THE EFFECT OF AGE OF SUNN HEMP (*CROTALARIA JUNCEA* L.) AS A COVER CROP AND SOIL AMENDMENT ON PHYSIOLOGY, NITROGEN UPTAKE AND GROWTH OF PAPAYA (*CARICA PAPAYA* L.)

By

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To my wife and children, who have been a constant source of support and encouragement during the challenges of graduate studies and life. I am truly thankful for having them in my life. This work is also dedicated to my parents, whose good examples have taught me to work hard for the things that I aspire to achieve

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(A)	Net CO_2 assimilation
ADF	Acid detergent fiber, which is predominantly cellulose and lignin
(E)	Transpiration
(g_s)	Stomatal conductance
N	Nitrogen
NDF	Neutral detergent fiber, which is predominantly hemicellulose, cellulose and lignin
OM	Organic matter content

Abstract of Thesis Presented to the Graduate School
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Growth of several crops in south Florida, including papaya, have benefited from the use of sunn hemp (*Crotalaria juncea*)as a cover crop, which is grown for several months (generally to a height of 2.5-3.0 meters) and then mowed and incorporated into the soil prior to crop planting. An experiment was conducted at the University of Florida, Tropical Research and Education Center (TREC) to assessthe effects of sunn hemp age at the time of mowing on decomposition rate and N release in the soil. Pots 57 L were filled with Krome very gravelly loam soil. Polyester screen bags containing chopped leaves and stems of one-, two-, or three-month(s)-old sunn hemp (Treatments 1-3 as described for the other experiment) were buried approximately 25 cm below the soil surface in each pot. The sunn hemp was weighed prior to being placed in each bag. Each pot contained 10 bags of sunn hemp and all 10 bags per pot contained plant tissues from the same sunn hemp treatment. There were 4 replications (pots) per treatment. At two-week intervals, 1-2 bags from each replication were removed from the soil and changes in sunn hemp fresh and dry weights, N, and fiber contents (ADF and NDF) were determined over time. Age of sunn hemp at the time of mowing and burying stem and leaf tissues into Krome very gravelly loam soil affected the decomposition rate

of the buried plant tissues. For all sunn hemp treatments, there was a rapid decrease in dry weight of the plant tissues during the first 14 days after burying tissues in the soil, followed by a very slow gradual decrease over the rest of the study period. The possible reasons for this are discussed.This study suggests that instead of the standard practice of mowing and incorporating sunn hemp into the soil when it is approximately three months old, an earlier age (one-month-old) will facilitate breakdown of the plant material and also provide a longer lasting source of slow-release N.

In a concurrent experiment,preformed to investigatephysiology, growth, and nitrogen (N) uptake of 'Red Lady' papaya (*Carica papaya* L.) plants. Sunn hemp was planted in Krome very gravelly loam soil, resulting in the following treatments: one-, two-, and three-months-old sunn hemp incorporated into the soil, and 4) a control treatment with no sunn hemp. Papaya plants were planted in the field at TREC in 57 L plastic pots containing soil from one of the four sunn hemp treatments. Pots were buried in the field so that approximately the top 10 % of each pot protruded above the soil surface. Each sunn hemp treatment was subdivided into two inorganic N fertilizer treatments: standard N and low N applied to the soil at two-week intervals. Thus, there were 4 sunn hemp treatments and 2 nitrogen treatments for a total of 8 treatments with 5 replications per treatment. Soil N and organic matter (OM) contents, and papaya physiology, petiole nitrate-N content, plant growth, time to first flowering and fruit yield were assessed for plants in each treatment. In general, there were no significant effects of sunn hemp treatment, regardless of the amount of inorganic N fertilizer application, on soil OM or N or physiology, growth and yield of papaya plants. The possible reasons for this are discussed.

CHAPTER 1
INTRODUCTION AND LITERATURE REVIEW

Introduction

Papaya (*Carica papaya* L.) is an herbaceous perennial fruit bearing plant cultivated widely in approximately 60 countries (Evans et al. 2012). Although, the exact center of origin has not been determined, papaya is considered to be native to southern Mexico and Central America (Campostrini and Glenn, 2007). The center of origin of Carica papaya is believed to be the Caribbean coast of Central America (Van Droogenbroeck et al. 2004; Aradhya et al. 1999). However, papaya may have originated in the West Indies (Crane, 2016).

Papaya is grown in most tropical and subtropical countries for its nutritional value, easy cultivation, fast economic returns, and adaptation to various tropical soils and climates (Evans et al. 2012; Crane, 2016). India, Brazil, Indonesia, Nigeria and Mexico are the main papaya producing countries (Evans et al. 2012). In 2010, the total world papaya production reached more than 11 million metric tons. Annual papaya production in the United States was 14,000 tons in 2011 (Evans et al. 2012). Florida and Hawaii have most of the commercial production in the United States due to their suitable climatic conditions, additionally more than 95% of U.S papaya exports was from the state of Hawaii. (Evans et al. 2012; Gonçalves de Oliveira and Pierre-Vitória, 2011).

Botanically, the papaya plant is a giant herb that may reach a height of approximately 9 m (Campostrini and Glenn, 2007). Compared to most fruit crops, it is short-lived, with a rapid growth rate. Some papaya plants yield fruit for more than 20 years (Malo and Campbell, 1994). Papaya leaves are soft, lobulated, with long petioles that measure up to 50 cm long (Paull and Duarte, 2011). The fruits grow in clusters from the top of the plant. Papaya plants start fruiting approximately 10-14 months after germination. Depending on the cultivar and orchard management practices, the fruit needs approximately 5-6 months to grow and develop (Paull and Duarte, 2011).

Papaya belongs to the plant family Caricaceae (Manshardt, 2012). Recently, classification of the Caricaceae has been revised to divide the family into six genera: Cylicomorpha, Horovitzia, Vasconcella, Jacarita, Jacarilla, and Carica (Aradhya et al. 1999; Van Droogenbroeck et al. 2002, 2004; Kubitzki, 2003; Badillo, 2000; Badillo, 2001; Costa et al. 2008). The mountain papaya species were originally considered to be in the genus Carica, but are now classified into the genus Vasconcella, which has 21 species (Badillo, 1993, 2000, 2001; Costa et al. 2008). All of the Vasconcellea are native to South America.

There are two types of papaya, small fruit bearing (aka Hawaiian type) and large fruit bearing (aka Mexican type). Solo type papaya is the most widely known of the Hawaiian type. The Solo type papaya originated in Barbados, was introduced to the Hawaiian Islands, and exported from there as “Hawaiian papaya” (Evans et al. 2012). ‘Maradol’ is the best known of the large fruit-bearing papaya cultivars (Evans et al. 2012). ‘Maradol’ originated in Cuba from a breeding program (Evans et al. 2012).

Papaya Cultivation and Production

Papayas are usually grown from seeds, which undergo germination 2 to 3 weeks after sowing (Fisher, 1980). Some papaya plants are dioecious whereas some plants produce hermaphrodite flowers. Also some plants are monoecious, having both male and female flowers. Depending on the season, they will produce either male or female flowers (Paull and Duarte, 2011). It usually takes approximately 6 months after germination to be able to visually differentiate the sex of papaya plants (Gonsalves, 1998). For high fruit yield, a male to female plant ratio of one male per 8 to 10 female plants is recommended for dioecious plants (Paull and Duarte, 2011; Chay-Prove et al. 2000).

Papaya is a frost sensitive plant that can only be grown in tropical and subtropical climates. Typically, papaya grows best in warm areas with high humidity. A suitable climate for papaya production occurs at latitudes between 32° North and South (Litz, 1984). Temperatures for optimal plant growth range from 22 to 26oC. The crop may be cultivated in most well drained soils and does best in fertile soils (Morton, 1987). Optimum rainfall of approximately 100 to 150 cm distributed throughout growing period is ideal for non-irrigated papaya (Litz et al. 1983; Morton, 1987). Papaya fruit production is best when at least 100 mm of water is supplied per month through rain and/or irrigation (Nishina et al. 2000; Chan and Paull, 2008).

Effects of Nutrients on Papaya Growth and Production

Papaya production and quality is greatly influenced by unfavorable environmental and edaphic conditions such as soil fertility, soil drainage, flooding, unfavorable ambient temperatures, drought, and wind (Campostrini et al. 2010). Papaya plants tolerate an extensive range of soil conditions and pH levels from highly acidic (pH=4) to alkaline (pH=9) soils (Marler, 1998). However, papaya develops best in well-aerated soils rich in organic matter with a pH of 5.5 to 6.7 (Litz, 1984; Morton, 1987). Papaya plants can show nutrient deficiency symptoms when grown at a lower or higher pH (Samson, 1986; Manshardt and Zee, 1994; Marler et al. 1994; Wang et al. 2009).

Papaya growth, development, and leaf gas exchange significantly increased with increased light exposure; leaf gas exchange responded rapidly to changes in light intensity and soil moisture content (Marler et al. 1994; Clemente and Marler, 1996; Marler and Mickelbart, 1998). Papaya fruit developed much more quickly when plants were exposed to full sunlight compared to shaded conditions (Samson, 1986).

Studies of papaya nutrition have shown an ideal plant response to fertilizer rates of approximately 300 g each of N, P2O5, and K2O (Kumar et al. 2010). Reducing N supply by 25%, when provided through drip irrigation, resulted in plants with the same net photosynthesis, water use efficiency, fruit yield and quality, as plants that receive total recommended N rate through soil application (Jeyakumar et al. 2010).

Increasing soil organic matter content has been shown to increase growth and yields of papaya. In south Florida, growing plants in Krome very gravelly loam soil amended with municipal solid waste compost increased the number of early fruit (Basso-Figuera et al. 1994) compared to plants in non-amended soil. Studies performed in India of organic papaya production practices include the use of sunn hemp (*Crotalaria juncea* L.) residue as an organic nutrient amendment. One study found a decrease in papaya yield when soil was amended with sunn hemp residue compared to conventional fertilization (Reddy et al. 2010). Another study showed no yield differences between papaya plants fertilized with 40 kg sunn hemp and plants receiving conventional fertilization. However, papaya fertilized with 25 kg sunn hemp showed a yield reduction (Ravishankar et al. 2010a; Ravishankar et al. 2010b).

Few papaya studies addressed intercropping as a method to increase soil nutrient availability. A recent study by (Vincent et al. 2017) showed that intercropping papaya with sunn hemp increased papaya growth and productivity. This study indicated that sunn hemp intercropping helped the plant to cope with unfavorable environmental conditions such as high wind speeds and diseases, mainly papaya ringspot virus (PRSV) responsible for the devastating damage to the papaya industry in United States and many other papaya production regions throughout the world (Mossler and Crane, 2013 ;Evans et al. 2012.).

One study reported that intercropping of papaya with okra and cucumber reduced yields from 55 t ha-1 to 45 t ha-1 (Olubode et al. 2012). Another study comparing conventionally N-fertilized papaya with unfertilized papaya intercropped with four low growing legume crops: jack bean (*Canavalia ensiformis*), velvet bean (*Mucuna pruriens*), cowpea (*Vigna unguiculata*), and lablab (*Lablab purpureus*), (Vieira Neto, 1995). Papaya growth and yield were similar for the N-fertilized treatment and the unfertilized treatments intercropped with jack bean or velvet bean. However, intercropping papaya with cowpea or lablab caused growth and yield reductions.

Papaya Fertilization

Pre- and post-planting fertilizer applications are essential for ideal papaya production. Pre-planting fertilization involves phosphate applications in phosphorus poor soils and application of liming materials, which help adjust soil pH (Paull and Duarte, 2011). Most soil applied granular fertilizers include nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg). Foliar applied fertilizers include magnesium, manganese (Mn), zinc (Zn), iron (Fe), and boron (B) (Crane, 2016; Barker and Pilbeam, 2007; Paull and Duarte, 2011).

In general, papaya needs large amounts of fertilizer for good yields and fruit quality (Rajbhar et al. 2010). Vigorous and healthy plants are less susceptible to biotic and abiotic stresses (Hardisson et al. 2001). Nutrient fertilizer applications in commercial farms are based on experience, soil and petiole analyses, leaf color through visual assessments, and plant behavior (Awada et al. 1986; Paull and Duarte, 2011; Nishina et al. 2000). The ideal nitrogen concentration of the petiole ranges between 1.15 to 1.33% (Awada and Long, 1971b; Awada, 1977).

A recommended papaya fertilization program in Hawaii starts with 200 g per plant of granular superphosphate (0-45-0) along with microelements (Awada and Long, 1980; Nishina et al. 2000) applied before transplanting. After transplanting, 113.5 g of NPK fertilizer (16-16-16) is applied (Awada and Long, 1980; Nishina et al. 2000). Kumar et al. (2008, 2010) suggested a balanced fertilizer with NPK in the amount of 300 kg ha-1year-1 to boost latex production. For 'Solo' papaya in Hawaii, Awada (2007) suggested that 0.44 kg of N per plant applied at 6-week intervals was optimal for plant growth and development.

In Florida, regular applications of small amounts of complete fertilizers (N, P, K, Mg and micronutrients) are suggested for cultivating healthy papaya plants that produce acceptable quality fruit (Crane, 2016; Migliaccio et al. 2010). The suggested recommendations for N begin with applications of 0.11 kg per plant per month during the juvenile stage, which increases to 0.45-0.90 kg per plant per month when plants start bearing fruit (Crane, 2016; Migliaccio et al. 2010).

Nitrogen enriches the green color, size, and shape of papaya leaves (Awada and Long, 1971a). Nitrogen deficiency symptoms appear first in mature leaves where the color changes from green to light green; severely N-deficient leaves turn yellow and abscise (Mengel and Kirkby. 1987; Marschner, 1995; Epstein and Bloom. 2005). Nitrogen deficient new leaves have smaller petioles and the laminas are not well established compared to non-deficient leaves (Johnston, 2007; Costa and Costa, 2003; Cunha, 1979; Cibez and Gaztambide, 1978). N-deficient plants have reduced ability to tolerate strong winds (Awada, 1977; Cibes and Gaztambide, 1978).

When N is in excess, papaya plants may have excessive vegetative growth, causing increased internode length, less fruit set and lower fruit quality. Extra nitrogen fertilization has resulted in increased petiole concentrations of N, Fe, Cu, Mn, and Zn and reduced petiole concentrations of P, K, Ca, and B (Awada and Long, 1980).

Phosphorous is a crucial element for root development and function (Marschner, 1995; Epstein and Bloom, 2005). Phosphorus applications have been shown to maximize petiole weight and K assimilation and enhance fruit set of papaya (Cibes and Gaztambide, 1978). Phosphorous also improved the trunk growth rate of papaya. Petiole P concentrations were highly positively correlated with yield of marketable fruit (Awada and Long, 1978). Phosphorus fertilization enhanced petiole content of N, P, Fe, Mn, and Zn, and reduced Ca, K, S, and Cu concentrations (Awada et al. 1975; Cibes and Gaztambide, 1978). The ideal leaf petiole P concentrations range from 0.16 to 0.20% (Awada and Long, 1969, 1978).

High P application rates can lower N, Ca, and Mg uptake. Symptoms of P deficiency start in the oldest leaves, which exhibit a spotted yellow color along the margin of the mature leaf laminas; ultimately, leaves may appear dark green with some reddish and purple spots (Costa and Costa, 2003). When P deficiency is severe, plants develop new leaves, which are small in size, the lamina twists upward from the leaf edges, and leaves turn entirely yellow. Excess P causes leaf burning and eventually leaf abscission (Awada and Long, 1978).

Potassium is an essential element responsible for increasing papaya fruit size, quality and total soluble solids content (Gaillard, 1972; Coelho et al. 2001; Oliveira and Caldas, 2004). Potassium application increases papaya trunk thickness at the bearing stage (Olivera and Caldas et al. 2004). An N:K ratio close to 1:1 is recommended for achieving optimum yield (Coelho et al. 2001). Leaf symptoms of K deficiency appear in older leaves first, include yellowing and start from the central vein to the leaf edges (Mengel, and Kirkby. 1987; Epstein and Bloom. 2005). Also, petioles become smaller, leaves may become chlorotic and leaf abscission increases as a result of K deficiency in papaya (Thomas et al. 1995; Costa and Costa, 2003). Severe K deficiency results in a reduction of leaf and fruit numbers and trunk diameter (Awada, 1977). Excess K can cause leaf scorching and abscission (Cibes and Gastambide, 1978). Potassium fertilization increased K and Mn concentrations and increased N, Na, Ca, and Mg concentrations in the leaf petiole (Awada and Long, 1971a, 1980).

