST SD(STG 9) TO LST SD(STG 10) PHASE
10	9	INL	LIN	3	0.30	0.00	0.00	1ST SD(STG 9) TO PH MAT(STG 11) PHASE
11	11	NON	NON	1	0.00	0.00	0.00	PH MAT(STG 11) TO H-MAT(STG 12) PHASE
12	6	INL	LIN	2	-0.70	0.00	0.00	1ST FL(STG 6) TO LST VST(STG 13) PHASE
13	6	INL	LIN	2	-0.70	0.00	0.00	1ST FL(STG 6) TO LST LF(STG 14) PHASE

!\*CANOPY HEIGHT AND WIDTH GROWTH PARAMETERS

! VSTAGE, FOLLOWED BY INTERNODE LENGTH PER NODE, THEN CANOPY WIDTH PER NODE

0.00	1.00	4.00	6.00	8.00	10.00	14.00	16.00	20.00	40.00	XVSHT(1-10)
.0150	.0265	.0315	.0330	.0345	.0330	.0310	.0255	.0170	.0030	YVSHT(1-10)
.0150	.0255	.0310	.0320	.0330	.0315	.0295	.0230	.0125	.0005	YVSWH(1-10)

-50.0	00.0	15.0	30.0	60.0
0.55	0.55	0.55	1.00	1.00

XHWTEM(1-5),TEMPERATURES
YHWTEM(1-5),RELATIVE EXPAN

0.00	5.00	7.50	10.00	15.00	20.00	30.00	80.00
4.00	2.00	1.50	1.25	1.05	1.00	1.00	1.00

XHWPAR(1-8),PAR VALUES

YHWPAR(1-8),RELATIVE EXPAN

!\*EVAPOTRANSPIRATION

0.70	1.0	KEP, EORATIO
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APPENDIX C  
SPECIES, CULTIVAR, AND ECOTYPE FILES FOR THE FORAGE VERSION OF  
CROPGRO

Species file:

\*BAHIA SPECIES COEFICIENTS

!\*PHOTOSYNTHESIS PARAMETERS

60.0	90.0	0.55									PARMAX,PHTMAX,KCAN
11.0	1.23	.0081									CCMP,CCMAX,CCEFF; CO2 EFFECT ON PGCAN
0.75	3.0	10.0	10.0	QDR							FNPGN(4),TYPPGN-LF N EFFECT ON PG
12.0	25.0	38.0	50.0	LIN							FNPGT(4),TYPPGT-TEMP EFFECT-CANOPY PG
-5.0	7.0	35.0	45.0	55.0	60.0						XLMAXT (6 VALUES)
0.0	0.0	1.0	1.0	0.0	0.0						YLMAXT (6 VALUES)
7.0	18.0	45.0	57.0	QDR							FNPGL(4),TYPPGL-TMIN EFFECT-LEAF PG
.0650	0.20	0.80	2.0								PGEFF SCV KDIF, LFANGB 11/5/02
.0035	.0002	.2000	3.00	1.760							SLWREF,SLWSLO,NSLOPE,LNREF,PGREF
0.0	.001	.002	.003	.0035	.004	.005	.006	.008	.010		XPGSLW(1-10)
.162	.679	.867	.966	1.000	1.027	1.069	1.100	1.141	1.167		YPGSLW(1-10)

0.4	3.0	5.650	4.660	C4	CICA, CCNEFF, CMXSF, CQESF, PGPATH
!	0.7	10.0	4.272	4.191	C4 CICA, CCNEFF, CMXSF, CQESF, PGPATH

!\*RESPIRATION PARAMETERS

3.5E-05	.0029					RES30C,R30C2
2.556	2.556	.360	2.830			RNO3C,RNH4C,RPRO,RFIXN
1.242	3.106	2.174	.929	0.05	1.13	RCH20,RLIP,RLIG,ROA,RMIN,PCH20

!\*PLANT COMPOSITION VALUES

.220	.110	.050	.110	.070	.033	PROLFI,PROLFG,PROLFF,PROSTI,PROSTG,PROSTF
.101	.040	.022	.039	.039	.038	PRORTI,PRORTG,PRORTF,PROSHI,PROSHG,PROSHF
.115	.115	.300	.015	.019	.800	SDPROS,SDPROG,PRONOD,PROMIN,PROMAX,THETA
.602	.697	.702	.251	.750	.480	PCARLF,PCARST,PCARRT,PCARSH,PCARSD,PCARNO
.025	.020	.020	.011	.050		PLIPLF,PLIPST,PLIPRT,PLIPSH,PLIPNO
.040	.060	.070	.100	.030	.070	PLIGLF,PLIGST,PLIGRT,PLIGSH,PLIGSD,PLIGNO
.050	.050	.050	.040	.040	.050	POALF,POAST,POART,POASH,POASD,POANO
.063	.063	.057	.100	.030	.050	PMINLF,PMINST,PMINRT,PMINSH,PMINSD,PMINNO
.092	.064	.056				PROSRI,PROSRG,PROSRF
.711	.020	.070	.050	.057		PCARSR,PLIPSR,PLIGSR,POASR,PMINSR
0.05						KCOLD

!\*SEED COMPOSITION VALUES

7.168 23.65 0.908 0.430

LIPTB,LIPOPT,SLOSUM\*100,CARMIN

!\*CARBON AND NITROGEN MINING PARAMETERS

0.025	0.75	.280	0.050	1.00	0.15	CMOBMX,CADSTF,CADPR1,NMOBMX,NVSMOB,NRCVR
PD						XPODF
0.04	0.08	0.04	0.08	0.20		ALPHL,ALPHS,ALPHR,ALPHSH, ALPHSR
0.01	0.05	0.65	0.01	0.08		CMOBSRN, CMOBSRX, CADSRF, NMOBSRN, NMOBSRX
0.00	0.00	1.00	3.00	SIN		LRMOB(4), TYPLMOB LAI EFF ON MOBILIZATION
0.30	0.70	10.00	10.0	SIN		NRMOB(4), TYPNMOB N-STATUS EFF ON MOBILIZATION

!\*NITROGEN FIXATION PARAMETERS

.050	.160	0.01	0.0	0.04	0.05	SNACTM,NODRGM,DWNODI,TTFIX,NDTHMX,CNODCR
------	------	------	-----	------	------	--

7.00	28.0	35.0	44.0	LIN	FNNGT(4),TYPNGT-TEMP EFF ON NOD GROWTH
5.00	23.0	35.0	44.0	LIN	FNFXT(4),TYPFXT-TEMP EFF ON N FIX
-.15	0.20	1.00	10.0	LIN	FNFXD(4),TYPFXD-REL SW-DRY EFF ON N FIX
-.02	.001	1.00	2.00	LIN	FNFXW(4),TYPFXW-REL SW-WET EFF ON N FIX
0.00	0.10	1.00	0.00	INL	FNFXA(4),TYPFXA-AGE EFF ON N FIX

!\*VEGETATIVE PARTITIONING PARAMETERS

0.0	1.5	2.0	3.0	5.0	7.0	30.0	40.0	XLEAF VALUES
0.60	0.60	0.60	0.40	0.25	0.20	0.20	0.20	YLEAF VALUES
0.10	0.10	0.10	0.10	0.05	0.05	0.05	0.05	YSTEM VALUES
0.55	0.00	0.05	0.20	1.00	0.00	WTFSD,PORPT,FRSTMF,FRLFF,ATOP,FRCNOD		
0.60	FRLFMX							
0.10	0.10	0.20	0.30	0.35	0.40	0.45	0.45	YSTOR VALUES
0.10	0.90	FRSTRF, FRSTRMX						
2.00	1.50	1.00	1.00	PWLF, PWST, PWRT, PWSR				

!\*LEAF GROWTH PARAMETERS

144.	285.	2.0	0.0	00.0	FINREF,SLAREF,SIZREF,VSSINK,EVMODC			
350.	200.	-.048	1.20	SLAMAX,SLAMIN,SLAPAR,TURSLA				
0.0	5.0	10.0	15.0	20.0	25.0	XVGROW(1-6), VSTAGE VALUES		
0.0	10.0	20.0	30.0	40.0	50.0	YVREF(1-6), LEAF AREA VALUES,CM2		
-50.0	00.0	10.0	30.0	60.0	XSLATM(1-5),TEMP VALUES			
0.25	0.25	0.25	1.00	1.0	YSLATM(1-5),EFFECT ON SLA			



!\*LEAF SENESCENCE FACTORS

0.80 0.20 0.06 -5.0 -18.0

SEN RTE,SEN RT2,SEN DAY,FREE Z1,FREE Z2

0.80 25.0

ICMP,TCMP(Light comp, time constant-senes)

! 0.01 35.0

ICMP,TCMP(Light comp, time constant-senes)

! .....XSTAGE..... XSENMX.....

0.0 5.0 9.0 50.0 3.0 5.0 10.0 50.0

! .....SENPOR..... SENMAX.....

0.0 0.0 0.12 0.12 0.0 0.2 0.6 0.6

!\*ROOT PARAMETERS

20.0 7500. 0.020 0.1 0.02 1.50 0.04 RTDEPI,RFAC1,RTSEN,RLDSM,RTSDF,RWUEP1,RWUMX

0.0 2.50 3.0 2.50 6.0 2.50 30.0 2.50 XRTFAC,YRTFAC

0.006 0.006 0.02 0.10

RTNO3,RTNH4,PORMIN,RTEXF

!\*SEED AND SHELL GROWTH PARAMETERS

0.60 0.3 0.00 100.

SETMAX,SRMAX,RFLWAB,XMPAGE

15.0 0.0 0.0

DSWBAR,XFRMAX,SHLAG

14.0 21.5 26.5 40.0 QDR

FNPDT(1-4),TYP PDT-TEMP EFFECT ON POD SET

6.0 21.0 23.5 41.0 QDR

FNSDT(1-4),TYP SDT-TEMP EFFECT ON SD GRWTH

0.00 10.00 20.00 26.00 32.00 60.00

XXFTEM(1-6),TEMPERATURES

1.00 1.00 1.00 1.00 1.00 1.00

YXFTEM(1-6),REL CHG IN PARTIT

0.00 0.50 1.00 1.00

XSWFAC(1-4)

0.00 1.00 1.00 1.00

YSWFAC(1-4)

0.00 0.01 0.25 1.00 1.00

XSWBAR(1-5),REL WATER TOPSOIL

1.00	1.00	1.00	1.00	1.00	YSWBAR(1-5),EFFECT ON SEED ADDITION
0.00	0.50	0.75	1.00		XTRFAC(1-4),TURFAC
0.00	0.00	0.00	0.00		YTRFAC(1-4),ENHANCE REPROD. GROWTH

!\*POD LOSS PARAMETERS

N	6.0	.3961	-.865	1.00	0.00	DETACH,DWC,PR1DET,PR2DET,XP1DET,XP2DET
---	-----	-------	-------	------	------	--

!\*PHENOLOGY PARAMETERS

!	TB	TO1	TO2	TM	I
	9.0	32.0	40.0	45.0	1 VEGETATIVE DEVELOPMENT
	10.0	28.0	32.0	45.0	2 EARLY REPRODUCTIVE DEVELOPMENT
	10.0	28.0	32.0	45.0	3 LATE REPRODUCTIVE DEVELOPMENT

!FOLLOWING LINE: STAGE; REF STAGE; PHOTOPERIOD FUNCTION; TEMPERATURE FUNCT;  
 !POINTER TO VEGD(1) OR REPDA(2) OR REPDB(3) TEMP SENS; SENS TO WATER;N; AND P

1	1	NON	LIN	1	-0.50	0.00	0.00	PLANT(STG 1) TO EMERG(STG 2) PHASE
2	2	NON	LIN	1	-0.50	0.00	0.00	EMERG(STG 2) TO V1(STG 3) PHASE
3	2	NON	LIN	1	-0.50	0.00	0.00	EMERG(STG 2) TO END JV(STG 4) PHASE
4	4	INL	LIN	1	-0.40	0.00	0.00	END JV(STG 4) TO FL IND(STG 5) PHASE
5	5	INL	LIN	1	-0.40	0.00	0.00	FL IND(STG 5) TO 1ST FL(STG 6) PHASE
6	6	INL	LIN	1	-0.50	0.00	0.00	1ST FL(STG 6) TO 1ST PEG(STG 7) PHASE
7	6	INL	LIN	2	-0.50	0.00	0.00	1ST FL(STG 6) TO 1ST POD(STG 8) PHASE
8	6	INL	LIN	2	-0.50	0.00	0.00	1ST FL(STG 6) TO 1ST SD(STG 9) PHASE
9	9	INL	LIN	3	0.30	0.00	0.00	1ST SD(STG 9) TO LST SD(STG 10) PHASE
10	9	INL	LIN	3	0.30	0.00	0.00	1ST SD(STG 9) TO PH MAT(STG 11) PHASE

11	11	NON	NON	1	0.00	0.00	0.00	PH MAT(STG 11) TO H-MAT(STG 12) PHASE
12	6	INL	LIN	2	-0.70	0.00	0.00	1ST FL(STG 6) TO LST VST(STG 13) PHASE
13	6	INL	LIN	2	-0.70	0.00	0.00	1ST FL(STG 6) TO LST LF(STG 14) PHASE

!\*CANOPY HEIGHT AND WIDTH GROWTH PARAMETERS

! VSTAGE, FOLLOWED BY INTERNODE LENGTH PER NODE, THEN CANOPY WIDTH PER NODE

0.00	1.00	4.00	6.00	8.00	10.00	14.00	16.00	20.00	40.00	XVSHT(1-10)
.0150	.0265	.0315	.0330	.0345	.0330	.0310	.0255	.0170	.0030	YVSHT(1-10)
.0150	.0255	.0310	.0320	.0330	.0315	.0295	.0230	.0125	.0005	YVSWH(1-10)

-50.0	00.0	15.0	30.0	60.0						XHWTEM(1-5),TEMPERATURES
0.55	0.55	0.55	1.00	1.00						YHWTEM(1-5),RELATIVE EXPAN
0.00	5.00	7.50	10.00	15.00	20.00	30.00	80.00			XHWP(1-8),PAR VALUES
4.00	2.00	1.50	1.25	1.05	1.00	1.00	1.00			YHWP(1-8),RELATIVE EXPAN

!\*EVAPOTRANSPIRATION

0.55	1.0		KEP, EORATIO
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!\*STORAGE ORGAN PARAMETERS -

1.000	0.000	STRSRFL, STRLYR1- STOR on soil surface and in soil layer 1
0.015		SENSR - rate for senescence of storage organ tissue

!\*DORMANCY PARAMETERS - DAYLENGTH TO INDUCE/DEEPEN/END DORMANCY

0.00	10.5	12.5	0.000	INL	FNPTD(4),TYPPTD-DAYLENGTH EFFECT-PARTITIONING
------	------	------	-------	-----	---

10.5	12.5	0.10	1.000	DRD	FNPMD(4),TYPPMD-DAYLENGTH EFFECT ON MOBILIZATION
0.00	0.00	0.00	1.000	DRD	FMPGD(4),TYPPGD-DAYLENGTH EFFECT ON PG
-18.0	-25.0	0.050			HARD1, HARD2, FRZDC - Freezing temperatures and death rate
-25.0	-25.0	-25.0	0.16	REV	FRZHRD(4),TYPHRD-COLD HARDENING RESPONSE
-25.0	-25.0	-25.0	0.80	DHD	FRZDHD(4),TYPDHD-COLD DEHARDENING RESPONSE

Cultivar File:

\*BAHIA GENOTYPE COEFFICIENTS

```

!
! COEFF  DEFINITIONS
! =====
! ECO#    Code for the ecotype to which this cultivar belongs (see *.eco file)
! CSDL    Critical Short Day Length below which reproductive development
!          progresses with no daylength effect (for shortday plants) (hour)
! PPSEN   Slope of the relative response of development to photoperiod with time
!          (positive for shortday plants) (1/hour)
! EM-FL   Time between plant emergence and flower appearance (R1)
!          (photothermal days)
! FL-SH   Time between first flower and first pod (R3) (photothermal days)
! FL-SD   Time between first flower and first seed (R5) (photothermal days)
! SD-PM   Time between first seed (R5) and physiological maturity (R7)
!          (photothermal days)
! FL-LF   Time between first flower (R1) and end of leaf expansion
!          (photothermal days)
! LFMAX   Maximum leaf photosynthesis rate at 30 C, 350 vpm CO2, and high light
!          (mg CO2/m2-s)
! SLAVR   Specific leaf area of cultivar under standard growth conditions
!          (cm2/g)
! SIZLF   Maximum size of full leaf (three leaflets) (cm2)
! XFRT    Maximum fraction of daily growth that is partitioned to seed + shell
! WTPSD   Maximum weight per seed (g)
! SFDUR   Seed filling duration for pod cohort at standard growth conditions

```

```

!          (photothermal days)
! SDPDV    Average seed per pod under standard growing conditions (#/pod)
! PODUR    Time required for cultivar to reach final pod load under optimal
!           conditions (photothermal days)
!
@VAR#  VRNAME..... ECO#  CSDL PPSEN EM-FL FL-SH FL-SD SD-PM FL-LF LFMAX SLAVR
SIZLF  XFRT WTPSD SFDUR SDPDV PODUR
!
10     11     12     13     14     15
UF0001 PENSACOLA BAHIA  G00001 12.00 0.200 99.0 10.0 18.0 33.00 25.00 1.76 285.
2.0 0.01 0.020 15.0 2.05 20.0

```

Ecotype File:



\*BAHIA ECOTYPE COEFFICIENTS

!  
! COEFF    DEFINITIONS  
! =====  
! ECO#     Code for the ecotype to which a cultivar belongs (see \*.cul  
!           file)  
! ECONAME Name of the ecotype, which is referenced from \*.CUL file  
! MG       Maturity group number for this ecotype, such as maturity  
!           group in soybean  
! TM       Indicator of temperature adaptation  
! THVAR    Minimum rate of reproductive development under short days  
!           and optimal temperature  
! PL-EM    Time between planting and emergence (V0) (thermal days)  
! EM-V1    Time required from emergence to first true leaf (V1), thermal  
!           days  
! V1-JU    Time required from first true leaf to end of juvenile phase,  
!           thermal days  
! JU-R0    Time required for floral induction, equal to the minimum  
!           number of days for floral induction under optimal temperature and  
!           daylengths, photothermal days  
! PM06    Proportion of time between first flower and first pod for  
!           first peg (peanut only)  
! PM09    Proportion of time between first seed and physiological  
!           maturity that the last seed can be formed  
! LNGSH    Time required for growth of individual shells (photothermal

! days)  
 ! R7-R8 Time between physiological (R7) and harvest maturity (R8) (days)  
 ! FL-VS Time from first flower to last leaf on main stem (photothermal  
 ! days)  
 ! TRIFL Rate of appearance of leaves on the mainstem (leaves per  
 ! thermal day) default was 0.10, not getting enough leaves, changed to 0.15  
 2/21/03  
 ! RWDTH Relative width of this ecotype in comparison to the standard  
 ! width per node (YVSWH) defined in the species file (\*.SPE)  
 ! RHGHT Relative height of this ecotype in comparison to the  
 ! standard height per node (YVSHT) defined in the species file  
 ! (\*.SPE)  
 ! THRSH The maximum ratio of (seed/(seed+shell)) at maturity.  
 ! Causes seed to stop growing as their dry weights  
 ! increase until shells are filled in a cohort.  
 ! (Threshing percentage).  
 ! SDPRO Fraction protein in seeds (g(protein)/g(seed))  
 ! SDLIP Fraction oil in seeds (g(oil)/g(seed))  
 ! R1PPO Increase in daylength sensitivity after R1 (CSDVAR and CLDVAR  
 ! both decrease with the same amount) (h)  
 ! OPTBI Minimum daily temperature above which there is no effect on  
 ! slowing normal development toward flowering (oC)  
 ! SLOBI Slope of relationship reducing progress toward flowering if  
 ! TMIN for the day is less than OPTBI  
 ! RDRMT Relative dormancy sensitivity of this cultivar to daylength - partitioning (0-1)

! RDRMG Relative dormancy sensitivity of this cultivar to daylength - photosynthesis (0-1)

! RDRMM Relative dormancy sensitivity of this cultivar to daylength - mobilization (0-1)

! RCHDP Relative cold hardening potential (0-1)

!

@ECO# ECONAME..... MG TM THVAR PL-EM EM-V1 V1-JU JU-R0 PM06 PM09 LNGSH R7-R8 FL-

VS TRIFL RWDTH RHGHT THRSH SDPRO SDLIP R1PPO OPTBI SLOBI RDRMT RDRMG RDRMM RCHDP

! 1 2 3 4 5 6 7 8 9

10 11 12 13 14 15 16 17 18 19 20 21 22 23

G00001 PENSACOLA BAHIA 00 01 1.00 0.0 0.0 0.0 9999. 0.0 0.75 10.0 9999.

9999. 0.15 1.0 1.0 78.0 .115 .035 .000 0.0 .000 1.000 1.000 1.000 1.000

## APPENDIX D

### NEW PARAMETER CODE DEFINITIONS FOR THE FORAGE VERSION OF CROPGRO

Variable definitions listed in order of their appearance in the species file, followed by those in the ecotype file.

CICA – The ratio of intercellular:atmospheric CO<sub>2</sub> concentration used to calculate CO2MAX (0.7 for C<sub>3</sub> species, suggest 0.4 for C<sub>4</sub> species).

CCNEFF – CO<sub>2</sub>-concentrating factor, used for C<sub>4</sub> species to determine photosynthetic response to CO<sub>2</sub>.

CMXSF – Factor to scale CO2MAX to 1.0 at 30°C and 350 µL CO<sub>2</sub> L<sup>-1</sup> (varies with CICA and CCNEFF).

CQESF – Factor to scale CO2QE to 1.0 at 30°C and 350 µL CO<sub>2</sub> L<sup>-1</sup> (varies with CCNEFF).

PGPATH – Species' photosynthetic pathway. Currently recognizes two codes "C<sub>3</sub>" and "C<sub>4</sub>". If code is "C<sub>3</sub>" then model uses unmodified CSM code to predict daily canopy and leaf-level photosynthesis.

PROSRI – Maximum protein composition in storage organ during growth with luxurious supply of N (g[protein] g[storage]<sup>-1</sup>).

PROSRG – Normal growth protein composition in storage organ during growth (g[protein] g[storage]<sup>-1</sup>).

PROSRF - Minimum storage organ protein composition after N mining (g[protein] g[storage]<sup>-1</sup>).

PCARSR - Carbohydrate-cellulose concentration of storage tissue (fraction).

PLIPSR - Proportion of storage tissue that is lipid (fraction).

PLIGSR - Proportion of storage tissue that is lignin (fraction).

POASR - Proportion of storage tissue that is organic acid (fraction).

PMINSR – Proportion of storage tissue that is mineral (fraction).

KCOLD – Curvature factor (K value) for exponential function limiting refilling of N to older tissues (NDMOLD) when photosynthesis is low. Part of new functionality to prevent expending all assimilate on N uptake and leaving none for new growth.

CMOBSRN – "Normal" / minimum fraction of CH<sub>2</sub>O which can be mobilized from storage organ in a day.

CMOBSRX – Maximum fraction of  $\text{CH}_2\text{O}$  which can be mobilized from storage organ in a day.

CADSRF – Proportion of  $\text{CH}_2\text{O}$  reserves that are added to storage organ (fraction).

NMOBSRN – "Normal" / minimum fraction of N which can be mobilized from storage organ in a day

NMOBSRX – Maximum fraction of N which can be mobilized from storage organ in a day.

LRMOB(1-4)– Critical LAI for function to increase mobilization of  $\text{CH}_2\text{O}$  and N from STOR due to low leaf area (4 values for function CURV). This is a two-sided generic curve using only the two rightmost points to describe mobilization response to LAI. LRMOB(3) is the (low) LAI where mobilization from STOR is maximum. LRMOB(4) is the (high) LAI where there is no increased mobilization of  $\text{CH}_2\text{O}$  or N from STOR.

TYPLMOB – Character variable specifying the type of function to use for the relationship between LAI and mobilization of  $\text{CH}_2\text{O}$  and N from STOR (for use in function subroutine CURV). SIN defines a sinusoidal curve that decreases from 1.0 at an LAI of LRMOB(3) to its minimum of 0.0 at an LAI of LRMOB(4).

NRMOB(1-4) - Critical vegetative N-status for function to increase mobilization of  $\text{CH}_2\text{O}$  and N from STOR due to high N-status (4 values for function CURV). This is a two-sided generic curve using only the two leftmost points to describe mobilization response to N-status. NRMOB(1) is the lowest N-status where there is no increase in mobilization from STOR. LRMOB(2) is the (high) N-status where mobilization of  $\text{CH}_2\text{O}$  or N from STOR is increased to maximum.

TYPNMOB – Character variable specifying the type of function to use for the relationship between vegetative N-status and mobilization of  $\text{CH}_2\text{O}$  and N from STOR (for use in function subroutine CURV). SIN defines a sinusoidal curve that increases from 0.0 at an N-status of NRMOB(1) to its maximum of 1.0 at an N-status of NRMOB(2).

YSTOR(1-8) - Partitioning fraction to storage tissue growth at V-stage XLEAF(I) ( $\text{g[STOR]} \text{ g[vegetation. plant]}^{-1}$ ).

FRSTRF – Fraction of daily dry weight increase in vegetative plant parts which goes to storage organ after the day on which the maximum number of V-stages occurs (NDVSTG). ( $\text{g[storage]} \text{ g[vegetation]}^{-1}$ ).

FRSTRMX – Maximum storage organ partitioning ( $\text{g[storage]} \text{ g[vegetation]}^{-1}$ ). Occurs during dormancy.

PWLF – Weighting factors for partitioning N when refilling old leaf tissues.

PWST – Weighting factors for partitioning N when refilling old stem tissues.

PWRT – Weighting factors for partitioning N when refilling old root tissues.

PWSR - Weighting factors for partitioning N when refilling old STOR tissues.

STRSRFL – Proportion of storage organ mass occurring on/above the soil surface.

STRLYR1 - Proportions of storage organ mass occurring in soil layer 1.

SENSR - Constant for senescence of storage organ tissue (proportion of cumulative STOR mass lost / physiological day).

FNPTD(1-4) – Parameters defining the daylength effect on partitioning of new growth to STOR. FNPTD(1) is ignored (set value to 0.0). FNPTD(2) is the daylength threshold (h) when the dormancy effect is maximum. FNPTD(3) is the daylength threshold (h) that induces (starts) dormancy. FNPTD(4) is the fraction increase (from FRSTR to FRSTRMX) in partitioning to STOR when the crop is non-dormant - always set to 0.0 as we want no dormancy effect when crop is not dormant.

TYPPTD - Character variable specifying the type of function to use for the relationship between dormancy and partitioning of new growth to STOR (for use in function subroutine CURV). INL or SHO used for species that are dormant during short daylengths. This is an inverse linear response. The fraction increase (from FRSTR to FRSTRMX) in partitioning to STOR is lowered from 1.0 (100% of FRSTRMX) at a daylength for maximum dormancy of FNPTD(2) to its minimum or non-dormant, fraction of FNPTD(4) (0% increase over FRSTR) at a daylength of FNPTD(3).

FNPMMD(1-4) - Parameters defining the daylength effect on mobilization of CH<sub>2</sub>O and N from STOR:. FNPMMD(1) is the daylength (h) when the dormancy effect is maximum, FNPMMD(2) is the daylength (h) when dormancy ceases to affect mobilization, FNPMMD(3) is the (low) proportion of the LAI- and N-status-adjusted fraction of mobilizable CH<sub>2</sub>O and N that can potentially be mobilized from STOR at peak dormancy, and FNPMMD(4)=1.0 or the proportion (100%) of the LAI- and N-status-adjusted fraction of mobilizable CH<sub>2</sub>O and N that can potentially be mobilized from STOR when non-dormant.

TYPMD - Character variable specifying the type of function to use for the relationship between dormancy and mobilization of CH<sub>2</sub>O and N from STOR (for use in function subroutine CURV). DRD is a new CURV function that is similar to LIN except that response values (proportion of the LAI- and N-status-adjusted fraction of mobilizable CH<sub>2</sub>O and N that can potentially be mobilized from STOR) vary from FNPMMD(3) to FNPMMD(4) instead of 0 to 1. This is a linear response that increases from FNPMMD(3) at a daylength of FNPMMD(1) (maximum dormancy) to its maximum of FNPMMD(4) at a daylength of FNPMMD(2) (non-dormant). This is a new CURV function added for the forage version of CROPGRO.

FMPGD(1-4) - Parameters defining the daylength effect on photosynthesis - currently not in use.

TYPFGD - Character variable specifying the type of function to use for the relationship between dormancy and photosynthesis (for use in function subroutine CURV) - currently not in use.

HARD1 – Freezing temperature that will kill storage organ if no cold-hardening has occurred. Should be the same as FREEZ2. If TMIN gets to this temperature, all STOR is killed and the simulation is terminated.

- HARD2 - Freezing temperature that will kill storage organ if cold-hardening is maximum. Should be the lower than FREEZ2 if species exhibits cold-hardening, or equal to FREEZ2 if it doesn't. If TMIN gets to this temperature, all STOR is killed and the simulation is terminated.
- FRZDC - Freezing leaf and stem death constant. Fraction of leaf and stem mass that will be killed or lost in a day for every °C that TMIN drops below the FREEZ1 threshold.
- FRZHRD(1-4) - Cold hardening response parameters, not used for bahiagrass. Reduces FREEZ2 from HARD1 to HARD2 with increasing exposure to cold (but non-lethal) temperatures. The function is reversible as warm temperatures will reduce the amount of cold-hardening. Prolonged periods of warm temperatures will increase FREEZ2 to HARD1 (if hardening has already occurred).
- TYPHRD - Character variable specifying the type of function to use for the relationship between TMIN and cold-hardening (linear progression of FREEZ2 from HARD1 to HARD2) for use in subroutine CURV. REV is used for species that exhibit reversible cold-hardening. Increases the rate of progression of FREEZ2 from HARD1 to HARD2 [°C drop in FREEZ2 per degree TMIN drops below FRZHD(2)] linearly as TMIN drops from FRZHD(2) to FRZHD(1), with a maximum rate of FRZHD(4) when TMIN=FRZHRD(1). If TMIN is greater than FRZHD(2), cold-hardening is reversed (FREEZ2 increases linearly towards HARD1), reaching a rate of [-FRZHD(4)] when TMIN=FRZHD(3). This is a new CURV function added for the forage version of CROPGRO.
- FRZDHD(1-4), - Non-reversible cold-dehardening response parameters, not used for bahiagrass. Increases FREEZ2 towards HARD1. Differs from the reverse cold-hardening simulated by FRZHD(1-4) as dehardening can only occur when daylength is increasing and dehardening is not reversible (i.e. cold temperatures will not reduce the amount of dehardening).
- TYPDHD - Character variable specifying the type of function to use for the relationship between TMIN and cold-dehardening (for use in function subroutine CURV). DHD is a new CURV function, essentially a positive linear response from 0.0 to FRZDHD(4) as TMIN increases from FRZDHD(1) to FRZDHD(2). Allows dehardening only when daylength is increasing. Increases the rate of progression of FREEZ2 from current value to HARD1 linearly as TMIN increases from FRZDHD(1) to FRZDHD(2), with a maximum rate of FRZDHD(4) [°C increase in FREEZ2 per degree TMIN increases above FRZHD(1)]. FRZDHD(3) is ignored. Dehardening cannot raise FREEZ2 above HARD1. This is a new CURV function added for the forage version of CROPGRO.
- RDRMT - Relative dormancy sensitivity of ecotype to daylength for partitioning (0–1). If ecotype exhibits less shift in partitioning to STOR during short daylengths than the standard species ecotype, RDRMT<1.0. If ecotype exhibits a greater shift in partitioning during short daylengths than the standard species ecotype, RDRMT>1.0.