Calcium is an important nutrient for root growth and development and to increase new root dry weight in papaya seedlings (Gaillard, 1972; Bohn et al. 1979; Texeira da Silva et al. 2007). Calcium fertilization increased root length of papaya growing in a tropical volcanic acid subsoil (Marler and de la Cruz, 2001). Calcium uptake can increase P, K, and Mg in leaves (Cibes and Gaztambide, 1978). Calcium deficiency initially appears in meristematic regions and in actively photosynthesizing young leaves (Epstein and Bloom, 2005). Symptoms of Ca deficiency include chlorosis of young leaves and necrotic spots on the leaf laminae. Severe Ca deficiency results in fewer leaf lamina lobes with a curled appearance. Ultimately, leaves become twisted with weak petioles and eventually abscise. Calcium deficiency resulted in fruit pulp softening and decreased postharvest shelf life (Cibes and Gaztambide, 1978; Mengel and Kirkby, 1987; Marschner, 1995; Costa and Costa, 2003; Epstein and Bloom, 2005).

Magnesium is a component of the chlorophyll molecule and therefore essential for photosynthesis (Merhaut, 2007). Deficiencies of Mg appear initially in old leaves, which turn yellow in color, but the vein borders and internal veins of the leaf laminae stay green (Thomas et al. 1995; Epstein and Bloom. 2005). Leaves may also show several small necrotic spots that fuse to form large straw colored areas. Severe Mg deficiency symptoms on young leaves are similar to those on older leaves (Cibes and Gaztambide, 1978). Leaf petiole Mg content is increased by P fertilization, but is decreased with increased K and Ca uptake (Awada, 1977).

Sulfur is an important nutrient for papaya growth and development and influences yield and fruit quality (Haneklaus et al. 2008). Sulfur has been shown to increase plant starch and protein buildup and is a constituent of papain (Costa and Costa, 2003). Sulfur deficiency develops in young leaves, which change color from light green to yellow. Severe S deficiency results in complete yellowing of old leaves (Cibes and Gaztambide, 1978), Moreover, plants become thin and grow poorly if they are deficient in S (Epstein and Bloom, 2005).

Micronutrients are needed in smaller amounts than macronutrients. Micronutrients important to papaya include iron (Fe), manganese (Mn), boron (B), copper (Cu), molybdenum (Mo), zinc (Zn), chlorine (Cl), and nickel (Ni) (Mengel and Kirkby, 1987; Brown et al. 1987).

Manganese deficiency appears first on young leaves as a minor chlorosis with a mottling along the veins of the leaf lamina (Mengel and Kirkby, 1987; Marschner, 1995; Epstein and Bloom, 2005). Severe Mn deficiency resulted in leaf color change from green to yellow (Cibes and Gaztambide, 1978; Thomas et al. 1995; Costa and Costa, 2003). Additionally, necrotic regions may form and leaves develop misshapen and undersized (Epstein and Bloom, 2005). Manganese toxicity is characterized by brown spots on older leaves bounded by chlorotic areas, loss of apical dominance, and the creation of auxiliary shoots (Mengel and Kirkby, 1987).

Zinc is a vital element required for N metabolism, protein synthesis, leaf expansion, and in certain enzyme systems in the cytoplasm and the chloroplasts of plants (Mengel and Kirkby, 1987; Marschner, 1995; Epstein and Bloom, 2005). Zinc deficiency first occurs in young leaves and results in poor leaf growth. Symptoms of Zn deficiency are leaf wrinkling with mottled spots that expand rapidly. Severe Zn deficiency results in young leaves remaining small in size and reduced internodes forming a rosette of chlorotic leaves which turn yellow with necrotic areas along the borders of the leaf laminae (Costa and Costa, 2003; Epstein and Bloom, 2005). Zinc toxicity causes a reduction of leaf lamina area and a decline in root development (Mengel and Kirkby, 1987).

Iron is an important microelement that contributes to nearly 140 enzymes that catalyze biochemical reactions in plants (Brittenham, 1994). Iron deficiency appears as a general interveinal chlorosis in young leaves (Epstein and Bloom. 2005). Iron fulfills several vital roles in plant growth and development; including chlorophyll synthesis, thylakoid synthesis and chloroplast development. Iron is required at several steps in the biosynthetic pathways (Sanz et al. 2002). Typical iron deficiency symptoms include interveinal chlorosis, i.e., the laminae becomes increasing chlorotic between the viens, but the veins remain dark green (Marchner, 1995). Iron deficiency constrains leaf growth, cell number, size and cell division, as well as chlorophyll, protein, starch and sugar content (Marschner, 1995). Severe iron deficiency symptoms in young leaves are characterized by a color change from entirely yellow to white (Thomas et al. 1995).

Boron is an important microelement. Boron deficiency may cause an accumulation of N, P, K, Ca, and Mg (Cibes and Gaztambide, 1978; Marschner, 1995) and ultimately leaves may abscise (Thomas et al. 1995). Boron deficient plants exhibit elongated growth, increased abnormal flower abortion, reduced fruit set, and the plant may die back (Cibes and Gaztambide, 1978). Boron toxicity results in leaf tip yellowing followed by necrosis, and premature leaf drop causing a reduction in plant growth (Mengel and Kirkby. 1987).

Cover Crops

Cover crops are commonly defined as crops planted between cash crops to control loss of nutrients, pesticides, or residue from agricultural fields and provide a soil cover to decrease soil erosion (Reeves, 1994; Dabney et al. 2001; Phatak et al. 2002). Cover crops may be used in farming systems as companion crops to cash crops or may be grown during fallow times between cash crops in crop rotations. Cover crop incorporation into soil results in many benefits such as maximized residue cover, integrated pest management, carbon sequestration, increased soil productivity, and recycled nutrients (Marshall et al. 2002; Taboada-Castro et al. 2006; Balkcom et al. 2007). Cover crop debris additionally affect the volume of nutrients from soils accessible to subsequent crops (Dalal, 1989; Mehdi et al. 1999).

Recently, with the rapid increase of chemical fertilizer costs, many farmers have begun searching for alternative nutrient sources to meet their production targets. These alternative nutrient sources include the use of cover crops. Apart from financial concerns, ecological concerns regarding producers' dependency on chemicals, such as fertilizer leaching into the groundwater, has increased the desirability of biological sources of N (Aulakh et al. 1991). Leguminous cover crops deliver additional benefits due to their ability to fix atmospheric N and P (Vaughn and Evanylo, 1998; Cherr et al. 2006a). Several field studies have indicated that effects of legumes as cover crops on N accumulation, biomass production, and the crop C: N ratios are greatly variable, partly because they are influenced environmental conditions, legume selection, growth phase, and crop management (Aulakh et al. 1991; Reeves, 1994; Ranells and Wagger, 1996; Mansoer et al. 1997; Cline and Silvernail, 2001; Balkcom and Reeves, 2005).

Nitrogen from cover crop incorporation into the soil generally involves quick immobilization and extended mineralization of N (Aulakh et al. 1991; Maskina et al. 1993; McKenney et al. 1995; Mansoer et al. 1997; Medhdi et al. 1999). Therefore, cash crop planting dates after cover crops must be designed to maximize the use of nutrients released from the cover crop residue. Yadvinder et al. (1992) found that biomass production occurs in tropical legumes at a more rapid rate than that of temperate legumes. While incapable of withstanding hard freezes, tropical legumes keep growing at temperatures from 35°C to 40°C, while growth of temperate legumes declines at temperatures from 25°C to 30°C (Cherr et al. 2006a). Tropical legumes have been found to increase soil N and organic matter contents during the period before winter freezes (Creamer and Baldwin, 2000; Marshall et al. 2002).

Sunn Hemp

The use of sunn hemp (*Crotalaria juncea* L.) as a tropical cover crop started with its use as a fiber crop and soil amendment in India (Montgomery, 1954; Bhardwaj et al. 2005). Distribution of most sunn hemp varieties is exclusive to specific regions (Kundu, 1964). Sunn hemp breeders have concentrated on enhancing fiber yield, insect resistance, and speeding crop maturity (Ribeiro et al. 1977; Miranda, 1991). These breeding studies identified a correlation between plant height and basal stem circumference, showing that the possibility exists to develop sunn hemp cultivars capable of producing much greater biomass then the currently available cultivars.

The sunn hemp cultivar Tropic Sun was initially introduced by the USDA, Natural Resources Conservation Service and the College of Tropical Agriculture and Human Resources, University of Hawaii in 1983 (Mansoer et al. 1997; Balkcom and Reeves, 2005). 'Tropic Sun' was noted for yielding 5.9 Mg ha-1 biomass within a 9 -12 weeks period after August and mid-September when cultivated in Alabama (Mansoer et al. 1997; NRCS, 1999). Due to limited area fit for seed production and elevated seed cost, cultivars other than 'Tropic Sun' have not been as broadly studied for cover crop application (Cook and White, 1996).

The major sunn hemp seed production areas such as Hawaii, Brazil, and India, have high relative humidity, standard rainfall averaging between 150 to 200 mm, and daily temperatures between 23°C and 29.4°C during the crop growth and development period (Dempsey, 1975). Southern Texas has been an area of small scale seed production, although harvests have been variable due to early freezes (Cook and White, 1996). Recently, sunn hemp seed has been produced commercially in Miami-Dade County, Florida (Bruce Schaffer, personal communication).

Sunn hemp dry matter production and N content during the early growth stages were recorded by Cherr et al. (2006b). Four weeks after planting, dry matter of leaves ranged from 50 to 60% of the total plant dry matter (Cherr et al. 2006b). After four weeks, the greatest amount of dry matter was shifted to the stem. Leaves and flowers incorporated into the soil at 8-10 weeks after planting had more than 50% higher nitrogen concentration than 14-week-old leaves and flowers when incorporated into the soil (Cherr et al. 2006b). Sunn hemp produces a large amount of biomass ranging from 4.8-7.3 Mg ha-1 in a sandy loam soil (Mansoer et al. 1997) but may reach up to 6.1-9.6 Mg ha-1 (Ramos et al. 2001). In one study, fertilized sunn hemp produced 7.6 Mg ha-1 biomass by 14 weeks after planting (Balkcom and Reeves, 2005). In another study of sunn hemp, 12.1 Mg ha-1 biomass was produced by 14 weeks after planting (Steinmaier and Ngoliya, 2001).

Establishment dates of different sunn hemp cultivars vary depending on cultivation areas based on temperature and soil moisture in each region (White and Haun, 1965; Cook and White, 1996; Bhardwaj et al. 2005; Schomberg et al. 2007). Photoperiod length greatly affects sunn hemp biomass (Pandey and Sinha, 1979). According to Pandey and Sinha (1979), sunn hemp dry weight and leaf area reached maximum levels with a day length of 14 hours. Sunn hemp enters a reproductive growth phase in response to declining photoperiods. This developmental response makes sunn hemp a short day crop (White and Haun, 1965; Qi et al. 1999).

Marshall et al. (2002) stated that the sunn hemp cultivar 'Tropic Sun' yielded 56-19-36 Kg ha-1 of N-P2O5-K2O, which is equivalent to 3:1:2 N-P-K fertilizer ratio. In the same study, plant incorporation at mid-bloom was considered to be optimal for vegetable crops due to higher macronutrient availability and a low C:N ratio (Marshall et al. 2002). A study of 'Tropic Sun' found that the C:N ratio in the stem was greater than 20:1, whereas the leaf C:N ratio was less than 20:1 (Mansoer et al, 1997). Cherr et al. (2006b) concluded that sunn hemp reserves large quantities of N and reduced breakdown linked to the structural partitioning of dry matter and minerals in the stem. Sunn hemp residue rapidly decomposes in humid weather (Cherr et al. 2006a), mainly the leaves and flowers that comprise approximately 80.6% of the overall nitrogen and 66.5% of the total P concentrations (Marshall et al. 2002).

Research Objectives

The overall objectives of this study were to examine the effects of the stage of development (age) of sunn hemp incorporated into the soil on the rate of sunn hemp decomposition, soil nitrogen and organic matter content and physiology and growth of papaya planted in sunn hemp amended soil. The hypotheses tested were: 1) the stage of development (age) of sunn hemp prior to mowing and incorporation into soil will significantly affect soil nitrogen and organic matter contents and growth and physiology of papaya planted in the amended soil; 2) the minimum rates of inorganic N required for papaya plants when sunn hemp is incorporated into the soil prior to papaya planting will be reduced significantly compared to control treatment with no sunn hemp added to the soil; 3) the time needed for decomposition of sunn hemp to achieve maximum release of nitrogen into the soil will occur during the first 10-14 days after sunn hemp incorporation into the soil; and 4) Fiber content(NDF-ADF) will be inversely related to N availability in sunn hemp plant tissues.

CHAPTER 2
DECOMPOSITION OF SUNN HEMP IN KROME VERY GRAVELLY LOAM SOIL

Introduction

The use of cover crops, including sunn hemp (*Crotalaria juncea* L.) has provided several benefits for growth and production of cash crops. Cover crops have been shown to reduce weed infestation, soil erosion and insect predation, and to increase soil nitrogen (N) and organic matter (OM) contents (Phatak et al. 2002). Leguminous cover crops such as sunn hemp, capable of N fixation, are beneficial for increasing soil N content in areas where inorganic N fertilizers are regulated, predominantly in organic and sustainable farming systems.

In south Florida, many tropical legumes are well suited as summer cover crops capable of yielding from 3 to 9 Mg dry matter ha-1 in 50 to 60 days through summer (Yadvinder et al. 1992). Sunn hemp is a tropical legume primarily used as a fiber crop, but also used as a soil amendment in the tropics (Duke, 1981; Cook and White, 1996). Studies with sunn hemp have primarily focused on its use as a cover crop following corn (Zea mays L.) (Mansoer et al. 1997; Balkcom and Reeves, 2005; Cherr et al. 2006) or intercropped with other vegetable crops such as okra (*Abelmoschus esculentus* L.) and cucumber (*Cucumis sativus* L.) (Olubode et al. 2012). A recent study by Vincent et al. (2017) showed that intercropping papaya with sunn hemp and then mowing and using the sunn hemp as a mulch when papaya plants were established, increased papaya plant growth and productivity.

The sunn hemp cultivar, Tropic Sun, from Hawaii is widely used as a cover crop because of its rapid growth and high biomass production (Rotar and Joy, 1983). Sunn hemp decomposes slowly in the soil and provides suitable cover and added N for the cash crop planted after the sunn hemp is mowed and incorporated into the soil (Mansoer et al. 1997; Balkcom and Reeves, 2005; Cherr et al. 2006). In south Florida, 'Tropic Sun' sunn hemp yielded more than 0.8 Mg ha-1 of biomass and approximately 150 kg N ha-1 when grown for 12 weeks in summer and then incorporated into the soil (Cherr et al. 2006).

In southern Florida, sunn hemp is increasingly used as a soil amendment for crops planted in Krome very gravelly loam soil, a porous oolitic limestone soil classified as a loamy-skeletal, carbonatic, hyperthermic lithic udorthents (Noble et al. 1996). In this soil, sunn hemp is typically grown for several months, to a height of approximately 2.5-3 meters, and then mowed and incorporated into the soil prior to planting the cash crop. At that stage of growth, sunn hemp stems are large and highly lignified (Yuncong Li, personal communication). Allowing sunn hemp to get to this stage of development prior to mowing and soil incorporation may result in a slow decomposition rate due to the high fiber content of the stem. This may reduce the effects of amending soil with sunn hemp on increasing soil N and OM contents. A better approach to using sunn hemp as a cover crop may be to mow the sunn hemp at an earlier growth stage (younger age) when stems are less lignified, which may hasten decomposition and yield of N from the sunn hemp incorporated into the soil.

The objective of this study was to determine the effects of sunn hemp age at the time of mowing and soil incorporation on the decomposition rate of sunn hemp in Krome very gravelly loam soil.

Materials and Methods

The experiment was conducted from August to December 2016 at the University of Florida's Tropical Research and Education Center (UF-TREC) in Homestead, Florida (25.5°N latitude and 85.5°W longitude).

Sunn hemp (*Crotalaria juncea* L.) cv. Tropic Sun seeds were planted in the field at the University of Florida's Tropical Research and Education Center in Homestead, Florida (latitude: 25º 30' 40.809" N; longitude: 80º 30' 3.983" W) on three dates with approximately 30 days between each planting as described in Chapter 3of this thesis. Planting dates were 3 May, 6 June, and 11 July 2016. Seeds were planted in Krome very gravelly loam soil, classified as a loamy-skeletal, carbonatic, hyperthermic lithic udorthents (Noble et al. 1996) in rows using a 2-m wide seed drill at a 30-mm depth with in-row spacing of 0.03 m and between row spacing of 0.76 m. Each sunn hemp planting consisted of three, 30 x 0.75-m plots. Thus, the planting dates resulted in three sunn hemp treatments based on plant age: 1) one-month-old sunn hemp, 2) two-months-old sunn hemp, and 3) three-months-old sunn hemp.

Above-ground plant tissue (leaves and stems) of sunn hemp was collected from each treatment and chopped into small pieces, first with pruning shears for the stem tissues and then with a razor blade and stainless steel herb scissors. Chopped leaf and stem tissues were then placed in 10 cm^2 polyester mesh screen bags with a screen size of 53 µm. Although fresh tissue was placed in each bag, the amount of tissue per bag per treatment was standardized so that the tissue in each bag would have approximately the same amount of dry weight, regardless of treatment. This was done by determining the difference between fresh and dry weight tissue weight for each treatment at the time of sunn hemp mowing in order to determine the percentage of water comprising the fresh weight of each treatment. The amount of combined fresh leaf and stem tissue placed in each bags was 30.27, 23.82, and 20.18 g fresh weight for the one-, two- and 3-months-old sunn hemp treatments, respectively

Plastic pots (57 L) were filled with Krome very gravelly loam soil. Prior to filling the pots with soil, holes slightly larger than the pot circumference were augured into the soil in the field to a depth of approximately 2/3 of the pot. The spacing between each hole was 2.1 x 3.6 meters. One pots was placed in each augured holes. In each pot, 10 mesh bags containing the sunn hemp tissues were placed under the soil at equidistant lateral locations at a depth of 10-15 cm. All 10 bags buried with a pot were from the same sunn hemp treatment. There were 4 pots (replications) per sunn hemp treatment arranged in a randomized complete block design.

An automated irrigation system with one microsprinkler (94.6 L\hr) per pot was used to irrigate the soil. Tensiometers (Irrometer Company, Riverside, CA, USA) were installed in two 2 randomly selected pots per treatment to monitor soil water tension and adjust irrigation accordingly. Tensiometers were maintained between 5 to 7 kPa during the experiment. Soil temperature was monitored in every pot with a Hobo Tidbit v2 datalogger (Onset Computer, Bourne, Massachusetts, USA) 10 cm below soil surface. Air temperature data during the experiment were from a weather station of the Florida Automated Weather Network (FAWN; http://fawn.ifas.ufl.edu/) located a few thousand meters from the experimental plots.

Measurements:Sunn Hemp

One week prior to mowing and incorporating sunn hemp into the soil, sunn hemp plant density, plant height, stem diameter, and fresh and dry weights were determined as described in Chapter 3 of this thesis. Plant density was measured by counting the number of plants in a 1 m^2 PVC frame. The PVC frame was randomly placed over a group of plants in a row in each treatment. This was done 8 times per treatment.

For plant height and stem diameter measurements, 20 sunn hemp plants were randomly selected in each treatment with sunn hemp treatment plants. Plant height was measured with a ruler and stem diameter was measured 10 cm above the soil surface with a caliper.

Sunn Hemp Tissue Decomposition

Every two weeks, one mesh bag was carefully extracted from the soil of each pot (replication) in each treatment. The exterior surface of each bag was cleaned thoroughly to eliminate soil particles attached to the outside surface of the bag. Each mesh bag was then weighed and the fresh weight of plant tissues in each bag was the determined by subtracting the bag weight (determined prior to placing tissue in the bag) from the total weight of the tissue and bag. Plant tissues were then removed from each bag and dried in a drying oven at 50°C to a constant weight. Tissue dry weights were then determined for each sample. This procedure was repeated every 2 weeks for 6 weeks. After 6 weeks, 2 bags were collected from each replication at each sampling period to provide a sufficient amount of tissue for N and fiber determinations. For tissue N and fiber content determination, dried tissue samples were milled through a Wiley Mill (Arthur H. Thomas Co., Philadelphia, PA, USA) to pass a 1-mm screen. The ground samples of each treatment were then placed in plastic bags and shipped to the Forage

Evaluation Support Laboratory of the University of Florida, Agronomy Department, Gainesville, Florida for total N and fiber analyses.

For Total N analysis, samples were digested using a modification of the aluminum block digestion procedure of Gallaher et al. (1975). Sample weight was 0.25 g, catalyst used was 1.5 g of 9:1 K_2SO_4:$CuSO_4$, and digestion was conducted for at least 4h at 375°C using 6 ml of H2SO4 and 2 ml H_2O_2. Nitrogen in the digestate was determined by semi-automated colorimetry (Hambleton, 1977).

Neutral detergent fiber (NDF) which is predominantly hemicellulose, cellulose and lignin) was determined using the ANKOM Technology Method 9 (http://agronomy.ifas.ufl.edu/pdfs/ndf_081606_a2000.pdf). Acid detergent fiber (ADF) which is predominantly cellulose and lignin were determined using the ANKOM Technology Method 8 (http://agronomy.ifas.ufl.edu/pdfs/adf_091606_a2000.pdf).

Soil Moisture and Temperature

Tensiometers readings were recorded twice weekly and irrigation was adjusted accordingly in order to keep the soil tension between 5 to 7 kPa in each treatment. At the end of the experiment temperature sensors/dataloggers were extracted from the soil and the soil temperatures throughout the experiment were downloaded to a desktop computer.

Data Analyses

Data were analyzed by one-way analysis of variance (ANOVA) and a Tukey's multiple range test at each sampling date to determine statistically significant differences in tissue decomposition, and tissue N and fiber contents among treatments.

The SAS statistical software package (SAS Institute, Cary, NC, USA) was used for all data analyses.

Results

Sunn Hemp Plant Density and Biomass Prior to Mowing

Prior to mowing the sunn hemp treatments and incorporating them into the soil, the mean plant density was 32, 28, and 36 plant m^{-2} for the one-month-old, two-months-old, and three-months-old sunn hemp treatments, respectively.

Just prior to mowing, above ground plant biomass was 2,211; 13,691; and 20,852 kg ha^{-1} for the one-month-old, two-months-old and three-months-old sunn hemp treatments, respectively. Mean stem height was 1052, 2259 and 2900 mm and mean stem diameter was 5.0, 10.5 and 16.4 mm for the one-month-old, two-months-old, and three-months-old sunn hemp treatments, respectively (Table 2-1).

Decomposition of Buried Sunn Hemp Tissues

Average air and soil temperatures, and soil moisture content (soil tension) during the experiment is shown in Figure 2-1.

There was a significant difference ($P<0.05$) in fresh weight among sunn hemp treatments on days 0, day 42, day 68 and day 80. On day 0 (prior to burying the tissue samples), the one-month-old sunn hemp treatment had highest fresh weight and the three-month old treatment had the lowest fresh weight. On days 42, 60 and 80, the one-month old treatment had significantly higher fresh weight than the three-month-old treatment (Figure 2-2).

There was a significant difference ($P < 0.05$) among treatments in dry weight of the buried tissues on days 28 and 80, with the one-month old treatment having a significantly higher dry weight than the other two treatments, but no significant difference between the other two- and three-month-old treatments on both of those days (Figure 2-3).There was a significant difference ($P < 0.05$) in tissue N content pf the buried plant tissues among sunn hemp treatments (Figure 2-3).

On each sampling date, buried plant tissue of the one-month-old sunn hemp treatment had a significantly higher ($P < 0.05$) N content than the other two treatments, but there was no significant difference ($P > 0.05$) in tissue N content between the two-month-old and three-month-old sunn hemp treatments.

There was a significant difference ($P < 0.05$) among treatments in NDF and ADF of the buried sunn hemp tissues on all sampling days except for day 56. On all sampling days except day 56, tissues of the one-month-old sunn hemp treatment had significantly lower NDF and ADF contents ($P < 0.05$). There were no significant differences ($P > 0.05$) in NDF or ADF among treatments on day 56 content than the three-months-old treatments (Figure 2-4).

Discussion

In this study, plant age at the time of mowing sunn hemp, prior to incorporating combined stem and leaf tissues into Krome very gravelly loam soil, affected the decomposition rate of the buried plant tissues. Prior to burying the plant tissues, there was a significant difference among treatments in tissue fresh weight, with the one-month-old treatment having the highest fresh weight, followed by the two-months-old treatment, with the 3-months-old treatment having the lowest fresh weight (Figure 2-2).

The amount of tissue placed in each bag was standardized based on tissue dry weight so that there was approximately the same amount of dry weight in each bag. This was calculated from the difference between the fresh and dry weights of a subsample of tissue collected from each treatment. Thus, the older the plant tissue, the more fresh weight was required to achieve similar fresh weights among treatments due to the difference in water-holding capacity of the different age plant tissues.

For all treatments, there was a rapid reduction in plant dry weight during the first 14 days after tissues were buried and after that time there was a large reduction in the rate of decrease of tissue dry weight over time (Figure 2-2). This was presumably due to a rapid decomposition of the leaf tissue during the first 14 days after burial, whereas the stem tissue most likely decomposed more slowly. Also, by the end of the study (Day 80), the one-month-old treatment had significantly lower tissue dry weight than the other treatments. Previously, the rate of sunn hemp decomposition has been related to soil moisture and temperature, and sunn hemp residue rapidly decomposes in humid weather (Cherr et al. 2006a). In the present study, the soil moisture and soil and air temperatures remained relatively constant throughout the experiment (Figure 2-1). Thus, the differences in the rate of decomposition over time was likely due to a rapid breakdown of the less dense leaf tissue first, followed by a slower breakdown of the denser stem tissue since buried samples contained combined leaf a stem tissues.

In the present study, N content of the excavated, buried sunn hemp tissue was significantly higher in the one-month-old treatment than the other treatments on most measurement dates (Figure 2-3). Cherr et al. (2006b) observed that during the early growth stages, sunn hemp leaf dry matter and N content ranged from 50 to 60% of the total plant dry matter. After four weeks, the greatest amount of dry matter was shifted to the stem. Also, leaves and flowers incorporated into the soil at 8-10 weeks after planting had more than 50% higher nitrogen concentration than 14-week-old leaves and flowers when incorporated into the soil. Thus, the higher tissue N content in the buried tissues of the one-month-old treatment compared to the other two treatments may have been due to the relatively higher leaf to stem tissue ratio in the one-month-old treatment compared to the other treatments. In a study with 'Tropic Sun' sunn hemp, Mansoer et al (1997) observed that the C:N ratio in the stems was greater than 20:1, whereas C:N ratio in the leaves was less than 20:1. Marshall et al. (2002) indicated the leaves and flowers comprise approximately 80.6% of the overall N content in sunn hemp tissue. In the present study, prior to mowing and soil incorporation, the one-month-old sunn hemp plants had less stem biomass as indicated by a significantly smaller stem diameter and stem height than the 3-month-old treatment (Table 2-1). Thus, the leaf to stem ratio of the one-month-old treatment was presumably greater than that of the 3-months-old treatment, resulting in a higher N content of the one-month-old treatment compared to the 3-months-old treatment.

In the present study, the three-months-old sunn hemp treatment had a higher fiber (NDF and ADF) content than the one-month-old treatment on all but one sampling date (Figure 2-4). Cherr et al. (2006a, b) found that reduced tissue breakdown of sunn hemp is linked to the structural partitioning of dry matter and minerals in the stem. The higher fiber content in the tissue of the three-months-old treatment compared to the one-month-old treatment in the present study was presumably related to the larger stems of the older sunn hemp plants and thus a greater fiber content in the combined leaf and stem tissues of the older plants.

Many studies have shown that N from a cover crop incorporation into the soil generally involves quick immobilization and extended mineralization of nitrogen (Aulakh et al. 1991; Maskina et al. 1993; McKenney et al. 1995; Mansoer et al. 1997; Medhdi et al. 1999). Therefore, planting dates after cover crops must be designed to maximize the use of nutrients released from the cover crop residue. The timing of cash crop planting after cover crops are mown and incorporated into the soil must be designed to maximize the use of nutrients released from the cover crop residue. Typical grower practices of allowing sunn hemp to grow for several months (generally to a height of 2.5-3 meters) prior to mowing and soil incorporation (Yuncong Li, personal communication) results in stems that are large and contain a large amount of fiber, which breaks down slowly in the soil. Thus, allowing sunn hemp plants to get that large prior to mowing and soil incorporation may result in a slow decomposition rate compared to mowing and incorporating tissues of younger plants into the soil. The typical practice of allowing sunn hemp to reach more than 2 meters high prior to mowing consequently may reduce the effectiveness of sunn hemp incorporation into the soil on increasing soil N and organic matter contents. A better approach may be to mow the sunn hemp at an earlier growth stage (younger age) when stems are less lignified which may hasten decomposition and yield of nitrogen from the sunn hemp incorporated into the soil.

Table 2-1. Mean plant stem height and diameter for one-, two-, and three-month(s)-old sunn treatments prior to mowing.

Sunn hemp treatment	Height (mm)	Stem diameter (mm)
One–month-old	1,052c[z]	5.0b
Two–months-old	2,259b	10.5ab
Three–months-old	2,900a	16.4a

[z]Different letters indicate a significant difference ($P \leq 0.05$) among treatments according to Tukey's multiple range test.

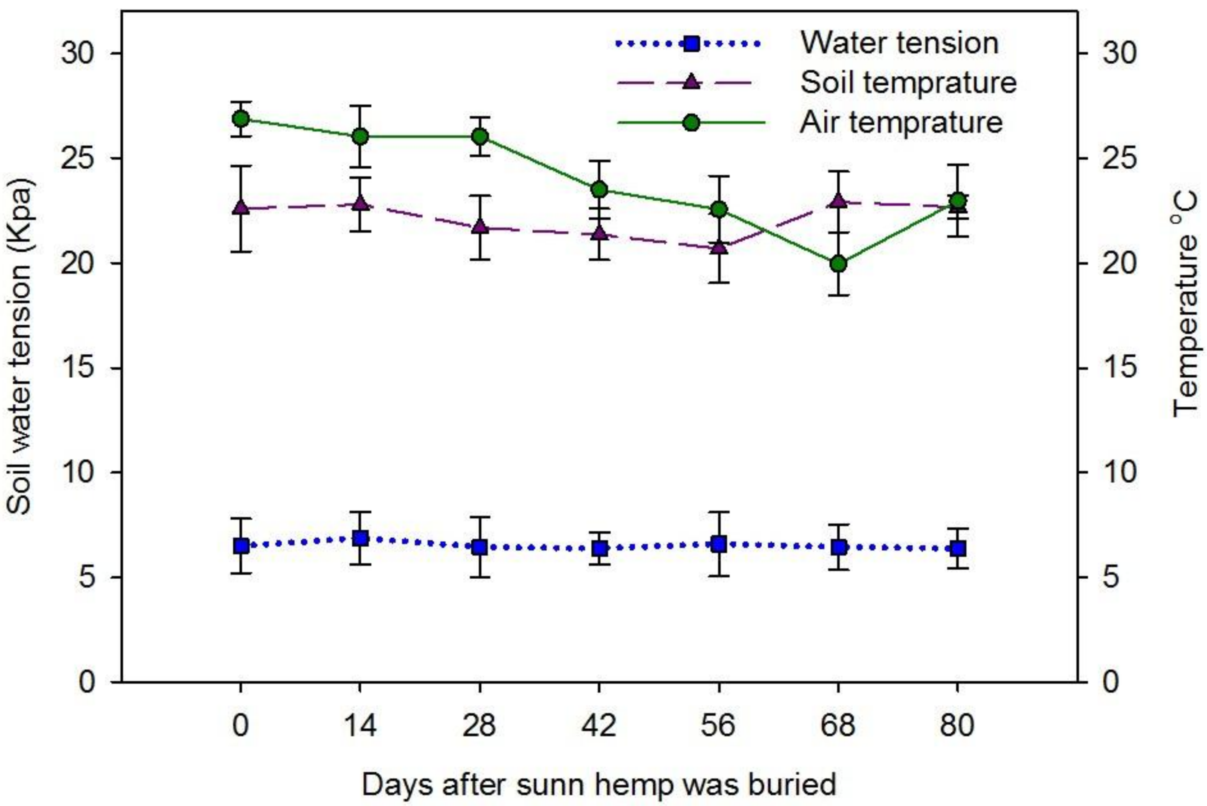

Figure 2-1. Soil moisture (soil water tension), soil temperature, and air temperature through the experiment. Symbols represent means of 4 replicates and error bars indicate + 1 standard deviation.