RDRMG - Relative dormancy sensitivity of ecotype to daylength for photosynthesis reduction (0–1). If ecotype exhibits less photosynthesis reduction during short daylengths than the standard species ecotype,  $RDRMG < 1.0$ . If ecotype exhibits a greater reduction in photosynthesis during short daylengths than the standard species ecotype,  $RDRMG > 1.0$ .

RDRMM - Relative dormancy sensitivity of ecotype to daylength for decreased mobilization of  $CH_2O$  and N from STOR (0–1). If ecotype exhibits less reduction in mobilization of  $CH_2O$  and N from STOR during short daylengths than the standard species ecotype,  $RDRMM < 1.0$ . If ecotype exhibits a greater reduction in mobilization of  $CH_2O$  and N during short daylengths than the standard species ecotype,  $RDRMM > 1.0$ .

RCHDP - Relative cold hardening potential (0–1) of ecotype. If ecotype exhibits less cold-hardening than the standard species ecotype,  $RCHDP < 1.0$ . If ecotype exhibits more cold hardening than the standard species ecotype,  $RCHDP > 1.0$ .



## APPENDIX E

### DORMANCY AND STOR CODES AND DEFINITIONS FOR DATA.CDE FILE

These lines should be added to the bottom of the DATA.CDE file to allow the GBUILD program to display the definitions of the new dormancy and STOR output codes along with the variable name.

*DORMANCY					
@CDE	LABEL	DESCRIPTION	OTHER CODE(S)	SO	SE
C%SR	%OF C IN STORE	% of CH2O reserves added to storage organ		.	0
FRZ2	FREEZE KILL TMP	Current freeze kill temperature		.	0
FSRX	MAX STORE PART	Max partitioning to storage organ		.	0
FZDC	FREEZE DEATH%	Freezing death coefficient / degree below FREEZ2		.	0
HRD1	SOFT FREEZE	Killing freeze temperature before cold hardening		.	00
HRD2	HARD FREEZE	Killing freeze temperature after cold hardening		.	0
LAIT	MOBIL THRESHOLD	LAI trigger - increased mobil from str organ		.	00
PPGF	DORM PG FACTOR	Proportion reduction in PG due to dormancy		.	0
PPMF	DORM MOBIL FAC	Proportion reduction in mobilization due to dormancy		.	0
PPTF	DORM PART FAC	Proportion reduction in partitioning due to dormancy		.	0
QDSD	DORM STATUS	Text variable listing dormancy status		.	0
RDMG	REL DORM PG	Relative dormancy effect on PG of cultivar		.	0
RDMM	REL DORM MOBIL	Relative dormancy effect on mobilization of cultivar		.	00
RDMT	REL DORM PART	Relative dormancy effect on partitioning of cultivar		.	0
SC%M	MAX STOR C MOBL	Maximum % of storage organ C to mobilize		.	00
SNSR	STOR SENES %	Senescence rate of storage organ /physiological day		.	00
SP%1	STOR PART FAC1	YSTOR1 - Storage partitioning factor for XLEAF(1)		.	00
SP%2	STOR PART FAC2	YSTOR2 - Storage partitioning factor for XLEAF(2)		.	00
SP%3	STOR PART FAC3	YSTOR3 - Storage partitioning factor for XLEAF(3)		.	00
SP%4	STOR PART FAC4	YSTOR4 - Storage partitioning factor for XLEAF(4)		.	00
SP%5	STOR PART FAC5	YSTOR5 - Storage partitioning factor for XLEAF(5)		.	00
SP%6	STOR PART FAC6	YSTOR6 - Storage partitioning factor for XLEAF(6)		.	0
SP%7	STOR PART FAC7	YSTOR7 - Storage partitioning factor for XLEAF(7)		.	00
SP%8	STOR PART FAC8	YSTOR8 - Storage partitioning factor for XLEAF(8)		.	00
SP%F	STOR FINAL PROT	Minimum storage organ protein % after N mining		.	00
SP%G	STOR GROW PROT%	Normal growth protein % of storage organ		.	00
SP%I	STOR INIT PROT%	Protein % of new storage organ growth		.	00
SR%C	%STORE MOBIL C	% CH2O in New storage organ growth		.	0
SRC%	STOR %CH2O	Proportion of storage organ that is CH2O		.	0
SRG%	STOR %LIGNIN	Proportion of storage organ that is lignin		.	0
SRG1	DORM PG DAYL1	Base daylength for dormancy effect on PG		.	0
SRG2	DORM PG DAYL2	1st optimum daylength for dormancy effect on PG		.	0
SRG3	DORM PG DAYL3	2nd optimum daylength for dormancy effect on PG		.	00
SRG4	DORM PG DAYL4	Max daylength for dormancy effect on PG		.	00
SRL%	STOR %LIPID	Proportion of storage organ that is lipid		.	0
SRL1	STOR LAYER1	Initial/normal % of storage organ below soil surface		.	0
SRM%	STOR %MINERAL	Proportion of storage organ that is mineral		.	00
SRM1	DORM MOB DAYL1	Base daylength for dormancy effect on mobilization		.	00
SRM2	DORM MOB DAYL2	1st optimum daylength for dormancy effect on mobil		.	00
SRM3	DORM MOB DAYL3	2nd optimum daylength for dormancy effect on mobil		.	00
SRM4	DORM MOB DAYL4	Max daylength for dormancy effect on mobilization		.	00

SRO%	STOR %ORG ACID	Proportion of storage organ that is organic acid	. 00
SRSF	STOR SURFACE	Initial/normal % of storage organ above soil surface	. 00
SRT1	DORM PART DAYL1	Base daylength for dormancy effect on partitioning	. 00
SRT2	DORM PART DAYL2	1st optimum daylength for dormancy effect on part	. 00
SRT3	DORM PART DAYL3	2nd optimum daylength for dormancy effect on part	. 00
SRT4	DORM PART DAYL4	Max daylength for dormancy effect on partitioning	. 00
TDHD	DEHARD CURV	Curve/response type for dehardening	. 00
THRD	HARDEN CURV	Curve/response type for cold hardening	. 0
TSDM	DRM MOBIL CURV	Curve/response type OF mobilization to dormancy	. 0
TSPG	DORM PG CURV	Curve/response type OF PG to dormancy	. 0
TSPT	DRM PART CURV	Curve/response type OF partitioning to dormancy	. 0
TSRD	S-TMP SOIL SURF	Soil temperature on soil surface (oC)	. 00
ZDH1	DEHARD TEMP1	Dehardening base temperature	. 00
ZDH2	DEHARD TEMP2	Dehardening temperature 1	. 0
ZDH3	DEHARD TEMP3	Dehardening temperature 2	. 0
ZDH4	DEHARD RATE	Relative rate of dehardening	. 0
ZHD1	HARDEN TEMP1	Cold hardening base temperature (max hardening)	. 0
ZHD2	HARDEN TEMP1	Cold hardening temperature 1 (no hardening)	. 0
ZHD3	HARDEN TEMP1	Cold hardening temperature 2 (reverse hardening)	. 0
ZHD4	HARDEN RATE	Relative rate of cold hardening	. 0

## \*STORAGE

@CDE	LABEL	DESCRIPTION	OTHER CODE(S)	SO	SE
Q1%D	STOR % SOIL	Proportion of storage organ mass below soil surface		. 00	
QC%D	STOR % CH2O	Fraction of storage organ tissue that is CH2O		. 00	
QC%M	STOR C MINE P	Potential C mining rate from storage organ		. 00	
QCAD	STOR CUM GROW	Cumulative storage organ growth		. 00	
QCAG	STOR NET C ADD	Net C addition to storage organ		. 0	
QCDAM	STOR DAMAGE	Calculated storage organ damage		. 0	
QCDD	STOR CUM DAM	Cumulative storage organ damage		. 0	
QCFD	STOR CUM FRZDM	Cumulative frozen storage organ tissue		. 00	
QCQD	STOR CH2O REQ	Mass CH2O required for new storage organ growth		. 00	
QCRD	STOR CH2O RESRV	Mass of CH2O reserves in storage organ		. 0	
QDAD	STOR CUM LOSS	Cumulative storage organ losses		. 0	
QDTD	STOR DESIRE WT	Desired storage organ mass		. 0	
QEAD	STOR SENES	Daily senescence of storage organ tissue		. 00	
QPWD	STOR SENES H2O	Daily senescence of storage organ due to H2O stress		. 00	
QFAD	STOR FRZ LOSS	Storage organ weight loss to freezing today		. 0	
QFD1	STR FRZDAM SOIL	Freeze damage to below ground storage organ mass		. 0	
QFDS	STR FRZDAM SURF	Freeze damage to above ground storage organ mass		. 00	
QHAD	STOR CH2O ADD	Mass of CH2O added to storage organ		. 00	
QL%1	STOR %DAM SOIL	Proportion of damaged storage organ below soil surface		. 00	
QL%S	STOR %DAM SURF	Proportion of damaged storage organ above soil surface		. 00	
QMAD	STOR C MOBIL	C mobilized from storage organ in a day		. 0	
QMAM	STOR PEST DAM	Weight of storage organ consumed by pests today		. 0	
QN%D	STOR N%	Storage organ N concentration (%)		. 0	
QN%I	STOR MIN N%	Minimum fraction N for growing storage organ tissue		. 00	
QN%N	STOR N %OF TOT	N content in storage organ (fraction)		. 00	
QN%X	STOR MAX N%	Maximum fraction N for growing storage organ tissue		. 0	
QNAA	STOR N ADD RES	N added to storage organ reserves		. 0	
QNAC	STOR CUM N ADD	Cumulative N added to storage organ		. 0	
QNAD	STOR N WT	Mass of N in storage organ		. 00	
QNAG	STOR N ADD	N added to storage organ today		. 00	
QNAL	STOR CUM N LOSS	Cumulative N lost from storage organ		. 0	
QNAL	STOR N LOSS	N loss from storage organ today		. 0	
QNAM	STOR N MOBIL	Actual n mobilized from storage organ in a day		. 00	
QNAM	STOR NET N ADD	Net n added to storage organ today		. 00	

QNAR	STOR N MINE P	Potential N mining rate from storage organ	. 00
QNMD	STOR N AVAIL	N available for mobilization from storage organ	. 00
QNRN	STOR MIN N DEM	Minimum N demand for storage organ	. 0
QNRX	STOR MAX N DEM	Maximum N demand for storage organ	. 0
QP%N	STR CP% NEW GRO	Protein fraction of new storage organ growth	. 0
QRAD	STOR RESP REQ	Respiration requirement for new storage growth	. 00
QS%D	STOR % SURFACE	Proportion of storage organ mass on soil surface	. 00
QT%1	STOR TEMPORARY1	Intermediate to calculate % storage organ below grouND	. 0
QT%S	STOR TEMPORARYS	Intermediate to calculate % storage organ above grouND	. 0
QV%D	STOR % OF VEG	Fraction of vegetative growth that goes to storage organ	. 0
QV%T	STOR % OF TOT	Fraction of growth going to storage organ	. 00
QW%C	STR CUM OBS DAM	Observed cumulative percentage storage organ mass damage	. 00
QWAD	STOR DRY MASS	Storage organ weight (kg dm/ha)	. 0
QWAI	STOR INITIAL WT	Initial storage organ weight	. 0
QWND	STOR NEW GROW	New storage tissue growth today	. 00
QWNG	STR NET GRO RTE	Net storage organ growth rate	. 00
XSTR	STOR PART DIFF	Diff. in storage organ partitioning between R1 and NDLEAF	. 00
LV%D	STOR % OF VEG	Fraction of vegetative growth that goes to leaf	. 0
SV%D	STOR % OF VEG	Fraction of vegetative growth that goes to stem	. 0
RV%D	STOR % OF VEG	Fraction of vegetative growth that goes to Root	. 0

## APPENDIX F

### CODE ADDITIONS AND CHANGES IN THE FORAGE VERSION OF CROPGRO

Code changes are listed by module, alphabetically. Bold, underlined text describes the change or addition and is not part of the computer code.

#### **MODULE: CROPGRO.FOR**

##### Add dormancy variables to SUBROUTINE statement

```

SUBROUTINE CROPGRO(CONTROL, ISWITCH,
& CO2, DAYL, EOP, YREND, HARVFRAC, NH4, NO3,    !Input
& PAR, SOILPROP, ST, SW, TAVG, TDAY, TGRO,      !Input
& TGROAV, TMIN, TRWUP, YRPLT,                  !Input
& CANHT, EORATIO, HARVRES, KEP, MDATE,         !Output
& NSTRES, PORMIN, RLV, RWUMX, SENESCE,         !Output
& STGDOY, UNH4, UNO3, XHLAI, XLAI)              !Output

```

##### Declare Dormancy and N returned N partitioning variables in CROPGRO

```

C      Storage organ parameters for forage model
      CHARACTER*6 DRMST

      CHARACTER*3  TYPPGD,TYPPTD, TYPPMD, TYPHRD, TYPDHD

      REAL AGRSTR, ALPHSR, CADSR, CADSRF, CLAIT, CMOBSR,
& CMOBSRN, CMOBSRX, CPFSTR, CRUSSR, CSRFRZ, CSRW, CSTRM,
& DSTOR, FNINSR, FNINSRG, FRSTR, FRSTRF, FRSTRM,
& FRSTRMX, FRZDC, FRZDL, HARD1, HARD2, NADSR,
& NGRSR, NGRSRG, NMOBSR, NMOBSRN, NMOBSRX, NRUSSR, NSRALL,
& NSRDOT, NSROFF, NVTSR, PCARSR, PCNSR, PCSTRD,
& PLIGSR, PLIPSR, PMINSR, POASR, PPGFAC, PPMFAC,
& PPTFAC, PROSRF, PROSRG, PROSRI, PROSRT,
& PSRLYR1, PSRLYRD, PSRSRFD, PSRSRFL, RCHDP, RDRMG,
& RDRMM, RDRMT, RHOSR, SENSR, SRDAM, SRFTEMP, SRLYRD,
& SRSRFD, SSRDOT, SSRNDOT, STRLYR1, STRSRFL, STRWT,
& TPSRLYR1, TPSRSRFL, WCRSR, WNRSR, WRCSRDT, WSFDOT,
& WSRDOT, WSRDOTN, WSRFDOT, WSRI, WSRIDOT, WTNSR,
& WTNSRA, WTNSRO, WTSRO, XSTR

      REAL FNPGRD(4), FNPMD(4), FNPTD(4), FRZDHD(4), FRZHRD(4),
& YSTOR(8)

      REAL CADRT, CADSH, NADSH, NRUSTOT
      REAL PNMLF, PNMRT, PNMSH, PNMSR, PNMST

```

REAL CSFRZ

REAL NVSTL, NVSTR, NVSTS, NVSTSR  
REAL NUPNH4(NL), NUPNO3(NL)

REAL LAIMOB, VNMOBR, VEGNCNT, VEGNCMX  
CHARACTER\*3 TYPLMOB, TYPNMOB  
REAL LRMOB(4), NRMOb(4), VEGNPCT, VEGNPMX, VNSTAT  
REAL CURV

### Add CALL statements for DORMANT

```
CALL DORMANT( CONTROL,
& DAYL, TMIN, !Input
& DRMST, FREEZ2, FRZDC, PPGFAC, PPTFAC, PPMFAC, !Output

& FNP GD, FNP MD, FNPTD, FRZDHD, FRZHRD, HARD1, !Output
& HARD2, RCHDP, RDRMG, RDRMM, RDRMT, TYPDHD, TYPHRD, !Output
& TYPPGD, TYPPMD, TYPPTD) !Output
```

### Reduce daily photosynthesis for Dormancy effect

```
C-----
C Reduce daily photosynthesis for Dormancy effect
PG = PG * PPGFAC
```

### Add storage organ to list of N and C mining sources. Default mobilization is 1% per day, modified by LAI and dormancy status. Low LAI, below threshold (LAI<CLAIT), triggers increased mobilization for regrowth after harvest or severe pest or frost damage. Slows mobilization during dormancy (PPMFAC>0.0), lowering mobilization as dormancy “deepens”.

```
LAIMOB = CURV(TYPLMOB,LRMOB(1),LRMOB(2),LRMOB(3),
& LRMOB(4), MIN(XLAI,LRMOB(4)))
```

```
C-----
C Increase mobilization from storage if N status of plant is high.
C-----
```

```
VEGNCNT = PCNL/100*WTLF + PCNST/100*STMWT +
& PCNRT/100*RTWT + PCNSR/100*STRWT
VEGNCMX = FNINL*WTLF + FNINS*STMWT + FNINR*RTWT +
FNINSR*STRWT
VNSTAT = MIN((VEGNCNT / VEGNCMX), 1.0)
```

```
VNMOBR =
CURV(TYPNMOB,NRMOb(1),NRMOb(2),NRMOb(3),NRMOb(4),VNSTAT)
C-----
```

```

C      Set N mobilization rate from storage
C      Default to NMOBSRN under most conditions
C      set to NMOBSRX (max rate) after harvest or severe damage
C      Reduce from either level depending on degree of dormancy
C      Mobilization from storage is unaffected by water or N stress
C      but is accelerated by low N status.
C-----
      NMOBSR = (NMOBSRN + (NMOBSRX-NMOBSRN)*VNMOBR)
      NMOBSR = (NMOBSR + (NMOBSRX-NMOBSR)*LAIMOBR)*PPMFAC
C-----
C      Set C mobilization rate from storage
C      Default to CMOBSRN under most conditions
C      set to CMOBSRX (max rate) after harvest or severe damage
C      Reduce from either level depending on degree of dormancy
C      Mobilization from storage is unaffected by water or N stress
C-----
      CMOBSR = (CMOBSRN + (CMOBSRX-CMOBSRN)*VNMOBR)
      CMOBSR = (CMOBSR + (CMOBSRX-CMOBSR)*LAIMOBR)*PPMFAC

      CMINEP=CMOBSR*(DTX+DXR57)*(WCRLF+WCRST+WCRSH)+
&          CMOBSR*(DTX+DXR57)*(PPMFAC)*WCRRT +
&          CMOBSR*WCRSR*(DTX+DXR57)

      PGAVL = PG + CMINEP

```

#### Deduct cost of new storage tissue from PGAVL and NAVL

```

C-----
C Deduct cost of new storage tissue from PGAVL and NAVL
C-----
      PGAVL = PGAVL - AGRVG * (WLDOTN + WSDOTN + WRDOTN +
      WSRDOTN)
      NAVL = NAVL - (NGRLEF + NGRST + NGRRT + NGRSR)
      NAVL = NAVL - (NADLEF + NADST + NADRT + NADSR)
      PGAVL = PGAVL - (CADST + CADLEF + CADSR) * PCH2O

```

#### Modify CALL IPPLNT statement to include storage variables

```

      CALL IPPLNT(CONTROL,
& CADPR1, CMOBSR, CROP, DETACH, ECONO, EORATIO,    !Output
& FILECC, FILEGC, FRCNOD, FREEZ1, FREEZ2, KCAN, KEP, !Output
& NOUTDO, PCARSH, PCH2O, PLIPSH, PLIGSD, PLIGSH,    !Output
& PMINSD, PMINSH, POASD, POASH, PORMIN, PROLF1,    !Output
& PRORTI, PROSHI, PROSTI, R30C2, RCH2O, RES30C,    !Output
& RFIXN, RLIG, RLIP, RMIN, RNH4C, RNO3C, ROA,      !Output
& RPRO, RWUEP1, RWUMX, TTFIX                      !Output
& PROSRI, STRSRFL, STRLYR1)                        !Output

```

**Initialize values for PSRSRFL and PSRLYR1**

PSRSRFL = STRSRFL

PSRLYR1 = STRLYR1

**Modify CALL PEST statement to include storage variables**

```
CALL PEST(CONTROL, ISWITCH,
& AREALF, CLW, CSW, LAGSD, LNGPEG, NR2, PGAVL,  !Input
& PHTIM, PLTPOP, RTWT, SLA, SLDOT, SOILPROP,  !Input
& SSDOT, STMWT, TOPWT, WLFDOT, WTLF, YRPLT,  !Input
& RLV, SDNO, SHELN, SWIDOT,  !Input/Output
& VSTAGE, WSHIDT, WTSD, WTSHE,  !Input/Output
& ASMDOT, DISLA, NPLTD, PPLTD,  !Output
& SDDDES, WLIDOT, WRIDOT, WSIDOT, SDWT,  !Output
& CSRW, SSRDOT, STRWT, WSFDOT, WSRFDOT,  !Input
& WSRIDOT,  !Output

& CSFRZ, CSRFRZ, CSTRM, DSTOR, SRDAM)  !Output
```

**Modify CALL PHOTO statement to include dormancy variables**

```
CALL PHOTO(CONTROL,
& BETN, CO2, DXR57, EXCESS, NR5, PAR, SLPF,  !Input
& RNITP, SLAAD, SWFAC, TDAY, XHLAI, XPOD,  !Input
& AGEFAC, PG)  !Output
```

**Modify CALL DEMAND statement to include storage variables**

```
IF (CROP .NE. 'FA') THEN
CALL DEMAND(SEASINIT,
& AGRRLF, AGRRT, AGRSH2, AGRSTM, CROP, DRPP, DXR57,  !Input
& FILECC, FILEGC, FILEIO, FNINSH, FRACDN, LAGSD,  !Input
& LNGPEG, NDLEAF, NSTRES, PAR, PCNL, PCNRT, PCNST,  !Input
& PGAVL, PUNCSD, PUNCTR, PLTPOP, RPROAV, RTWT,  !Input
& SDDDES, SDNO, SDVAR, SHELN, SHVAR, STMWT, SWFAC,  !Input
& TAVG, TDUMX, TDUMX2, TGRO, TURFAC, VSTAGE, WCRLF,  !Input
& WCRRT, WCRST, WNRLF, WNRRT, WNRSH, WNRST, WTLF,  !Input
& WTSD, WTSHE, XPOD, YRDOY, NVEG0, NR1, NR2, NR5,  !Input
& NR7, YRSIM,  !Input

& AGRSD1, AGRSD2, AGRVG, AGRVG2, CDMREP, F, FNINL,  !Output
& FNINR, FNINS, FNINSR, FRLF, FRRT, FRSTM, GDMSD,  !Output
& GRRAT1, NDMNEW, NDMOLD, NDMREP, NDMSDR, NDMTOT,  !Output
& NDMVEG, NMINEP, NMOBR, PHTIM, PNTIM, POTCAR,  !Output
& POTLIP, SDGR, TURADD, XFRT,  !Output
& NMOBSR, PPMFAC, PPTFAC, PCNSR, STRWT,  !Input
& WCRSR, WLIDOT, WNSR, XLAI,  !Input
& AGRSTR, FNINSR, FRSTR,  !Output
```

```

& FRSTRF, FRSTRM, FRSTRMX, LRMOB, NMOBSRN, NMOBSRX, !Output
& NRMOB, NVSTL, NVSTR, NVSTS, NVSTSR, TYPLMOB      !Output
& TYPNMOB, XSTR, YSTOR)                             !Output

```

**Modify CALL NUPTAK statement to include CH2O supply/requirement variables to limit N uptake by PGAVL**

```

CALL NUPTAK(
& BD, DLAYR, DUL, FILECC, LL, NDMSDR, NDMTOT, NH4, !Input
& NO3, NLAYR, PGAVL, RLV, RNH4C, RNO3C, SAT, SW,   !Input
& NUPNH4, NUPNO3, TRNH4U, TRNO3U, TRNU, UNH4, UNO3, !Output
& RUNINIT)                                     !Control

```

**Modify CALL INCOMP statement to include storage variables**

```

CALL INCOMP(
& ECONO, FILECC, FILEGC, FRLF, FRRT,              !Input
& FRSTM,                                           !Input
& AGRLF, AGRNOD, AGRRT, AGRSD1, AGRSD2,           !Output
& AGRSH1, AGRSH2, AGRSTM, AGRVG, AGRVG2,          !Output
& SDPROR,                                         !Output
& AGRSTR, FRSTR,                                  !Output
& DYNAMIC)

```

**Modify CALL SENES statement to include storage variables**

```

CALL SENES(
& FILECC, CLW, DTX, NR7, NRUSLF, PAR, RHOL,       !Input
& SLAAD, STMWT, SWFAC, VSTAGE, WTLF, XLAI,        !Input
& YRDOY, YRSIM,                                   !Input
& SLDOT, SLNDOT, SSDOT, SSNDOT,                   !Output
& STRWT,                                           !Input
& SSRDOT, SSRNDOT,                                !Output

& SENSR,                                           !Output

& INTEGR)                                     !Control

```

**Modify CALL GROW statement to include storage variables**

```

CALL GROW(CONTROL, ISWITCH, RUNINIT, SOILPROP,
& AGEFAC, CADLF, CADST, CRUSLF, CRUSRT, CRUSH,    !Input
& CRUSST, DISLA, F, FILECC, FILEGC, FRLF, FRSTM, !Input
& NADLF, NADRT, NADST, NDTH, NFIXN, NGRLF, NGRRT, !Input
& NGRSD, NGRSH, NGRST, NMINEA, NODGR, NOUTDO,    !Input
& NPLTD, NRUSLF, NRUSRT, NRUSH, NRUSST, POTCAR,  !Input

```



```

& POTLIP, PPLTD, SDIDOT, SDPROR,           !Input
& SENNOD, SENRT, SLDOT, SLNDOT, SRDOT, SSDOT,   !Input
& SSNDOT, TRNH4U, TRNO3U, TRNU,             !Input
& TURFAC, WLDOTN, WLIDOT, WRDOTN, WRIDOT, WSDDTN, !Input
& WSDOTN, WSHDTN, WSIDOT, WTABRT, WTSHMT, YRNR1, !Input
& MDATE, YRPLT,                             !Input
& SWIDOT, WLFDOT, WSHIDT, WTNFX, XHLAI,       !Input/Output
& AREALF, BETN, CANNAA, CANWAA, CLW, CSW, DWNOD, !Output
& DWNODA, GROWTH, GRWRES, LAIMX, PCCSD, PCLSD,  !Output
& PCNL, PCNRT, PCNSD, PCNSH, PCNST, PLTPOP,    !Output
& PLIGLF, PLIGNO, PLIGRT, PLIGSD, PLIGSH, PLIGST, !Output
& PODWT, PUNCSD, PUNCTR, RHOL, RHOS, RNITP,    !Output
& ROWSPC, RTWT, SDNPL, SDRATE, SDWT, SDWTAM,   !Output
& SEEDNI, SEEDNO, SENESCE, SHELWT, SLA,        !Output
& SLAAD, STMWT, TOPWT, TOTWT, WCRLF, WCRRT, WCRSH, !Output
& WCRST, WNRLF, WNRRT, WNRSH, WNRST, WTCO,     !Output
& WTLF, WTLO, WTMAIN, WTNCAN, WTNEW, WTNLA, WTNLF, !Output
& WTNLO, WTNNA, WTNNAAG, WTNNO, WTNNOOD, WTNNO, !Output
& WTNRA, WTNRO, WTNRT, WTNSA, WTNSD, WTNSDA,   !Output
& WTNSDO, WTNSH, WTNSHA, WTNSHO, WTNSO, WTNST, !Output
& WTNUP, WTRO, WTSDO, WTSO, XLA, XPOD,        !Output

& CADRT, CADSH, NADSH,
    !Input
& CADSR, CRUSSR, FRSTR, NADSR, NGRSR, NRUSSR,   !Input
& PSRLYRD, PSRSRFD, PSRSRFL, PSRLYR1, SSRDOT,   !Input
& SSRNDOT, STRSRFL, STRLYR1, WSRDOTN, WSRIDOT,   !Input
& WSFDOT, WSRFDT,                             !Input/Output
& CSRW, PCNSR, PLIGSR, RHOSR, STRWT, WCRSR,     !Output
& WNRSR, WTNSR, WTNSRA, WTNSRO, WTSRO,         !Output

& ALPHSR, PCARSR, PLIPSR, PMINSR, POASR, PROSRF, !Output
& CPFSTR, NSRALL, NSRDOT, NSROFF, TPSRLYR1,     !Output
& TPSRSRFL, WRCSRDT, WSRDOT, WSRI,             !Output

& VSTAGE)                                     !Input/Output

```

**Move CALL DEMAND statement in EMERG step in front of CALL GROW to set proper initial partitioning of transplant DM**

```

!-----
    IF (DAS .EQ. NVEG0) THEN
!-----
!   On day of emergence, initialize:
!-----
        CALL DEMAND(EMERG,
& AGRLF, AGRRT, AGRSH2, AGRSTM, CROP, DRPP, DXR57, !Input

```

```

& FILECC, FILEGC, FILEIO, FNINSH, FRACDN, LAGSD,  !Input
& LNGPEG, NDLEAF, NSTRES, PAR, PCNL, PCNRT, PCNST, !Input
& PGAVL, PUNCSD, PUNCTR, PLTPOP, RPROAV, RTWT,    !Input
& SDES, SDNO, SDVAR, SHELN, SHVAR, STMWT, SWFAC,  !Input
& TAVG, TDUMX, TDUMX2, TGRO, TURFAC, VSTAGE, WCRLF, !Input
& WCRRT, WCRST, WNRLF, WNRRT, WNRSH, WNRST, WTLF, !Input
& WTSD, WTSHE, XPOD, YRDOY, NVEG0, NR1, NR2, NR5, !Input
& NR7, YRSIM,                                     !Input

& AGRSD1, AGRSD2, AGRVG, AGRVG2, CDMREP, F, FNINL, !Output
& FNINR, FNINS, FNINSR, FRLF, FRRT, FRSTM, GDMSD,  !Output
& GRRAT1, NDMNEW, NDMOLD, NDMREP, NDMSDR, NDMTOT, !Output
& NDMVEG, NMINEP, NMOBR, PHTIM, PNTIM, POTCAR,    !Output
& POTLIP, SDGR, TURADD, XFRT,                     !Output
& NMOBSR, PPMFAC, PPTFAC, PCNSR, STRWT,           !Input
& WCRSR, WLIDOT, WNRSR, XLAI,                     !Input
& AGRSTR, FNINSR, FRSTR,                          !Output

& FRSTRF, FRSTRM, FRSTRMX, LRMOB, NMOBSRN, NMOBSRX, !Output
& NRMOB, NVSTL, NVSTR, NVSTS, NVTSR, TYPLMOB,      !Output
& TYPNMOB, XSTR, YSTOR)                          !Output

```

!-----

```

CALL GROW(CONTROL, ISWITCH, EMERG, SOILPROP,
& AGEFAC, CADLF, CADST, CRUSLF, CRUSRT, CRUSH,  !Input
& CRUSST, DISLA, F, FILECC, FILEGC, FRLF, FRSTM, !Input
& NADLF, NADRT, NADST, NDTH, NFIXN, NGRLF, NGRRT, !Input
& NGRSD, NGRSH, NGRST, NMINEA, NODGR, NOUTDO,    !Input
& NPLTD, NRUSLF, NRUSRT, NRUSH, NRUSST, POTCAR,  !Input
& POTLIP, PPLTD, SDIDOT, SDPROR,                 !Input
& SENNOD, SENRT, SLDOT, SLNDOT, SRDOT, SSDOT,    !Input
& SSNDOT, TRNH4U, TRNO3U, TRNU,                  !Input
& TURFAC, WLDOTN, WLIDOT, WRDOTN, WRIDOT, WSDDTN, !Input
& WSDOTN, WSHDTN, WSIDOT, WTABRT, WTSMT, YRNR1, !Input
& MDATE, YRPLT,                                  !Input
& SWIDOT, WLFDO, WSHIDT, WTNFX, XHLAI,           !Input/Output
& AREALF, BETN, CANNA, CANWAA, CLW, CSW, DWNOD,  !Output
& DWNODA, GROWTH, GRWRES, LAIMX, PCCSD, PCLSD,   !Output
& PCNL, PCNRT, PCNSD, PCNSH, PCNST, PLTPOP,      !Output
& PLIGLF, PLIGNO, PLIGRT, PLIGSD, PLIGSH, PLIGST, !Output
& PODWT, PUNCSD, PUNCTR, RHOL, RHOS, RNITP,      !Output
& ROWSPC, RTWT, SDNPL, SDRATE, SDWT, SDWTAM,     !Output
& SEEDNI, SEEDNO, SENESCE, SHELWT, SLA,          !Output
& SLAAD, STMWT, TOPWT, TOTWT, WCRLF, WCRRT, WCRSH, !Output
& WCRST, WNRLF, WNRRT, WNRSH, WNRST, WTCO,       !Output
& WTLF, WTLO, WTMAIN, WTNCAN, WTNEW, WTNLA, WTNLF, !Output

```

```

& WTNLO, WTNNA, WTNNAG, WTNNO, WTNNOD, WTNOO,      !Output
& WTNRA, WTNRO, WTNRT, WTNSA, WTNSD, WTNSDA,      !Output
& WTNSDO, WTNSH, WTNSHA, WTNSHO, WTNSO, WTNST,    !Output
& WTNUP, WTRO, WTSDO, WTSHO, WTSO, XLAI, XPOD,     !Output

& CADRT, CADSH, NADSH,                               !Input
& CADSR, CRUSSR, FRSTR, NADSR, NGRSR, NRUSSR,      !Input
& PSRLYRD, PSRSRFD, PSRSRFL, PSRLYR1, SSRDOT,      !Input
& SSRNDOT, STRSRFL, STRLYR1, WSRDOTN, WSRIDOT,      !Input
& WSFDOT, WSRFDOT,                                   !Input/Output
& CSRW, PCNSR, PLIGSR, RHOSR, STRWT, WCRSR,        !Output
& WNRSR, WTNSR, WTNSRA, WTNSRO, WTSRO,           !Output

& ALPHSR, PCARSR, PLIPSR, PMINSR, POASR, PROSRF, !Output
& CPFSTR, NSRALL, NSRDOT, NSROFF, TPSRLYR1,        !Output
& TPSRSRFL, WRCSRDT, WSRDOT, WSRI,                !Output

& VSTAGE)                                           !Input/Output

```

**Modify CALL MOBIL statement to include storage variables and proportions of N mobilized from each organ**

```

CALL MOBIL(
& NDMNEW, NMINEP, NMOBR, RPRO, TRNU,              !Input
& WNRLF, WNRRT, WNRSH, WNRST,                    !Input
& NMINEA, NRUSLF, NRUSRT, NRUSSH, NRUSST,        !Output
& NMOBSR, PPMFAC, WNRSR,                          !Input
& NRUSSR, PNMLF, PNMST, PNMRT, PNMSR, PNMSH,      !Output
& SEASINIT)                                       !Control

```

**Add stem and storage organ variables to CALL FREEZE statement, then reset freeze damage variables for days without freeze**

```

C-----
C   Call freeze damage routine if TMIN is less than FREEZ1 deg C
C-----
IF (TMIN .LT. FREEZ1 .OR. TMIN .LT. FREEZ2) THEN
  CALL FREEZE(FILEIO, RUN,
& FREEZ1, FREEZ2, IDETO, NOUTDO, NRUSLF, SLDOT, !Input
& TMIN, WTLF, YRDOY, YRPLT,                    !Input
& MDATE,                                         !Input/Output
& WLFDOT,                                       !Output
& FRZDC, NRUSSR, NRUSST, PSRSRFL, PSRLYR1,      !Input
& SRFTEMP, SSDOT, SSRDOT, ST, STMWT, STRWT,      !Input

& PSRLYRD, PSRSRFD, WSFDOT, WSRFDOT,           !Output

```

```

& FRZDL, SRLYRD, SRSRFD, VSTAGE)                                !Output
ELSE
  WLFDOT = 0.0
  WSRFDOT = 0.0
  WSFDOT = 0.0

```

### Modify CALL VEGGR statement to include storage variables

```

CALL VEGGR(
&  AGRLF, AGRRT, AGRSTM, CMINEP, CSAVEV,      !
&  DTX,  DXR57, ECONO, FILECC, FILEGC, FNINL, !
&  FNINR, FNINS, NAVL,  NDMNEW, NDMOLD,      !
&  NR1, NVSTL, NVSTR, NVSTS, NVSTSR,        !
&  PAR, PCH2O, PCNL, PCNST, PCNRT, PCNSR, PG,  !Input
&  PGAVL, ROWSPC, RTWT, RVSTGE, STMWT,  TGRO,  !
&  TURFAC, VSTAGE, WCRLF, WCRRT,  WCRSH,      !
&  WCRST, WTLF,  XLAI,  YRDOY, YREMRG, YRSIM, !

&  AGRVG, FRLF,  FRRT,  FRSTM, NMINEA,      !Input/Output
&  NFIXN, TRNU,

&  CADLF, CADST, CANHT, CANWH, CMINEA,      !
&  CRUSLF, CRUSRT, CRUSSH, CRUSST, EXCESS, NADLF, !
&  NADRT, NADST, NGRLF, NGRRT, NGRST,      !Output
&  NSTRES, TNLEAK, WLDOTN, WRDOTN, WSDOTN,  !

&  CLAIT, NRUSTOT,                                !Input
&  PNMLF, PNMRRT, PNMSH, PNMSR,PNMST,RPRO,    !
&  CADRT, CADSH, NADSH,                                !Output
&  AGRSTR, CMOBSR, FNINSR, PPMFAC, STRWT, WCRSR, !Input
&  FRSTR,                                !Input/Output
&  CADSR, CRUSSR, NADSR, NGRSR, WSRDOTN,      !Output

&  CADSRF, CMOBSRN, CMOBSRX,                                !Output
&  FNINSRG, NGRSRG, PROSRG, PROSRT,            !Output

&  NLAYR, NUPNH4, NUPNO3, PROLFI, PRORTI,      !Input
&  PROSTI, PROSRI, RFIXN, RNH4C, RNO3C, TRNH4U, !
&  TRNO3U,

&  SEASINIT)                                !Control

```

### Modify CALL PlantNBal statement to include storage variables

```

IF (DYNAMIC .EQ. FINAL) THEN
  IF (CROP .NE. 'FA') THEN
    CALL PlantNBal (CONTROL, ISWITCH,
&  SEEDNI, TNLEAK, WTNFX, WTNLA, WTNLF, WTNLO,  !Input

```

```

&   WTNNA, WTNNO, WTNNO, WTNNO, WTNNO, WTNNO, WTNRT,   !Input
&   WTNSA, WTNSD, WTNSDA, WTNSDO, WTNSH, WTNSHA,   !Input
&   WTNSHO, WTNSO, WTNST, WTNUP,   !Input
&   WTNSR, WTNSRA, WTNSRO)   !Input

```

```

ENDIF

```

### Define Dormancy variables at end of subroutine

```

! CMOBSRN   Minimum fraction of C which can be mobilized from
!            storage organ in a day
! CMOBSRX   Maximum fraction of C which can be mobilized from
!            storage organ in a day
! DRMST     Dormancy status (NODORM=not dormant, DORM=dormant -
reversible,
! FRZDL     Todays death loss of storage tissue/plant population due to freezing
(proportion of STRWT and PLNTPOP)
! NADSH     N added to shell N reserves (g[N] / m2 / d)
! NMOBSRN   Minimum/ "normal" fraction of N which can be mobilized from
!            storage organ in a day
! NMOBSRX   Maximum fraction of N which can be mobilized from
!            storage organ in a day
! PPGFAC     Reduction in photosynthetic rate due to dormancy
! PPMFAC     Reduction in mobilization rate due to dormancy
! PNMLF     Proportion of actually mobilized N mobilized from leaves in a day
! PNMST     Proportion of actually mobilized N mobilized from stems in a day
! PNMRT     Proportion of actually mobilized N mobilized from roots in a day
! PNMSR     Proportion of actually mobilized N mobilized from storage organ in a day
! PNMSH     Proportion of actually mobilized N mobilized from shells in a day
! PPTFAC     Reduction in partitioning to vegetative tissues during dormancy
! WSFDOT     Stem weight losses due to freezing (g[stem]/m2-d)

```

**MODULE: DEMAND.FOR****Add storage/dormancy variables to SUBROUTINE command**

```

SUBROUTINE DEMAND(DYNAMIC,
& AGRLF, AGRRT, AGRSH2, AGRSTM, CROP, DRPP, DXR57, !Input
& FILECC, FILEGC, FILEIO, FNINSH, FRACDN, LAGSD, !Input
& LNGPEG, NDLEAF, NSTRES, PAR, PCNL, PCNRT, PCNST, !Input
& PGAVL, PUNCSD, PUNCTR, PLTPOP, RPROAV, RTWT, !Input
& SDDDES, SDNO, SDVAR, SHELN, SHVAR, STMWT, SWFAC, !Input
& TAVG, TDUMX, TDUMX2, TGRO, TURFAC, VSTAGE, WCRLF, !Input
& WCRRT, WCRST, WNRLF, WNRRT, WNRSH, WNRST, WTLF, !Input
& WTSD, WTSHE, XPOD, YRDOY, NVEG0, NR1, NR2, NR5, !Input
& NR7, YRSIM, !Input

& AGRSD1, AGRSD2, AGRVG, AGRVG2, CDMREP, F, FNINL, !Output
& FNINR, FNINS, FNINSR, FRLF, FRRT, FRSTM, GDMSD, !Output
& GRRAT1, NDMNEW, NDMOLD, NDMREP, NDMSDR, NDMTOT, !Output
& NDMVEG, NMINEP, NMOBR, PHTIM, PNTIM, POTCAR, !Output
& POTLIP, SDGR, TURADD, XFRT, !Output
& NMOBSR, PPMFAC, PPTFAC, PCNSR, STRWT, !Input
& WCRSR, WLIDOT, WNRSR, XLAI, !Input
& AGRSTR, FNINSR, FRSTR, !Output

& FRSTRF, FRSTRM, FRSTRMX, LRMOB, NMOBSRN, NMOBSRX, !Output
& NRMOB, NVSTL, NVSTR, NVSTS, NVSTSR, TYPLMOB, !Output
& TYPNMOB, XSTR, YSTOR) !Output

```

**Declare Storage organ and dormancy variables**

```

REAL SDAGPL
!-----
C Variables for adding storage organ and dormancy functions
!-----

REAL AGRSTR, FNINSR, FRSTR, WLIDOT,
& FRSTRF, FRSTRM, FRSTRMX, NMOBSR, NMOBSRN, NMOBSRX,
& NVSTSR, PCNSR, PPMFAC, PPTFAC, PROSRF, PROSRI,
& STRWT, TFRLF, TFRSTM, TFRSTR, TFRRT, WCRSR, WNRSR,
& XLAI, XSTR, YSTOR(25)

```

**Declare new variables for apportioning NDMVEG & NDMOLD as function of PGAVL**

```

!-----
C Variables for apportioning NDMVEG and NDMOLD
!-----

REAL CDMOLD, CHOPRO, FROLDA, KCOLD

```

### Declare new variables for modifying mobilization from storage

```
CHARACTER*3 TYPLMOB, TYPNMOB
REAL LRMOB(4), NRMOB(4)
```

### Add storage, mobilization modifiers, and NDMOLD variables to CALL IPDMND statement

```
CALL IPDMND(
& FILECC, FILEGC, FILEIO,           !Input
& CARMIN, FINREF, FNSDT, FRLFF, FRLFMX, FRRTMX,   !Output
& FRSTMF, LIPOPT, LIPTB, LNGSH, NMOBMMX,         !Output
& NRCVR, NVSMOB, PLIGSD, PMINSD, POASD,         !Output
& PROLFF, PROLFI, PRORTE, PRORTI, PROSTF, PROSTI, !Output
& RCH2O, RLIG, RLIP, RMIN, RNO3C, ROA,          !Output
& RPRO, SDLIP, SDPRO, SHLAG, SLAMAX, SLAMIN,      !Output
& SLAPAR, SLAREF, SLAVAR, SLOSUM, SIZELF, SIZREF, !Output
& SRMAX, THRESH, TURSLA, TYPSTDT, VSSINK, XFRMAX, !Output
& XFRUIT, XLEAF, XSLATM, XTRFAC, XVGROW, XXFTEM, !Output
& YLEAF, YSLATM, YSTEM, YTRFAC, YVREF, YXFTEM,   !Output
& FRSTRF, FRSTRMX, LRMOB, NMOBSRN, NMOBSRX,      !Output
& NRMOB, PLME, PROSRF, PROSRI, SDAGPL, TYPLMOB,  !Output
& TYPNMOB, YSTOR, KCOLD )                    !Output
```

### Initialize FNINSR

```
FNINSR=0.0
```

### Add FRSTR to initial partitioning for seeded crops

```
C-----
C  INITIALIZE PARTITIONING PARAMETERS - seedlings
C-----
          FRLF = TABEX(YLEAF,XLEAF,0.0,8)
          FRSTM = TABEX(YSTEM,XLEAF,0.0,8)
          FRSTR = TABEX(YSTOR,XLEAF,0.0,8)
FRRT = 1.0 - FRLF - FRSTM - FRSTR
```

### Assign value to FNINSR

```
FNINSR = PROSRI * 0.16
```

### Calculate initial partitioning for transplants in EMERG step

```
C-----
C  INITIALIZE PARTITIONING PARAMETERS for transplants adjusted for
C  SDAGE and growth temperature )
C-----
          IF (PLME .EQ. 'T') THEN
          FRLF = TABEX(YLEAF,XLEAF,VSTAGE,8)
          FRSTM = TABEX(YSTEM,XLEAF,VSTAGE,8)
```

```
FRSTR = TABEX(YSTOR,XLEAF,VSTAGE,8)
```

```
FRRT = 1.0 - FRLF - FRSTM - FRSTR
ENDIF
```

**Calculate N available from storage organ – adjust for LAI, N status, and dormancy**

```
NMOBR = NVSMOB * NMOBMX * TDUMX
IF (DAS .GT. NR5) THEN
  NMOBR = NMOBMX * TDUMX2 * (1.0 + 0.5*(1.0 - SWFAC))
& * (1.0 + 0.3*(1.0 - NSTRES)) * (NVSMOB + (1. - NVSMOB)
& * MAX(XPOD,DXR57**2.))
ENDIF
```

**Add Storage N to CMINEP**

```
C-----
C      Add N from storage to N available for potential mobilization
C-----
  NMINEP = NMOBR * (WNRLF + WNRST + WNRSH) +
&        NMOBR * PPMFAC * WNRRT +
&        NMOBSR * WNRSR
```

**Include Storage organ in partitioning scheme, make behave like leaves and stems.  
Also allow rate to increase during dormancy**

```
!-----
C      Fraction of growth going to leaves, roots and storage decreases
C      linearly between R1 and NDLEAF.
C-----
  FRLFM = TABEX (YLEAF, XLEAF, VSTAGE, 8)
  FRSTM = TABEX (YSTEM, XLEAF, VSTAGE, 8)
  FRSTRM = TABEX (YSTOR, XLEAF, VSTAGE, 8)

  YY = FRLFM - FRLFF
  XX = FRSTM - FRSTMF
  XSTR = FRSTRM - FRSTRF

ENDIF

!-----
  IF (DAS .LT. NR1) THEN
C-----
C      Calculate Pattern of Vegetative Partitioning, a function of V-STAGE
C-----
  FRLF = TABEX(YLEAF,XLEAF,VSTAGE,8)
  FRSTM = TABEX(YSTEM,XLEAF,VSTAGE,8)
```



FRSTR = TABEX (YSTOR, XLEAF, VSTAGE, 8)

ELSE

C-----  
 C Partitioning between vegetative tissues depends on development  
 C as expressed by FRACDN, the relative development between R1 and NDLEAF  
 C-----

FRLF = FRLFM - YY \* FRACDN  
 FRSTM = FRSTM - XX \* FRACDN  
 FRSTR = FRSTRM - XSTR \* FRACDN

IF ( DAS .GE. NDLEAF) THEN

FRLF = FRLFF  
 FRSTM = FRSTM  
 FRSTR = FRSTR

ENDIF  
 ENDIF

FRRT = 1. - FRLF - FRSTM -FRSTR

IF (PPTFAC .GT. 0.0) THEN

FRSTR = (FRSTRM - FRSTR) \* PPTFAC + FRSTR  
 FRRT = (FRRTM - FRRT) \* PPTFAC + FRRT  
 TFRLF = FRLF/(FRLF + FRSTM) \* (1-FRSTR-FRRT)  
 TFRSTM = FRSTM/(FRLF + FRSTM) \* (1-FRSTR-FRRT)  
 ! TFRRT = FRRT/(FRLF + FRSTM + FRRT) \* (1-FRSTR)  
 ! FRLF=TFRLF  
 FRSTM=TFRSTM  
 FRLF=1.0 - (FRSTM + FRRT + FRSTR)  
 ! FRRT=1.0 - (FRLF + FRSTM + FRSTR)  
 ENDIF

#### Continuation of implementation of storage organ partitioning after adjusting FRLF for F and VSSINK

C-----  
 C Recompute FRSTM, FRSTR, and FRRT based on FRLF  
 C-----  
 FRSTM = (1. - FRLF) \* FRSTM / (FRSTM + FRRT + FRSTR)  
 FRSTR = (1. - FRLF) \* FRSTR / (FRSTM + FRRT + FRSTR)  
 FRRT = 1. - FRLF - FRSTM - FRSTR  
 C-----  
 ENDIF  
 C-----  
 C Compute CH<sub>2</sub>O cost per g of tissue, excluding cost for protein (AGRVG)

C and total CH<sub>2</sub>O cost per g of veg tissue (AGRVG2)

```
C-----
AGRVG = AGRLF * FRLF + AGRRT * FRRT + AGRSTM * FRSTM
&      + AGRSTR * FRSTR
AGRVG2 = AGRVG + (FRLF*PROLFI+FRRT*PRORTI+FRSTM*PROSTI+
&      FRSTR*PROSRI)*RPROAV
```

C-----

C Compute N Demand for New Tissue, including reproductive and vegetative

```
C-----
NDMVEG = (CDMVEG/AGRVG2) * (FRLF*FNINL+FRSTM*FNINS+
& FRRT*FNINR+FRSTR*FNINSR)
NDMNEW = NDMREP + NDMVEG
```

**Calculate value for NVSTSR for calculation of refilling of storage N during vegetative growth**

NVSTSR = FNINSR

**Calculate value for NVSTSR for calculation of refilling of storage N during reproductive growth**

NVSTSR = PROSRF\*0.16 + (FNINSR-PROSRF\*0.16) \* FRNLFT

**Calculate NDMOLD – refilling of N in old tissue, including storage organ**

```
NDMOLD = (WTLF - WCRLF) * MAX(0.0,(NVSTL - PCNL /100.))
&      + (STMWT - WCRST) * MAX(0.0,(NVSTS - PCNST/100.))
&      + (RTWT - WCRRT) * MAX(0.0,(NVSTR - PCNRT/100.))
&      + (STRWT - WCRSR) * MAX(0.0,(NVSTSR - PCNSR/100.))
```

**Recalculate NDMOLD and NDMVEG, limiting to a total CH<sub>2</sub>O demand=PGAVL**

C-----

```
C KJB/SJR New code to minimize/fix situation of overspending PGAVL on
C N demand. Original code uses all PGAVL for CDMREP and CDMVEG
C then goes ahead and calculates NDMOLD using CDMVEG again.
C Get to N uptake and can potentially take up more N than have CHO
C to reduce. Contributes to NLEAK.
```

C-----

IF (NDMOLD .GT. 0.0) THEN

CHOPRO = NDMOLD \* 6.25 \* RNO3C

FROLDA = 1-EXP(-KCOLD \* (CDMVEG / CHOPRO))

CDMOLD = CHOPRO \* FROLDA

NDMOLD = FROLDA \* NDMOLD

CDMVEG = CDMVEG - CDMOLD

```

&          NDMVEG = (CDMVEG/AGRVG2) * (FRLF*FNINL+FRSTM*FNINS+
&          FRRT*FNINR+FRSTR*FNINSR)

```

```

ENDIF

```

```

C-----
C      KJB/SJR End new code.  Now CDMTOT=PGAVL, not more.
C-----

```

### Add storage organ parameters to SUBROUTINE statement for IPDMND subroutine

```

SUBROUTINE IPDMND(
& FILECC, FILEGC, FILEIO,          !Input
& CARMIN, FINREF, FNSDT, FRLFF, FRLFMX, FRRTMX,    !Output
& FRSTMF, LIPOPT, LIPTB, LNGSH, NMOBMX,          !Output
& NRCVR, NVSMOB, PLIGSD, PMINSD, POASD,          !Output
& PROLFF, PROLFI, PRORTF, PRORTI, PROSTF, PROSTI, !Output
& RCH2O, RLIG, RLIP, RMIN, RNO3C, ROA,          !Output
& RPRO, SDLIP, SDPRO, SHLAG, SLAMAX, SLAMIN,      !Output
& SLAPAR, SLAREF, SLAVAR, SLOSUM, SIZELF, SIZREF, !Output
& SRMAX, THRESH, TURSLA, TYPSTD, VSSINK, XFRMAX, !Output
& XFRUIT, XLEAF, XSLATM, XTRFAC, XVGROW, XXFTEM, !Output
& YLEAF, YSLATM, YSTEM, YTRFAC, YVREF, YXFTEM,   !Output
& FRSTRF, FRSTRMX, LRMOB, NMOBSRN, NMOBSRX,      !Output
& NRMOB, PLME, PROSRF, PROSRI, SDAGPL, TYPLMOB,  !Output
& TYPNMOB, YSTOR, KCOLD )                    !Output

```

### Define storage organ parameters as REAL

```

REAL FRSTRF, FRSTRMX, NMOBSRX, PROSRF, PROSRI,
& SDAGPL,
REAL YSTOR(25)

```

### Define NDMOLD curvature (K) factor as REAL

```

REAL KCOLD

```

### Declare mobilization rate modifiers

```

CHARACTER*3 TYPLMOB, TYPNMOB

REAL LRMOB(4)
REAL NRMOB(4), VEGNPCT, VEGNPMX, VNMOBR, VNSTAT

```

### Add read statement for storage protein concentration parameters

```

CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(F6.0,6X,F6.0)',IOSTAT=ERR) PROSRI,PROSRF
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

```

Add read statement for KCOLD parameter

```
CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(F6.0)',IOSTAT=ERR) KCOLD
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)
```

Add read statement for storage N mobilization parameter NMOBSRX mobilization modifiers

```
CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(18X,2F6.0)',IOSTAT=ERR) NMOBSRN, NMOBSRX
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(4(1X,F5.2),3X,A3)',IOSTAT=ERR)
&      (LRMOB(II),II=1,4), TYPLMOB
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(4(1X,F5.2),3X,A3)',IOSTAT=ERR)
&      (NRMOb(II),II=1,4), TYPNMOB
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)
```

Add READ statement for storage partitioning parameters

```
CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(8F6.0)',IOSTAT=ERR)(YSTOR(II),II=1,8)
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(3F6.0)',IOSTAT=ERR) FRSTRF,FRSTRMX,FRRTMX
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

! AGRSTR   Mass of CH2O required for new storage organ growth
!           (g[CH2O] / g[storage])
! CDMOLD   Total CH2O demand for refilling old tissue N
!           (g[CH2O] / m2 / d)
! CHOPRO   CHO required for uptake and reduction of N to fully
!           refill old tissue N (g[CH2O] / m2 / d)
! CMOBSRX  Maximum storage organ C pool mobilization rate (g[CH2O] / m2 / d)
! DRMRD    Intermediate value calculated in determining reduction in
!           mobilization due to dormancy
! FNINSR   Maximum fraction of N for growing storage tissue
!           (g[N] / g[storage])
! FROLDA   Fraction of max potential NDMOLD allowed to be met given
```

! today's level of CDMVEG. Prevents refilling old tissue  
! without allowing any new growth due to low PG.  
! FRRTMX Maximum proportion of vegetative growth that goes to roots on  
! a day. Occurs only during dormancy. ( $g[\text{root}] / g[\text{veg}]$ )  
! FRSTR Fraction of vegetative tissue growth that goes to storage organ  
! on a day ( $g[\text{storage}] / g[\text{veg}]$ )  
! FRSTRF Fraction of daily dry weight increase in vegetative plant parts  
! which goes to storage organ after the day on which the maximum  
! number of V-stages occurs (NDVSTG). ( $g[\text{storage}] / g[\text{veg}]$ )  
! FRSTRM Fraction of growth going to storage organ decreases linearly  
! between R1 and NDLEAF ( $g[\text{stem}] / g[\text{veg}]$ )  
! FRSTRMX Maximum storage organ partitioning ( $g[\text{storage}] / g[\text{veg}]$ )  
! KCOLD Curvature factor (K value) for exponential function limiting  
! NDMOLD when PG is low  
! LAIMOB Effect of LAI on N & C mobilization. (0= no effect,  
! mobilization at minimum rate, 1.0 = increase mobilization  
! to maximum rate. Increases mobilization after harvest, damage.  
! LRMOB(4) CURV response of mobilization to current LAI  
! NMOBSR Stage-dependent potential N mining rate from storage organ  
! expressed as a fraction of the maximum rate (NMOBSRX)  
! NMOBSRN Minimum/ "normal" fraction of N which can be mobilized from  
! storage organ in a day  
! NMOBSRX Maximum fraction of N which can be mobilized from  
! storage organ in a day! NVSTSR N content in storage tissue  
(fraction)  
! NRMOB(4) CURV response of mobilization to current vegetative N status  
! of plant relative to maximum N concentration  
! PCNSR Percent N in storage organ tissue ( $100 g[\text{N}] / g[\text{storage}]$ )  
! PPMFAC Reduction in mobilization from storage organ due to photoperiod  
! induced dormancy  
! PPTFAC Reduction in partitioning to shoot due to photoperiod  
! induced dormancy  
! PROSRF Minimum storage organ protein composition after N mining  
! ( $g[\text{protein}] / g[\text{storage}]$ )  
! PROSRI Maximum protein composition in storage organ during growth  
! with luxurious supply of N ( $g[\text{protein}] / g[\text{storage}]$ )  
! STRWT Dry mass of storage organ tissue, including C and N  
! ( $g[\text{storage}] / m2[\text{ground}]$ )  
! TYPLMOB Shape of CURV response for mobilization to LAI  
! TYPNMOB Shape of CURV response for mobilization to current vegetative N  
! status of plant relative to maximum N concentration  
! WCRSR Mass of CH<sub>2</sub>O reserves in storage organ  
! ( $g[\text{storage CH}_2\text{O}] / m2[\text{ground}]$ )  
! WNRSR N available for mobilization from storage organ above lower  
! mining ( $g[\text{N}] / m2$ )  
! XLAI Leaf area (one side) per unit of ground area

! XSTR            Difference between partitioning fraction to storage organ at  
!            beginning bloom (R1) and at the day on which the maximum  
!            number of V-stages occurs (NDLEAF)  
! YSTOR(I) Partitioning factor for storage organ growth at V-stage XSTOR(I)  
!            ( $g[\text{storage}] / g[\text{veg. plant}]$ )

MODULE: DORMANCY.FOR

Calculate effect of dormancy on partitioning, photosynthesis, and mobilization for the current day. Also calculate cold-hardening and dehardening for current day. Update FREEZ2 for cold-hardening/dehardening. Add new .OUT output files for dormancy and STOR-related variables.

```
C=====
C DORMANCY Subroutine 6/20/03 SJR
C Fall Dormancy with cold hardening for perennial grasses and legumes
C Separate functions for effects on partitioning, photosynthesis, mobilization
C Generate a reduction factor for each for use in appropriate modules
C Factor is 0-1 value adjusted for cultivar sensitivity to daylength
C Cold hardening lowers the minimum survivable temperature for the crop
C with increased exposure to low temperatures.
C This subroutine also provides a death rate to allow partial
C or total depletion of the stand by a freeze event
C-----
C Called by: CROPGRO
C Calls   : None
C=====
```

```
      SUBROUTINE DORMANCY( CONTROL,
&   DAYL, TMIN,                                     !Input
&   DRMST, FREEZ2, FRZDC, PPGFAC, PPTFAC, PPMFAC,   !Output

&   FNPGD, FNPMD, FNPTD, FRZDHD, FRZHRD, HARD1,     !Output
&   HARD2, RCHDP, RDRMG, RDRMM, RDRMT, TYPDHD, TYPHRD, !Output
&   TYPPGD, TYPPMD, TYPPTD)                         !Output
```

```
      USE ModuleDefs   !Definitions of constructed variable types,
                        ! which contain control information, soil
                        ! parameters, hourly weather data.
```

```
C-----
```

```
      IMPLICIT NONE
```

```
C-----
```

```
      CHARACTER*1  BLANK
      CHARACTER*3  TYPPGD,TYPPTD, TYPPMD, TYPHRD, TYPDHD
      CHARACTER*6  SECTION, ECOTYP, ECONO, ERRKEY, DRMST
      CHARACTER*12 FILEIO, FILEC, FILEE
      CHARACTER*16 ECONAM
      CHARACTER*80 PATHCR, PATHEC, CHAR
```

```
      CHARACTER*92 FILECC, FILEGC
      CHARACTER*255 C255
```

```

!   INTEGER RUNINIT, SEASINIT, RATE, EMERG, INTEGR, OUTPUT, FINAL,
!   $           DYNAMIC
!   PARAMETER (RUNINIT = 1, SEASINIT = 2, EMERG = 3, RATE = 3,
!   &           INTEGR = 4, OUTPUT=5, FINAL = 6)

```

```

INTEGER DYNAMIC, II, LUNIO, LUNECO
INTEGER LUNCRP, ISECT, ERRNUM, PATHL
INTEGER ERR, LINC, LNUM, FOUND

```

```

PARAMETER (BLANK = '')
PARAMETER (ERRKEY = 'DORMAN')

```

```

PARAMETER (LUNIO=21, LUNCRP=10, LUNECO=10)

```

```

REAL DAYL, CURV, TMIN
REAL PPGFAC, PPTFAC, PPMFAC, RDRMT, RDRMG, RDRMM
REAL FNPGD(4), FNPTD(4), FNPMD(4), FRZHRD(4), FRZDHD(4)
REAL DAYLY, RCHDP
REAL DHARDR, FREEZ2, FRZDC, HARD1, HARD2, HARDR

```

C The variable "CONTROL" is of type "ControlType".

```

TYPE (ControlType) CONTROL
!   TYPE (SwitchType) ISWITCH
C   Transfer values from constructed data types into local variables.
DYNAMIC = CONTROL % DYNAMIC
FILEIO = CONTROL % FILEIO
!   LUNIO = CONTROL % LUNIO
!   LUNECO = CONTROL % LUNECO

```

```

C*****
*

```

C Run Initialization - Called once per simulation

```

C*****
*

```

```

IF (DYNAMIC .EQ. RUNINIT) THEN

```

```

C-----
C   Initialize Dormancy variables
C-----

```

```

PPGFAC = 0.0
PPTFAC = 0.0
PPMFAC = 0.0

```



```
DRMST = 'NODORM'
```

```
DAYLY = 0.0
```

```
RDRMT = 1.0
```

```
RDRMG = 1.0
```

```
RDRMM = 1.0
```

```
C-----
```

```
C  Read in values from temporary file, which were previously input
C  in Subroutine IPIBS.
```

```
C-----
```

```
OPEN (LUNIO, FILE = FILEIO, STATUS = 'OLD', IOSTAT=ERRNUM)
IF (ERRNUM .NE. 0) CALL ERROR(ERRKEY,ERRNUM,FILEIO,0)
```

```
READ (LUNIO,100) FILEC, PATHCR
100 FORMAT(//////,15X,A12,1X,A80)
```

```
READ (LUNIO,105) FILEE, PATHEC
105 FORMAT(15X,A12,1X,A80)
```

```
C-----
```

```
C  Subroutine FIND finds appropriate SECTION in a file by
C  searching for the specified 6-character string at beginning
C  of each line.
```

```
C-----
```

```
SECTION = '*HARVE'
CALL FIND(LUNIO, SECTION, LNUM, FOUND)
IF (FOUND .EQ. 0) CALL ERROR (ERRKEY,2,FILEIO,LNUM)
```

```
C-----
```

```
C  Find and read Cultivar Section
```

```
C-----
```

```
SECTION = '*CULTI'
CALL FIND(LUNIO, SECTION, LNUM, FOUND)
IF (FOUND .EQ. 0) CALL ERROR (ERRKEY,2,FILEIO,LNUM)
READ(LUNIO,1650) ECONO
1650 FORMAT(24X,A6)
```

```
CLOSE (LUNIO)
```

```
C-----
```

```
C  Open FILEE
```

```
C-----
```

```
LNUM = 0
PATHL = INDEX(PATHEC,BLANK)
```

```

IF (PATHL .LE. 1) THEN
  FILEGC = FILEE
ELSE
  FILEGC = PATHEC(1:(PATHL-1)) // FILEE
ENDIF