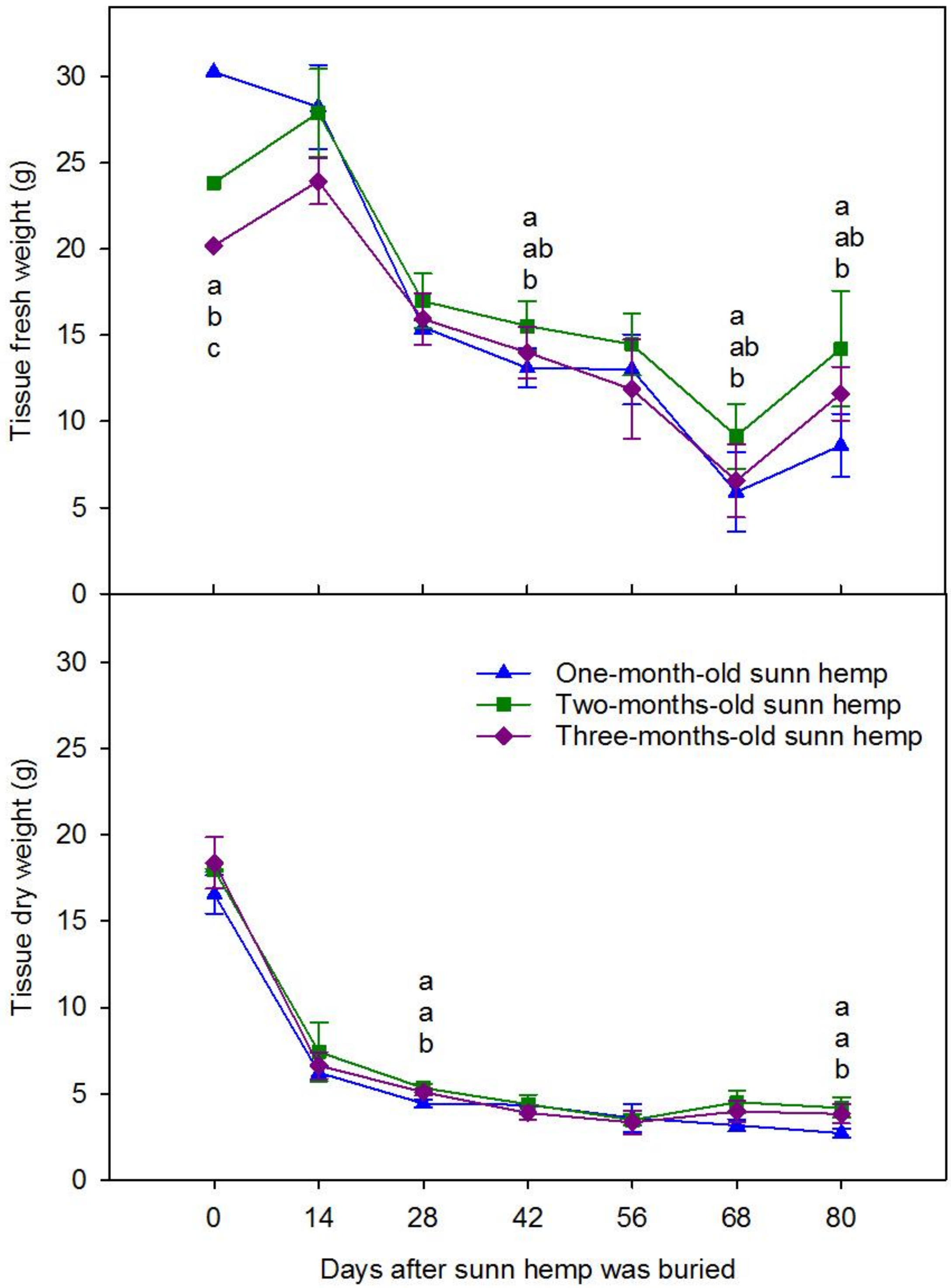

Figure 2-2. Dry and fresh weights of combined leaf and stem tissues of sunn hemp after burying tissues in Krome very gravelly loam soil. Different letters indicate a significant difference among treatments ($P \leq 0.05$). Symbols represent means of 4 replicates and error bars indicate $\pm$ 1 standard deviation.

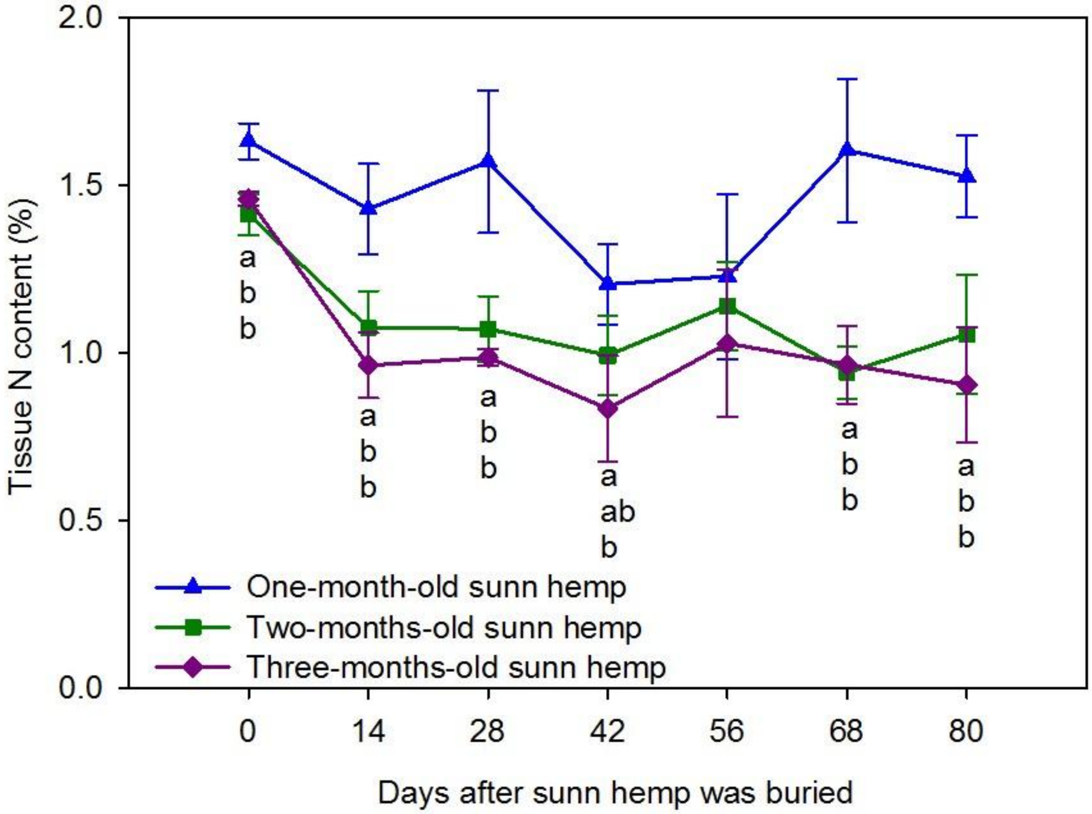

Figure 2-3. Nitrogen content of combined leaf and stem tissues of sunn hemp after burying tissues in Krome very gravelly loam soil. Different letters indicate a significant difference among treatments ($P \leq 0.05$). Symbols represent means of 4 replicates and error bars indicate $\pm$ 1 standard deviation.

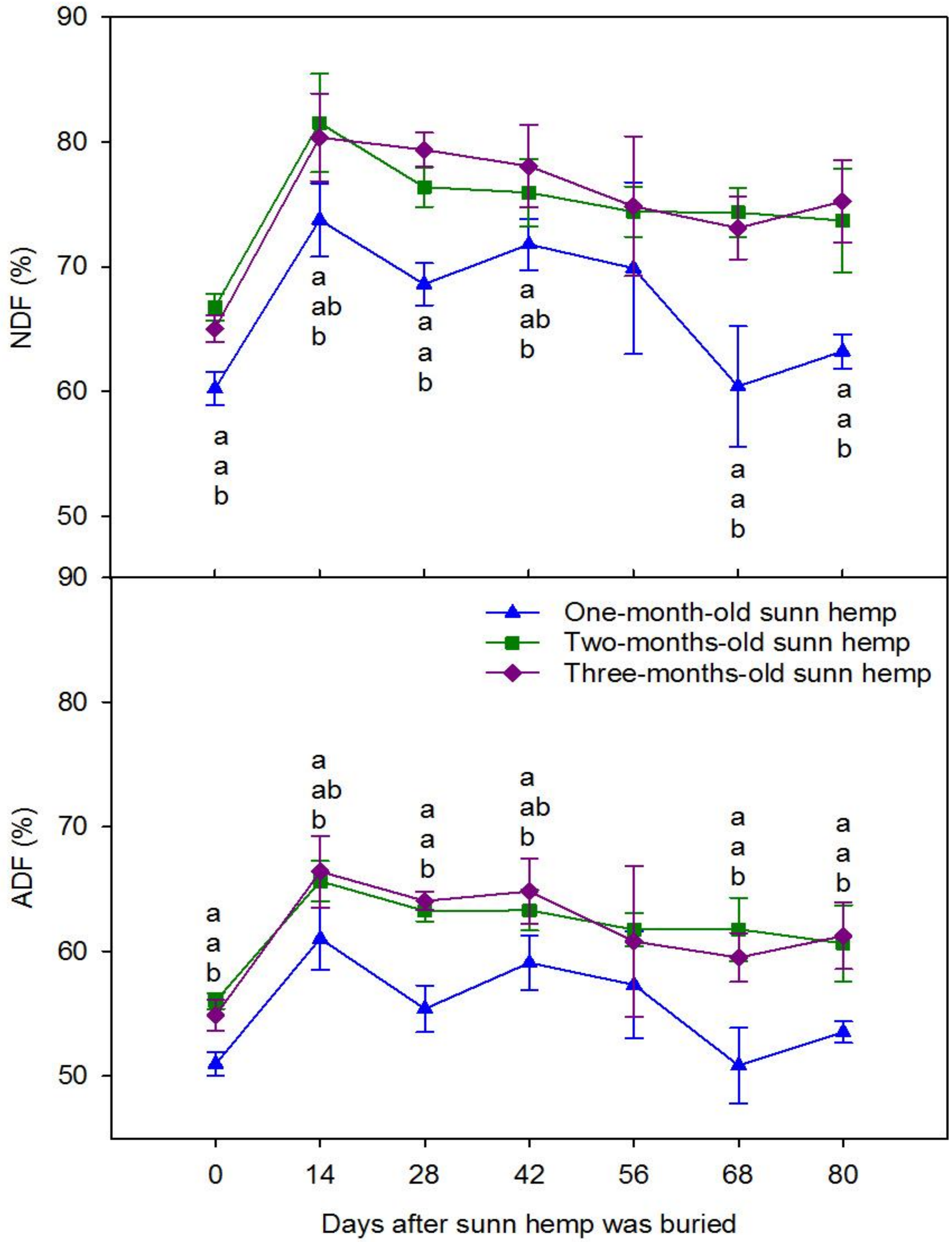

Figure 2-4. Neutral detergent fiber (NDF) and acid detergent fiber (ADF) contents of combined leaf and stem tissues of sunn hemp after burying tissues in Krome very gravelly loam soil. Different letters indicate a significant difference among treatments ($P \leq 0.05$). Symbols represent means of 4 replicates and error bars indicate $\pm$ 1 standard deviation.

CHAPTER 3
EFFECTS OF SOIL INCORPORATION OF SUNN HEMP AT DIFFERENT GROWTH STAGES ON WHOLE PLANT PHYSIOLOGY, GROWTH AND YIELD OF PAPAYA

Introduction

Papaya (*Carica papaya* L.) is a large stem herbaceous fruit crop cultivated throughout tropical and subtropical regions of the world (Crane, 2016). It was introduced to the United States (Hawaii) by native Hawaiians years before the discovery of the islands by Englishmen in 1778 (Pope, 1930). In the United States, papaya is cultivated predominantly in Hawaii, Florida, Texas and California (Evans et al. 2012.). Papaya's commercial importance has decreased throughout the United States due to reduced profits as a result of low prices and limited yields (Evans et al. 2012; Evans and Ballen, 2014). According to Evans et al. (2012), papaya yields in south Florida are lower than those in other production areas of the world. Thus, increasing average papaya yields would help the papaya industry in south Florida.

Increasing costs of fertilizers have negatively impacted the papaya industry in south Florida (W. Huang, 2009) because papaya needs large amounts of fertilizer for good yields and fruit quality (Rajbhar et al. 2010). Also, vigorous and healthy papaya plants are less susceptible to biotic and abiotic stresses (Hardisson et al. 2001). Fertilizer applications in commercial papaya plantings are based on experience, soil and petiole analyses, leaf color through visual assessments, and plant behavior (Awada et al. 1986; Paull and Duarte, 2011; Nishina et al. 2000). The ideal nitrogen (N) concentration of the petiole ranges between 1.15 to 1.33% (Awada and Long, 1971b; Awada, 1977). In south Florida, regular applications of small amounts of complete fertilizers (N, P, K, Mg and micronutrients) are suggested for cultivating healthy papaya that produce acceptable quality fruit (Crane, 2016; Migliaccio et al. 2010). The suggested rates for N in south Florida begins with applications of 0.11 kg per plant per month during the juvenile stage, which is increased to 0.45-0.90 kg per plant per month when plants start bearing fruit (Crane, 2016; Migliaccio et al. 2010).

Increasing soil organic matter (OM) content has been shown to increase growth and yields of papaya. In south Florida, growing papaya in Krome very gravelly loam soil amended with municipal solid waste compost increased the number of early fruit (Basso-Figuera et al. 1994) compared to plants in non-amended soil. Studies of organic papaya production in India included the use of sunn hemp (*Crotalaria juncea* L.) residue as a soil amendment to increase soil OM and N contents. One study found a decrease in papaya yield when soil was amended with sunn hemp residue compared to conventional fertilization (Reddy et al. 2010). Another study showed no yield differences between papaya plants fertilized with 40 kg sunn hemp and plants receiving conventional fertilization. In that study, papaya fertilized with 25 kg sunn hemp showed a yield reduction (Ravishankar et al. 2010a, and 2010b). A recent study by Vincent et al. (2017) showed that intercropping papaya with sunn hemp and then mowing the sunn hemp for use as a mulch increased papaya growth and productivity. That study indicated that sunn hemp reduced the negative effects of high wind speeds and the incidence of papaya ringspot virus (PRSV), a common and devastating disease of papaya in south Florida and many other parts of the world (Mossler and Crane, 2013; Evans et al. 2012.).