```

```

C-----
C  Read Ecotype Parameter File
C-----

```

```

C-----
C  READ FILEE
C-----

```

```

OPEN (LUNECO,FILE = FILEGC,STATUS = 'OLD',IOSTAT=ERR)
IF (ERRNUM .NE. 0) CALL ERROR(ERRKEY,ERRNUM,FILEE,0)

```

```

ECOTYP = '  '
DO WHILE (ECOTYP .NE. ECONO)

```

```

CALL IGNORE(LUNECO, LNUM, ISECT, C255)
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILEGC,0)
IF ((ISECT .EQ. 1) .AND. (C255(1:1) .NE. '*')) THEN
  READ (C255,'(A6,1X,A16,121X,4F6.0)',IOSTAT=ERR)
&   ECOTYP, ECONAM, RDRMT,RDRMG,RDRMM, RCHDP

```

```

IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILEGC,LNUM)
IF (ECOTYP .EQ. ECONO) THEN
  EXIT
ENDIF
ELSE IF (ISECT .EQ. 0) THEN
  IF (ECONO .EQ. 'DFAULT') CALL ERROR(ERRKEY,3,FILEGC,LNUM)
  ECONO = 'DFAULT'
  REWIND(LUNECO)
ENDIF
ENDDO
CLOSE (LUNECO)

```

```

C-----
C  Open FILEC
C-----

```

```

LINC = 0

```

```

PATHL = INDEX(PATHCR,BLANK)
IF (PATHL .LE. 1) THEN
  FILECC = FILEC
ELSE
  FILECC = PATHCR(1:(PATHL-1)) // FILEC
ENDIF

OPEN (LUNCRP,FILE = FILECC, STATUS = 'OLD',IOSTAT=ERR)
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,0)

C-----
C READ DORMANCY PARAMETERS *****
C-----
  SECTION = '!*DORM'
  CALL FIND(LUNCRP, SECTION, LINC, FOUND)
  IF (FOUND .EQ. 0) THEN
    CALL ERROR(ERRKEY, 1, FILECC, LINC)
  ELSE

CALL IGNORE(LUNCRP,LINC,ISECT,CHAR)

  READ(CHAR,'(4F6.0,3X,A3)',IOSTAT=ERR) (FNPTD(II),II=1,4), TYPPTD
  IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LINC)

CALL IGNORE(LUNCRP,LINC,ISECT,CHAR)

  READ(CHAR,'(4F6.0,3X,A3)',IOSTAT=ERR) (FNPMD(II),II=1,4), TYPPMD
  IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LINC)

CALL IGNORE(LUNCRP,LINC,ISECT,CHAR)

  READ(CHAR,'(4F6.0,3X,A3)',IOSTAT=ERR) (FNPGD(II),II=1,4), TYPPGD
  IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LINC)

!      ENDIF
!-----
! Find and read Temperature threshold for cold hardening in
!-----
  CALL IGNORE(LUNCRP,LINC,ISECT,CHAR)
  READ(CHAR,'(3F6.0)',IOSTAT=ERR)HARD1,HARD2,FRZDC
  IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LINC)

  CALL IGNORE(LUNCRP,LINC,ISECT,CHAR)
  READ(CHAR,'(4F6.0,3X,A)',IOSTAT=ERR)
&      (FRZHRD(II), II=1,4), TYPHRD

```

```

      IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LINC)

      CALL IGNORE(LUNCRP,LINC,ISECT,CHAR)
      READ(CHAR,'(4F6.0,3X,A)',IOSTAT=ERR)
&      (FRZDHD(II), II=1,4), TYPDHD
      IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LINC)
      ENDIF

      CLOSE (LUNCRP)

```

```

!*****
!   Seasonal initialization - run once per season
!*****
!*****
!   Initialize yesterdays daylength to that passed in from PLANT
!*****

```

```

      ELSE IF (DYNAMIC .EQ. SEASINIT) THEN

```

```

      DAYLY=DAYL

```

```

C-----
C   All cultivars share the same freeze-killing temperature before
C   cold hardening
C
C   Minimum survivable temperature after hardening varies with the
C   cold hardening potential of the cultivar
C-----
      FREEZ2=HARD1
      HARD2 = HARD1-(HARD1-HARD2)*RCHDP
C-----
C
C   THE FOLLOWING GENERATES HEADINGS FOR NEW OUTPUT FILE
DORMANT.OUT
C
C-----
!   OPEN(UNIT = NOUTDT, FILE = OUTT, STATUS = 'UNKNOWN')
!
!   IF (IDETL .EQ. 'Y') THEN
!
!
C-----
C   Variable heading for DORMANT.OUT
C-----

```

```

!
!   WRITE (NOUTDT,2202) NREP,TITLET,
!   &   MODEL,CROPD,EXPER,CROP,ENAME,TRTNO,TITLET, ECOTYP,
ECONAM
! 2202  FORMAT (/'*RUN ',I3,8X,': ',A25,/,
!   &   1X,'MODEL',10X,': ',1X,A8,' - ',A10,/,
!   &   1X,'EXPERIMENT',5X,': ',1X,A8,1X,A2,4X,A47,/,
!   &   1X,'TREATMENT',I3, 3X,': ',1X,A25,/,
!   &   1X,'ECOTYPE',8X,': ',1X,A6,1X,A16,/)
!
!
!   WRITE (NOUTDT,2203)
! 2203  FORMAT('@DATE',
!   &   ' DAYL DRMST PPGFAC  PRTFAC WTLF WCRLF LFDM  STMWT',
!   &   ' WCRST STDN  STRWT  WCRSR SRDM  RTWT WCRRT  RTDM')
!   ENDIF

      ELSE IF (DYNAMIC .EQ. EMERG) THEN
!       NONE
C*****
*
C   Daily Rate Calculations
C*****
*

      ELSE IF (DYNAMIC .EQ. RATE) THEN

!       NONE
C*****
*
C   Daily Integration
C*****
*

      ELSE IF (DYNAMIC .EQ. INTEGR) THEN

C*****
C   Calculate cold-hardening status for day
C   Killing freeze temperature decreases as cold hardening proceeds.
C   Cold hardening is reversible while days are getting shorter.
C   Maximum rate of hardening (degrees C decrease in FREEZ2 per day)
C   occurs at FRZHRD(1) with fractional rates between FRZHRD(1) and
FRZHRD(2)
C   Cold hardening is reversed between FRZHRD(2) and FRZHRD(3).

```

```

C   Dehardening will not occur until daylength begins to increase.
C   Dehardening is not reversible.
C   FRZDC is the rate of plant/tissue death per degree C below FREEZ2.
C   This allows gradual killing of the stand with increased rate at
C   lower temperatures.
C   Adapted from ALFACOLD model (Kanneganti et al., 1998, Agron J. 90:687-697)
C   Note: this routine allows hardening and dehardening to occur on the
C   same day with reverse hardening and dehardening combining to
C   accelerate dehardening at higher temperatures.
C*****

```

```

      IF (DAYL .LE. DAYLY) THEN

```

```

        HARDR =
        CURV(TYPHRD,FRZHRD(1),FRZHRD(2),FRZHRD(3),FRZHRD(4),TMIN)
        DHARDR = 0.0

```

```

      ELSE
        HARDR =
        CURV(TYPHRD,FRZHRD(1),FRZHRD(2),FRZHRD(3),FRZHRD(4),TMIN)
        DHARDR =
        CURV(TYPDHD,FRZDHD(1),FRZDHD(2),FRZDHD(3),FRZDHD(4),TMIN)

```

```

      ENDIF

```

```

      FREEZ2 = FREEZ2 - (HARDR - DHARDR)*RCHDP

```

```

      FREEZ2 = MIN(HARD1, FREEZ2)
      FREEZ2 = MAX(FREEZ2, HARD2)

```

```

C*****
C   Calculate Partitioning, Pg, and mobilization reduction
C   factors and dormancy state for day
C*****

```

```

      PPTFAC=CURV(TYPPTD,FNPTD(1),FNPTD(2),FNPTD(3),FNPTD(4),DAYL)
      PPTFAC=RDRMT * PPTFAC
      PPTFAC=MIN (PPTFAC,1.0)

```

```

      FNPGD(4) = RDRMG * FNPGD(4)

```

```

PPGFAC=CURV(TYPPGD,FNPGD(1),FNPGD(2),FNPGD(3),FNPGD(4),DAY
L)
PPGFAC=MIN (PPGFAC,1.0)

FNPMD(4) = RDRMM * FNPMD(4)

PPMFAC=CURV(TYPPMD,FNPMD(1),FNPMD(2),FNPMD(3),FNPMD(4),DA
YL)
PPMFAC=MIN (PPMFAC,1.0)

IF (PPTFAC .GT. 0.0 .OR. PPGFAC .LT. 1.0
&      .OR. PPMFAC .LT. 1.0) THEN
DRMST='DORM'
ELSE
DRMST='NODORM'
ENDIF

DAYLY=DAYL

ELSE IF (DYNAMIC .EQ. OUTPUT) THEN
C-----
C   Calculate new variables for DORMANT.OUT
C-----

C-----
C   Sent daily growth and partitioning detail to DORMANT.OUT
C-----

!   IF (IDETL .EQ. 'Y') THEN
C-----
C   Print out dormancy parameters - TEMPORARY
C-----
!
!       WRITE (NOUTDT,401) YRDOY, DAYL, DRMST, PPGFAC,
! &           PPTFAC, WTLF, WCRLF, LFDM,
! &           STMWT, WCRST, STDm, STRWT, WCRSR, SRDM,
! &           RTWT, WCRRT, RTDM
! 401   FORMAT (1X,I5,1X,F5.2,1X,A6,1X,F5.3,1X,F5.3,1X,F6.1,
! &           1X,F6.1,1X,F6.1,1X,F7.1,1X,F6.1,1X,F6.1,1X,F7.1,
! &           1X,F6.1,1X,F6.1,1X,F6.1,1X,F6.1,1X,F6.1)
!   ENDIF

```

```

|*****
!  FINAL
|*****

      ELSE IF (DYNAMIC .EQ. FINAL) THEN
C-----
C   Close DORMANT.OUT
C-----

!      CLOSE (NOUTDT)

      END IF
      RETURN
      END  !SUBROUTINE DORMANT

!-----
!  DORMANT VARIABLES
!-----
! BLANK      ''
! C255      255 character record
! DAYL      Current daylength (hours)
! DAYLY     Yesterdays daylength (hours)
! DRMST     Dormancy status (NODORM=not dormant, DORM=dormant -
reversible,
! DYNAMIC   Controls run sequence: DYNAMIC =RUNINIT, SEASINIT, RATE,
!           EMERG, INTEGR, OUTPUT, or FINAL
! ECONAM    Ecotype name - not used
! ECONO     Used to match ECOTYP in .ECO file
! ECOTYP    Ecotype code
! ERR
! ERRKEY
! ERRNUM
! FILEC, FILEE  Filenames for Crop and Species files
! FILECC, FILEGC File+pathname for Crop and Eco files
! FILEIO     Filename for Input file
! FNP GD(1) Base daylength for CURV function for daylength effect on Pg
!           for short-day dormancy (daylength when dormancy is maximum)
! FNP GD(2) Daylength threshold where dormancy effect begins
!           for daylength effect on Pg (for short-day dormancy)
! FNP GD(3) Longest daylength threshold where there is no dormancy effect
!           for daylength effect on Pg (for long-day dormancy)
! FNP GD(4) Daylength when dormancy effect is maximum
!           for daylength effect on Pg (long-day dormancy)
! FNP MD(1) Base daylength for CURV function for daylength effect on mobilization
!           for short-day dormancy (daylength when dormancy is maximum)
! FNP MD(2) Daylength threshold where dormancy effect begins

```



! for daylength effect on mobilization (for short-day dormancy)  
 ! FNPMD(3) Longest daylength threshold where there is no dormancy effect  
 ! for daylength effect on mobilization (for long-day dormancy)  
 ! FNPMD(4) Daylength when dormancy effect is maximum  
 ! for daylength effect on mobilization (long-day dormancy)  
 ! FNPTD(1) Ignored for short-day dormancy  
 ! FNPTD(2) Daylength threshold where dormancy effect is maximum  
 ! for daylength effect on partitioning (for short-day dormancy)  
 ! FNPTD(3) Shortest daylength threshold where there is no dormancy effect  
 ! for daylength effect on partitioning (for short-day dormancy)  
 ! FNPTD(4) Minimum relative effect of dormancy when crop is non-dormant (set to 0.0)  
 ! FREEZ2 Temperature below which plant growth stops completely. (°C)  
 ! FRZDC Freezing death coefficient - percentage tissue/population death per day  
 per degree below FREEZ2)  
 ! FRZDHD(1) Minimum temperature at which dehardening begins (relative rate=0)  
 ! FRZDHD(2) Temperature at which dehardening reaches maximum rate (relative rate=1)  
 ! FRZDHD(3) Not used  
 ! FRZDHD(4) Maximum (absolute) rate of dehardening (degrees C increase above  
 HARD2 per day)n of STRWT and PLNTPOP)  
 ! FRZHRD(1) Temperature at which cold hardening reaches maximum rate (relative  
 rate=1)  
 ! FRZHRD(2) Temperature below which cold hardening begins (relative rate=0)  
 ! FRZHRD(3) Temperature at which hardening is reversed at maximum rate (relative  
 rate=-1)  
 ! FRZHRD(4) Maximum (absolute) rate of cold hardening (degrees C decrease towards  
 HARD2 per day)  
 ! HARD1 Killing low temperature before cold hardening (begins killing storage  
 organ)  
 ! HARD2 Killing low temperature after cold hardening (begins killing storage  
 organ)  
 ! ISECT  
 ! LNUM  
 ! LUNECO Logical unit number for ECO files  
 ! LUNIO Input file logical unit no.  
 ! PATHL  
 ! PPGFAC Reduction in photosynthetic rate due to dormancy  
 ! PPMFAC Reduction in mobilization rate due to dormancy  
 ! PPTFAC Reduction in partitioning to vegetative tissues during dormancy  
 ! RCHDP Ecotype relative cold hardening potential (0-1)  
 ! RDRMG Relative sensitivity of ecotype to daylength/dormancy effects on Pg  
 ! RDRMM Relative sensitivity of ecotype to daylength/dormancy effects on  
 mobilization  
 ! RDRMT Relative sensitivity of ecotype to daylength/dormancy effects on  
 partitioning to perenniating tissues  
 ! SECTION Heading name in input files  
 ! TMIN Daily average temperature

```

! TYPDHD      Response type for cold dehardening
! TYPHRD      Response type for cold hardening
! TYPPGD      Type of response curve for effect of daylength/dormancy on Pg
! TYPPMD      Type of response curve for effect of daylength/dormancy on
!              mobilization
! TYPPTD      Type of response curve for effect of daylength/dormancy on
!              partitioning to perenniating organ
!-----
!  END SUBROUTINE DORMANT
!-----

```

MODULE: ETPHOT.FOR

**Declare photosynthetic pathway parameter variables**

```
CHARACTER PGPATH*2
REAL CCNEFF, CICAD, CMXSF, CQESF
```

**Add photosynthetic pathway parameters to CALL PGINP statement**

```
IF (MEPHO .EQ. 'L' .AND. CROP .NE. 'FA') THEN
  CALL PGINP(
    & FILEIO, LUNIO, SALB,           !Input
    & AZIR, BETN, FNPGL, FNPGL, LFANGD, LMXREF,   !Output
    & LNREF, NSLOPE, PALBW, QEREF, ROWSPC,       !Output
    & SCVP, SLWREF, SLWSLO, TYPPGL, TYPPGN,      !Output
    & XLMAXT, YLMAXT, PHTHR10,
    !
    & CCNEFF, CICAD, CMXSF, CQESF, PGPATH)      !Output
```

**Add photosynthetic pathway parameters to SUBROUTINE PGINP statement**

```
SUBROUTINE PGINP(
  & FILEIO, LUNIO, SALBW,           !Input
  & AZIR, BETN, FNPGL, FNPGL, LFANGD, LMXREF,   !Output
  & LNREF, NSLOPE, PALBW, QEREF, ROWSPC,       !Output
  & SCVP, SLWREF, SLWSLO, TYPPGL, TYPPGN,      !Output
  & XLMAXT, YLMAXT, PHTHR10,
  !
  & CCNEFF, CICAD, CMXSF, CQESF, PGPATH)      !Output
```

**Declare photosynthetic pathway parameter variables in PGINP**

```
CHARACTER PGPATH*2
REAL CCNEFF, CICAD, CMXSF, CQESF
```

**Declare photosynthetic pathway parameter variables in CANOPG subroutine**

```
CHARACTER PGPATH*2
REAL CCNEFF, CICAD, CMXSF, CQESF
```

**Read photosynthetic pathway parameters from species file**

```
CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
CALL IGNORE(LUNCRP,LNUM,ISECT,C80) !12th line
READ(C80,'(4F6.0,2X,A)',IOSTAT=ERRNUM) CICAD,CCNEFF,
& CMXSF,CQESF,PGPATH
IF (ERRNUM .NE. 0) CALL ERROR(ERRKEY,ERRNUM,FILECC,LNUM+12)
```

**Add photosynthetic pathway parameters to CALL ETPHR statement**

```
CALL ETPHR(
  & CANHT, CEC, CEN, CLOUDS, CO2HR, DAYTIM,   !Input
```

```

& DLAYR2, DULE, FNPGL, FNPGN, FRACSH, FRSHV,  !Input
& KDIRBL, LAISH, LAISHV, LAISL, LAISLV, LLE,  !Input
& LMXREF, LNREF, LWIDTH, MEEVP, MEPHO, NLAYR,  !Input
& NSLOPE, PARSH, PARSUN, QEREF, RABS, RCUTIC,  !Input
& REFHT, RHUMHR(H), RNITP, RWUH, SHCAP, SLAAD, !Input
& SLWREF, SLWSLO, STCOND, SWE, TAIRHR(H), TA,  !Input
& TMIN, TYPPGL, TYPPGN, WINDHR(H), XHLAI,     !Input
& XLMAXT, YLMAXT,                             !Input
& AGEFAC, EHR, LFMXSH, LFMXSL, PCNLSH, PCNLSL, !Output
& PGHR, SLWSH, SLWSL, T0HR, TCAN(H), THR, TSHR, !Output
& TSURF,                                       !Output
& CCNEFF, CICAD, CMXSF, CQESF, PGPATH)      !Input

```

**MODULE: ETPHR.FOR****Add photosynthetic pathway parameters to SUBROUTINE ETPHR statement**

```

SUBROUTINE ETPHR(
& CANHT, CEC, CEN, CLOUDS, CO2HR, DAYTIM,      !Input
& DLAYR2, DULE, FNPGL, FNPGR, FRACSH, FRSHV,    !Input
& KDIRBL, LAISH, LAISHV, LAISL, LAISLV, LLE,     !Input
& LMXREF, LNREF, LWIDTH, MEEVP, MEPHO, NLAYR,    !Input
& NSLOPE, PARSH, PARSUN, QEREF, RABS, RCUTIC,    !Input
& REFHT, RHUMHR, RNITP, RWUH, SHCAP, SLAAD,      !Input
& SLWREF, SLWSLO, STCOND, SWE, TAIRHR, TA,       !Input
& TMIN, TYPPGL, TYPPGN, WINDHR, XHLAI,          !Input
& XLMAXT, YLMAXT,                               !Input
& AGEFAC, EHR, LFMXSH, LFMXSL, PCNLSH, PCNLSL,    !Output
& PGHR, SLWSH, SLWSL, T0HR, TCAN, THR, TSHR,      !Output
& TSURF,                                         !Output
& CCNEFF, CICAD, CMXSF, CQESF, PGPATH)           !Input

```

**Declare photosynthetic pathway parameter variables in ETPHR**

```

CHARACTER PGPATH*2
REAL CCNEFF, CICAD, CMXSF, CQESF

```

**Add photosynthetic pathway parameters to CALL CANOPG statement**

```

CALL CANOPG(
& CO2HR, FNPGL, FNPGR, LAISH, LAISL, LMXREF, !Input
& LNREF, NSLOPE, PARSH, PARSUN, QEREF, RNITP, !Input
& SLAAD, SLWSLO, TMIN, TSURF, TYPPGL, TYPPGN, !Input
& XLMAXT, YLMAXT,                               !Input
& AGEFAC, CONDSH, CONDSL, CSHSTR, CSLSTR,      !Output
& LFMXSH, LFMXSL, PCNLSH, PCNLSL, PGHR,        !Output
& SLWREF, SLWSH, SLWSL, STRESS,                !Output
& CCNEFF, CICAD, CMXSF, CQESF, PGPATH)         !Input

```

**Add photosynthetic pathway parameters to SUBROUTINE CANOPG statement**

```

SUBROUTINE CANOPG(
& CO2HR, FNPGL, FNPGR, LAISH, LAISL, LMXREF,    !Input
& LNREF, NSLOPE, PARSH, PARSUN, QEREF, RNITP,    !Input
& SLAAD, SLWSLO, TMIN, TSURF, TYPPGL, TYPPGN,    !Input
& XLMAXT, YLMAXT,                               !Input
& AGEFAC, CONDSH, CONDSL, CSHSTR, CSLSTR,        !Output
& LFMXSH, LFMXSL, PCNLSH, PCNLSL, PGHR,          !Output
& SLWREF, SLWSH, SLWSL, STRESS,                 !Output
& CCNEFF, CICAD, CMXSF, CQESF, PGPATH)           !Input

```

**Declare photosynthetic pathway parameter variables in CANOPG**

CHARACTER PGPATH\*2  
 REAL CCNEFF, CICAD, CMXSF, CQESF

**Add photosynthetic pathway parameters to CALL PGLFEQ statement**

```
CALL PGLFEQ(
& CO2HR, FNPGL, FNPGRN, LMXREF, LNREF, QEREF,      !Input
& PCNLSH, SLWSH, SLWREF, TEMPSH, TMIN, TYPPGL,      !Input
& TYPPGN, XLMAXT, YLMAXT,                          !Input
& AGMXSH, LFMXSH, QEFSH,                          !Output
& CCNEFF, CICAD, CMXSF, CQESF, PGPATH)              !Input
```

```
CALL PGLFEQ(
& CO2HR, FNPGL, FNPGRN, LMXREF, LNREF, QEREF,      !Input
& PCNLSL, SLWSL, SLWREF, TEMPSL, TMIN, TYPPGL,      !Input
& TYPPGN, XLMAXT, YLMAXT,                          !Input
& AGMXSL, LFMXSL, QEFFSL,                          !Output
& CCNEFF, CICAD, CMXSF, CQESF, PGPATH)              !Input
```

**Add photosynthetic pathway parameters to CALL PGLEAF statement**

```
CALL PGLEAF(
& CO2HR, LFMXSL, PARSUN(I), QEFSL, TEMPSL,          !Input
& CONSUN, PGSUN,                                    !Output
& CCNEFF, CICAD, PGPATH)                            !Input
```

```
IF (I .EQ. 2) THEN
  PGSUM = PGSUM + PGSUN*1.6
  CONSUM = CONSUM + CONSUN*1.6
ELSE
  PGSUM = PGSUM + PGSUN
  CONSUM = CONSUM + CONSUN
ENDIF
ENDDO
PGSL = PGSUM / 3.6
CONDSL = CONSUM / 3.6
```

C    Compute photosynthesis and leaf CO<sub>2</sub> conductance for shaded leaves

```
CALL PGLEAF(
& CO2HR, LFMXSH, PARSH, QEFSH, TEMPSH,             !Input
& CONDSH, PGSH,                                    !Output
& CCNEFF, CICAD, PGPATH)                            !Input
```

**Add photosynthetic pathway parameters to SUBROUTINE PGLFEQ statement**

```
SUBROUTINE PGLFEQ(
& CO2HR, FNPGL, FNPGRN, LMXREF, LNREF, QEREF,      !Input
```

```

& RNITP, SLW, SLWREF, TEMPHR, TMIN, TYPPGL,      !Input
& TYPPGN, XLMAXT, YLMAXT,                        !Input
& AGEMXL, LFMAX, QEFF,                          !Output
& CCNEFF, CICAD, CMXSF, CQESF, PGPATH)          !Input
IMPLICIT NONE

```

### Declare photosynthetic pathway parameter variables in PGLFEQ

```

CHARACTER PGPATH*2
REAL CCNEFF, CICAD, CMXSF, CQESF

```

### Adjust TAU for CO<sub>2</sub> concentrating effect in C4's

```

IF (RT .GT. 1000.) THEN
  IF (PGPATH .EQ. "C3" .OR. PGPATH .EQ. "c3") THEN
    TAU = EXP(-3.949 + 28990.0/RT)
  ELSE
    TAU = EXP(-3.949 + 28990.0/RT) * CCNEFF
  ENDIF
  GAMST = 0.5 * O2 / TAU
ELSE
  TAU = 1E10
  GAMST = 0.0
ENDIF

```

### Rescale CO2MAX for C4's, including changing CICA to 0.4 (set in species file).

```

IF (PGPATH .EQ. "C3" .OR. PGPATH .EQ. "c3") THEN
  CICA = 0.7
  CINT = CICA*CO2HR + (1.0-CICA)*GAMST
  CINT = MAX(CINT,GAMST)
  CO2MAX = 7.179 * (CINT-GAMST) / (4.0*CINT+8.0*GAMST)
ELSE
  CICA = CICAD
  CINT = CICA*CO2HR + (1.0-CICA)*GAMST
  CINT = MAX(CINT,GAMST)
  CO2MAX = CMXSF * (CINT-GAMST) / (4.0*CINT+8.0*GAMST)
ENDIF

```

### Rescale CO2QE for C4's, including changing CICA to 0.4 (set in species file).

```

CINT = MAX(CO2HR,GAMST)
IF (PGPATH .EQ. "C3" .OR. PGPATH .EQ. "c3") THEN
  CO2QE = 6.225 * (CINT-GAMST) / (4.*CINT+8.*GAMST)
ELSE
  CO2QE = CQESF * (CINT-GAMST) / (4.*CINT+8.*GAMST)
ENDIF

```

### Add photosynthetic pathway parameters to SUBROUTINE PGLEAF statement

```

SUBROUTINE PGLEAF(
& CO2HR, LFMAX, PARLF, QEFF, TEMPHR,          !Input
& CONDLF, PGLF,                                !Output
& CCNEFF, CICAD, PGPATH)                      !Input

```

**Declare photosynthetic pathway parameter variables in PGLEAF**

```

CHARACTER PGPATH*2
REAL CCNEFF, CICAD

```

**Adjust TAU for CO<sub>2</sub> concentrating effect in C4's**

```

IF (RT .GT. 1000.) THEN
  IF (PGPATH .EQ. "C3" .OR. PGPATH .EQ. "c3") THEN
    TAU = EXP(-3.9489 + 28990.0/RT)
  ELSE
    TAU = EXP(-3.9489 + 28990.0/RT) * CCNEFF
  ENDIF
  GAMST = 1.0E6 * 0.5 * 0.21 / TAU
ELSE
  TAU = 1E10
  GAMST = 0.0
ENDIF

```

**Adjust CICA to 0.4 (set in species file) for other than C3's.**

```

C  CICA = 0.4+0.6*EXP(-0.002*CO2HR)
  IF (PGPATH .EQ. "C3" .OR. PGPATH .EQ. "c3") THEN
    CICA = 0.7
  ELSE
    CICA=CICAD
  ENDIF
  CINT = CICA*CO2HR + (1.0-CICA)*GAMST
  CCO2LF = MAX(PNLF/(CO2HR-CINT),0.0)

```



**MODULE: FREEZE.FOR****Add storage parameters to SUBROUTINE FREEZE statement**

```

SUBROUTINE FREEZE(FILEIO, RUN,
&  FREEZ1, FREEZ2, IDETO, NOUTDO, NRUSLF, SLDOT,  !Input
&  TMIN, WTLF, YRDOY, YRPLT,                    !Input
&  MDATE,                                       !Input/Output
&  WLFDOT,
      !Output
&  FRZDC, NRUSSR, NRUSST, PSRSRFL, PSRLYR1,      !Input
&  SRFTEMP, SSDOT, SSRDOT, ST, STMWT, STRWT,    !Input

&  PSRLYRD, PSRSRFD, WSFDOT, WSRFDOT,          !Output

&  FRZDL, SRLYRD, SRSRFD, VSTAGE)              !Output

```

**Add USE ModuleDefs statement for access to array size of ST (soil temperature by layer)**

```

USE ModuleDefs  !Definitions of constructed variable types,

```

**Declare storage variables**

```

REAL FRZDC, FRZDL, NRUSSR, NRUSST, PSRSRFL, PSRLYR1, SRSRFD,
&  PSRLYRD, SRLYRD, SRFTEMP, SRSRFD, SSRDOT, SSDOT, STMWT,
&  STRWT, VSTAGE, WSFDOT, WSRFDOT
REAL, DIMENSION(NL) :: ST

```

**Test for and calculate freeze-damage to above and below ground portions of storage organ and sum for total storage organ damage. Set MDate to 0.0 if total freeze kill of storage organ.****Set storage organ freeze damage variables to 0.0, part of abandoned strategy to allow partial to total kill of the storage organ. Plant would live as long as there was storage organ left. May want to revisit this if modeling alfalfa.**

```

WSRFDOT = 0.0

```

```

PSRSRFD = 0.0

```

```

PSRLYRD = 0.0

```

**Calculate freeze damage to above ground plant mass. Is a progressive function, the colder it gets, the more of the plant dies. Reset VSTAGE accordingly.**

```

C-----
C      Calculate proportion of above-ground plant mass that will
C      be lost to frost. Function of number of degrees below threshold
C      temperature multiplied by the proportion lost per degree below
C      threshold. For total kill (like DSSAT35) set FRZDC=1.0

```

```

C-----
FRZDL = (FREEZ1 - TMIN) * FRZDC
FRZDL = MAX(FRZDL,0.0)

WLFDOT = (WTLF - SLDOT - NRUSLF/0.16) * FRZDL
WLFDOT = MIN ((WTLF - SLDOT - NRUSLF/0.16), WLFDOT)

C-----
C    SJR 5/12/04 Moved VSTAGE adjustment to GROW
C    to be compatible with adjustment for senescence
C-----
!          VSTAGE = ((WTLF-WLFDOT)/WTLF) * VSTAGE

WSFDOT = (STMWT - SSDOT - NRUSST/0.16) * FRZDL
WSFDOT = MIN ((STMWT - SSDOT - NRUSST/0.16), WSFDOT)

If TMIN < FREEZ2, then kill the plant and end the simulation
      IF (TMIN .LE. FREEZ2) THEN
        IF (MDATE .LT. 0) THEN
          MDATE = YRDOY
        ENDIF

        WLFDOT = WTLF - SLDOT - NRUSLF/0.16

C-----
C    SJR 5/12/04 Moved VSTAGE adjustment to GROW
C    to be compatible with adjustment for senescence
C-----
!          VSTAGE = 0.0
          WSFDOT = STMWT - SSDOT - NRUSST/0.16

      ENDIF