Due to the rapid increase of chemical fertilizer costs, many growers have begun searching for alternative nutrient sources to meet their production targets. These alternative nutrient sources include the use of cover crops. Apart from financial concerns, ecological concerns regarding producers' dependency on chemicals, such as fertilizer leaching into the groundwater has increased the desirability of biological sources of N (Aulakh et al. 1991). Leguminous cover crops deliver additional benefits due to their ability to fix atmospheric N and P (Vaughn and Evanylo, 1998; Cherr et al. 2006a). Nitrogen from cover crop incorporation into the soil generally involves quick immobilization and extended mineralization of N (Aulakh et al. 1991; Maskina et al. 1993; McKenney et al. 1995; Mansoer et al. 1997; Medhdi et al. 1999). Therefore, the timing of cash crop planting after cover crops are mown and incorporated into the soil must be designed to maximize the use of nutrients released from the cover crop residue. In south Florida, the popularity of using sunn hemp as a cover crop has increased dramatically during the past 3 years due to a drastic reduction in the price of sunn hemp seed (B. Schaffer, personal communication). Sunn hemp is grown for several months (generally to a height of 2.5-3 meters), then mowed, and incorporated into the soil prior to crop planting. At this time the stems are large and very lignified (Yuncong Li, personal communication). In many legume species, such as sunn hemp the C:N ratio increases in stems as the plants age making it more difficult to break down old plants in the soil (Akin, 1989). Allowing the sunn hemp to get this large prior to mowing and soil incorporation may result in a slow decomposition rate. This may therefore reduce the effects of sunn hemp incorporation into the soil on increasing soil N and OM contents. A better approach may be to mow the sunn hemp at an earlier growth state (younger age) when stems are less lignified which may hasten decomposition and yield of N from the sunn hemp incorporated into the soil.

The objectives of this study were: 1) to determine the effects of incorporation of sunn hemp at different stages of development (ages) on N and OM contents of Krome very gravely loam soil, and 2) to determine the effects of soil incorporation of sunn hemp at different stages of development on soil N and OM content and physiology, growth and yield of papaya plants in Krome very gravelly loam soil.

Materials and Methods

Study Site and Sunn Hemp Treatments

Sunn hemp (Crotalaria juncea L.) cv. Tropic Sun seeds were planted at the University of Florida's Tropical Research and Education Center (UF-TREC) in Homestead, Florida (latitude: 25º 30' 40.809" N; longitude: 80º 30' 3.983" W) on three dates with approximately 30 days between each planting. Planting dates were 3 May, 6 June, and 11 July 2016. Seeds were planted in Krome very gravelly loam soil, classified as a loamy-skeletal, carbonatic, hyperthermic lithic udorthents (Noble et al. 1996) in rows using a 2-m wide seed drill at a 30-mm depth with in-row spacing of 0.03 m and between row spacing of 0.76 m. Each sunn hemp planting consisted of three 30 x 0.75-m plots. A fourth 30 x 0.75-m plot had no sunn hemp. All sunn hemp plots were mowed and rototilled into the soil on 22 August 2016. Thus, there were 4 sunn-hemp amended soil treatments based on the age of sunn hemp when it was mowed and incorporated into the soil: 1) one-month-old, 2) two-months-old, or 3) three-months-old sunn hemp incorporated into the soil, and 4) a control treatment with no sunn hemp incorporated into the soil. A previous study showed that sunn hemp grows well in Krome very gravelly loam soil in southern Florida during the spring and summer with no irrigation or fertilization (Vincent et al. 2017). Therefore, the sunn hemp was not irrigated or fertilized during the growing period.

Papaya Site Preparation and Treatments

Papaya (*Carica papaya* L.) cv. Red Lady seeds were soaked in water for 24 hours and then sown in flats containing Promix® potting medium. After two months (on 12 September 2016), papaya seedlings were transplanted into 57-L plastic pots that were filled with soil from one of the four sunn hemp treatments (10 pots per sunn hemp treatment). Prior to transplanting papaya into the pots, planting holes (slightly larger than the pot circumference) were augured into the soil (approximately 2/3 the depth of the pot) in a field adjacent to the sunn hemp plots. The spacing between each hole was 2.1 x 3.6 meters. Pots were placed in the augured holes and one papaya plant was transplanted into each pot.

An automated irrigation system with one microsprinkler (94.6 L hr^{-1}) was installed into each pot. Tensiometers (Irrometer Company, Riverside, CA, USA) were installed in two randomly selected pots per treatment to monitor soil water tension and adjust irrigation accordingly. Tensiometers were maintained between 5 to 7 kPa during the experiment. Soil temperature was monitored and recorded 10 cm below soil surface with a Hobo Tidbit v2 datalogger (Onset Computer, Bourne, Massachusetts, USA) in two randomly selected pots in the experiment. Air temperature during the experiment was monitored and downloaded from a weather station of the Florida Automated Weather Network (FAWN; http://fawn.ifas.ufl.edu/) located at UF-TREC, a few thousand meters from the experimental plots.

Each sunn hemp treatment was subdivided into two nitrogen (N) treatments, standard N (a typical grower application rate; Jonathan Crane, personal communication) and low N (1/2 of a typical grower application rate). For each N treatment, fertilizer was applied as (5N-10P-15K) (Diamond R Fertilizer, Winter Garden, FL, USA) plus (21-0-0) N in the form of $(NH_4)_2SO_4$, (Diamond R Fertilizer, Winter Garden, FL, USA) at the rates described below for each treatment.

The experimental design was a randomized complete block with a 4 x 2 (4 sunn hemp treatments and 2 N rates) factorial combination of treatments. There were 5 replicates (one replicate = one pot with one papaya plant) per treatment combination. The four sunn hemp treatments as stated above were: 1) one-month-old sunn hemp, 2) two-months-old sunn hemp, 3) 3-months-old sunn hemp, and 4) no sunn hemp control. The two N treatments were: 1) standard N (a typical grower application rate (Jonathan Crane, personal communication), and 2) low N applied to the soil at two-weeks intervals with application rates depending on plant age. From the time of transplanting to when plants were 4 weeks old, the standard N rate was 3.1 g $plant^{-1}$ and the low N rate was 1.55 g $plant^{-1}$. When plants were 4-12 weeks old, the standard N rate was 6.2 g $plant^{-1}$ and the low N rate was 3.1 g $plant^{-1}$. When plants were 12 weeks old, the standard N rate was 12.3 g $plant^{-1}$ and the low N rate was 6.15 g $plant^{-1}$. When plants were more than 12 weeks old (plants were flowering and fruiting) until the end of the experiment, the standard N rate was 17.9 g $plant^{-1}$ and the low N rate was 8.95 g $plant^{-1}$.

Measurements

One week prior to mowing and incorporating sunn hemp into the soil, sunn hemp plant density, plant height, stem diameter, and fresh and dry weights were determined.

Plant density was measured by counting the number of plants in a 1 m^2 PVC frame. The PVC frame was randomly placed over a group of plants in a row in each treatment. This was done 8 times per treatment.

For plant height and stem diameter measurements, 20 sunn hemp plants were randomly selected in each sunn hemp treatment (treatments 1, 2 and 3). Plant height was measured with a ruler and stem diameter was measured 10 cm above the soil surface with a caliper.

Whole plant fresh weights were measured for 8 plants per treatment with sunn hemp (treatments 1, 2 and 3). Plants were than dried in an oven at 70^{o}C to a constant weight and dry weights were determined.

Soil N and OM contents were determined for samples collected from pots in each treatment combination prior to planting papaya and every six weeks thereafter until the end of the study. Soil samples were dried and sieved in a Wiley mill through a 2-mm mesh screen and then N concentrations were determined with a CNS auto-analyzer (VarioMAXCube, Elementar Analysensysteme GmbH, Donaustrasse 7, 63452, Hanau, Germany). Soil OM content was determined by the weight-loss-on-ignition method (Wang, 2005)

Net gas exchange (net CO_2 assimilation, stomatal conductance and transpiration) were determined at six week intervals for each replication of each treatment combination by with a CIRAS 3 portable gas analyzer (PP Systems Inc., Amesbury, MA, USA).

The leaf chlorophyll index was determined from the average of three randomly selected leaves per replication in each treatment combination at six-week intervals with a SPAD-502 meter (Minolta, Inc., Osaka, Japan).

Nitrate (NO3) concentration was determined from the leaf petiole sap for each treatments at 6-week intervals using a LAQUA twin nitrate meter (Horiba Scientific Inc., Singapore).

The time of papaya flowering was observed and recorded for each replication in each treatment combination. Fruit were harvested from each papaya plant at the end of the experiment and the number of fruit per plant were counted. Also, fruit weight was determined for plants in each treatment combination.

Data Analyses

Data were analyzed by two-way analysis of variance (ANOVA) to determine if there were statistically significant interactions between sunn hemp and nitrogen fertilizer treatments. A repeated measures ANOVA was used to determine differences in physiological variables among sunn hemp treatments and between nitrogen treatments. A one-way ANOVA and Tukey’s Range Test were used to determine differences in fruit number and fruit weight among sun hemp treatments. All data were analyzed using the SAS statistical software package (SAS Institute, Cary, NC, USA).

Results

Sunn Hemp Plant Density and Biomass Prior to Mowing

Prior to mowing the sunn hemp treatments and incorporating them into the soil, the mean plant density was 32, 28, and 36 plant m^{-2} for the one-month-old, two-months-old, and three-months-old sunn hemp treatments, respectively.

Just prior to mowing, above ground plant biomass was 2,211; 13,691; and 20,853 kg ha^{-1} for the one-month-old, two-months-old and three-months-old sunn hemp treatments, respectively. Mean stem height was 1052, 2259 and 2900 mm and mean stem diameter was 5.0, 10.5 and 16.4 mm for the one-month-old, two-months-old, and three-months-old sunn hemp treatments, respectively (Table 3-1).

Soil Moisture, Soil and Air Temperatures, and Rainfall

There was no significant difference ($P > 0.05$) in the soil water tension among treatments at any time during the experiment. Average daily soil water tension averaged over the entire experiment was 6.5, 6.7, 6.6, and 7.1 kPa for the no sunn hemp, one-month, two-months and three-months-old sunn hemp treatments, respectively.

There was no significant difference ($P > 0.05$) in the average maximum or minimum daily soil temperatures among treatments on any day during the experiment. The average daily maximum soil temperature for all treatments combined for the entire experimental period was 33.5 ^{o}C and the average minimum soil temperature was 13.2 ^{o}C. The average maximum air temperature for entire experiment was 30.2 ^{o}C, and average minimum air temperature was 12.7 ^{o}C.

Soil Nitrogen and Dry Matter Contents

There was a significant statistical interaction ($P < 0.05$) between sunn hemp and nitrogen treatments for soil N content on some measurement dates. There was no significant difference in soil N content among sunn hemp treatments in the low N treatments. For the standard N treatment, a significant difference was observed only at 140 days after transplanting papaya plants (Figure 3-1), when the three-months old sunn hemp treatment had significantly higher soil N than the other treatments (Figure 3-1)

There was a significant statistical interaction ($P < 0.05$) between sunn hemp and N treatments for soil OM content on some measurement dates. There were no significant differences ($P > 0.05$) in soil OM content between N treatments. In the standard N treatment, a significant difference was observed among sunn hemp treatments only at 182 days after transplanting the papaya plants (Figure 3-2). On that day, the highest soil OM content was observed in the one-month-old treatment, followed by the three-months-old treatment, and then the no sunn hemp treatment, with the two-months-old sunn hemp treatment having the lowest soil OM content.

Papaya Plant Growth and Physiology Variables

There was no significant statistical interaction ($P > 0.05$) between sunn hemp and N treatments for stem height. However, on some measurement dates, there was a significant interaction ($P<0.05$) between sunn hemp and nitrogen treatments for stem diameter. A significant difference in stem height among sunn hemp treatments was observed only on day 0 (prior to the application of N fertilizer) in both N treatments (Figure 3-3). A significant difference in stem diameter among sunn hemp treatments was observed only on day 55 in the low N treatment and on days 0 and 55 in the standard N treatment (Figure 3-4).

There was a significant statistical interaction ($P < 0.05$) between sunn hemp and N treatments for net CO_2 assimilation on some measurement dates. For plants receiving low N, there was no significant difference in net CO_2 assimilation among sunn hemp treatments except on day 182 when the no sunn hemp treatment had significantly higher net CO_2 assimilation than the one-month-old sunn hemp treatment (Figure 3-5). For plants receiving standard N, there was a significant difference in net CO_2 assimilation among sunn hemp treatments on days 0 and 55 (Figure 3-5). On day 0 (before the application of N fertilizer) significantly higher net CO_2 assimilation was observed for the three–months-old sunn hemp treatment compared to the one- and two–months-old treatments. On day 55, significantly higher net CO_2 assimilation was detected for the three–months-old sunn hemp treatment than the one–month-old treatment.

For stomatal conductance, there was a significant statistical interaction ($P \leq 0.05$) between sunn hemp and N treatments on some sampling days. For plants receiving low N, there was a significant effect of sunn hemp treatment on stomatal conductance prior to the first N fertilizer application (day 0). Stomatal conductance was higher in the three–months-old treatment compared to the no sunn hemp and one–month-old treatments. However, after N fertilizer was applied, there were no significant differences in stomatal conductance among sunn hemp treatments (Figure 3-6).

There was a significant statistical interaction between sunn hemp and N treatments for transpiration. In the low N treatment, there was only a significant sunn hemp treatment effect prior to application of nitrogen fertilizer (sampling day 0), where the three–months-old treatment had significantly higher ($P \leq 0.05$) transpiration than the one–month-old treatment. In the standard N treatment, there was only significant sunn hemp treatment effect on day 140, when the three–months-old treatment had significantly higher transpiration than the other sunn hemp treatments (Figure 3-7).

There was a significant statistical interaction ($P \leq 0.05$) between sunn hemp and N treatments for leaf chlorophyll index on some sampling dates. For plants in the low N treatment, a significant difference among sunn hemp treatments was observed at days 99 and 140. The leaf chlorophyll index on day 99 was significantly higher for the three–months-old sunn hemp treatment than the one–month-old and no sunn hemp treatments. On day 140, the leaf chlorophyll index was higher for the one- and three–months-old sunn hemp and no sunn hemp treatments compared to the two–months-old sunn hemp treatment. For plants in the standard N treatment, there was a significant difference in the leaf chlorophyll index among sunn hemp treatments only on day 55. On that sampling date, the leaf chlorophyll index was higher for the one, and two –months-old sunn hemp and no sunn hemp treatments compared to the three-months-old treatment (Figure 3-8).

There was a no significant statistical interaction ($P > 0.05$) between the sunn hemp and N treatments for petiole sap nitrate (NO_3-N) concentration. In both N treatments, a significant difference in petiole sap NO_3-N concentration was observed among sunn hemp treatments only on day 182. For plants in the low N treatment, a significantly higher ($P < 0.05$) petiole sap NO_3-N concentration was detected in the no sunn hemp treatment compared to the other sunn hemp treatments. However, for plants in the standard N treatment, a significantly higher ($P < 0.05$) petiole sap NO_3-N concentration was observed in the two–months-old sunn hemp treatment compared to the no sunn hemp treatment (Figure 3-9).

There were no sunn hemp x N treatment interactions or differences among sunn hemp or between N treatments ($P > 0.05$) for the numbers of days until the first flowers were observed (data not shown). In both N treatments, there were no significant differences ($P > 0.05$) among sunn hemp treatments in fruit number or fruit weight among treatments (Table 3-2).

Discussion

In the present study, there were no strong effects of incorporating sunn hemp into Krome very gravelly loam on OM content of the soil, regardless of the age of the sunn hemp at the time of mowing and soil incorporation, or the N fertilizer application. In contrast, Wang et al. (2009) found that hemp as a mulch increased OM in Krome very gravelly loam soil. The difference between results of Wang et al. (2009) and those of the current study may be due to a much greater sunn hemp plant density prior to planting in the by Wang et al.'s (2009) study. In that study, the sunn hemp was cut 30 cm above the ground in August to stimulate lateral branching and then mowed and incorporated into the soil in September. Lateral branching was not stimulated in the present study of papaya. Lateral branching causes the development of a much denser plant canopy which may have resulted in higher soil OM after mowing and soil incorporation in Wang et al.'s study compared to the current study.

In the present study, when the N fertilizer application rate was low, there was no effect of soil incorporation of sunn hemp on the soil N content. However, when papaya plants received N fertilizer at a standard grower application rate, soil amended with the three-months-old sunn hemp treatment tended to have higher N content at the end of the study than the other sunn hemp treatments. Soil microbes are necessary for the breakdown of cover crops after they are incorporated into the soil (Elfstrand et al. 2007). It is possible that in the soil receiving the low N fertilizer application rate, there was insufficient N to facilitate a large enough population of microbes to breakdown the buried sunn hemp tissue. Papaya plants fertilized with the low rate of N fertilizer did not show an increase in petiole sap NO_3-N, whereas petiole sap NO_3-N increased over time when plants received standard application rates of N fertilizer. It is possible that when N application rates are low, much of the N in the soil was leached from the pots or consumed by microbes and therefore not available for plant uptake. However, when N fertilizer rates were adequate, there was presumably sufficient soil N for plant uptake, despite leaching and N consumption by microbes. Also in the present study, when the N fertilizer application rate was adequate, the no sunn hemp treatment showed less of an increase in petiole sap NO_3-N over time compared to the other treatments. This may have been due to greater N leaching from the pots with no sunn hemp than those of the other treatments, resulting in less N for plant uptake. In contrast to the results of this study, other studies have found measurable changes in soil N content as a result of amending soil with sunn hemp. For example, Seaman (2004) found that cutting sunn hemp new growth tips at 0.4 to 0.8 meter from the plant apex and incorporating the plant material into the soil resulted in a 4% increase in N from sunn hemp biomass. Wang et al. (2009) also found that amending Krome very gravelly loam soil with large quantities of sunn hemp increased the soil N content. In the present study, sunn-hemp amended soil was placed in pots buried in the soil rather than planted directly in the field. The reason for this was to provide a uniform volume of soil for each sunn hemp treatment. However, placing the sunn hemp amended soil in pots may have inhibited the population of microbes from building up to a sufficient level to enhance breakdown of sunn hemp tissue, especially when the inorganic N application rate was low.

In the present study, amending Krome very gravelly loam soil with sunn hemp had little significant effect on leaf gas exchange (net CO_2 assimilation, transpiration and stomatal conductance), the leaf chlorophyll index, stem growth, time of flowering, or yield of papaya. Over the course of the experiment, net CO_2 assimilation, transpiration and stomatal conductance declined even though a new leaf was chosen (of approximately the same physiological age for each treatment) at each sampling date. This decline may have been due to heavy rains which resulted in long periods of flooding (Figure3-10). Marler (1995) observed that just one day of flooding reduced leaf gas exchange of potted papaya. Similarly, Rodriquez et al. (2014) and Thani et al. (2016) observed a decline in net CO_2 assimilation, transpiration and stomatal conductance of potted 'Red Lady' papaya plants after just two days of flooding. Thus, it is quite possible that the declining gas exchange values during this study were a result of flooding caused by heavy rains. The effects of flooding stress on leaf gas exchange may have obscured and difference in leaf gas exchange measurements among treatment and subsequent plant growth and yield effects. Furthermore, flooding from heavy rains may have leached N from the pots thus obfuscating the effects of sunn hemp treatment on soil N content.

In the present study, regardless of the age of sunn hemp or the inorganic N fertilizer application rate, incorporating sunn hemp into Krome very gravelly loam soil did not increase plant growth, time of flowering or yield. In contrast, other studies with herbaceous vegetable crops (Wang et al. 2006, 2009; Hooks et al. 2007). Increased yields in those studies may have been due to the relatively faster growth rate of those crops compared to papaya crops. Sunn hemp decomposes rapidly in the soil (see Chapter 2 of this thesis). Thus, the growth rate of papaya may have been too slow to reap the benefits of amending soil with sunn hemp at the rates used in this study.

Table 3-1. Mean plant stem height and diameter for one-, two-, and three-month(s)-old sunn treatments prior to mowing.

Sunn hemp treatment	Height (mm)	Stem diameter (mm)
One–month-old	1,052c[z]	5.0b
Two–months-old	2,259b	10.5ab
Three–months-old	2,900a	16.4a

[z]Different letters indicate a significant difference ($P \leq 0.05$) among treatments according to Tukey's multiple range test.

Table 3-2. Means papaya fruit number and weight for low and standard nitrogen (N) treatments.

Sunn hemp treatment	Fruit number	Fruit weight (Kg)
	Low N	
No sunn hemp	7.4a[z]	2.63a
one-month-old	11.4a	2.68a
Two-months-old	8.6a	3.33a
Three-months-old	9.2a	1.86a
	Standard N	
No sunn hemp	14.4a	5.08a
One-month-old	15.4a	5.58a
Two-months-old	13.6a	5.22a
Three-months-old	11.8a	2.99a

[z]Different letters indicate a significant difference ($P \leq 0.05$) according to Tukey's multiple range test.

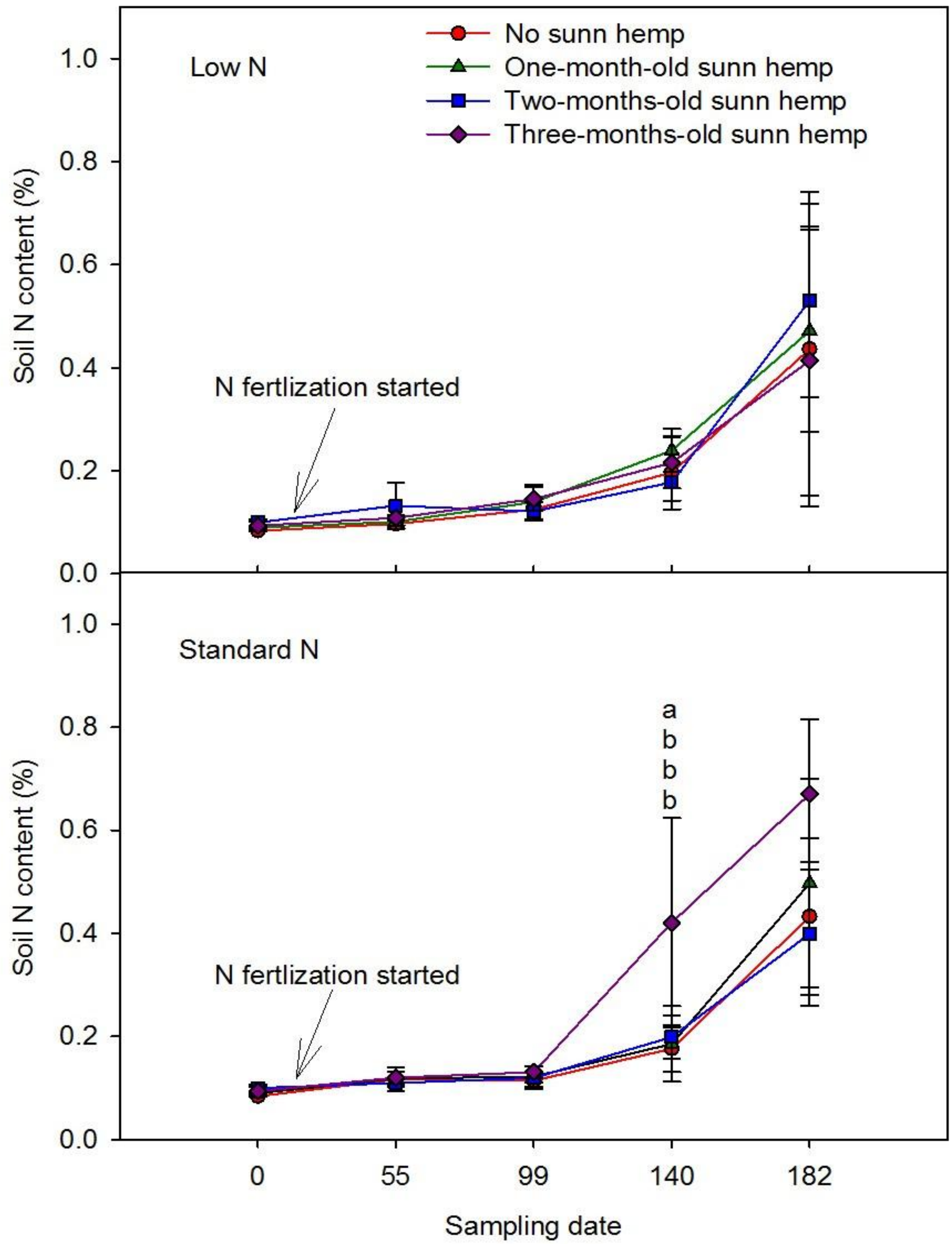

Figure 3-1. Effect of soil incorporation of sunn hemp at different ages on soil N content in Krome very gravelly loam soil with papaya plants fertilized with a low N or a standard N rate. Different letters indicate a significant difference among treatments (P $\leq$ 0.05). Symbols represent means of 5 replicates. Error bars represent $\pm$ 1 standard deviation.

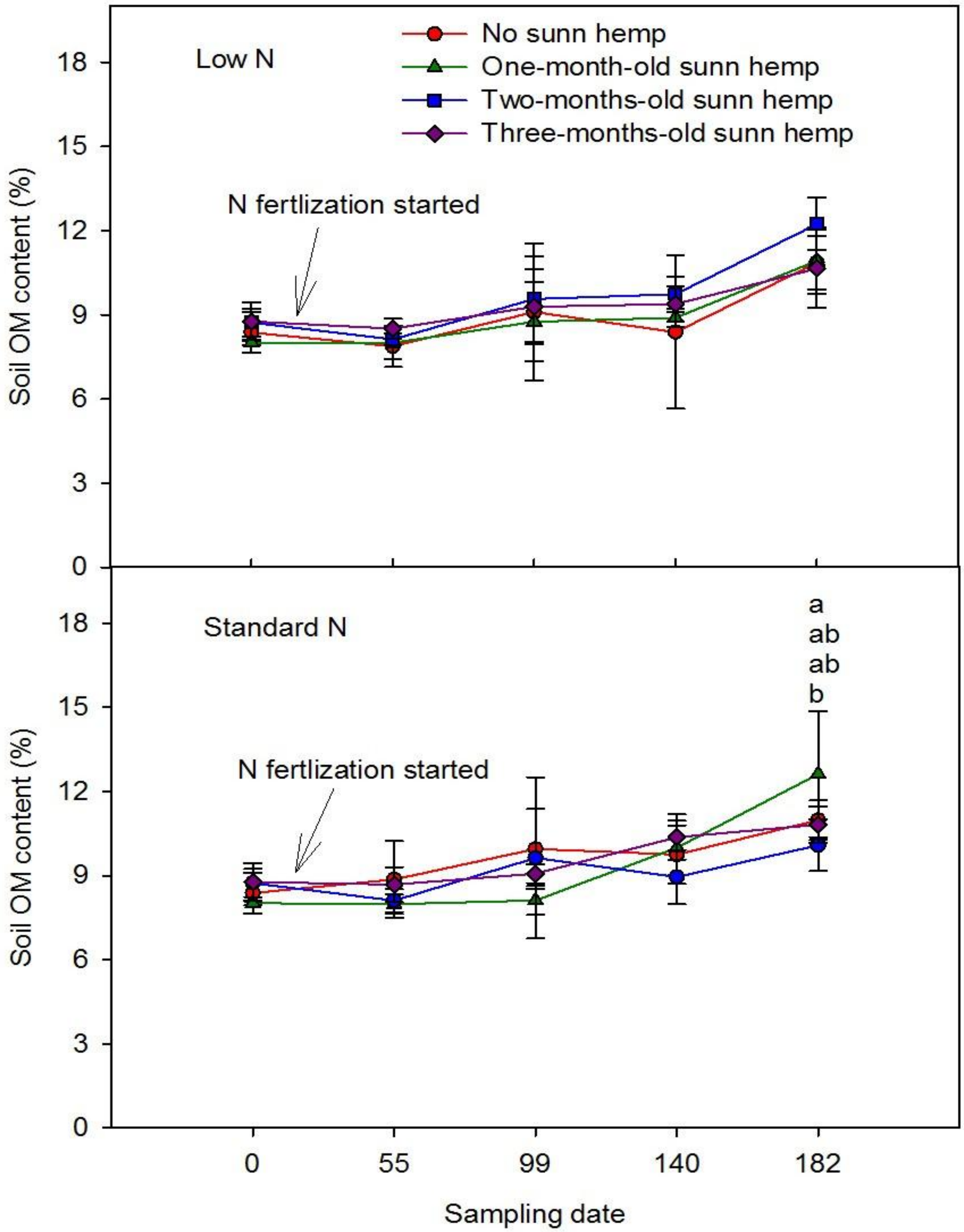

Figure 3-2. Effect of soil incorporation of sunn hemp at different ages on soil organic matter (OM) in Krome very gravelly loam soil with papaya plants fertilized with a low N or a standard N rate. Different letters indicate a significant difference among treatments (P < 0.05). Symbols represent means of 5 replicates. Error bars represent + 1 standard deviation.

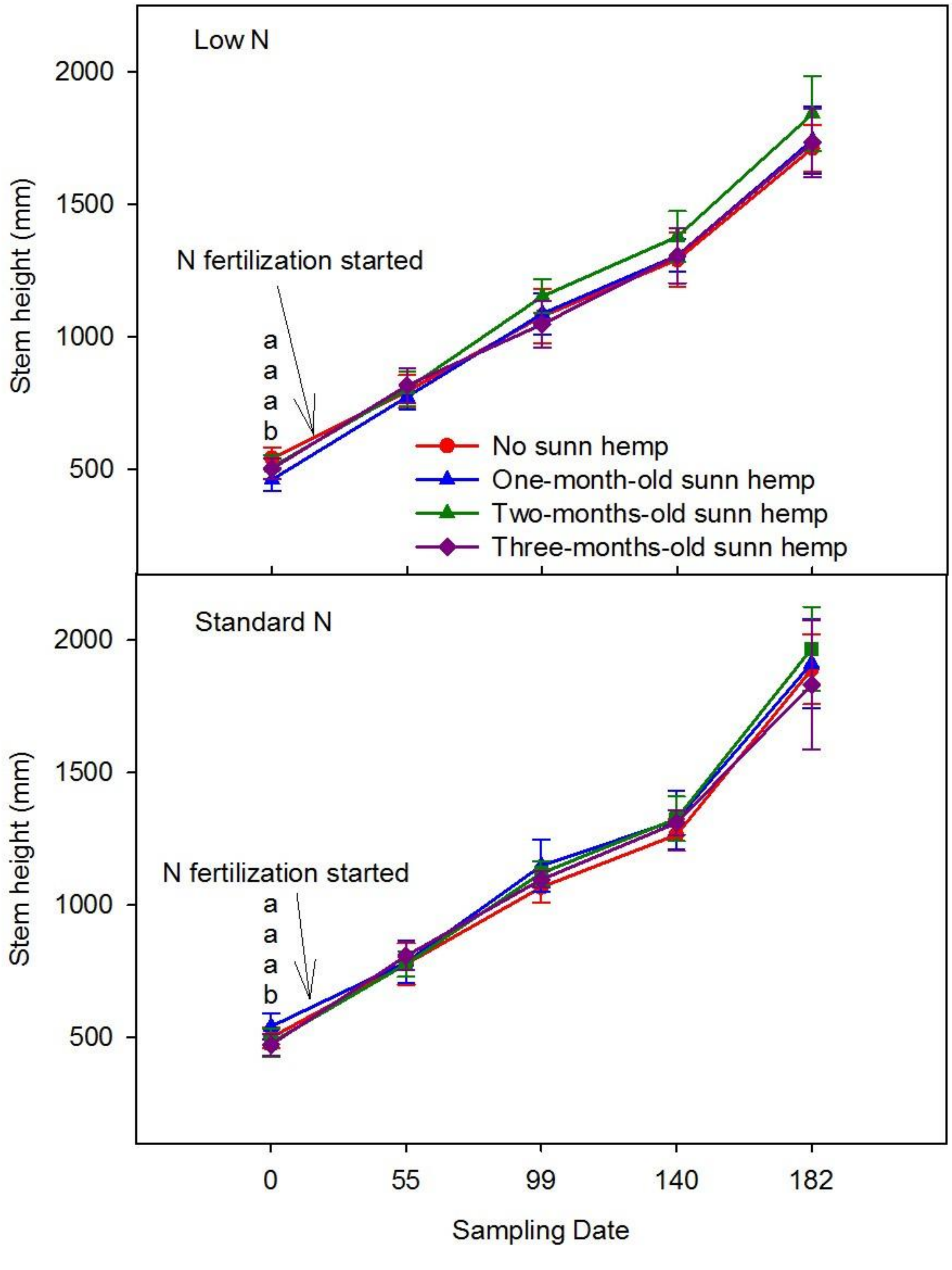

Figure 3-3. Effect of soil incorporation of sunn hemp at different ages on stem height of papaya plants fertilized with a low N or a standard N rate. Different letters indicate a significant difference among treatments (P $\leq$ 0.05). Symbols represent means of 5 replicates. Error bars represent $\pm$ 1 standard deviation.