```

**List storage variables at end of subroutine**

```

! FRZDC      Freezing death coefficient - percentage tissue/population death per day
per degree below FREEZ2
! FRZDL      Todays death loss of storage tissue/plant population due to freezing
(proportion of STRWT and PLNTPOP)
! NRUSSR N    actually mobilized from storage organ in a day (g[N]/m2-d)
! NRUSST N    actually mobilized from stems in a day (g[N]/m2-d)
! PSRLYRD     Proportion of total storage organ tissue loss from below ground tissue
! PSRLYR1     Proportion of storage organ tissue in soil layer 1 (below soil surface)
! PSRSRFD     Proportion of total storage organ tissue loss from above ground tissue
! PSRSRFL     Proportion of storage organ tissue on/above soil surface
! SRFTEMP     Temperature of soil surface (degrees C)

```

! SRLYRD    Freeze damage to below ground storage organ tissue  
! SRSRFD   Freeze damage to above ground storage organ tissue  
! SSDOT    Stem loss due to daily senescence (g/m<sup>2</sup>/day)  
! SSRDOT   Storage organ loss due to daily senescence (g/m<sup>2</sup>/day)  
! ST(I)    Temperature in soil layer (I) (degrees C)  
! STMWT    Dry mass of stem tissue, including C and N (g[stem] / m<sup>2</sup>[ground])  
! VSTAGE    Number of nodes on main stem of plant  
! WSFDOT   Stem weight losses due to freezing (g[stem]/m<sup>2</sup>-d)  
! WSRFDOT   Storage organ weight losses due to freezing (g[storage]/m<sup>2</sup>-d)

C-----

C New storage variables for forage model

```
C-----
      REAL CADSR, CRUSSR, FRSTR, NADSR, NGRSR, NRUSSR,
& SSRDOT, SSRNDOT, WSRDOTN, WSRIDOT,
& WSRDOT, WSRFDOT,

& CSRW, PCNSR, PLIGSR, RHOSR, STRWT, WCRSR,
& WNRSR, WTNSR, WTNSRA, WTNSRO, WTSRO,

& CPFSTR, NSRDOT, ALPHSR,
& PCARSR, PLIPSR, PMINSR, POASR, PROSRI, PROSRF,
& WSRI, WRCSTRDT, NSROFF, NSRALL,
& PSRLYRD, PSRSRFD, PSRSRFL, PSRLYR1, STRSRFL,
& STRLYR1, TPSRSRFL, TPSRLYR1
```

C-----  
C New shell and root variables for N accounting

```
C-----
      REAL CADRT, CADSH, NADSH
```

C-----  
C New stem freeze damage variables for forage model

```
C-----
      REAL WSFDOT
```

C-----  
C VSTAGE for adjustment due to senescence and freeze damage

```
C-----
      REAL VSTAGE
```

### Add storage variables tot the CALL IPGRO statement

```
CALL IPGROW(
& FILEIO, FILECC, FILEGC, CROP,                !Input
& ALPHL, ALPHR, ALPHS, ALPHSH,                !Output
& PCARLF, PCARST, PCARRT, PCARSH, PCARSD, PCARNO, !Output
& PLIGLF, PLIGST, PLIGRT, PLIGSH, PLIGSD, PLIGNO, !Output
& PLIPLF, PLIPST, PLIPRT, PLIPSH,              PLIPNO, !Output
& PMINLF, PMINST, PMINRT, PMINSH, PMINSO, PMINNO, !Output
& POALF, POAST, POART, POASH, POASD, POANO,    !Output
& PROLFF, PROSTF, PRORTF, PROSHF,              PRONOD, !Output
& PROLFI, PROSTI, PRORTI,                      !Output
& PLTPOP, ROWSPC, RMIN, PLME, SDWTPL,          !Output
& SDLIP, SDPRO, WTFSD, WTPSD, XPODF,           !Output
& ALPHSR, PCARSR, PLIGSR, PLIPSR, PMINSR, POASR, !Output
& PROSRF, PROSRI)                             !Output
```

### Calculate net respiration requirement for net storage organ tissue growth

$CPFSTR = 30./44. * (PLIPSR * 1.720 + PLIGSR * 0.659 + POASR * (-0.011))$

& + PMINSR\*RMIN + PCARSR\*0.170)

#### Initialize storage variables

CSRW= 0.0 !Cumulative storage organ growth  
 NSRDOT = 0.0  
 PCNSR = 0.0  
 RHOSR = 0.0  
 STRWT = 0.0  
 WCRSR = 0.0  
 WNRSR = 0.0  
 WTNSR = 0.0  
 WTNSRA = 0.0  
 WTNSRO = 0.0  
 WTSRO = 0.0  
 WSFDOT = 0.0  
 WSRDOT = 0.0  
 WSRFDOT= 0.0

#### Calculate initial storage tissue weight for transplants

TOPWT = WTLF + STMWT  
 STRWT = FRSTR \* TOTWT  
 RTWT = TOTWT - TOPWT - STRWT  
 WSRI = STRWT

#### Initialize cumulative storage mass

CSRW = STRWT

#### Initialize storage tissue CH<sub>2</sub>O reserves

WCRSR = ALPHSR \* STRWT

#### Carbohydrate composition of storage tissue (fraction)

RHOSR = ALPHSR

#### Initialize net carbon addition for storage tissue

WRCSRDT= 0.0

#### Compute N in storage tissue

WTNSR = WSRTI \* PROSRI \* 0.16  
 WTNTOT = WTNLF + WTNST + WTNRT + WTNSH + WTNSD + WTNSR

#### Calculate seed or transplant N at planting

SDNPL = WTPSD \* SDPRO \* 0.16 \* 0.75 \* PLTPOP -  
 & (WTNLF + WTNST + WTNRT + WTNSR)  
 SDNPL = MAX(SDNPL,0.0)  
 SEEDNI = WTNLF + WTNST + WTNRT + SDNPL + WTNSR

Initialize cumulative N variable for storage tissue

WTNSRA = WTNSR

Percent N in storage tissue

PCNSR = WTNSR / WSRI \* 100

Begin daily integration stepsAdd storage dry weight growth rate to total plant growth rate

GROWTH = WLDOTN + WSDOTN + WRDOTN + WSHDTN + WSDDTN +  
NODGR

& + WSRDOTN

GRWRES = WLDOTN\*CPFLF + WSDOTN\*CPFSTM + WRDOTN\*CPFRT +

& NODGR\*CPFNOD + WSHDTN\*CPFH1 + WSDDTN\*CPFSD1 +

& WSRDOTN\*CPFSTR +

& 30./44\*(TRNO3U/0.16 \* 1.798 + TRNH4U/0.16 \* 0.462 +

& NFIXN/0.16 \* 1.798)

Calculate stem tissue net growth rate including freeze losses

C-----

C WSDOT = Net stem growth rate

C-----

WSDOT = WSDOTN - SSDOT - WSIDOT - WSFDOT - NRUSST / 0.16 - CRUSST

IF (STMWT .GT. 0.0) THEN

WSDOT = WSDOT + (CADST+NADST/0.16) \*

& (1. - MIN(1.0,(SSDOT+WSIDOT+WSFDOT)/STMWT))

ENDIF

IF (WSDOT .LT. 0.0) THEN

WSDOT = MAX(WSDOT, -STMWT)

ENDIF

Calculate storage tissue net growth rate and new proportions of above and below ground storage organ tissue

C-----

C WSRDOT = Net storage tissue growth rate

C-----

WSRDOT = WSRDOTN - SSRDOT - WSRIDOT - WSRFDOT - NRUSSR /

& 0.16 - CRUSSR

IF (STRWT .GT. 0.0) THEN

WSRDOT = WSRDOT + (CADSR+NADSR/0.16) \*

& (1. - MIN(1.0,(SSRDOT+WSRIDOT+WSRFDOT)/STRWT))

ENDIF

IF (WSRDOT .LT. 0.0) THEN

WSRDOT = MAX(WSRDOT, -STRWT)

ENDIF

```

C-----
C   Allocate net growth to above and below ground storage organ tissue
C   using initial partitioning strategy from species file.
C   Allocate freeze losses according to the proportions calculated in FREEZE
C   Allocate all other losses using current "actual" proportions.
C   If losses for one portion are greater than available mass
C   the excess loss is taken from the other portion
C   NOTE: using TPSRLYR1 and TPSRSRFL to hold intermediate values for
C   themselves before calculating actual new proportions.
C-----

```

```

TPSRLYR1 = (WSRDOTN * STRLYR1) - (SSRDOT + WSRIDOT + NRUSSR / .16
&          + CRUSSR) * PSRLYR1 - WSRFDOT * PSRLYRD

```

```

TPSRSRFL = (WSRDOTN * STRSRFL) - (SSRDOT + WSRIDOT + NRUSSR / .16
&          + CRUSSR) * PSRSRFL - WSRFDOT * PSRSRFD

```

```

IF (STRWT .GT. 0.0) THEN
  WSRDOT = WSRDOT + (CADSR+NADSR/0.16) *
& (1. - MIN(1.0,(SSRDOT+WSRIDOT+WSRFDOT)/STRWT))

```

```

  TPSRLYR1 = TPSRLYR1 + (CADSR+NADSR/0.16) *
& (1. - MIN(1.0,(SSRDOT+WSRIDOT+WSRFDOT)/STRWT))*STRLYR1

```

```

  TPSRSRFL = TPSRSRFL + (CADSR+NADSR/0.16) *
& (1. - MIN(1.0,(SSRDOT+WSRIDOT+WSRFDOT)/STRWT))*STRSRFL

```

```

C-----
C   Check to make sure not losing more mass from above or below ground
C   portions than exist in each. If so, allocate excess loss to the
C   other portion. If total loss is more than storage organ mass,
C   limit loss to actual mass of storage organ present
C   NOTE: must be done even when net gain is positive because freeze
C   damage could result in a net loss of above ground tissue and a net
C   gain of total and below ground tissue.
C-----

```

```

IF (-TPSRSRFL .GE. STRWT*PSRSRFL) THEN
  TPSRLYR1 = TPSRLYR1 + (TPSRSRFL+(STRWT*PSRSRFL))

```



```

TPSRSRFL = -STRWT * PSRSRFL
  IF (-TPSRLYR1 .GE. STRWT*PSRLYR1) THEN
    TPSRLYR1 = -STRWT * PSRLYR1
    TPSRSRFL = -STRWT * PSRSRFL
  ENDIF
ENDIF

  IF (-TPSRLYR1 .GE. STRWT*PSRLYR1) THEN
    TPSRSRFL = TPSRSRFL + (TPSRLYR1+(STRWT*PSRLYR1))
    TPSRLYR1 = -STRWT * PSRLYR1
    IF (-TPSRSRFL .GE. STRWT*PSRSRFL) THEN
      TPSRLYR1 = -STRWT * PSRLYR1
      TPSRSRFL = -STRWT * PSRSRFL
    ENDIF
  ENDIF

ENDIF
ENDIF

```

```

IF (WSRDOT .LT. 0.0) THEN
  WSRDOT = MAX(WSRDOT, -STRWT)
ENDIF

```

```

C-----
C   Calculate proportions of below and above ground storage organ
C   tissue at end of day - with new growth and losses.
C   Still need current days proportions for allocating senesced
C   nutrients to appropriate soil layers for CENTURY
C-----
  TPSRLYR1 = (TPSRLYR1 + (STRWT*PSRLYR1))/(STRWT+ WSRDOT)
  TPSRSRFL = (TPSRSRFL + (STRWT*PSRSRFL))/(STRWT+ WSRDOT)

```

### Calculate root tissue net growth rate – including returning N/CH<sub>2</sub>O from excess N mobilization

```

C-----
C   Net root growth rate
C-----
  WRDOT = WRDOTN - SRDOT - NRUSRT/0.16 - CRUSRT - WRIDOT
  IF (RTWT .GT. 0.0) THEN
    WRDOT = WRDOT + (CADRT + NADRT/0.16) *
& (1. - MIN(1.0,(SRDOT+WRIDOT)/RTWT))
  ENDIF
  IF (WRDOT .LT. 0.0) THEN
    WRDOT = MAX(WRDOT, -RTWT)
  ENDIF

```

ENDIF

**Calculate shell tissue net growth rate – including returning N/CH<sub>2</sub>O from excess n mobilization**

```

C-----
C   Net shell growth rate
C-----
  WSHIDT = MIN(WSHIDT,SHELWT)  ! pest damage to shells
  WSHDOT = WSHDTN - WSHIDT - WTABRT - NRUSSE / 0.16 - CRUSSE
  IF (SHELWT .GT. 0.0) THEN
    WSHDOT = WSHDOT + (CADSH + NADSH/0.16) *
    & (1. - MIN(1.0,WTABRT/RTWT))
  ENDIF

```

**Calculate total net plant growth rate**

WDOT = WLDOT + WSDOT + WRDOT + WPDOT + WNDOT + WSRDOT

**Reduce VSTAGE by proportion of WTLF lost due to freezing**

```

C-----
C   Integration, Add Today's Net Growth to Existing Weights
C-----
C-----
C   SJR 5/12/04 reduce VSTAGE for forage model
C   Lower VSTAGE for leaf lost to freezing
C-----
  IF ((SLDOT + WLDOT) .GE. WTLF) THEN
    VSTAGE=0.0
  ELSE
C   SJR 5/19/04 - drop leaf loss due to senescence - per discussion
C   with KJB - decided that it was a bad idea
    !   VSTAGE = ((WTLF-(SLDOT+WLFDOT))/WTLF) * VSTAGE
    VSTAGE = ((WTLF-WLFDOT)/WTLF) * VSTAGE
  ENDIF

```

**Integrate- add today's storage tissue growth to existing mass**

STRWT = STRWT + WSRDOT

**Calculate cumulative storage tissue growth**

CSRW= CSR + WSRDOTN

**Carbon Reserve accounting – NOTE: Originally noticed that WLDOTN was used in calculating WRCLDT but WSDOT, WSHDOT, and WRDOT used for calculating Net C addition to other organs – changed code to use WSDOTN, WSHDTN, and WRDOTN and WSRDOTN - changed back after discussions with Dr. Boote (8/7/03) – Plants did not recover from freeze (70 kg N ha<sup>-1</sup>) switched back to using**

the “N” values. Also changed SLNDOT, SSNDOT, and SSRNDOT (senescence due to water stress) to SLDOT (daily senescence – includes the “N” senescence).

```

C-----
C   Carbon Reserves: Net Growth Rates for Mobile Carbohydrates
C-----
C   Account for N added to existing plant tissue, e.g., NADLF, that
C   is damaged by insects, freezing, or senesced. Otherwise, could
C   get increase in tissue N composition when tissue is aborted. Need
C   to account for mass, N and C lost this way in sections below
C   Original code commented out
C-----
!   WRCLDT = ALPHL * WLDOTN - CRUSLF -
RHOL*(SLNDOT+WLIDOT+WLFDOT)
   WRCLDT = ALPHL * WLDOTN - CRUSLF -
RHOL*(SLDOT+WLIDOT+WLFDOT)
   IF (WTLF .GT. 0.0) THEN
     WRCLDT = WRCLDT + CADLF *
&   (1. - MIN(1.0,(SLDOT+WLIDOT+WLFDOT)/WTLF))
   ENDIF

C-----
C   Original code commented out
C   Appears to be double accounting for C in new C reserves in stem
C   Changed WSDOT to WSDOTN to fix this/be consistent with leaf code
C
C-----
!   WRCSDT = ALPHS * WSDOT - CRUSST - RHOS * SSNDOT
   WRCSDT = ALPHS * WSDOTN - CRUSST - RHOS *
(SSDOT+WSFDOT+WSIDOT)
   IF (STMWT .GT. 0.0) THEN
     WRCSDT = WRCSDT + CADST *
&   (1. - MIN(1.0,(SSDOT+WSIDOT+WSFDOT)/STMWT))
   ENDIF

!   WRCSRDT = ALPHSR * WSRDOT - CRUSSR - RHOSR * (SSRNDOT
!   &           +WSRIDOT + WSRFDOT)

   WRCSRDT = ALPHSR * WSRDOTN - CRUSSR - RHOSR * (SSRDOT
&           +WSRIDOT + WSRFDOT)
   IF (STRWT .GT. 0.0) THEN
     WRCSRDT = WRCSRDT + CADSR *
&   (1. - MIN(1.0,(SSRDOT+WSRIDOT+WSRFDOT)/STRWT))
   ENDIF

!   WRCRDT = ALPHR * WRDOT - CRUSRT - RHOR * SRDOT

```

```

WRCRDT = ALPHR * WRDOTN - CRUSRT - RHOR * (SRDOT + WRIDOT)
!   WRCSHD = ALPHSH * WSHDOT - CRUSSH -
RHOSH*(WTABRT+WTSHMT+WSHIDT)
WRCSHD = ALPHSH * WSHDTN - CRUSSH -
RHOSH*(WTABRT+WTSHMT+WSHIDT)

```

#### Update C storage in storage tissues

```
WCRSR = WCRSR + WCRSRDT
```

```
IF (WCRSR .LE. 1.0E-30) WCRSR = 0.0
```

#### Compute cumulative C lost from stem & storage tissue over the season

```
WTSRO = WTSRO + SSRDOT + WSRIDOT + WSRFDOT
WTSO = WTSO + SSDOT + WSIDOT + WSFDOT
```

#### Compute CH<sub>2</sub>O fraction of storage tissue

```
IF (STRWT .GT. 0.0001) THEN
  RHOSR = WCRSR/STRWT
ELSE
  RHOSR = 0.0
ENDIF
```

#### Change calculation of net growth rate of N in shell tissue to include excess mobilized N returned to shell.

```

C-----
C   Net growth rate of nitrogen in shells
C-----
NSHDOT = NGRSH - NSHOFF - NRUSSH
IF (SHELWT .GT. 0.0) THEN
  NSHDOT = NSHDOT + NADSH *
&      (1. - MIN(1.0,(WTABRT+WSHIDT) / SHELWT))
ENDIF

```

#### Calculate stem tissue N balance

```

C-----
C   Stem nitrogen senescence and pest damage loss
C-----
NSOFF = (SSNDOT+WSIDOT+WSFDOT) * (PCNST/100.) + (SSDOT -
SSNDOT)
&      * PROSTF * 0.16
IF (NSOFF .LT. 0.0) THEN
  NSOFF = 0.0
ENDIF

```

```
C-----
```

C Net growth rate of nitrogen in the stems

```
C-----
NSDOT = NGRST - NSOFF - NRUSST
IF (STMWT .GT. 0.0) THEN
  NSDOT = NSDOT + NADST *
&      (1. - MIN(1.0,(SSDOT+WSIDOT+WSFDOT) / STMWT))
ENDIF
```

### Calculate storage tissue N balance

```
C-----
C Storage tissue nitrogen senescence and pest damage loss
C Using different strategy - Stolon not abscised like leaf
C therefore, are assuming senesced tissue lost at average
C N concentration
C-----
! NSROFF = (SSRNDOT + WSRIDOT + WSRFDOT) * (PCNSR/100.) +
! & (SSRDOT-SSRNDOT) * PROSRF * 0.16
NSROFF = (SSRDOT + WSRIDOT + WSRFDOT) * (PCNSR/100.)
IF (NSROFF .LT. 0.0) THEN
  NSROFF = 0.0
ENDIF
```

C-----  
C Net growth rate of nitrogen in the storage tissues

```
C-----
NSRDOT = NGRSR - NSROFF - NRUSSR
IF (STRWT .GT. 0.0) THEN
  NSRDOT = NSRDOT + NADSR *
& (1. - MIN(1.0,(SSRDOT + WSRIDOT + WSRFDOT) / STRWT))
ENDIF
```

C-----  
C Total nitrogen in the storage tissues

```
C-----
IF ((NSRDOT .LT. 0.0) .AND. (ABS(NSRDOT) .GT. WTNSR)) THEN
  NSRDOT = - WTNSR
ENDIF
WTNSR = WTNSR + NSRDOT
```

C-----  
C Total nitrogen in the plant

```
C-----
WTNTOT = WTNLF + WTNST + WTNSR + WTNRT + WTNSH + WTNSD +
WTNNOD
```

### Compute cumulative N added to stem tissues over the season

```

!   Stem
    NSALL = NGRST - NRUSST
    IF (STMWT .GT. 0.0) THEN
        NSALL = NSALL + NADST *
&          (1. - MIN(1.0,(SSDOT+WSIDOT+WSFDOT) / STMWT))
    ENDIF

```

#### Compute cumulative N added to storage tissues over the season

```

!   Storage tissues
    NSRALL = NGRSR - NRUSSR
    IF (STRWT .GT. 0.0) THEN
        NSRALL = NSRALL + NADSR *
&          (1. - MIN(1.0,(SSRDOT + WSRIDOT + WSRFDOT)
&                    / STRWT))
    ENDIF

```

#### Compute cumulative N added to shell tissues over the season

```

!   Shell and seed
    NSHALL = NGRSH - NRUSSH
C-----
C      Added these lines after adding NADSH variable
C-----

    IF (SHELWT .GT. 0.0) THEN
        NSHALL = NSHALL + NADSH *
&          (1. - MIN(1.0,(WTABRT+WSHIDT) / SHELWT))
    ENDIF

```

#### Compute cumulative N added to storage tissues over the season

```

    WTNSRA = WTNSRA + NSRALL

```

#### Compute cumulative N loss from storage tissues over the season

```

    WTNSRO = WTNSRO + NSROFF

```

#### Compute percentage N in storage tissues

```

    IF ((STRWT .GT. 0.0) .AND. (STRWT .GT. WTNSR) .AND.
&      (WTNSR .GT. 0.0)) THEN
        PCNSR = WTNSR / STRWT * 100.0
    ELSE
        PCNSR = 0.0
    ENDIF

```

#### Calculate remaining N in storage tissues that can be mined

```

    IF ((STRWT - WCRSR) .GT. 0.0) THEN
        WNSR = MAX (WTNSR - PROSRF * 0.16 * (STRWT-WCRSR), 0.0)
    ELSE

```

```

WNRSR = 0.0
ENDIF

```

### Distribute senesced storage tissue C to soil surface and soil layer 1 C pools

```

C-----
C   This section added to provide senescence parameters to the
C   Soil N routines (senescence and freeze values are added to soil
C   residue; pest damage components are lost from the system)
C-----
C   Surface carbon includes all senescence and freeze variables for
C   leaf (SLDOT, WLFDOT), stem (SSDOT), storage organ (SSRDOT, WSRFDOT)
C   and shell (WTABRT). At this time, the model does not senesce seed.
C   Convert from biomass to C with a factor 0.40.
C   NOTE storage organ senescence is apportioned to both surface layer
C   and soil layer1 according to proportions PSRSRFD and PSRLYRD from
FREEZE
C-----
!   SENCLN(0,1) = (SLDOT + WLFDOT + SSDOT + WTABRT) * 0.40
    SenWt(0) = (SLDOT + WLFDOT + SSDOT + WSFDOT + WTABRT +
&             SSRDOT * PSRSRFL) + WSRFDOT * PSRSRFD
C   Convert from g/m2 to kg/ha with a factor of 10.
!   SENCLN(0,1) = AMAX1(SENCLN(0,1), 0.) * 10.0   !kg[C]/ha
    SenWt(0) = AMAX1(SenWt(0), 0.) * 10.0   !kg[dry matter]/ha

C-----
C   Surface nitrogen includes nitrogen losses computed above minus the
C   pest damage components.
C-----
!   SENCLN(0,3) = (NLOFF - WLIDOT * PCNL / 100.) +
    SenE(0,1) = (NLOFF - WLIDOT * PCNL / 100.) +                !Leaf
&             (NSOFF - WSIDOT * PCNST / 100.) +                !Stem
&             (NSHOFF - WSHIDT * PCNSH / 100.) +                !Shell
&             (NSROFF - (WSRIDOT + WSRFDOT) * PCNSR /
100.*PSRSRFL)
&             + WSRFDOT * PCNSR / 100 * PSRSRFD
    !Storage
C   Convert from g/m2 to kg/ha with a factor of 10.
!   SENCLN(0,3) = AMAX1 (SENCLN(0,3),0.) * 10.0   !kg[N]/ha
    SenE(0,1) = AMAX1 (SenE(0,1),0.) * 10.0   !kg[N]/ha

C-----
C   Contribution of lignin to surface litter from senesced and frozen
C   plant matter
C-----
!   SENCLN(0,2) = (SLDOT + WLFDOT) * PLIGLF + SSDOT * PLIGST +
    SenLig(0) = (SLDOT + WLFDOT) * PLIGLF + (SSDOT+WSFDOT) * PLIGST +

```

```

      & WTABRT * PLIGSH + (SSRDOT*PSRSRFL + WSRFDOT*PSRSRFD)*
      PLIGSR
C   Convert from g/m2 to kg/ha with a factor of 10.
!   SENCLN(0,2) = AMAX1 (SENCLN(0,2),0.) * 10.0      !kg[lig]/ha
      SenLig(0) = AMAX1 (SenLig(0),0.) * 10.0      !kg[lig]/ha

C-----
C   Senescence of roots, nodules, and subsurface storage organs (kg/ha)
C-----
      DO L = 1, NLAYR
        IF L=1 THEN
          !   SENCLN(L,1) = (SENRT(L) + SENNOD(L)) * 0.40 !kg[C]/ha
          SenWt(L) = SENRT(L) + SENNOD(L)+
          & (SSRDOT*PSRLYR1 + WSRFDOT*PSRLYRD)
          !kg[dry matter]/ha
          !   SENCLN(L,2) = SENRT(L) * PLIGRT + SENNOD(L) * PLIGNO !kg[lig]/ha
          SenLig(L) = SENRT(L) * PLIGRT + SENNOD(L) * PLIGNO +
          & (SSRDOT*PSRLYR1 + WSRFDOT*PSRLYRD)*
          PLIGSR      !kg[lig]/ha
          !   SENCLN(L,3) = (SENRT(L)* PRORTF + SENNOD(L) * PRONOD) * 0.16
          SenE(L,1) = (SENRT(L)* PRORTF + SENNOD(L) * PRONOD) * 0.16 +
          & (NSROFF- (WSRIDOT + WSRFDOT) * PCNSR /
          100.*PSRLYR1)
          & + WSRFDOT * PCNSR / 100 * PSRLYRD
        ELSE
          !   SENCLN(L,1) = (SENRT(L) + SENNOD(L)) * 0.40 !kg[C]/ha
          SenWt(L) = (SENRT(L) + SENNOD(L))      !kg[dry matter]/ha
          !   SENCLN(L,2) = SENRT(L) * PLIGRT + SENNOD(L) * PLIGNO !kg[lig]/ha
          SenLig(L) = SENRT(L) * PLIGRT + SENNOD(L) * PLIGNO !kg[lig]/ha
          !   SENCLN(L,3) = (SENRT(L)* PRORTF + SENNOD(L) * PRONOD) * 0.16
          SenE(L,1) = (SENRT(L)* PRORTF + SENNOD(L) * PRONOD) * 0.16
        ENDIF
      ENDDO

```

#### Update PSRSRFL and PSRLYR1 to reflect today's growth and losses

```

C-----
C   Update distribution of storage tissue above and below soil surface
C-----
      PSRLYR1 = TPSRLYR1
      PSRSRFL = TPSRSRFL

```

#### Add line to prevent AREALF (and XLAI) from going below 0.0

```

      AREALF = AREALF + ALFDOT

C-----
C   New line for Forage model to prevent negative LAI's in winter

```



C-----

AREALF = MAX(AREALF, 0.0)

**Add condition that plant cannot die if there is storage tissue left**

C-----

C Terminate growth if stress causes extremely low plant weights

C-----

```

      IF (STRWT .LT. 0.00001) THEN
        IF (TOPWT .LT. 0.00001 .OR. STMWT .LT. 0.00001) THEN
          CALL STRESS(FILEIO, RUN,
&   AGEFAC, DWNOD, IDETO, IHARI, NOUTDO, PODWT,   !Input
&   RTWT, SDWT, SHELWT, STMWT, TOPWT,           !Input
&   TOTWT, TURFAC, WTLF, YRDOY, YRPLT,          !Input
&   MDATE,                                     !Output
&   STRWT)                                     !Input
          RETURN
        ENDIF

        IF (IHARI .NE. 'R' .AND. IHARI .NE. 'D') THEN
          IF (RTWT .LT. 0.00001 .OR. WTLF .LT. 0.00001) THEN
            CALL STRESS(FILEIO, RUN,
&   AGEFAC, DWNOD, IDETO, IHARI, NOUTDO, PODWT,   !Input
&   RTWT, SDWT, SHELWT, STMWT, TOPWT,           !Input
&   TOTWT, TURFAC, WTLF, YRDOY, YRPLT,          !Input
&   MDATE,                                     !Output
&   STRWT)                                     !Input
            RETURN
          ENDIF
        ENDIF
      ENDIF

```

**Add STRWT to the CALL STRESS statement**

```

SUBROUTINE STRESS(FILEIO, RUN,
& AGEFAC, DWNOD, IDETO, IHARI, NOUTDO, PODWT,   !Input
& RTWT, SDWT, SHELWT, STMWT, TOPWT,           !Input
& TOTWT, TURFAC, WTLF, YRDOY, YRPLT,          !Input
& MDATE,                                     !Output
& STRWT)                                     !Input

```

**Add STRWT to the SUBROUTINE STRESS statement**

```

SUBROUTINE STRESS(FILEIO, RUN,
& AGEFAC, DWNOD, IDETO, IHARI, NOUTDO, PODWT,   !Input
& RTWT, SDWT, SHELWT, STMWT, TOPWT,           !Input
& TOTWT, TURFAC, WTLF, YRDOY, YRPLT,          !Input

```

```

& MDATE, !Output
& STRWT) !Input

```

### Declare STRWT REAL

```
REAL STRWT
```

### Prevent reported STRWT from being below 0

```
STRWT = MAX(0.,STRWT)
```

### Add Storage parameters to the IPGROW SUBROUTINE statement

```

SUBROUTINE IPGROW(
& FILEIO, FILECC, FILEGC, CROP, !Input
& ALPHL, ALPHR, ALPHS, ALPHSH, !Output
& PCARLF, PCARST, PCARRT, PCARSH, PCARSD, PCARNO, !Output
& PLIGLF, PLIGST, PLIGRT, PLIGSH, PLIGSD, PLIGNO, !Output
& PLIPLF, PLIPST, PLIPRT, PLIPSH, PLIPNO, !Output
& PMINLF, PMINST, PMINRT, PMINSH, PMINSR, PMINNO, !Output
& POALF, POAST, POART, POASH, POASD, POANO, !Output
& PROLFF, PROSTF, PRORTF, PROSHF, PRONOD, !Output
& PROLFI, PROSTI, PRORTI, !Output
& PLTPOP, ROWSPC, RMIN, PLME, SDWTPL, !Output
& SDLIP, SDPRO, WTFSD, WTPSD, XPODF, !Output
& ALPHSR, PCARSR, PLIGSR, PLIPSR, PMINSR, POASR, !Output
& PROSRF, PROSRI) !Output

```

### Declare storage parameters REAL

```

REAL ALPHSR, PCARSR, PLIGSR, PLIPSR, PMINSR, POASR,
& PROSRF, PROSRI

```

### Read Storage tissue composition parameter values

```

CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(F6.0, 6X, F6.0)',IOSTAT=ERR)
& PROSRI, PROSRF
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(5F6.0)',IOSTAT=ERR)
& PCARSR, PLIPSR, PLIGSR, POASR, PMINSR
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

```

### Read ALPHSR value

```

CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(5F6.0)',IOSTAT=ERR)
& ALPHL, ALPHS, ALPHR, ALPHSH, ALPHSR
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)
ENDIF