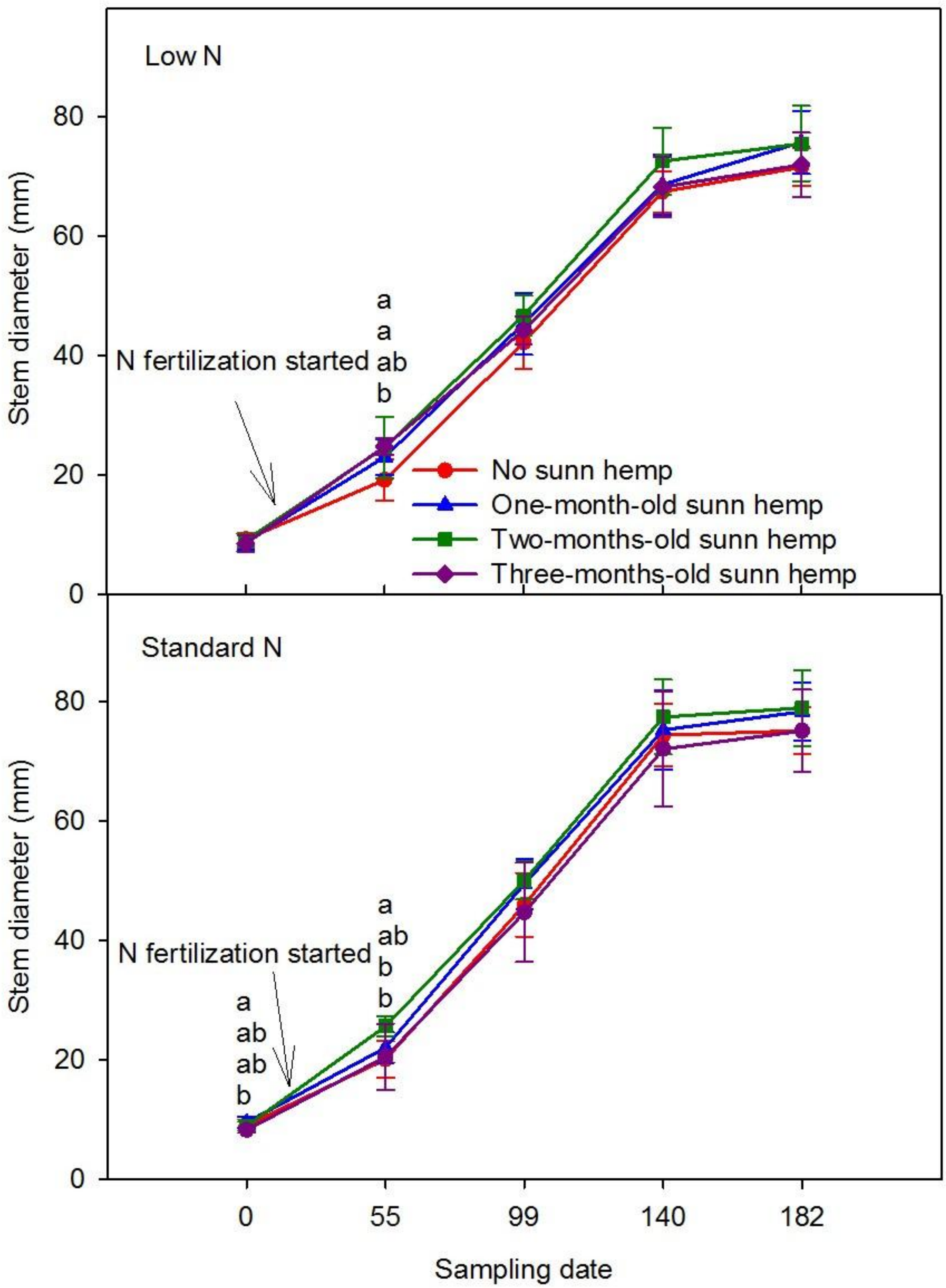

Figure 3-4. Effect of soil incorporation of sunn hemp at different ages on stem diameter of papaya plants fertilized with a low N or a standard N rate. Different letters indicate a significant difference between treatments (P $\leq$ 0.05). Symbols represent means of 5 replicates. Error bars represent $\pm$ 1 standard deviation.

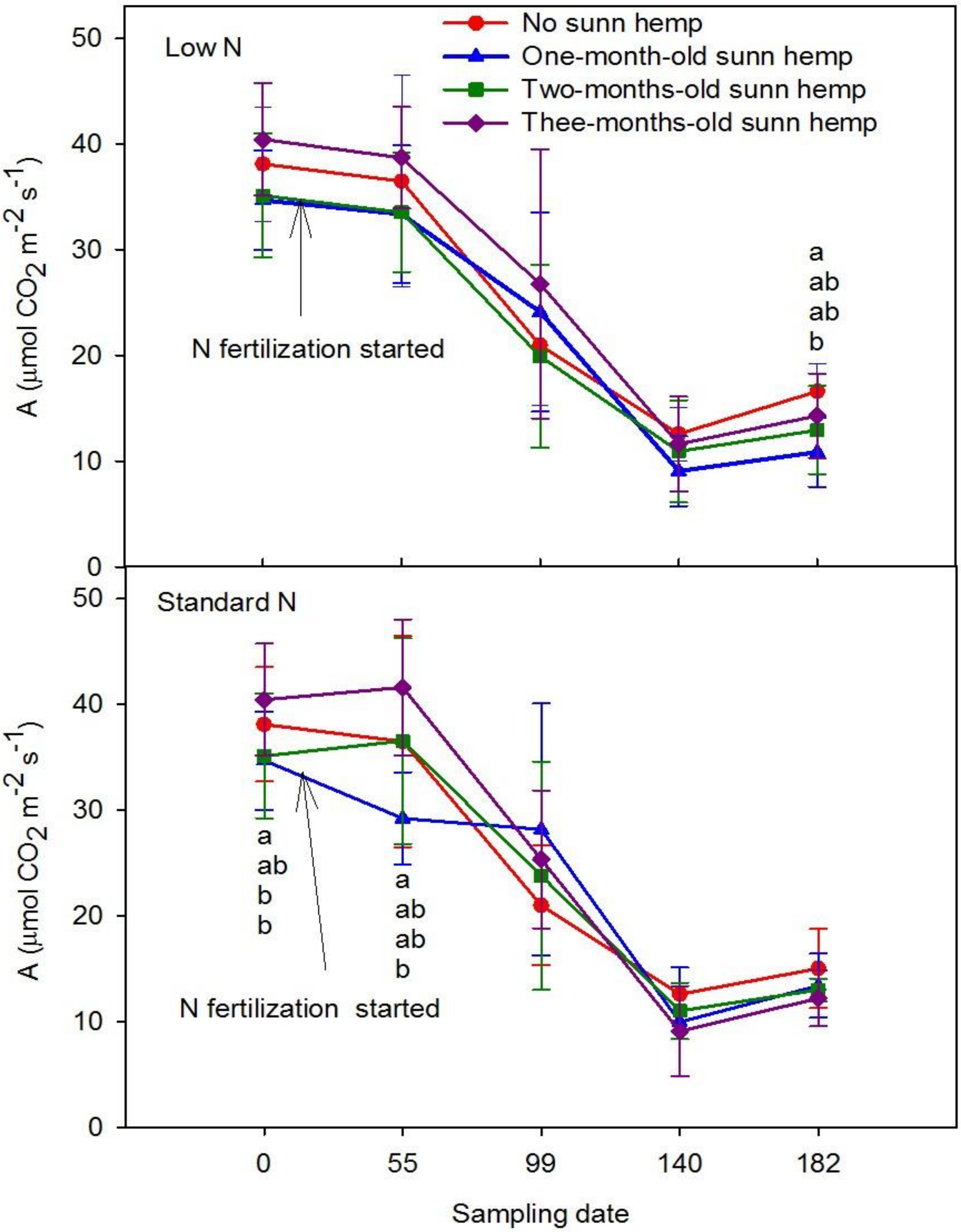

Figure 3-5. Effect of soil incorporation of sunn hemp at different ages on net CO_2 assimilation (A) of papaya plants fertilized with a low N or a standard N rate. Different letters indicate a significant difference among treatments ($P \leq 0.05$). Symbols represent means of 5 replicates. Error bars represent $\pm$ 1 standard deviation.

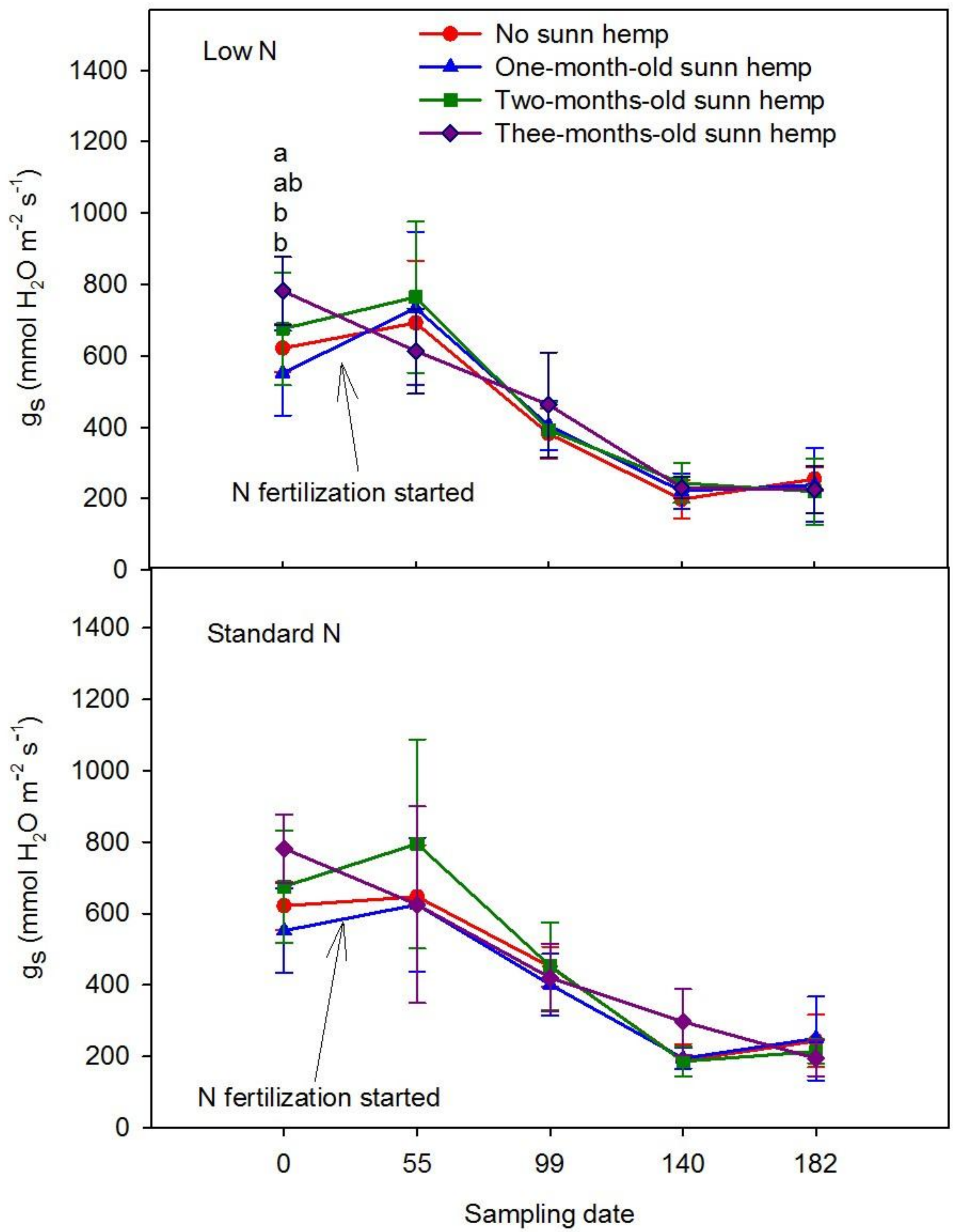

Figure 3-6. Effects of soil incorporation of sunn hemp at different ages on stomatal conductance (g_s) of papaya plants fertilized with a low N or a standard N rate. Different letters indicate a significant difference among treatments ($P \leq 0.05$). Symbols represent means of 5 replicates. Error bars represent $\pm$ 1 standard deviation.

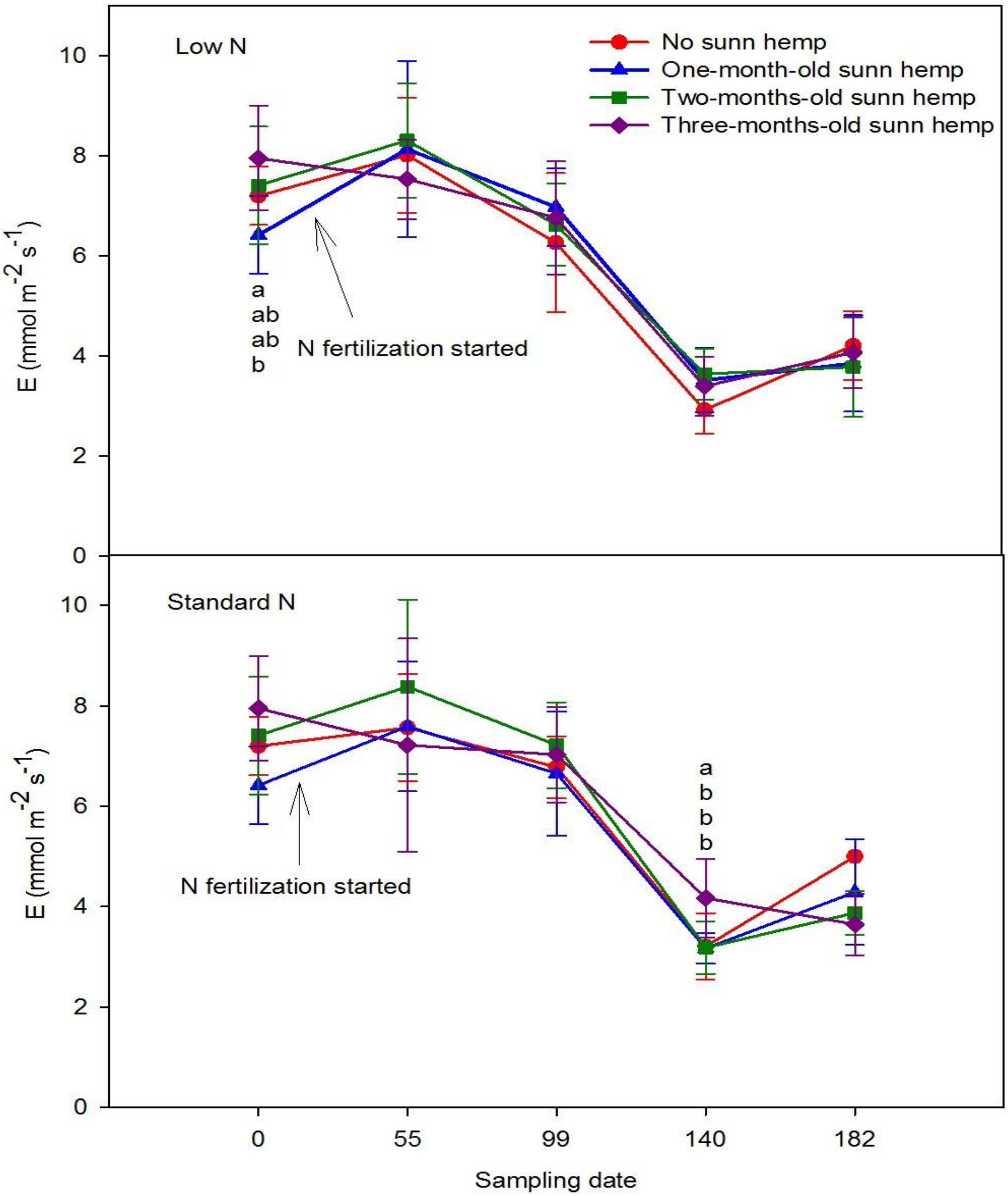

Figure 3-7. Effects of incorporation of sunn hemp at different ages into Krome very gravelly loam soil on transpiration (E) of papaya plants fertilized with a low N or a standard N rate. .Different letters indicate significant difference among treatments (P<0.05). Symbols represent means of 5 replicates. Error bars represent + 1 standard deviation.