```

**List all storage and dormancy variables at end of GROW subroutine**

! ALPHSR Fraction of new storage organ growth that is mobile C (fraction)  
! CADRT Mass of CH<sub>2</sub>O added back to roots for CH<sub>2</sub>O cost of excess mobilized N  
! (never really mobilized) ( $\text{g}[\text{CH}_2\text{O}] / \text{m}^2 / \text{d}$ )  
! CADSH Mass of CH<sub>2</sub>O added back to shells for CH<sub>2</sub>O cost of excess mobilized N  
! (never really mobilized) ( $\text{g}[\text{CH}_2\text{O}] / \text{m}^2 / \text{d}$ )  
! CADSR Mass of CH<sub>2</sub>O added to storage organs ( $\text{g}[\text{CH}_2\text{O}] / \text{m}^2 / \text{d}$ )  
! CPFSTR Respiration requirement for net storage organ growth  
! ( $\text{g}[\text{CH}_2\text{O}] / \text{g}[\text{tissue}]$ )  
! CRUSSR C mobilized from storage organs in a day ( $\text{g}[\text{CH}_2\text{O}] / \text{m}^2 / \text{d}$ )  
! CSRW Cumulative storage growth ( $\text{g}[\text{storage}] / \text{m}^2$ )  
! FRSTR Fraction of vegetative tissue growth that goes to storage organs  
! on a day ( $\text{g}[\text{storage}] / \text{g}[\text{veg}]$ )! NADSR N added to storage organ N reserves  
( $\text{g}[\text{N}] / \text{m}^2 / \text{d}$ )  
! NADSH N added to shell N reserves ( $\text{g}[\text{N}] / \text{m}^2 / \text{d}$ )  
! NADSR N added to storage organ N reserves ( $\text{g}[\text{N}] / \text{m}^2 / \text{d}$ )  
! NGRSR Maximum N demand for storage organ growth  
! ( $\text{g}[\text{stem N}] / \text{m}^2[\text{ground}] / \text{d}$ )  
! NRUSSR N actually mobilized from storage organs in a day ( $\text{g}[\text{N}] / \text{m}^2 - \text{d}$ )  
! NSRALL N added to storage organ today ( $\text{g}[\text{N}] / \text{m}^2 - \text{d}$ )  
! NSRDOT Net N addition for storage organ ( $\text{g}[\text{N}] / \text{m}^2[\text{ground}] / \text{d}$ )  
! NSROFF N loss from storage organ in a day ( $\text{g}[\text{N}] / \text{m}^2 - \text{d}$ )  
! PCARSR Proportion of storage tissue that is carbohydrate (fraction)  
! PCNSR Percent N in storage organ ( $100 \text{ g}[\text{N}] / \text{g}[\text{storage}]$ )  
! PLIGSR Proportion of storage organ that is lignin (fraction)  
! PLIPSR Proportion of storage tissue that is lipid (fraction)  
! PMINSR Proportion of storage tissue that is mineral (fraction)  
! POASR Proportion of storage tissue that is organic acid (fraction)  
! PROSRF Minimum storage organ protein composition after N mining  
! ( $\text{g}[\text{protein}] / \text{g}[\text{storage}]$ )  
! PROSRI Maximum protein composition in storage organ during growth  
! with luxurious supply of N ( $\text{g}[\text{protein}] / \text{g}[\text{storage}]$ )  
! PSRLYRD Proportion of total storage organ tissue loss from below ground tissue  
! PSRLYR1 Proportion of storage organ tissue in soil layer 1 (below soil surface)  
! PSRSRFD Proportion of total storage organ tissue loss from above ground tissue  
! PSRSRFL Proportion of storage organ tissue on/above soil surface  
! RHOSR Fraction of storage tissue which is carbohydrate  
! ( $\text{g}[\text{CH}_2\text{O}] / \text{g}[\text{storage}]$ )  
! SSRDOT Daily senescence of storage organ tissue ( $\text{g} / \text{m}^2 / \text{d}$ )  
! SSRNDOT Daily senescence of storage organ due to water stress ( $\text{g} / \text{m}^2 / \text{day}$ )  
! STRLYR1 Proportion of storage organ dry mass in soil layer 1  
! STRSRFL Proportion of storage organ dry mass on soil surface  
! STRWT Dry mass of storage organ, including C and N ( $\text{g}[\text{storage}] / \text{m}^2[\text{ground}]$ )  
! TPSRLYR1 Intermediate value used in updating value of PSRLYR1  
! TPSRSRFL Intermediate value used in updating value of PSRSRFL

! VSTAGE Number of nodes on main stem of plant  
 ! WCRSR Mass of CH<sub>2</sub>O reserves in storage organ ( $g[\text{storage CH}_2\text{O}] / m2[\text{ground}]$ )  
 ! WNRSR N available for mobilization from storage organ above lower  
 !     limit of mining ( $g[\text{N}] / m2$ )  
 ! WCSRDT Net C addition for storage organ ( $g[\text{CH}_2\text{O}] / m2 / d$ )  
 ! WSFDT Stem weight losses due to freezing ( $g[\text{stem}] / m2 - d$ )  
 ! WSRI Initial weight of storage organ ( $g[\text{storage}] / m2$ )  
 ! WSRDOT Net storage organ growth rate ( $g[\text{storage}] / m2 / d$ )  
 ! WSRDOTN New storage tissue growth today ( $g[\text{storage}] / m2 / d$ )  
 ! WSRFDT Storage organ weight losses due to freezing ( $g[\text{storage}] / m2 - d$ )  
 ! WSRIDOT Weight of storage organ consumed by pests today ( $g[\text{storage}] / m2 - d$ )  
 ! WTNSR Mass of N in storage organ ( $g[\text{storage N}] / m2[\text{ground}]$ )  
 ! WTNSRA Cumulative N added to storage organ ( $g[\text{N}] / m2 - d$ )  
 ! WTNSRO Cumulative N loss from storage organ ( $g[\text{N}] / m2$ )  
 ! WTSRO Cumulative storage organ losses ( $g[\text{storage}] / m2$ )

**MODULE: INCOMP.FOR****Add storage terms to SUBROUTINE line and 2 CALL lines in CROPGRO**

```

SUBROUTINE INCOMP(
& ECONO, FILECC, FILEGC, FRLF, FRRT,           !Input
& FRSTM,                                     !Input
& AGRLF, AGRNOD, AGRRT, AGRSD1, AGRSD2,       !Output
& AGRSH1, AGRSH2, AGRSTM, AGRVG, AGRVG2,     !Output
& SDPROR,                                   !Output
& AGRSTR, FRSTR,
    !Output
& DYNAMIC)

```

**Declare storage parameters as REAL**

```

REAL PROSRI, PLIPSR, PLIGSR, POASR, PMINSR, PCARSR,
& AGRSTR, AGRSR2, FRSTR

```

**Read in storage composition parameters**

```

C-----
C  Read New Storage Organ Composition Parameters
C-----

```

```

CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(F6.0)',IOSTAT=ERR)
& PROSRI
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)
ENDIF

```

```

CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(5F6.0)',IOSTAT=ERR)
& PCARSR, PLIPSR, PLIGSR, POASR, PMINSR
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

```

**Calculate AGRSTR**

```

AGRSTR = PLIPSR*RLIP + PLIGSR*RLIG + POASR*ROA
& + PMINSR*RMIN + PCARSR*RCH2O

```

**Add AGRSTR to AGRVG and AGRVG2**

```

AGRVG = AGRLF * FRLF + AGRRT * FRRT + AGRSTM * FRSTM
& + AGRSTR * FRSTR

```

```

AGRVG2 = AGRVG + (FRLF*PROLFI+FRRT*PRORTI+FRSTM*PROSTI
& +FRSTR*PROSRI)*RNO3C

```

**Define storage parameters at end of subroutine.**

! AGRSTR Mass of CH<sub>2</sub>O required for new storage tissue growth

! FRSTR Fraction of vegetative tissue growth that goes to storage on a day

```

! PCARSR Proportion of storage tissue that is carbohydrate
!      (fraction)", "IPGROW, INCOMP
! PLIGSR Proportion of storage tissue that is lignin
!      (fraction)", "IPGROW, INCOMP
! PLIPSR Proportion of storage tissue that is lipid
!      (fraction)", "IPGROW, INCOMP
! PMINSR Proportion of storage tissue that is mineral
!      (fraction)", "IPGROW, INCOMP
! POASR Proportion of storage tissue that is organic acid
!      (fraction)", "IPGROW, INCOMP
! PROSRI Maximum protein composition in storage during growth with luxurious
!      supply of N (g[protein] / g[stem]), "IPPLNT, IPDMND, IPGROW,

```

**MODULE: IPPLNT.FOR****Add storage parameters to SUBROUTINE IPPLNT statement**

```

SUBROUTINE IPPLNT(CONTROL,
& CADPR1, CMOBMX, CROP, DETACH, ECONO, EORATIO,    !Output
& FILECC, FILEGC, FRCNOD, FREEZ1, FREEZ2, KCAN, KEP, !Output
& NOUTDO, PCARSH, PCH2O, PLIPSH, PLIGSD, PLIGSH,    !Output
& PMINSD, PMINSH, POASD, POASH, PORMIN, PROLFI,    !Output
& PRORTI, PROSHI, PROSTI, R30C2, RCH2O, RES30C,    !Output
& RFIXN, RLIG, RLIP, RMIN, RNH4C, RNO3C, ROA,      !Output
& RPRO, RWUEP1, RWUMX, TTFIX,                    !Output
& PROSRI, STRSRFL, STRLYR1)                      !Output

```

**Declare storage parameter types**

```

REAL PROSRI, STRSRFL, STRLYR1

```

**Read in value for PROSRI**

```

CALL IGNORE(LUNCRP,LINC,ISECT,CHAR)
READ(CHAR,'(F6.0)',IOSTAT=ERR) PROSRI

```

**Read in values for STRSRFL and STRLYR1**

```

C-----
C
C  ***** READ STORAGE ORGAN PARTITIONING PARAMETERS *****
C
C-----

```

```

SECTION = '!*STOR'
CALL FIND(LUNCRP, SECTION, LNUM, FOUND)
IF (FOUND .EQ. 0) THEN
  CALL ERROR(ERRKEY, 1, FILECC, LNUM)
ELSE
  CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
  READ(C80,'(2F6.0)',IOSTAT=ERR) STRSRFL, STRLYR1
  IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)
ENDIF

```

**Define parameters at end of subroutine.**

```

! PROSRI Maximum protein composition in storage during growth with luxurious
!      supply of N (g[protein] / g[stem])"
! STRLYR1 Initial proportion of storage organ dry mass in soil layer 1
! STRSRFL Initial proportion of storage organ dry mass on soil surface

```

**MODULE: MOBIL.FOR****List Storage variables in the SUBROUTINE MOBIL statement**

```

SUBROUTINE MOBIL(
&  NDMNEW, NMINEP, NMOBR, RPRO, TRNU,          !Input
&  WNRLF, WNRRT, WNRSH, WNRST,                !Input
&  NMINEA, NRUSLF, NRUSRT, NRUSSH, NRUSST,      !Output
&  NMOBSR, PPMFAC, WNRSR,                      !Input
&  NRUSSR, PNMLF, PNMST, PNMRT, PNMSR, PNMSH,   !Output
&  DYNAMIC)                                     !Control

```

**Declare variables REAL**

```

REAL NRUSSR, WNRSR, NMOBSR
REAL NRUSTOT, PNMLF, PNMST, PNMRT, PNMSR, PNMSH

```

**Initialize NRUSSR**

```

NRUSSR = 0.0
PNMLF=0.0
PNMST=0.0
PNMRT=0.0
PNMSR=0.0
PNMSH=0.0

```

**Adjust NRUSRT for dormancy and calculate NRUSSR**

```

NRUSRT = NMINEP * WNRRT * (1-PPMFAC)
NRUSSR = NMINEA * WNRSR * NMOBSR / NMINEP

```

**Add code to calculate proportion of mobilized N coming from each organ. Elected to calculate proportion from shell by difference so sum would always be 1.0 and shell will be 0 or small for forages.**

```

NRUSTOT = NRUSLF+NRUSST+NRUSSH+NRUSRT+NRUSSR
IF (NRUSTOT .GT. 0.0) THEN
  PNMLF=NRUSLF/NRUSTOT
  PNMST=NRUSST/NRUSTOT
  PNMRT=NRUSRT/NRUSTOT
  PNMSR=NRUSSR/NRUSTOT
  PNMSH=1.0-(PNMLF+PNMST+PNMRT+PNMSR)
ELSE
  PNMLF=0.0
  PNMST=0.0
  PNMRT=0.0
  PNMSR=0.0
  PNMSH=0.0
ENDIF

```

**List storage variables at end of subroutine**

```

! NMOBSR Stage dependent N mining rate for storage organ

```



! NRUSSR N actually mobilized from storage organ in a day ( $g[N]/m^2-d$ )  
 ! NRUSTOT Total N actually mobilized in a day ( $g[N]/m^2-d$ )  
 ! PPMFAC Reduction in mobilization from storage organ due to photoperiod  
 ! induced dormancy  
 ! PNMLF Proportion of actually mobilized N mobilized from leaves in a day  
 ! PNMST Proportion of actually mobilized N mobilized from stems in a day  
 ! PNMRT Proportion of actually mobilized N mobilized from roots in a day  
 ! PNMSR Proportion of actually mobilized N mobilized from storage organ in a day  
 ! PNMSH Proportion of actually mobilized N mobilized from shells in a day  
 ! WNRSR N available for mobilization from storage organ above lower  
 ! limit of mining ( $g[N] / m^2$ )

**MODULE: NUPTAK.FOR****Add code to prevent cost of N uptake and reduction from exceeding PGAVL  
Bring PGAVL, RNH4C, and RNO3C into NUPTAK**

```

SUBROUTINE NUPTAK(
& BD, DLAYR, DUL, FILECC, LL, NDMSDR, NDMTOT, NH4, !Input
& NO3, NLAYR, PGAVL, RLV, RNH4C, RNO3C, SAT, SW, !Input
& NUPNH4, NUPNO3, TRNH4U, TRNO3U, TRNU, UNH4, UNO3, !Output
& DYNAMIC) !Control

```

**Declare new variables as REAL**

```

REAL PGAVL, PRSPNH4, PRSPNO3, PTRNH4U, PTRNO3U, RNH4C,
RNO3C
REAL NUPNH4(NL), NUPNO3(NL)

```

**Initialize new totalizing variables in INTEGR step**

```

PTRNO3U = 0.0
PTRNH4U = 0.0

```

**Calculate new variables – total potential NO3 & NH4 uptake**

```

C-----
C   SJR 10/17/03 - Calculate potential total NO3 and NH4 uptake
C-----
PTRNO3U = PTRNO3U + RNO3U(L)
PTRNH4U = PTRNH4U + RNH4U(L)

```

**Calculate cost for uptake and reduction of total potential NO3 and NH4 uptake**

```

C-----
C   SJR 10/17/03 - Calculate cost of uptake and reduction of CP
C   from potential NO3 and NH4
C-----

```

```

PRSPNO3 = (PTRNO3U/10)/0.16 * RNO3C
PRSPNH4 = (PTRNH4U/10)/0.16 * RNH4C

```

**Check cost of uptake of potential NO3 and NH4 against PGAVL to set the upper  
limit of N uptake – prevents RSPNO3 + RSPNH4 from exceeding PGAVL in  
CROPGRO.FOR**

```

C-----
C   SJR 10/17/03 - Check that cost of uptake and reduction of CP
C   from TRNU does not exceed PGAVL
C-----

```

```

IF (PGAVL .LT. (PRSPNO3 + PRSPNH4)) THEN
  TRNU = (PGAVL / (PRSPNO3+PRSPNH4)) * TRNU
ENDIF

```

**Create new DO loop at end of actual uptake loop to calculate the proportion of NO<sub>3</sub> and NH<sub>4</sub> taken up from each soil layer – used in VEGGR to put NLEAK back.**

```

C-----
C      Calculate proportion of TRNU coming from NO3 and NH4 in each layer
C      for use in "returning" NLEAK
C-----
      DO L=1,NLAYR
          IF (TRNO3U .GT. 0.0) THEN
              NUPNO3(L) = UNO3(L) / TRNO3U
          ENDIF

          IF (TRNH4U .GT. 0.0) THEN
              NUPNH4(L) = UNH4(L) / TRNO3U
          ENDIF
      ENDDO

```

**Define all new variables**

```

! NUPNO3(L) Proportion of TRNU from a soil layer that is nitrate
! NUPNH4(L) Proportion of TRNU from a soil layer that is ammonium
! PGAVL   Total available CH2O available for growth & respiration
!         (g[CH2O] / m2)
! PRSPNO3   Respiration cost to fix and reduce all potentially available NO3
!           g CH2O/M2 to CP
! PRSPNH4   Respiration cost to fix and reduce all potentially available NH4
!           g CH2O/M2 to CP
! PTRNO3U   Total potential NO3 uptake
!           (kg [N] / ha)
! PTRNH4U   Total potential NH4 uptake
!           (kg [N] / ha)
! RNH4C     CH2O required for protein synthesis when source of N is
!           ammonium uptake (g[CH2O] / g[protein])
! RNO3C     Respiration required for reducing NO3 to protein
!           (g[CH2O] / g[protein])

```

**MODULE: OPGROW.FOR****Add dormancy and storage variables to SUBROUTINE OPGROW statement**

```

SUBROUTINE OPGROW(CONTROL, ISWITCH,
& CADLF, CADST, CANHT, CANWH, CMINEA, DWNOD,
& GROWTH, GRWRES, MAINR, MDATE, NFIXN, NSTRES,
& PCLSD, PCCSD, PCNL, PCNRT, PCNSD, PCNSH, PCNST,
& PG, PODNO, PODWT, PODWTD, RHOL, RHOS, RLV, RSTAGE,
& RTDEP, RTWT, SATFAC, SDWT, SEEDNO, SLA, STMWT, SWFAC,
& TGRO, TGROAV, TOPWT, TOTWT, TURFAC, VSTAGE, WTCO,
& WTLF, WTLO, WTNCAN, WTNLF, WTNST, WTNSD, WTNUP,
& WTNFX, WTSO, XLAI, YRPLT,
& CADSR, PCNSR, PSRSRFD, PSRSRFL, RHOSR, STRWT,
& WTNSR, WTSRO,

& DRMST, PPGFAC, PPMFAC, PPTFAC, SRFTEMP, ST(1), FREEZ2,

& AGRSTR, CADSR, CMOBSR, CPFSTR, CRUSSR, CSRFRZ, CSRW,
& CSTRM, DSTOR, FNINSR, FNINSRG, FRSTR, FRSTRM, NADSR,
& NGRSR, NGRSG, NMOBSR, NRUSSR, NSRALL, NSRDOT, NSROFF,
& NVRSTR, PCNSR, PCSTRD, PROSRT, PSRSRFD, PSRLYRD,
& PSRSRFL, PSRLYR1, RHOSR, SRDAM, SRSRFD, SRLYRD, SSRDOT,
& SSRNDOT, STRWT, TPSRSRFL, TPSRLYR1, WCRSR, WNRSR,
& WCRSRDT, WSRDOT, WSRDOTN, WSRFDT, WSRI, WSRIDOT,
& WTNSR, WTNSRA, WTNSRO, WTSRO, XSTR,

& PROSRF, PROSRG, PROSRI, PCARSR, PLIGSR,
& PLIPSR, POASR, PMINSR, ALPHSR, CMOBSRX, CADSRF, NMOBSRX,
CLAIT,
& YSTOR, FRSTRF, FRSTRMX, STRSRFL, STRLYR1, SENSR,
& FNPTD, TYPPTD, FNPMD, TYPPMD, FNPGRD, TYPPGRD, HARD1, HARD2,
& FRZDC, FRZHRD, TYPHRD, FRZDHD, TYPDHD, RDRMG, RDRMM,
RDRMT)

```

**Declare dormancy and storage variables**

```

CHARACTER*6 DRMST
REAL PPGFAC, PPMFAC, PPTFAC, SRFTEMP, ST(1), FREEZ2

REAL AGRSTR, CADSR, CMOBSR, CPFSTR, CRUSSR, CSRFRZ, CSRW,
& CSTRM, DSTOR, FNINSR, FNINSRG, FRSTR, FRSTRM, NADSR,
& NGRSR, NGRSG, NMOBSR, NRUSSR, NSRALL, NSRDOT, NSROFF,
& NVRSTR, PCNSR, PCSTRD, PROSRT, PSRSRFD, PSRLYRD,
& PSRSRFL, PSRLYR1, RHOSR, SRDAM, SRSRFD, SRLYRD, SSRDOT,
& SSRNDOT, STRWT, TPSRSRFL, TPSRLYR1, WCRSR, WNRSR,
& WCRSRDT, WSRDOT, WSRDOTN, WSRFDT, WSRI, WSRIDOT,
& WTNSR, WTNSRA, WTNSRO, WTSRO, XSTR

```

```

      REAL PROSRF, PROSRG, PROSRI, PCARSR, PLIGSR,
&   PLIPSR, POASR, PMINSR, ALPHSR, CMOBSRX, CADSRF, NMOBSRX,
CLAIT,
&   YSTOR, FRSTRF, FRSTRMX, STRSRFL, STRLYR1, SENSR,
&   FNPTD, TYPPTD, FNPMD, TYPPMD, FNPGRD, TYPPGRD, HARD1, HARD2,
&   FRZDC, FRZHRD, TYPHRD, FRZDHD, TYPDHD, RDRMG, RDRMM,
RDRMT

```

#### Add DORMANCY.OUT output file

```

OUTDRM = 'Dormancy.OUT'
CALL GETLUN('OUTDRM', NOUTDRM)

```

#### Add STORAGE.OUT output file

```

OUTSTR = 'Storage.OUT '
CALL GETLUN('OUTSTOR', NOUTSTOR)

```

#### Add INSTORAGE.OUT output file

```

OUTINSTR = 'StorSpIn.OUT'
CALL GETLUN('OUTINSTR', NOUTINSTR)

```

#### Write headers to new output files

```

!-----
!   Initialize daily Dormancy output file
      INQUIRE (FILE = OUTDRM, EXIST = FEXIST)
      IF (FEXIST) THEN
        OPEN (UNIT = NOUTDRM, FILE = OUTDRM, STATUS = 'OLD',
&   IOSTAT = ERRNUM, ACCESS = 'APPEND')
        FIRST = .FALSE.
      ELSE
        OPEN (UNIT = NOUTDRM, FILE = OUTDRM, STATUS = 'NEW',
&   IOSTAT = ERRNUM)
        WRITE(NOUTDRM,('**PLANT DORMANCY OUTPUT FILE'))
        FIRST = .TRUE.
      ENDIF

      !Write headers
      CALL HEADER(SEASINIT, FILEIO, NOUTDRM, RUN)

      WRITE (NOUTDRM,270)
270  FORMAT('@YEAR DOY  DAS  DAP',
&   ' QDSD PPGF PPMF PPTF TSRD TS1D FRZ2')

```

```

!-----
!   Initialize daily Storage output file

```

```

INQUIRE (FILE = OUTSTOR, EXIST = FEXIST)
IF (FEXIST) THEN
  OPEN (UNIT = NOUTSTOR, FILE = OUTSTOR, STATUS = 'OLD',
&   IOSTAT = ERRNUM, ACCESS = 'APPEND')
  FIRST = .FALSE.
ELSE
  OPEN (UNIT = NOUTSTOR, FILE = OUTSTOR, STATUS = 'NEW',
&   IOSTAT = ERRNUM)
  WRITE(NOUTSTOR,('"*PLANT STORAGE OUTPUT FILE"))
  FIRST = .TRUE.
ENDIF

```

!Write headers

```
CALL HEADER(SEASINIT, FILEIO, NOUTSTOR, RUN)
```

```

WRITE (NOUTSTOR,280)
280 FORMAT('@YEAR DOY  DAS  DAP TWAD  PHAD',
          ' QCQD QHAD QC%M QRAD QMAD QCFD QCAD
QCDD QDTD',
          ' QN%X QN%I QV%D QV%T QNAA QNRX QNRN
QNAR QNAM',
          ' QNAG QNAN QNAL QN%N QN%D QWAC QP%W
QL%S QL%I',
          ' QS%D Q1%D QC%D QCAM QFDS QFD1 QEAD QEWD
QWAD',
          ' QT%S QT%I QCRD QNMD QCAG QWNG QWND
QFAD QWAI',
          ' QMAM QNAD QNAC QNLC QDAD XSTR')

```

!-----

! Initialize Storage inputs output file

```

INQUIRE (FILE = OUTINSTOR, EXIST = FEXIST)
IF (FEXIST) THEN
  OPEN (UNIT = NOUTINSTR, FILE = OUTSTOR, STATUS = 'OLD',
&   IOSTAT = ERRNUM, ACCESS = 'APPEND')
  FIRST = .FALSE.
ELSE
  OPEN (UNIT = NOUTINSTR, FILE = OUTSTOR, STATUS = 'NEW',
&   IOSTAT = ERRNUM)
  WRITE(NOUTINSTR,('"*PLANT STORAGE INPUTS OUTPUT FILE"))
  FIRST = .TRUE.
ENDIF

```

!Write headers

```
CALL HEADER(SEASINIT, FILEIO, NOUTINSTR, RUN)
```

```

WRITE (NOUTINSTR,290)
290  FORMAT(' SP%F SP%G SP%I SRC% SRG% SRL% SRO% SRM%',
&    ' SR%L SC%M C%SR SMNX LAIT SP%1 SP%2 SP%3 SP%4',
&    ' SP%5 SP%6 SP%7 SP%8 FRSR FSRX SRSF SRL1 SNSR',
&    ' SRT1 SRT2 SRT3 SRT4 TSPT SRM1 SRM2 SRM3 SRM4',
&    ' TSPM SRG1 SRG2 SRG3 SRG4 TSPG HRD1 HRD2 FZDC',
&    ' ZHD1 ZHD2 ZHD3 ZHD4 THRD ZDH1 ZDH2 ZDH3 ZDH4',
&    ' TDHD RDMG RDMM RDMT')

```

**Write daily data to DORMANCY.OUT and STORAGE.OUT output files**

```

WRITE (NOUTDRM,610) YEAR, DOY, DAS, DAP,
&    DRMST, PPGFAC, PPMFAC, PPTFAC, SRFTEMP, ST(1), FREEZ2
610  FORMAT(1X,I4,1X,I3.3,2(1X,I5),A6,1X,F5.1,3(1X,F5.3),
&    2(1X,F5.1))

```

```

WRITE (NOUTSTOR,710) YEAR, DOY, DAS, DAP,
&    AGRSTR, CADSR, CMOBSR, CPFSTR, CRUSSR, CSRFRZ, CSRW,
&    CSTRM, DSTOR, FNINSR, FNINSRG, FRSTR, FRSTRM, NADSR,
&    NGRSR, NGRSG, NMOBSR, NRUSSR, NSRALL, NSRDOT,
NSROFF,
&    NVRSTR, PCNSR, PCSTRD, PROSRT, PSRSRFD, PSRLYRD,
&    PSRSRFL, PSRLYR1, RHOSR, SRDAM, SRSRFD, SRLYRD,
SSRDOT,
&    SSRNDOT, STRWT, TPSRSRFL, TPSRLYR1, WCRSR, WNRSR,
&    WCRSRDT, WSRDOT, WSRDOTN, WSRFDOT, WSRI, WSRIDOT,
&    WTNSR, WTNSRA, WTNSRO, WTSRO, XSTR

710  FORMAT(1X,I4,1X,I3.3,2(1X,I5),9(1X,F5.2),4(1X,F5.3),
&    9(1X,F5.2),8(1X,F5.3),6(1X,F5.2), 2,(1X,F5.3),
&    13(1X,F5.2))

```

**Write data to INSTORAGE.OUT output file at end of simulation**

```

WRITE (NOUTINSTR,810) PROSRF, PROSRG, PROSRI, PCARSR, PLIGSR, ,
&    PLIPSR, POASR, PMINSR, ALPHSR, CMOBSRX, CADSRF, NMOBSRX,
CLAIT,
&    YSTOR(1), YSTOR(2), YSTOR(3), YSTOR(4), YSTOR(5), YSTOR(6),
&    YSTOR(7), YSTOR(8), FRSTRF, FRSTRMX, STRSRFL, STRLYR1, SENSR,
&    FNPTD(1), FNPTD(2), FNPTD(3),FNPTD(4), TYPPTD, FNPMD(1),
&    FNPMD(2), FNPMD(3), FNPMD(4), TYPPMD, FNPGD(1), FNPGD(2),
&    FNPGD(3), FNPGD(4), TYPPGD, HARD1, HARD2, FRZDC, FRZHRD(1),
&    FRZHRD(2), FRZHRD(3), FRZHRD(4), TYPHRD, FRZDHD(1), FRZDHD(2),
&    FRZDHD(3), FRZDHD(4), TYPDHD, RDRMG, RDRMM, RDRMT)

810  FORMAT(8(1X,F5.3),15(1X,F5.2),3(1X,F5.3),4(1X,F5.1),3X,A3,

```

& 4(1X,F5.1),3X,A3,4(1X,F5.1),3X,A3,2(1X,F5.1),1X,F5.3,  
 & 4(1X,F5.1),3X,A3,4(1X,F5.1),3X,A3,3(1X,F5.3))



**MODULE: PEST.FOR****Add storage parameters to SUBROUTINE PEST statement**

```

SUBROUTINE PEST(CONTROL, ISWITCH,
& AREALF, CLW, CSW, LAGSD, LNGPEG, NR2, PGAVL,    !Input
& PHTIM, PLTPOP, RTWT, SLA, SLDOT, SOILPROP,      !Input
& SSDOT, STMWT, TOPWT, WLFDOT, WTLF, YRPLT,      !Input
& RLV, SDNO, SHELN, SWIDOT,                      !Input/Output
& VSTAGE, WSHIDT, WTSD, WTSHE,                  !Input/Output
& ASMDOT, DISLA, NPLTD, PPLTD,                  !Output
& SDDDES, WLIDOT, WRIDOT, WSIDOT, SDWT,
!Output
& CSRW, SSRDOT, STRWT, WSFDOT, WSRFDOT,          !Input
& WSRIDOT,                                     !Output

& CSFRZ, CSRFRZ, CSTRM, DSTOR, SRDAM)           !Output

```

**Declare Stem freeze variable as REAL**

```

REAL CSFRZ, WSFDOT

```

**Declare storage variables as REAL**

```

REAL CSRW, CSTRM, SSRDOT, STRWT, WSRFDOT, WSRIDOT

```

**Add storage variables to the CALL VEGDM statement**

```

CALL VEGDM(
& AREALF, CLW, CSW, PCLMA, PCLMT,                !Input
& PCSTMD, PDLA, PLFAD, PLFMD, PSTMD,             !Input
& PVSTGD, SLA, SLDOT, SSDOT, STMWT,              !Input
& TDLA, VSTGD, WLFDOT, WSTMD, WTLF,              !Input
& TLFAD, TLFMD, VSTAGE, WLIDOT,                  !Input/Output
& CLAI, CLFM, CSTEM, DISLA, DISLAP,              !Output
& LAIDOT, WSIDOT,                                !Output
& CSRW, PCSTRD, PSTRD, SSRDOT, STRWT,             !Input
& WSFDOT, WSRFDOT, WSTRD,                        !Input
& CSTRM, WSRIDOT,                                !Output

& CSRFRZ, DSTOR, SRDAM,                          !Output

& SEASINIT)                                     !Control

```

**List storage variables at end of subroutine**

```

! CSFRZ      Cumulative frozen stem tissue (g[stem]/m2)
! CSRW       Cumulative storage organ growth (g[storage]/m2)
! CSTRM      Cumulative storage organ mass destroyed (g/m2)
! SSRDOT     Daily senescence of storage organ (g / m2 / d)
! STRWT      Dry mass of storage organ tissue, including C and N
!            (g[storage] / m2[ground])

```

! WSFDOT      Stem weight losses due to freezing (g[stem]/m<sup>2</sup>-d)  
! WSRFDOT    Storage organ weight losses due to freezing (g[storage]/m<sup>2</sup>-d)  
! WSRIDOT    Daily pest damage to storage organ mass (g/m<sup>2</sup>/day)

**MODULE: PESTCP.FOR****Add storage variables to SUBROUTINE PESTCP statement**

```

SUBROUTINE PESTCP(
&  PCN, PCPID, PCTID, PDCF1,                !Input
&  PL, PLTPOP, PNO, RTWT, SLA, STMWT, TOPWT,    !Input
&  TSDNOL, TSDNOM, TSDNOS, TSDWTL, TSDWTM, TSDWTS, !Input
&  TSHNOL, TSHNOM, TSHNOS, TSHWTL, TSHWTM, TSHWTS, !Input
&  VSTAGE, WTLF,                            !Input

&  NSDDL, NSDDM, NSDDS, NSHDL, NSHDM, NSHDS,    !Input/Output
&  PPLTD, TLFAD, TLFMD, TRTLV,                !Input/Output
&  WRTMD, WSDDL, WSDDM, WSDDS,                !Input/Output
&  WSHDL, WSHDM, WSHDS,                      !Input/Output

&  CPPLTD, NPLTD, PCLMA, PCLMT,              !Output
&  PCSTMD, PDLA, PLFAD, PLFMD, PPSR,          !Output
&  PRTLFD, PRTLVD, PRTMD, PSDDL, PSDDM, PSDDS, !Output
&  PSHDL, PSHDM, PSHDS, PSTMD, PVSTGD,        !Output
&  TDLA, TPSR, TRTLF, VSTGD, WSTMD,          !Output

&  PCSTRD, PSRMD, WSTRMD,
    !Output

&  DYNAMIC, WSDD, PSDD, PRLV)

```

Declare storage variables REAL

```

C  Storage Variables
    REAL PCSTRD, PSRMD, WSTRMD

```

**Initialize storage variables**

```

C -- Storage Variables --
    WSTRD = 0.0
    PSTRD = 0.0
    PCSTRD = 0.0

```

**Change MOW option to not alter VSTAGE**

```

C-----
C      Mowing option
C-----
    IF (INDEX( PCPID(I,J), 'TOPWT') .GT. 0.0) THEN
C-----
C  SJR 3/16/04 Divide PL(K) by 10 to allow MOW input as kg/ha
C                      instead of old g/m2
C-----
    IF (TOPWT .GT. 0.0 .AND. TOPWT .GT. PL(K)/10.) THEN
C-----

```

```

C      Determine the fraction of the top weight that will be
C      removed by mowing. Include an IF statement to protect
C      against the condition that PL=0 (fileT with grazing or
C      mowing has a sequence of zero damage - real damage -
C      zero damage), would otherwise result in 100% damage.
C-----
      IF (PL(K) .GT. 0.0) THEN
        DAM = (TOPWT - PL(K)/10.) / TOPWT * 100. * PDCF1(I,J)
      ELSE
        DAM = 0.0
      ENDIF
      ELSE
        DAM = 0.0
      ENDIF
C-----
C      Set the top weight to the desired value after mowing.
C      This also corrects the LAI in subroutine VEGDM.
C-----
      PLFMD = PLFMD + DAM
      PSTMD = PSTMD + DAM
!      PVSTGD = PVSTGD + DAM
      ENDIF

```

**Add new code to allow user to set number of leaves to remain after harvest – uses new PEST code MVS**

```

C-----
C SJR 5/19/04
C   MVS Leaf Number reduction option - used in conjunction with MOW
C-----
      IF (INDEX( PCPID(I,J),'NOLF') .GT. 0.0) THEN
C-----
C SJR 5/19/04 PL(K) input as number of leaves left after mowing
C-----
      IF (VSTAGE .GT. 0.0 .AND. VSTAGE .GT. PL(K)) THEN
C-----
C      Determine the fraction of leaves that will be
C      removed by mowing. Include an IF statement to protect
C      against the condition that PL=0 (fileT with grazing or
C      mowing has a sequence of zero damage - real damage -
C      zero damage), would otherwise result in 100% damage.
C-----
      IF (PL(K) .GT. 0.0) THEN
        DAM = (VSTAGE - PL(K)) / VSTAGE * 100. * PDCF1(I,J)
      ELSE
        DAM = 0.0

```

```
ENDIF  
ELSE  
  DAM = 0.0  
ENDIF
```

List storage variables at end of subroutine

```
! PCSTRD   Observed cumulative percentage storage organ mass damage (%)  
! PSTRD    Daily percent storage organ mass damage (%)  
! WSTRD    Daily absolute storage mass damage (g/m2/day)
```

**MODULE: PHENOL.FOR**

**Relocate calculation of FT(2) in RATE step on emergence day to earlier in the subroutine.**

```

C-----
C      Transplants
C      SJR 5/26/04 moved statement to this location - must appear before
C      calculation of today's FT(2). Otherwise sets DTX using ATEMP
C      instead of TGRO(I) on emergence day - results in inaccurate
C      estimate of today's increase in VSTAGE
C-----
      IF (PLME .EQ. 'T' .AND. YRPLT .EQ. YRDOY) THEN
        K = TSELC(2)
        FT(2) = CURV(CTMP(2),TB(K),TO1(K),TO2(K),TM(K),ATEMP)
        PHZACC(2) = FT(2) * SDAGE
      ENDIF

C-----
C      Compute dev rates for all other phases, using hourly air temp
C-----
      DO J = 2,NPHS
        K = TSELC(J)
        FT(J) = 0.0
        DO I = 1,24
          FTHR = CURV(CTMP(J),TB(K),TO1(K),TO2(K),TM(K),TGRO(I))
          FT(J) = FT(J) + FTHR/24.
        ENDDO

        IF (DAS .LT. NR1) THEN
          FUDAY(J) = CURV(DLTYP(J),1.0,CSDVAR,CLDVAR,THVAR,DAYL)
        ELSE
          FUDAY(J) = CURV(DLTYP(J),1.0,CSDVRR,CLDVRR,THVAR,DAYL)
        ENDIF

        FSW(J) = 1. + (1. - SWFAC) * WSENP(J)
        FNSTR(J) = 1. + (1. - NSTRES) * NSENP(J)
        FPSTR(J) = 1.

C-----
C      Add FPSTR(J) later for phosphorus effects on development
C-----
      ENDDO

```

**Notation on behavior of model with VSTAGE on day of emergence of transplants – final VSTAGE for day reflects initial VSTAGE plus day's growth. This VSTAGE is what is used for initial partitioning of transplant DM. Made no change in code, just noted how can override day's growth and end day with initial VSTAGE**

```

!-----
!   V-Stage for transplants
!       SJR - note - Will end day with initial VSTAGE calculated here plus
!       increase for the emergence day. If don't want any increase in
!       VSTAGE on emergence day - move this statement to end of
!       subroutine to re-calculate VSTAGE to this value and ignore any
!       new leaves.
!-----
      IF (PLME .EQ. 'T' .AND. YRPLT .EQ. YRDOY) THEN
        VSTAGE = 1. + (PHZACC(2) - MNEMV1) * TRIFOL
      ENDIF

!-----
      IF (DAS .GE. NVEG0 .AND. DAS .LE. NDVST) THEN
        IF (DAS .LT. NVEG1) THEN
          VSTAGE = PHZACC(2)/MNEMV1
        ELSE
          IF (VSTAGE .LT. ABS(EVMODC) .AND.
&      ABS(EVMODC) .GT. 0.0001) THEN
            EVMOD = 1.0 + (ABS(EVMODC)- VSTAGE) / EVMODC
            EVMOD = AMIN1(2.0,EVMOD)
            EVMOD = AMAX1(0.0,EVMOD)
          ELSE
            EVMOD = 1.0
          ENDIF
          VSTAGE = VSTAGE + DTX * TRIFOL * EVMOD*TURFAC*(1.0-XPOD)
        ENDIF
      ENDIF

!*****
!*****
!   End of DYNAMIC IF construct
!*****

```

**MODULE: SENES.FOR****Add storage variables to the SUBROUTINE SENES statement**

```

SUBROUTINE SENES(
&  FILECC, CLW, DTX, NR7, NRUSLF, PAR, RHOL,      !Input
&  SLAAD, STMWT, SWFAC, VSTAGE, WTLF, XLAI,      !Input
&  YRDOY, YRSIM,                                !Input
&  SLDOT, SLNDOT, SSDOT, SSNDOT,                !Output
&  STRWT,                                       !Input
&  SSRDOT, SSRNDOT,                            !Output

&  SENSR,                                       !Output

&  DYNAMIC)                                !Control

```

**Declare variables as REAL**

```

REAL SENSR, STRWT, SSRDOT, SSRNDOT

```

**READ SENSR from species file**

```

C-----
C
C  ***** READ Storage organ senescence parameters *****
C
C-----
SECTION = '!*STOR'
CALL FIND(LUNCRP, SECTION, LINC, FOUND)
IF (FOUND .EQ. 0) THEN
  CALL ERROR(ERRKEY, 1, FILECC, LINC)
ELSE
  CALL IGNORE(LUNCRP,LINC,ISECT,CHAR)
  CALL IGNORE(LUNCRP,LINC,ISECT,CHAR)
  READ(CHAR,'(F6.0)',IOSTAT=ERR) SENES
  IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LINC)
ENDIF

```

**Initialize SSRDOT & SSRNDOT**

```

SSRDOT = 0.0
SSRNDOT = 0.0

```

**Calculate daily senescence from storage organ**

```

C-----
C  This section calculates natural senescence of storage organ tissue
C  Thought about moving this below the IF...Then line but did not
C  Don't want to senesce if seedling but do want to senesce mature
C  stand after it has been cut or frozen back
C-----
SSRDOT = STRWT * SENSR * DTX
SSRDOT = MIN(SSRDOT,STRWT)

```



**Fix calculation of senescence due to low light in lower canopy so SLDOT never > WTLF**

SLDOT = SLDOT + LTSEN \* 10000. / SLAAD

SLDOT = MIN(WTLF,SLDOT)

**Fix calculation of senescence due to water stress so SLDOT never > WTLF**

SLDOT = SLDOT + SLNDOT

SLDOT = MIN(WTLF,SLDOT)

**Add “hook” to allow future manipulation of senescence as function of water stress**

SSRDOT = SSRDOT + SSRNDOT

SSRDOT = MIN(STRWT,SSRDOT)

**List storage variables at end of subroutine**

! SENSR        Constant for senescence of storage organ tissue  
 !                (proportion of cumulative storage weight lost / physiological day)  
 ! SSRDOT    Daily senescence of storage organ tissue (g / m<sup>2</sup> / d)  
 ! SSRNDOT   Storage organ senescence due to water stress (g/m<sup>2</sup>/day)  
 ! STRWT     Dry mass of storage organ tissue, including C and N

UTILS.FOR

Add new output files to SUBROUTINE GETLUN

```
CASE ('OUTDRM'); LUN = 47 !Dormancy.OUT
CASE ('OUTSTOR'); LUN = 48 !Storage.OUT
CASE ('OUTINSTR'); LUN = 74 !StorSpIn.OUT - List of storage inputs
```

Add new curve types for cold hardening and dehardening to SUBROUTINE CURV

```
C-----
C Curve type REV - Reversible process - used for cold hardening
C Rate of cold hardening increases as TMIN decreases from X1 to XB
C Cold hardening reverses at an increasing rate as TMIN increases from X1 to X2
C Process at maximum rate at or below XB
C Rate decreases linearly to 0 at X1
C Process reverses at a linear rate from X1 to X2
C XM is the maximum absolute rate
```

```
C-----
IF(CTYPE .EQ. 'REV' .OR. CTYPE .EQ. 'rev') THEN
  CURV = 1.
  IF(X .GT. XB .AND. X .LT. X1)CURV = 1.0-((X-XB)/(X1-XB))
  IF(X .GE. X1 .AND. X .LE. X2)CURV = 0.0-((X-X1)/(X2-X1))
  IF(X .GT. X2 )CURV = -1.0
  CURV = MAX(CURV,-1.0)
  CURV = MIN(CURV,1.0)
  CURV = CURV * XM
ENDIF
```

```
C-----
C Curve type DHD - used for cold dehardening in spring
C No cold dehardening below XB (rate=0)
C Rate of cold dehardening increases as TMIN increases from XB to X1
C Process at maximum rate at or above X1
C XM is the maximum absolute rate
```

```
C-----
IF(CTYPE .EQ. 'DHD' .OR. CTYPE .EQ. 'dhd') THEN
  CURV = 0.
  IF(X .GT. XB .AND. X .LT. X1)CURV = (X-XB)/(X1-XB)
  IF(X .GE. X1 .AND. X .LE. X2)CURV = 1
  IF(X .GT. X2 )CURV = 1
  CURV = MAX(CURV,0.0)
  CURV = MIN(CURV,1.0)
  CURV = CURV * XM
ENDIF
```

```
C-----
C Curve type DRD - used for reducing rates of processes as dormancy advances
C Multiply rates by this factor to reduce them on short days,
```

C no effect on long days  
 C XM is the maximum reduction factor at full dormancy (daylength=XB)  
 C Less reduction as daylength gets longer  
 C Process at maximum rate at or above X1  
 C X2 is not used

C-----  
 IF(CTYPE .EQ. 'DRD' .OR. CTYPE .EQ. 'drd') THEN  
 CURV = X2  
 IF(X .GT. XB .AND. X .LT. X1)  
 & CURV = X2+(XM-X2)\*(X-XB)/(X1-XB)  
 IF(X .GE. X1 )CURV = XM  
 CURV = MAX(CURV,X2)  
 CURV = MIN(CURV,XM)  
 ENDIF

C-----  
 C Curve type CDD - used for reducing rates of processes as dormancy advances  
 C Multiply rates by this factor to reduce them on short days,  
 C Long day effect depends on value of XM  
 C X2 is the maximum reduction factor at full dormancy (daylength=XB)  
 C Less reduction as daylength gets longer  
 C Process at maximum rate at or above X1  
 C Curvilinear version of DRD

C-----  
 IF(CTYPE .EQ. 'CDD' .OR. CTYPE .EQ. 'cdd') THEN  
 CURV = X2  
 IF(X .GT. XB .AND. X .LT. X1)  
 & CURV = XM-((XM-X2)\*((X1-X)/(X1-XB))\*\*2)  
 IF(X .GE. X1)CURV = XM  
 CURV = MAX(CURV,X2)  
 CURV = MIN(CURV,XM)  
 ENDIF

### Assign file init numbers to new output files via GETLUN

C=====

---

C GETLUN, Subroutine, C. H. Porter

C-----

C Assigns unique output file unit numbers to input and output files  
 C based on file variable name. If valid file variable name is not  
 C specified, unit numbers are assigned incrementally starting with  
 C unit 90.

C-----

C REVISION HISTORY  
 C 10/17/2001 CHP Written.

C-----

! Called by: IRRIG, OPWBAL, OPGROW, . . .

! Calls: None

C=====

SUBROUTINE GETLUN(FileVarName, LUN)

!-----

IMPLICIT NONE

LOGICAL FEXIST, FPRINT(200)

INTEGER COUNTER, ERRNUM, Length, I, LUN, OUTLUN, StartLun

CHARACTER\*(\*) FileVarName

CHARACTER\*30 SaveName(200)

DATA StartLun /90/

DATA COUNTER /0/

DATA FPRINT /200\*.FALSE./

DATA OUTLUN /83/ !List.OUT - list of unit assignments

!-----

! On first call to subroutine, open new file to record

! input and output file information.

INQUIRE (FILE = 'LIST.OUT', EXIST = FEXIST)

IF (FEXIST) THEN

OPEN (UNIT = OUTLUN, FILE = 'List.OUT', STATUS = 'OLD',

& IOSTAT = ERRNUM, ACCESS = 'APPEND')

ELSE

OPEN (UNIT = OUTLUN, FILE = 'List.OUT', STATUS = 'NEW',

& IOSTAT = ERRNUM)

WRITE(OUTLUN,10)

10 FORMAT('\*Summary of files opened during simulation',

& //,'Unit File','/Num. Variable Name')

ENDIF

!-----

Length = Len(Trim(FileVarName))

SELECT CASE (FileVarName(1:Length))

! Input Files (Units 8 through 29):

CASE ('FILEA'); LUN = 8 !observed time series data

CASE ('FILEC', 'FILEE', 'FINPUT'); LUN = 10

!\*.spe, \*.eco, miscellaneous input files

CASE ('FILEW'); LUN = 11 !\*.wth - weather files

CASE ('FILEP'); LUN = 12 !\*.pst - pest files

CASE ('FILESS'); LUN = 13 !SOILN980.SOL

```

CASE ('BATCH'); LUN = 14 !Batch run input file
CASE ('ERRORX'); LUN = 15 !Model.err
CASE ('FILEIO'); LUN = 21 !temporary input file; dssat40.inp
CASE ('DTACDE'); LUN = 22 !DATA.CDE
CASE ('FILETMP'); LUN = 23 !Tony Hunt temp file

! Daily Output Files (Units 30 through 49): FName Code:
CASE ('OUTM'); LUN = 30 !MgmtOps.OUT
CASE ('OUTWTH'); LUN = 31 !Weather.OUT
CASE ('OUTG'); LUN = 32 !PlantGro.OUT
CASE ('OUTPN'); LUN = 33 !PlantN.OUT
CASE ('OUTPC'); LUN = 34 !PlantC.OUT
CASE ('OUTD'); LUN = 35 !Pest.OUT
CASE ('OUTT'); LUN = 36 !SoilTemp.OUT
CASE ('OUTWAT'); LUN = 37 !SoilWat.OUT
CASE ('OUTSN'); LUN = 38 !SoilN.OUT
CASE ('OUTSC'); LUN = 39 !SoilC.OUT
CASE ('OUTSP'); LUN = 40 !SoilP.OUT
CASE ('OUTSPAM'); LUN = 41 !SPAM.OUT
CASE ('OUTSOM'); LUN = 42 !SOMLIT.OUT
CASE ('OUTETP'); LUN = 43 !ETPhot.OUT
CASE ('OUTFLD'); LUN = 44 !Flood.OUT
CASE ('OUTCH'); LUN = 45 !Chemical.OUT
CASE ('FLDN'); LUN = 46 !FloodN.OUT
    CASE ('OUTDRM'); LUN = 47 !Dormancy.OUT
    CASE ('OUTSTOR'); LUN = 48 !Storage.OUT

! Daily Information files: (Units 50 through 59)
CASE ('SLDET'); LUN = 50 !Somlit1.OUT
CASE ('OUTWARN'); LUN = 51 !Warning.OUT
CASE ('WORK.OUT'); LUN = 52 !Work.OUT - for CSCERES
CASE ('ERRORO'); LUN = 53 !Error.OUT - echo of screen errors

! Seasonal output files (Units 60 through 79):
CASE ('SOUTM'); LUN = 60 !MgmtOpsSum.OUT
CASE ('SOUTWTH'); LUN = 61 !WeatherSum.OUT
CASE ('SOUTG'); LUN = 62 !PlantSum.OUT
!
CASE ('SOUTSPAM'); LUN = 65 !SPAMSum.OUT
CASE ('SOUTR'); LUN = 66 !Operat.OUT
CASE ('SOUTE'); LUN = 67 !Environ.OUT
CASE ('SEVAL'); LUN = 68 !Evaluate.OUT
CASE ('PNBAL'); LUN = 70 !PlantNbal.OUT
CASE ('PCBAL'); LUN = 71 !PlantCbal.OUT
CASE ('SNBAL'); LUN = 72 !SoilNbal.OUT
CASE ('SCBAL'); LUN = 73 !SoilCbal.OUT

```

```

CASE ('OUTINSTR'); LUN = 74 !StorSpIn.OUT - List of storage inputs

! Composite output files (Units 80 through 89):
CASE ('OUTO'); LUN = 80 !Overview.OUT
CASE ('OUTS'); LUN = 81 !Summary.OUT
CASE ('SWBAL'); LUN = 82 !SoilWatbal.OUT
!RESERVE UNIT 83 FOR LIST.OUT
CASE ('LIST'); LUN = 83 !List.OUT (list of unit assignments)
CASE ('OUTBAT'); LUN = 84 !TEMP.BAT file for DOS commands
CASE ('TEMP'); LUN = 85 !TEMP file
CASE ('OUTLST'); LUN = 86 !OUTPUT.LST list of output files

! Files not covered above will be assigned numbers
! incrementally starting with unit number 90.
CASE DEFAULT
!First check to see if a unit number has already been
!assigned to this FileVarName. If so, assign same LUN.
DO I = StartLun, StartLun + Counter
  IF (FileVarName .EQ. TRIM(SaveName(I))) THEN
    LUN = I
    EXIT
  ENDIF
ENDDO

!Assign a unique unit number to this FileVarName
IF (I .GT. StartLun + Counter) THEN
  LUN = StartLun + COUNTER
  COUNTER = COUNTER + 1
ENDIF

END SELECT

! Print to 'LIST.OUT' file each file assigned a unit number
! (only print the first time a unit is assigned)
! OUTPUT.LST - ICASA format headers, etc.
! Save FileVarName in case it is used again.
IF (.NOT. FPRINT(LUN)) THEN
  WRITE(OUTLUN, '(I4,2X,A)') LUN, FileVarName
  FPRINT(LUN) = .TRUE.
  SaveName(LUN) = FileVarName
ENDIF

CLOSE(OUTLUN)

RETURN
END SUBROUTINE GETLUN

```

**MODULE: VEGDM.FOR****Add storage parameters to SUBROUTINE VEGDM statement**

```

SUBROUTINE VEGDM(
&  AREALF, CLW, CSW, PCLMA, PCLMT,          !Input
&  PCSTMD, PDLA, PLFAD, PLFMD, PSTMD,       !Input
&  PVSTGD, SLA, SLDOT, SSDOT, STMWT,       !Input
&  TDLA, VSTGD, WLFDOT, WSTMD, WTLF,       !Input
&  TLFAD, TLFMD, VSTAGE, WLIDOT,           !Input/Output
&  CLAI, CLFM, CSTEM, DISLA, DISLAP,       !Output
&  LAIDOT, WSIDOT,                         !Output
&  CSRW, PCSTRD, PSTRD, SSRDOT, STRWT,      !Input
&  WSFDOT, WSRFDOT, WSTRD,                !Input
&  CSTRM, WSRIDOT,                        !Output

&  CSFRZ, CSRFRZ, DSTOR, SRDAM,            !Output

&  DYNAMIC)                               !Control

```

**Declare stem freeze variable as REAL**

```

REAL CSFRZ, WSFDOT

```

**Declare storage variables as REAL**

```

REAL CSRFRZ, CSRW, CSTRM, DSTOR, PCSTRD, PSTRD, SRDAM,
&  SSRDOT, STRWT, WSRFDOT, WSRIDOT, WSTRD

```

**Initialize storage variables**

```

CSTRM = 0.0
WSRIDOT = 0.0
CSFRZ = 0.0
CSRFRZ = 0.0

```

**Include freeze damage in calculation of observed stem damage**

```

IF (PCSTMD .GT. 0.0) THEN
C  Desired stem mass DSTEM after cumulative damage
  DSTEM = CSW * (1.0 - PCSTMD / 100.0)
  IF ((STMWT - SSDOT - WSFDOT) .GT. DSTEM) THEN
    SDAM = STMWT - SSDOT - WSFDOT - DSTEM
  ELSE
    SDAM = 0.0
  ENDIF
  WSIDOT = WSIDOT + SDAM
ENDIF

```

**Calculate daily storage organ damage**

```

C-----
C  Desired observed cumulative storage organ damage

```

```

C-----
C   When storage organ damage is reported as percent reduction of total
C   cumulative storage organ mass produced, use this section. The total
!   storage organ mass produced is CSRW. Part of the observed damage
!   comes from senescence and part from pests.
C-----

```

```

      IF (PCSTRD .GT. 0.0) THEN
C   Desired storage organ mass DSTOR after cumulative damage
      DSTOR = CSRW * (1.0 - PCSTRD / 100.0)
      IF ((STRWT - SSRDOT - WSRFDOT) .GT. DSTOR) THEN
        SRDAM = (STRWT - SSRDOT - WSRFDOT) - DSTOR
      ELSE
        SRDAM = 0.0
      ENDIF
      WSRIDOT = WSRIDOT + SRDAM
    ENDIF

```

```

C-----
C   Percent daily storage organ damage
C-----
      IF (PSTRD .GT. 0.0) THEN
        SRDAM = PSTRD*STRWT/100.0
        WSRIDOT = WSRIDOT + SRDAM
      ENDIF

```

```

C-----
C   Absolute daily amount of storage organ mass damaged
C-----
      IF (WSTRD .GT. 0.0) THEN
        SRDAM = MIN(WSTRD, STRWT)
        WSRIDOT = WSRIDOT + SRDAM
      ENDIF

```

```

      WSRIDOT = MAX(0., WSRIDOT)
      WSRIDOT = MIN(WSRIDOT, STRWT)

```

#### Maintain cumulative values for storage organ loss due to freeze

```

      IF (WSRFDOT .GT. 0.0) CSRFRZ = CSRFRZ + WSRFDOT

```

#### Maintain cumulative storage organ damage values

```

      CSTRM = CSRSM + WSRIDOT

```

List storage organ variables at end of subroutine

```

! CSRFRZ      Cumulative frozen stem tissue (g[stem]/m2)
! CSRFRZ      Cumulative frozen storage organ tissue (g[storage]/m2)
! CSRW        Cumulative storage organ growth (g[storage]/m2)

```



! CSTRM Cumulative storage organ mass destroyed (g/m<sup>2</sup>)  
 ! DSTOR Desired storage organ mass (g/m<sup>2</sup>/d)  
 ! PCSTRD Observed cumulative percentage storage organ mass damage (%)  
 ! PSTRD Daily percent storage organ mass damage (%)  
 ! SRDAM Calculated storage organ damage (g/m<sup>2</sup>/d)  
 ! SSRDOT Daily senescence of storage organ(g / m<sup>2</sup> / d)  
 ! STRWT Dry mass of storage organ, including C and N (g[storage] / m<sup>2</sup>[ground])  
 ! WSFDOT Stem weight losses due to freezing (g[stem]/m<sup>2</sup>-d)  
 ! WSRFDOT Storage organ weight losses due to freezing (g[storage]/m<sup>2</sup>-d)  
 ! WSRIDOT Daily pest damage to storage organ mass (g/m<sup>2</sup>/day)  
 ! WSTRD Daily absolute storage organ damage (g/m<sup>2</sup>/day)

**MODULE: VEGGR.FOR****Add storage and dormancy variables to the SUBROUTINE VEGGR statement**

```

SUBROUTINE VEGGR(
&  AGRLF, AGRRT, AGRSTM, CMINEP, CSAVEV,      !
&  DTX,  DXR57, ECONO, FILECC, FILEGC, FNINL, !
&  FNINR, FNINS, NAVL,  NDMNEW, NDMOLD,      !
&  NR1, NVSTL, NVSTR, NVSTS, NVSTSR,        !
&  PAR, PCH2O, PCNL, PCNST, PCNRT, PCNSR, PG,  !Input
&  PGAVL, ROWSPC, RTWT, RVSTGE, STMWT,  TGRO,  !
&  TURFAC, VSTAGE, WCRLF, WCRRT,  WCRSH,      !
&  WCRST, WTLF, XLAI, YRDOY, YREMRG, YRSIM, !

&  AGRVG, FRLF, FRRT, FRSTM, NMINEA,      !Input/Output
&  NFIXN, TRNU,                          !

&  CADLF, CADST, CANHT, CANWH, CMINEA,      !
&  CRUSLF, CRUSRT, CRUSH, CRUSST, EXCESS, NADLF, !
&  NADRT, NADST, NGRLF, NGRRT, NGRST,      !Output
&  NSTRES, TNLEAK, WLDOTN, WRDOTN, WSDOTN,  !

&  CLAIT, NRUSTOT,                        !Input
&  PNMLF, PNMRT, PNMSH, PNMSR, PNMST, RPRO,  !
&  CADRT, CADSH, NADSH,                  !Output

&  AGRSTR, CMOBSR, FNINSR, PPMFAC, STRWT, WCRSR, !Input
&  FRSTR,                                !Input/Output
&  CADSR, CRUSSR, NADSR, NGRSR, WSRDOTN,      !Output

&  CADSRF, CMOBSRN, CMOBSRX,              !Output
&  FNINSRG, NGRSRG, PROSRG, PROSRT,          !Output

&  NLAYR, NUPNH4, NUPNO3, PROLFI, PRORTI, !Input
&  PROSTI, PROSRI, RFIXN, RNH4C, RNO3C, TRNH4U, !
&  TRNO3U,                                !

&  DYNAMIC)                               !Control

```

**Declare variables as REAL**

```

REAL AGRSTR, CADSR, CADSRF, CLAIT, CMOBSR, CMOBSRN,
&  CMOBSRX, CRUSSR, FNINSR, FNINSRG, FRSTR,
&  NADSR, NGRSR, NGRSRG, PPMFAC, PROSRG,
&  PROSRI, PROSRT, STRWT, WCRSR, WSRDOTN

REAL NADSH, NRUSTOT, PNMLF, PNMRT, PNMSH, PNMSR, PNMST,
&  CADRT, CADSH, RPRO

```

```

C-----
C      New NDMOLD allocation variables for forage model
C      Used to weight partitioning in favor of one organ over others
C-----
      REAL NVSTL, NVSTR, NVSTS, NVSTSR, PCNL, PCNST, PCNRT, PCNSR,
&      PWLF, PWST, PWRT, PWSR, RTWT

C-----
C      New NLEAK distribution variables for all models
C      Used to "put back" and distribute NLEAK to new growth
C-----
      INTEGER L, NLAYR
      REAL AGRVGI, AGRVGPI, DNADRAT, NLKCOST, NLKGROW,
&      NRFRESP, PNTVG, NUPNH4(NL), NUPNO3(NL), ONDMOLD,
&      PNUPNH4, PNUPNO3, RFIXN, RNH4C, RNNU, RNO3C, TRNH4U,
&      TRNO3U, UNH4(NL), UNO3(NL), XTVEGM

```

**Read storage organ Protein parameters from plant composition section of species file**

```

      CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
      CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
      CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
      CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
      CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
      CALL IGNORE(LUNCRP,LNUM,ISECT,C80)

      CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
      READ(C80,'(2F6.0)',IOSTAT=ERR) PROSRI, PROSRG
      IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

```

**Read mobilization parameters from mining section of species file**

```

      CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
      CALL IGNORE(LUNCRP,LNUM,ISECT,C80)

      CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
      READ(C80,'(3F6.0)',IOSTAT=ERR) CMOBSRN, CMOBSRX,
&      CADSRF
      IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

```

**Read NDMOLD partitioning weighting factors from species file**

```

!-----
!      Find and Read Partitioning Section
!-----
      SECTION = '!*VEGE'
      CALL FIND(LUNCRP, SECTION, LNUM, FOUND)
      IF (FOUND .EQ. 0) THEN

```

```

CALL ERROR(ERRKEY, 1, FILECC, LNUM)
ELSE
  DO I=1,4
    ISECT = 2
    DO WHILE (ISECT .NE. 1)
      CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
    ENDDO
  ENDDO
  READ(C80,'(24X,F6.0)',IOSTAT=ERR) ATOP
  IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

```

```

CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
CALL IGNORE(LUNCRP,LNUM,ISECT,C80)
READ(C80,'(4F6.0)',IOSTAT=ERR) PWLF,PWST,PWRT,PWSR
IF (ERR .NE. 0) CALL ERROR(ERRKEY,ERR,FILECC,LNUM)

```

```

ENDIF

```

#### Initialize other variables

```

CADSR = 0.0
CRUSSR = 0.0
FNINSRG = 0.0
NADSR = 0.0
NGRSR = 0.0
WSRDOTN= 0.0

```

#### Calculate initial value for FNINSR

```

FNINSRG = PROSRG * 0.16

```

#### Add storage tissue to the partitioning scheme – NOTE: Dormancy adjustments were already made in DEMAND

```

C-----
C   0.6 IS A SCALAR, COULD BE LESS, was once 0.8 and 0.7
C   0.7 appears to be too much for peanut, but not for soybean.
C-----

```

```

FRSTR = (FRSTR/(FRLF+FRSTM+FRSTR))*(1-FRRT)

```

```

FRLF = (1.0 + 0.6*(1.0-CUMTUR))*(1-FRRT-FRSTR)*FRLF/
&      (FRLF + FRSTM)
FRLF = MIN(FRLF, 0.90*(1. - FRRT-FRSTR))

```

```

FRSTM = 1.0 - FRRT - FRLF - FRSTR

```

C-----  
 C To prevent negative partitioning to root and limit leaf plus  
 C stem to a maximum of 98 % of the vegetative partitioning  
 C NOTE - was 98% before adding storage organ to scheme  
 C-----

$$\begin{aligned} \text{FRLF} &= \text{MIN}(\text{FRLF}, \text{FRLF} * 0.98 / (\text{MAX}(0.001, \text{FRLF} + \text{FRSTM} + \text{FRSTR}))) \\ \text{FRSTM} &= \text{MIN}(\text{FRSTM}, \text{FRSTM} * 0.98 / (\text{MAX}(0.001, \text{FRLF} + \text{FRSTM} + \text{FRSTR}))) \\ \text{FRSTR} &= \text{MIN}(\text{FRSTR}, \text{FRSTR} * 0.98 / (\text{MAX}(0.001, \text{FRLF} + \text{FRSTM} + \text{FRSTR}))) \\ \text{FRRT} &= 1.0 - \text{FRLF} - \text{FRSTM} - \text{FRSTR} \end{aligned}$$

**Add storage tissue to AGRVG calculation – otherwise would have to come up with a fixed value for day's storage growth as done with seed+shell**

C-----  
 C Calculate weighted PHI + GR = 1/E = AGRVG for veg. growth  
 C-----

$$\begin{aligned} \text{AGRVG} &= \text{AGRFLF} * \text{FRLF} + \text{AGRRT} * \text{FRRT} + \text{AGRSTM} * \text{FRSTM} \\ &\& \text{AGRSTR} * \text{FRSTR} \end{aligned}$$

**Calculate new growth rate of storage organ**

$$\text{WRDOTN} = \text{FRRT} * \text{VGRDEM}$$

**Add storage into calculation of Max N required for vegetative growth**

$$\begin{aligned} \text{NGRSR} &= \text{WSRDOTN} * \text{FNINSR} \\ \text{NGRVEG} &= \text{NGRFLF} + \text{NGRST} + \text{NGRRT} + \text{NGRSR} \end{aligned}$$

**Add storage into calculation of minimum N required for tissue growth**

$$\begin{aligned} \text{NGRSRG} &= \text{WSRDOTN} * \text{FNINSRG} \\ \text{NGRVGG} &= \text{NGRFLG} + \text{NGRSTG} + \text{NGRRTG} + \text{NGRSRG} \end{aligned}$$

**Add storage into calculations for reducing leaf growth to prevent N conc of new tissue from being below the minimum for growth**

$$\begin{aligned} \text{WSRDOTN} &= \text{WSRDOTN} * \text{NRATIO} \\ \text{NGRSRT} &= \text{NGRSRG} * \text{NRATIO} \end{aligned}$$

**Add storage into calculation to adjust conversion costs to account for composition of tissue at lower N concentration**

$$\begin{aligned} \text{AGRVG} &= \text{AGRFLF} * \text{FRLF} * (1.0 - (\text{PROLFG} - \text{PROLFI}) / (1.0 - \\ &\& \text{PROLFI})) + \text{AGRRT} * \text{FRRT} * (1.0 - (\text{PRORTG} - \text{PRORTI}) / (1.0 - \\ &\& \text{PRORTI})) + \text{AGRSTM} * \text{FRSTM} * (1.0 - (\text{PROSTG} - \text{PROSTI}) / \\ &\& (1.0 - \text{PROSTI})) + \text{AGRSTR} * \text{FRSTR} * (1.0 - (\text{PROSRG} - \text{PROSRI}) \\ &\& / (1.0 - \text{PROSRI})) \end{aligned}$$

**Add storage into calculations when leaf expansion occurs as normal, but N concentration is reduced**

$$\text{NGRSR} = \text{MIN}(\text{NAVL} * \text{NGRSR} / \text{NGRVEG}, \text{NGRSR})$$

**Compute protein fraction of new storage tissue growth**

```
IF (WSRDOTN .GT. 0.0) THEN
  PROSRT = NGRSR * (100./16.)/WSRDOTN
ELSE
  PROSRT = 0.0
```

**Include storage in calculation of respiration costs if expansion occurs at low N-conc.  
To allow N dilution during growth**

```
AGRVG = AGRLF * FRLF * (1.0 - (PROLFT - PROLFI)/
& (1.0-PROLFI)) + AGRRT * FRRT * (1.0 - (PRORTT - PRORTI)/
& (1.0 - PRORTI)) + AGRSTM * FRSTM * (1.0 - (PROSTT -
& PROSTI)/(1.0 - PROSTI)) + AGRSTR * FRSTR * (1.0 - (PROSRT
& - PROSRI)/(1.0-PROSRI))
```

**Compute C and N remaining to add to reserves, including storage organ**

```
PGLEFT = MAX(0.0,PGAVL - ((WLDOTN + WSDOTN + WRDOTN +
& WSRDOTN)
& * AGRVG))
```

Initialize CADSR and CRUSSR as well as all NADXX variables

```
CADSR = 0.0
CRUSSR = 0.0
```

**Add storage organ to calculation to increase remobilizable C due to N shortage and  
add to Carbon Pool. Distribute to Leaves and Stems. Want half as much  
accumulation in stem in veg phase**

```
C-----
C Calculate Increase in Remobilizable C due to N shortage and
C add to Carbon Pool. Distribute to Leaves and Stems.
C-----
C Want half as much accumulation in stem in veg phase
C-----
! IF (DAS .LT. NR1) THEN
!   LSTR = (1.-0.6*CADSTF)/(0.6*CADSTF)
! ELSE
C-----
C 5/11/04 KJB/SJR Add code to allocate excess CH2O to Stolon as well
C as to leaf and stem. For forages chose to ignore different
C partitioning for vegetative vs. reproductive stages.
C-----

LSTR = CADSRF/(1-CADSRF)
LSTR = (1.-CADSTF)/CADSTF
!   ENDIF
IF (STMWT+WTLF .GT. 0.0) THEN
  LSTR = LSTR*STRWT/(STRWT*LSTR+STMWT)
```

```

      LSTR = LSTR * WTLF/(STMWT+WTLF*LSTR)
ENDIF
IF (PGLEFT .GE. CMINEP) THEN
  CADSR = (PGLEFT-CMINEP)/PCH2O * LSTSR
  CADLF = (PGLEFT-CMINEP)/PCH2O * LSTR*(1-LSTSR)
  CADST = (PGLEFT-CMINEP) * (1.-LSTR) - (1-LSTSR) / PCH2O
ELSE
C-----
C   Calculate actual C used (CMINEA) , compute how much is taken
C   from LF, ST, RT, and SH, which may be less than orig calc of CMINEP
C
C   8/26/97 KJB DTX IN PLACE OF 1 TO SLOW IT DOWN A BIT AT ALL TIMES
C   AND TO BE SENSITIVE TO TEMPERATURE PRIOR TO R5 STAGE, BUT
C   STILL WANT THE SPEED-UP CAUSED BY THE "+ DXR57" FEATURE AFTER
R5.
C
C-----
C       7/2/03 SJR added (PPMFAC) to limit mobilization from roots
C       while dormant
C-----
      IF (CMINEP .GT. 0) THEN
        CMINEA = CMINEP - PGLEFT
        CRUSLF = CMINEA / CMINEP * CMOBMX * WCRLF * (DTX + DXR57)
        CRUSST = CMINEA / CMINEP * CMOBMX * WCRST * (DTX + DXR57)
        CRUSSH = CMINEA / CMINEP * CMOBMX * WCRSH * (DTX + DXR57)
        CRUSRT = CMINEA / CMINEP * CMOBMX * PPMFAC * WCRRT *
&          (DTX + DXR57)
        CRUSSR = CMINEA/CMINEP * CMOBSR * WCRSR * (DTX +
DXR57)
      ENDIF
ENDIF
      CADSR = CADSR + CSAVEV/PCH2O * LSTSR
      CADLF = CADLF + CSAVEV/PCH2O * LSTR*(1-LSTSR)
      CADST = CADST + CSAVEV * (1. - LSTR)*(1-LSTSR)/PCH2O

```

**Include storage and shell tissue in increase in remobilizable N due to a C shortage,  
add to Nitrogen pool**

```

      NLEFT = MAX(0.0,NAVL - (NGRLF + NGRST + NGRRT + NGRSR))

```

**Move TNLEAK calculation to end of subroutine**

```

C-----
C   Eliminate existing code for NLEAK - is a loss to the system
C   that should not/does not exist
C-----
      IF (NLEFT .GT. NDMOLD) THEN
        NLEAK = NLEFT - NDMOLD

```

```

      NLEFT = NLEFT - NLEAK
ELSE
      NLEAK = 0.0
ENDIF

```

**Eliminate "false" NLEAK values due solely to rounding/precision errors**

```

C-----
C      SJR 10/20/03 Added code to fix/distribute NLEAK
C      NLEAK caused by 3 scenarios
C      I) Rounding/precision errors.
C      II) Changing FRRT & FRLF in VEGGR.FOR due to H2O or N stress,
C          changes N demand.
C      III) Low Pg - exhaust PGAVL on N uptake. Have N available but no
C          CH2O left for growth so N goes to refill old tissue.
C          Particularly a problem when LFWT is low. Also causes N% to
C          exceed initial or maximum concentrations set in species file.
C-----
C      SJR 10/16/03 Eliminate NLEAK values due to rounding errors
C          see I) above.
C-----
      IF (NLEAK .LT. 0.0001) NLEAK = 0.0

```

**If there still is NLEAK and NLEFT. Compare NLEFT to NDMOLD calculated when PGAVL is non-limiting (total amount of N required to refill all old tissue). This should be greater than NLEFT (NDMOLD) because of using PGAVL to limit NDMVEG and NDMOLD in DEMAND. If the capacity allows, put NLEAK there.**

```

      IF (NLEFT .GT. NDMOLD) THEN
C-----
C      Calculate capacity for refilling old tissue N if PGAVL were not
C      limiting. This is the original calculation with no modifiers.
C-----
      ONDMOLD = (WTLF - WCRLF) * MAX(0.0,(NVSTL - PCNL /100.))
&      + (STMWT - WCRST) * MAX(0.0,(NVSTS - PCNST/100.))
&      + (RTWT - WCRRT) * MAX(0.0,(NVSTR - PCNRT/100.))
&      + (STRWT - WCRSR) * MAX(0.0,(NVSTR - PCNSR/100.))
C-----
C      If total capacity for refilling N allows, put "NLEAK" into NLEFT
C      Otherwise, allocate NLEAK to NLEFT to the amount allowed by ONDMOLD
C-----
      IF (ONDMOLD .GT. NDMOLD) THEN
        IF (ONDMOLD - NDMOLD .GT. NLEAK) THEN

```



```

!           NLEFT = NLEFT
           NLEAK = 0.0
ELSE
           NLEFT = NLEFT + (ONDMOLD - NDMOLD)
           NLEAK = NLEAK - (ONDMOLD - NDMOLD)
ENDIF
ENDIF

```

```

!           NLEAK = NLEFT - NDMOLD

```

```

!           NLEFT = NLEFT - NLEAK
ELSE
           NLEAK = 0.0
ENDIF

```

**Fix proportioning of NDMOLD for refilling old tissue N – DSSAT4 scheme had two problems:**

**Used FRLF, FRSTM, FRRT – proportions of new growth. Can cause excessive N concentration if today's growth is small. Can have a high proportion of NDMOLD allocated to leaf but have very little leaf mass to "accept" it, resulting in very high leaf N%**

**Address problem – set allocation of NLEFT (NDMOLD) based on present tissue mass (WTLF, etc.) instead of proportions of new growth. Also add weighting factors (PWLF , etc.) to allow preferentially refilling some tissues before others.**

```

C-----
C   Original code allocated N back to only leaf, stem and root.
C   Uses FRxx which is the fraction of today's growth going to organ xx.
C   This is not indicative of the original "source" of the mobilized N being returned.
C-----
C-----
C       Allocate excess N uptake to refill old tissues
C-----

C-----
C       sjr 10/16/03 Revised scheme based on existing growth proportions
C-----
C       IF (NLEFT .GT. 0.0) THEN
C-----
C       Allocate excess N uptake to refill old tissues
C-----

```

$DNADRAT = PWLF * (WTLF - WCRLF) * MAX(0.0, (NVSTL - PCNL / 100.))$

```

& + PWST * (STMWT - WCRST) * MAX(0.0,(NVSTS - PCNST/100.))
& + PWRT * (RTWT - WCRRT) * MAX(0.0,(NVSTR - PCNRT/100.))
& + PWSR * (STRWT - WCRSR) * MAX(0.0,(NVSTSR - PCNSR/100.))

```

```

      IF (DNADRAT .GT. 0.0) THEN
        NADRAT = NLEFT / DNADRAT
      ELSE
        NADRAT = 0.0
      ENDIF

```

```

      NADLF = NADRAT *
& (WTLF - WCRLF) * PWLF * MAX(0.0,(NVSTL - PCNL /100.))
      NADST = NADRAT *
& (STMWT - WCRST) * PWST * MAX(0.0,(NVSTS - PCNST/100.))
      NADRT = NADRAT *
& (RTWT - WCRRT) * PWRT * MAX(0.0,(NVSTR - PCNRT/100.))
      NADSR = NADRAT *
& (STRWT - WCRSR) * PWSR * MAX(0.0,(NVSTSR - PCNSR/100.))

```

```

    ELSE
      NADRAT = 0.0
      NADLF = 0.0
      NADST = 0.0
      NADRT = 0.0
      NADSR = 0.0
    ENDIF

```

**If NLEAK exceeds N refill capacity, then put it back in the soil. NOTE: this doesn't seem to happen. Hopefully we can get rid of this.**

```

C-----
C   NLEAK caused by 3 scenarios
C   I) Rounding/precision errors.
C   II) Changing FRRT & FRLF in VEGGR.FOR due to H2O or N stress,
C       changes N demand.
C   III) Low Pg - exhaust PGAVL on N uptake. Have N available but no
C        CH2O left for growth so N goes to refill old tissue.
C        Particularly a problem when LFWT is low. Also causes N% to
C        exceed initial or maximum concentrations set in species file.
C-----
C   SJR 10/20/03 Added code to fix/distribute NLEAK
C   Fix for II) and III) above.
C   Basic strategy is to estimate how much growth could have been
C   achieved if CH2O that was used for N mobilization, fixation, or uptake

```

```

C      was used for growth instead. Then lower NLEAK and the appropriate
C      source by the amount of N used in and to fuel this growth.
C
C      Considered using PGAVL in this as well but did not because, to date,
C      NLEAK that would be addressed by this fix only occurs when PGAVL is
C      exhausted. If there were more PGAVL, more growth would have occurred
C      and there wouldn't be any NLEAK.
C
C      Strategy:
C      1) Figure out where it came from (mined, fixed or uptake)
C      2) Use appropriate respiration coefficient to calculate how much CH2O
C         was used to liberate that amount of N
C      3) Calculate how much new growth could be generated if that amount
C         of CH2O was used for growth and liberation of just enough
C         N for that new growth, no excess.
C      4) Recalculate N source (NMINEA, NFIXN, or TRNU). Recalculate NLEAK
C      5) In case of TRNU, distribute N to NO3 and NH4 in each soil layer
C      6) Recalculate growth rate and N concentration
C-----

```

```

      IF (NLEAK .GT. 0.0) THEN

```

```

      PNTVG=(FRLF*PROLFI+FRSTM*PROSTI+FRRT*PRORTI+FRSTR*PROSRI)*0.16

```

```

      AGRVGI=FRLF*AGRFLF+FRSTM*AGRSTM+FRRT*AGRRT+FRSTR*AGRSTR
      AGRVGPI=FRLF*PROLFI+FRSTM*PROSTI+FRRT*PRORTI+
&          FRSTR*PROSRI

```

```

      IF (TRNU .GT. 0.0) THEN
      PNUPNO3 = TRNO3U / TRNU
      PNUPNH4 = TRNH4U / TRNU
      RNNU= PNUPNO3 * RNO3C + PNUPNH4 * RNH4C

```

```

      CALL NLKDIST(
&  AGRVGI, AGRVGPI, FRLF, FRRT, FRSTM, FRSTR,      !Input
&  NLEAK, RNNU, TRNU, PNTVG,                      !
&  NGRLF, NGRRT, NGRST, NGRSR,
      !Input/Output
&  WLDOTN, WRDOTN, WSDOTN, WSRDOTN,                !
&  NLKCOST, NRFRESP, XTVEGM)
      !Output

```

```

      TRNU=TRNU-NRFRESP

```

NLEAK=NLEAK-NLK COST

C Allocate N "returned for respiration" (CH<sub>2</sub>O) to layers as NO<sub>3</sub>&NH<sub>4</sub>

```

      DO L = 1,NLAYR
        IF (TRNO3U .GT. 0.0) THEN
          UNO3(L) = UNO3(L) + NRFRESP * NUPNO3(L)
        ENDIF

        IF (TRNH4U .GT. 0.0) THEN
          UNH4(L) = UNH4(L) + NRFRESP * NUPNH4(L)
        ENDIF
      ENDDO

```

ENDIF

IF (NLEAK .LT. 0.0001) NLEAK = 0.0

TNLEAK = TNLEAK + NLEAK

ENDIF

#### Add NLKDIST subroutine to get rid of NLEAK

```

C-----
C Subroutine NLKDIST for distributing NLEAK
C For each potential source of NLEAK:
C 2) Use appropriate respiration coefficient (NRSPCST)to calculate
C how much CH2O was used to liberate that amount of N
C 3) Calculate how much new growth could be generated if that amount
C of CH2O was used for growth and liberation of just enough
C N for that new growth, no excess.
C-----

```

```

SUBROUTINE NLKDIST(
& AGRVGI, AGRVGPI, FRLF, FRRT, FRSTM, FRSTR,          !Input
& NLEAK, NRSPCST, NSOURCE, PNTVG,                    !
& NGRLF, NGRRT, NGRST, NGRSR,
  !Input/Output
& WLDOTN, WRDOTN, WSDOTN, WSRDOTN,                    !
& NLK COST, NRFRESP, XTVEGM)
  !Output

  REAL AGRVG2I, AGRVGI, AGRVGPI, CH2OCST, FRLF, FRRT,
& FRSTM, FRSTR, LKNRET, NLEAK, NRSPCST, NSOURCE,
& NGRLF, NGRRT, NGRST, NGRSR, PNTVG, RNNGR,
& WLDOTN, WRDOTN, WSDOTN, WSRDOTN,
& NLK COST, NLKGROW, NRFRESP, XTVEGM

```

```

AGRVG2I = 0.0
CH2OCST = 0.0
LKNRET = 0.0
NLKCOST = 0.0
NLKGROW = 0.0
NFRRESP = 0.0
RNNGR = 0.0
XTVEGM = 0.0

```

```

      IF (NLEAK .GT. NSOURCE) THEN

```

```

!   Use all NLEAK from NSOURCE for respiration, pull N for new growth
!   from excess NLEAK (from other N sources)

```

```

      LKNRET = NSOURCE
      AGRVG2I = AGRVGI + AGRVGPI * NRSPCST
      RNNGR = (0.16 / NRSPCST) * AGRVG2I
      XTVEGM = LKNRET / RNNGR
      CH2OCST = XTVEGM * AGRVG2I
      NFRRESP = (0.16 / NRSPCST) * CH2OCST
      NLKGROW = XTVEGM * PNTVG
      NLKCOST = NFRRESP + NLKGROW

```

```

      IF (NLKCOST .GT. NLEAK) THEN

```

```

!   Use all NLEAK from all sources. Allocate to respiration and new
!   growth. Some NLEAK from NSOURCE will be used for new growth

```

```

      LKNRET = NLEAK
      AGRVG2I = AGRVGI + AGRVGPI * NRSPCST
      RNNGR = (0.16 / NRSPCST) * AGRVG2I
      XTVEGM = LKNRET / (PNTVG + RNNGR)
      CH2OCST = XTVEGM * AGRVG2I
      NFRRESP = (0.16 / NRSPCST) * CH2OCST
      NLKGROW = XTVEGM * PNTVG
      NLKCOST = NFRRESP + NLKGROW
      ENDIF

```

```

      ELSE

```

```

!   Use all NLEAK. Allocate to respiration and new growth. Most NLEAK
!   from NSOURCE will be used for respiration, rest for new growth.
!   Thus, will end up with some remaining NSOURCE.

```

```

      LKNRET = NLEAK
      AGRVG2I = AGRVGI + AGRVGPI * NRSPCST
      RNNGR = (0.16 / NRSPCST) * AGRVG2I
      XTVEGM = LKNRET / (PNTVG + RNNGR)

```

```

CH2OCST = XTVEGM * AGRVG2I
NRFRESP = (0.16 / NRSPCST) * CH2OCST
NLKGROW = XTVEGM * PNTVG
NLKCOST = NRFRESP + NLKGROW
ENDIF

```

```

WLDOTN = WLDOTN + (FRLF * XTVEGM)
WSDOTN = WSDOTN + (FRSTM * XTVEGM)
WRDOTN = WRDOTN + (FRRT * XTVEGM)
WSRDOTN = WSRDOTN + (FRSTR * XTVEGM)

```

```

NGRLF = NGRLF + (FRLF * XTVEGM)
NGRST = NGRST + (FRSTM * XTVEGM)
NGRRT = NGRRT + (FRRT * XTVEGM)
NGRSTR = NGRSTR + (FRSTR * XTVEGM)

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RETURN

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C-----
END ! SUBROUTINE NLKDIST

```

#### List variable definitions at end of subroutine

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! AGRSTR Mass of CH2O required for new storage organ growth
!          (g[CH2O] / g[storage])
! AGRVG2I CH2O cost for new growth from NLEAK, including cost for
!          liberating and reducing N to CP (g[CH2O] / g[tissue])
!          - varies respiration cost depending on N source
! AGRVGI   CH2O cost for new growth from NLEAK, excludes cost for
!          liberating and reducing N to CP (g[CH2O] / g[tissue])
! AGRVGPI Intermediate value used to calculate AGRVG2I
! CADRT    Mass of CH2O added back to roots for CH2O cost of excess mobilized N
!          (never really mobilized) (g[CH2O] / m2 / d)
! CADSH    Mass of CH2O added back to shells for CH2O cost of excess mobilized N
!          (never really mobilized) (g[CH2O] / m2 / d)
! CADSR    Mass of CH2O added to storage organs (g[CH2O] / m2 / d)
! CADSRF   Proportion of CH2O reserves that are added to storage organ
!          (fraction)
! CH2OCST  CH2O cost for new growth generated from "recovering" NLEAK
!          (g[CH2O] / m2 / d)
! CLAIT    LAI threshold triggering increased mobilization from storage
!          organ tissue - represents dramatic loss due to harvest
!          or damage
! CMOBSR   Stage-dependent potential C mining rate from storage organ
!          expressed as a fraction of the maximum rate (CMOBSRX)
! CMOBSRN  Minimum fraction of C which can be mobilized from
!          storage organ in a day
! CMOBSRX  Maximum fraction of C which can be mobilized from

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! storage organ in a day  
 ! CRUSSR C mobilized from storage organ tissue in a day ( $g[CH_2O] / m^2 / d$ )  
 ! DNADRAT Denominator of calculation for NADRAT. Separated out to  
 ! prevent divide by 0.0 errors.  
 ! FNINSR Maximum fraction of N for growing storage organ tissue  
 ! ( $g[N] / g[storage]$ )  
 ! FNINSRG Minimum fraction of N for growing storage organ tissue  
 ! ( $g[N] / g[storage]$ )  
 ! FRSTR Fraction of vegetative tissue growth that goes to storage organs  
 ! on a day ( $g[storage] / g[veg]$ )  
 ! L A counting variable  
 ! LKNRET "Generic" variable for amount of NLEAK potentially attributed  
 ! to an N source (NMINEA, NFIXN, TRNU) ( $g[N] / m^2 / d$ )  
 ! NADSH N added back to shell N reserves - excess mobilized N  
 ! (never really mobilized)( $g[N] / m^2 / d$ )  
 ! NADSR N added to storage organ N reserves ( $g[N] / m^2 / d$ )  
 ! NGRSR Maximum N demand for storage organ growth  
 ! ( $g[storage\ N] / m^2[ground] / d$ )  
 ! NGRSRG Minimum N requirement for storage organ growth  
 ! ( $g[storage\ N] / m^2[ground] / d$ )  
 ! NL Maximum number of soil layers = 20  
 ! NLAYR Actual number of soil layers  
 ! NLKCOST "Generic" term for the original respiration cost for acquiring  
 ! and reducing all "recovered" NLEAK to CP. ( $g[CH_2O] / m^2 / d$ )  
 ! NLKCOST Total cost of N for new growth generated from NLEAK.  
 ! Includes both the actual N in the new tissue but the amount of N  
 ! "returned" to the source to "recover" the  $CH_2O$  used to acquire it.  
 ! ( $g[N] / m^2 / d$ )  
 ! NLKGROW N "returned" to the source to "recover" the  $CH_2O$  used to acquire it.  
 ! ( $g[N] / m^2 / d$ )  
 ! NRFRESP N "recovered for respiration". NLEAK "returned to source in  
 ! exchange for the  $CH_2O$  used to acquire it ( $g[N] / m^2 / d$ )  
 ! NRSPCST "Generic" variable name for N respiration cost or  $CH_2O$  cost  
 ! to acquire a gram of N from a given source. Assumes values of  
 ! RPRO, RFIXN, or RNNU depending on N source. ( $g[CH_2O] / g[protein]$ )  
 ! NSOURCE "Generic" variable name for N source that NLEAK is being "returned"  
 ! to. Assumes the values of NMINEA, NFIXN, or TRNU depending on  
 ! source of N ( $g[N] / m^2 / d$ )  
 ! NUPNO3(L) Proportion of TRNU from a soil layer that is nitrate  
 ! NUPNH4(L) Proportion of TRNU from a soil layer that is ammonium  
 ! PNTVG Percent N in vegetative tissues at initial or max protein concentration.  
 ! PNUPNH4 Proportion of TRNU that is  $NH_4$   
 ! PNUPNO3 Proportion of TRNU that is  $NO_3$   
 ! PPMFAC Reduction in mobilization from storage organ due to photoperiod  
 ! induced dormancy  
 ! PNMLF Proportion of actually mobilized N mobilized from leaves in a day

! PNMST Proportion of actually mobilized N mobilized from stems in a day  
 ! PNMRT Proportion of actually mobilized N mobilized from roots in a day  
 ! PNMSR Proportion of actually mobilized N mobilized from storage organ in a day  
 ! PNMSH Proportion of actually mobilized N mobilized from shells in a day  
 ! PROSRG Normal growth protein composition in storage organ during growth  
 !  $(g[\text{protein}] / g[\text{storage}])$   
 ! PROSRI Maximum protein composition in storage organ during growth with  
 ! luxurious supply of N  $(g[\text{protein}] / g[\text{storage}])$   
 ! PROSRT Protein fraction of new storage organ growth  $(g[\text{protein}] / g[\text{storage}])$   
 ! PWLF Weighting factors for partitioning N when refilling old leaf tissues  
 ! PWRT Weighting factors for partitioning N when refilling old root tissues  
 ! PWSR Weighting factors for partitioning N when refilling old STOR tissues  
 ! PWST Weighting factors for partitioning N when refilling old stem tissues  
 ! RFIXN  $\text{CH}_2\text{O}$  required for biological N fixation  $(g[\text{CH}_2\text{O}] / g[\text{protein}])$   
 ! RNH4C  $\text{CH}_2\text{O}$  required for protein synthesis when source of N is  
 ! ammonium uptake  $(g[\text{CH}_2\text{O}] / g[\text{protein}])$   
 ! RNNGR  $(g[\text{N}] / m^2 / d)$  that must be "returned" to "release" enough  $\text{CH}_2\text{O}$   
 ! to produce 1 gram of new growth  
 ! RNNU Actual  $\text{CH}_2\text{O}$  required for protein synthesis when source of N is  
 ! ammonium + nitrate uptake  $(g[\text{CH}_2\text{O}] / g[\text{protein}])$   
 ! RNO3C  $\text{CH}_2\text{O}$  required for protein synthesis when source of N is  
 ! nitrate uptake  $(g[\text{CH}_2\text{O}] / g[\text{protein}])$   
 ! RPRO Respiration required for re-synthesizing protein from mobilized N  
 !  $(g[\text{CH}_2\text{O}] / g[\text{protein}])$   
 ! STRWT Dry mass of storage organ tissue, including C and N  
 !  $(g[\text{storage}] / m^2[\text{ground}])$   
 ! UNO3 Uptake of  $\text{NO}_3$  from soil (interim value) (kg N/ha)  
 ! UNH4 Uptake of  $\text{NH}_4$  from soil (interim value) (kg N/ha)  
 ! WCRSR Mass of  $\text{CH}_2\text{O}$  reserves in storage organ  $(g[\text{storage CH}_2\text{O}] / m^2[\text{ground}])$   
 ! WSRDOTN Dry weight growth rate of new storage organ tissue including N  
 ! but not C reserves  $(g[\text{stem}] / m^2[\text{ground}]-d)$   
 ! XTVEGM "Extra" new growth generated from "returning" NLEAK to its sources  
 ! in exchange for the  $\text{CH}_2\text{O}$  used originally to acquire that amount  
 ! of N  $(g[\text{vegetative tissue}] / m^2-d)$



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## BIOGRAPHICAL SKETCH

Stuart James Rymph was born on June 10, 1961 in Ithaca, NY to Thelma S. and Donald E. Rymph. As his parents shifted careers from a private veterinary practice to a diversified crop farm, his home environment provided Stuart with broad experience, an intense interest in animals and plants, and a sense of practicality to complement the academic teachings he received. He received his high school diploma from Greenwich Central School in Greenwich, NY in 1979 and began studies at Cornell University, Ithaca, NY. While at Cornell, Stuart took a variety of courses in agronomy, animal science, agricultural engineering, and agricultural economics. He graduated with a degree in general agriculture in 1983.

On graduation he joined the Wayne Feed Division of Continental Grain Company as a sales trainee. One year later he married Mary Beth Hall and, after a brief honeymoon, moved to Western NY as a district salesman, supporting independent feed dealers in Western NY and Northern PA. In 1988, he left Wayne Feeds to work as a nutritionist for Ag Network, Inc., an independent feed processor/manufacturer and fertilizer blender. Two years later he and his wife returned to the Ithaca area so that Mary Beth could pursue a Ph.D. degree in ruminant nutrition at Cornell. While there, Stuart worked as a nutritionist for a local feed mill and fertilizer blender, Ward & VanScoy, Inc., and became a Certified Crop Adviser.

On completion of her degree in 1996, Mary Beth was hired as an assistant professor by the University of Florida. Stuart seized the opportunity to pursue answers to questions

that arose in his nutrition work and completed a Master of Science degree program in agronomy with a minor in dairy science at UF in 1999. His Ph.D. program was undertaken to expand his experience with forage crops and further his qualifications for working in nutrient management with dairy farms.