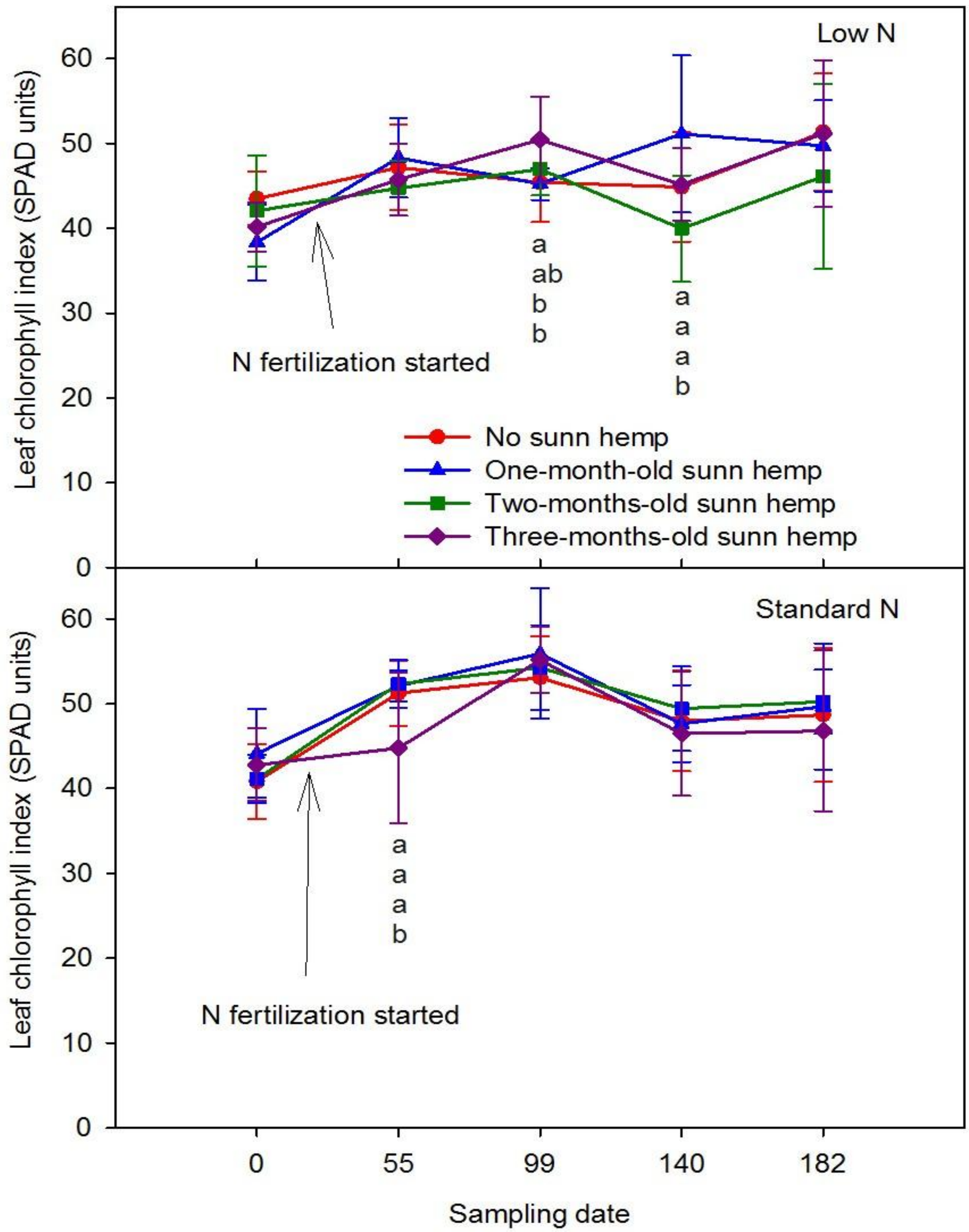

Figure 3-8. Effects of sunn hemp incorporation into Krome very gravelly loam soil on leaf chlorophyll index of papaya plants fertilized with a low N or a standard N rate. Asterisks indicate a significant difference among treatments (P < 0.05). Symbols represent means of 5 replicates. Error bars represent + 1 standard deviation.

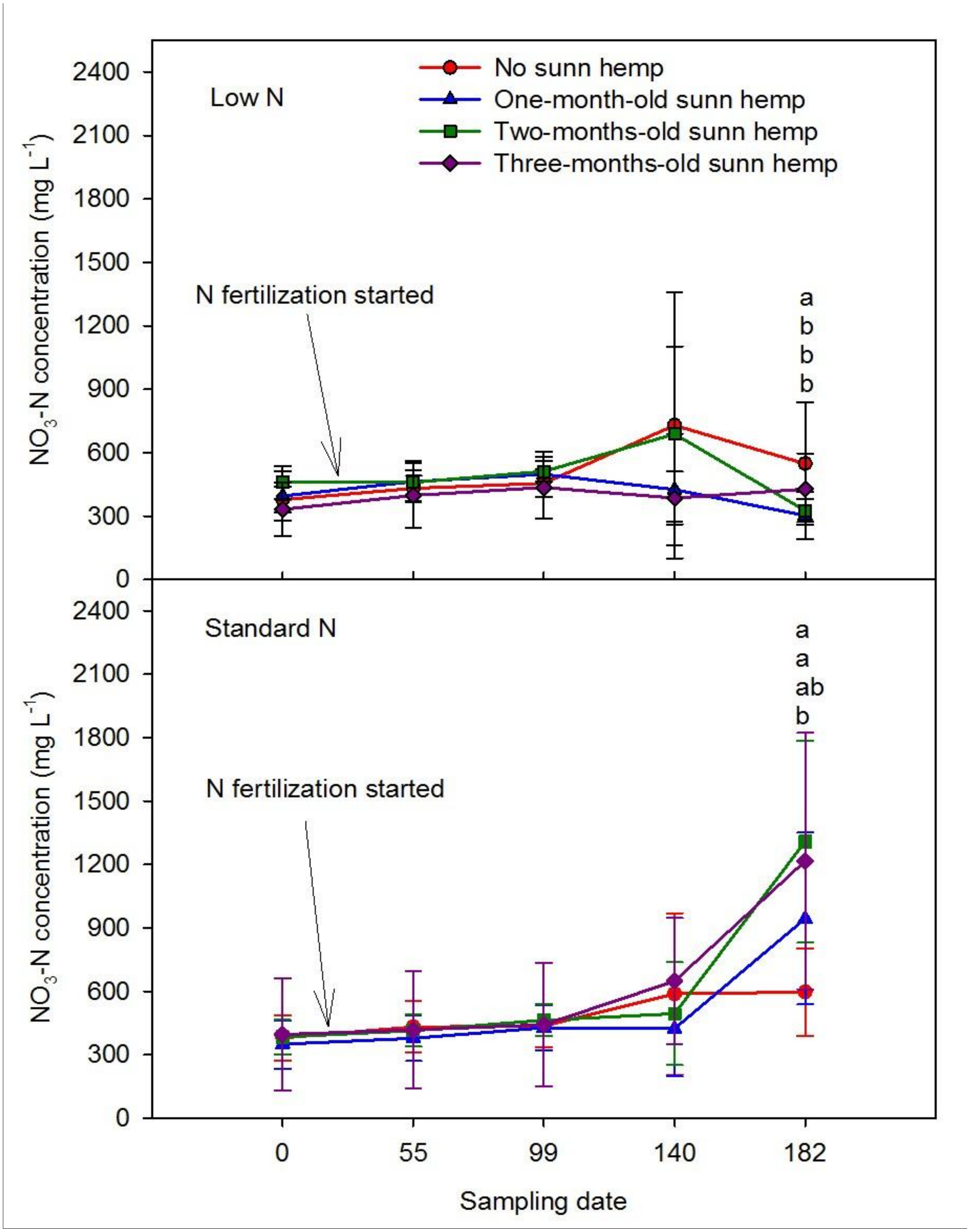

Figure 3-9. Effects of sunn hemp incorporation to soil on fresh petiole sap nitrate (NO_3-N) of papaya plants fertilized with a low N or a standard N rate. Asterisks indicate a significant difference among treatments ($P \leq 0.05$). Symbols represent means of 5 replicates. Error bars represent $\pm$ 1 standard deviation.

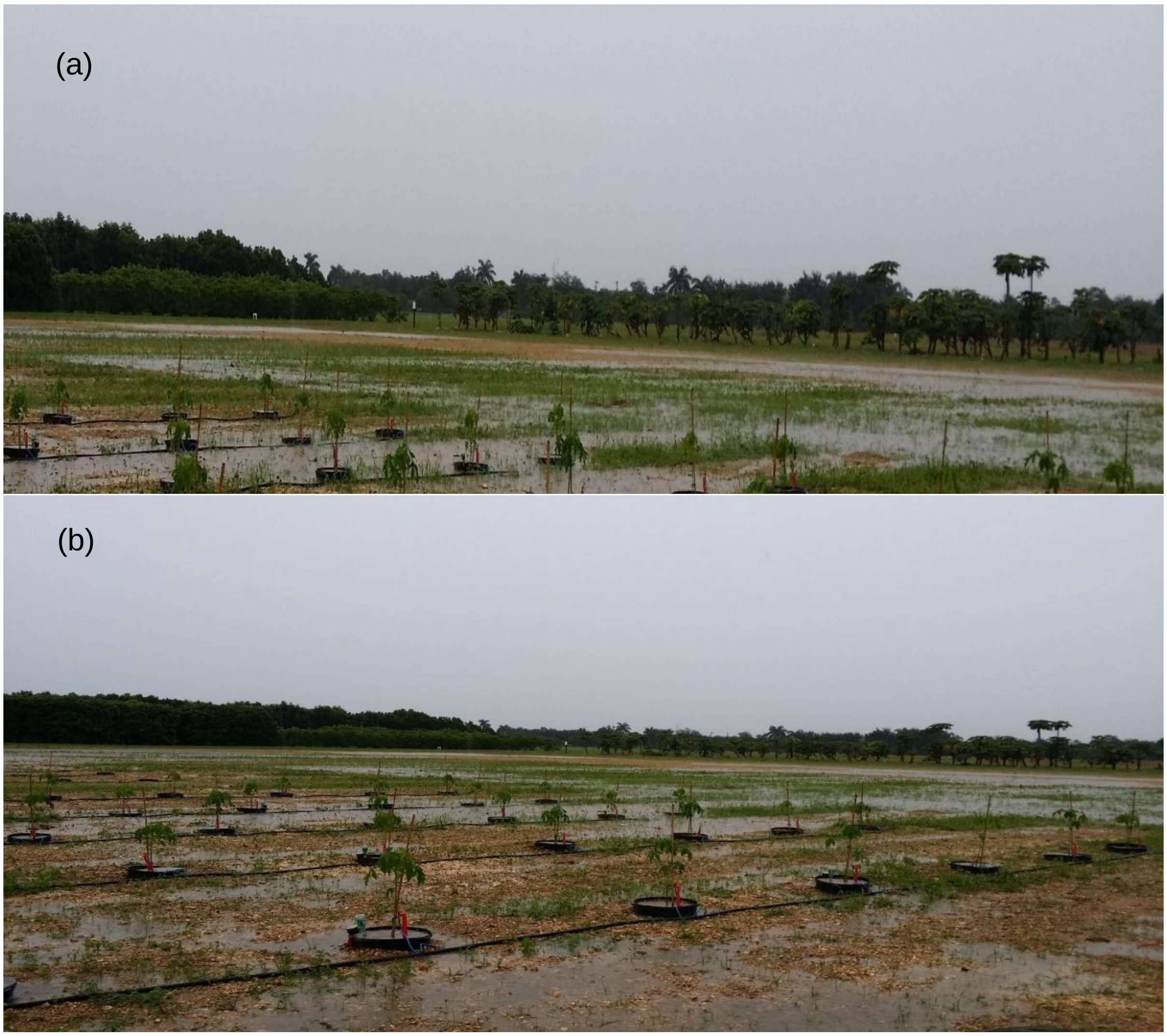

Figure 3-10. (a) The experimental field at the University of Florida, Tropical Research and Education center (TREC) after several hours of heavy rains. (b) Papaya plants in the experiment showing flooding stress symptoms.

CHAPTER 4
SUMMARY AND CONCLUSION

Papaya cultivation in Florida is concentrated in the agricultural area of Miami-Dade County. In south Florida, papaya production is not as profitable as it could be due to low yields and high prices (Evans et al. 2012; Evans and Ballen, 2014). The Krome very gravelly loam soils in which papaya is planted in the area contains little organic matter (OM) and is very porous, resulting in a low nutrient- and water-holding capacity. Excellent potential exists for increasing soil OM matter and nutrient content in this soil by planting cover crops in rotation with cash crops and mowing and incorporating the cover crops into the soil prior to planting the cash crop (Wang et al. 2015a). One species that has shown tremendous potential as a cover crop in south Florida is sunn hemp (*Crotalaria juncea* L.), a leguminous plant which grows very rapidly in the summer in south Florida (Wang et al, 2015a, b). Thus, the potential exists to increase the profitability of papaya production in southern Florida with the use of sunn hemp as a cover crop (Wang et al. 2015b). Typically in south Florida, sunn hemp is grown for several months (generally to a height of 2.5-3 meters), then mowed, and incorporated into the soil prior to crop planting. At this time the stems are large and very fibrous (Yuncong Li, personal communication). Therefore, it may be more beneficial to mow the sunn hemp at an earlier growth stage (younger age) when stems are less fibrous, thus hastening tissue decomposition and build up of OM and release of N from the sunn hemp tissues incorporated into the soil.

Two experiments were conducted to investigate the effects of stage of development (age) of sunn hemp prior to mowing and soil incorporation on of decomposition of sunn hemp tissue in the soil and physiology, growth, and yield of papaya planted in sunn hemp-amended Krome very gravelly loam soil. The hypotheses tested were: 1) the age of sunn hemp prior to mowing and incorporation into Krome very gravelly loam soil will significantly affect soil N and OM contents and physiology, growth and yield of papaya planted in sunn hemp-amended soil, 2) the minimum rates of inorganic N required for papaya plants when sunn hemp is incorporated into the soil prior to papaya planting will be reduced compared to a control treatment with no sunn hemp added to the soil, 3) the time needed for decomposition of sunn hemp to achieve maximum release of N into the soil will occur during the first 10-14 days after sunn hemp is incorporated into the soil, and 4) plant fiber content will be inversely related to N availability in sunn hemp plant residues. The specific objectives of the first experiment were to determine the effects of incorporation of sunn hemp at different ages on N and OM content of Krome very gravely loam soil and to determine the effects of soil incorporation of sunn hemp at different stages of development on physiology, and growth yield of papaya plants in Krome very gravelly loam soil. The objectives of the second experiment were to determine the effects of sunn hemp age at the time of mowing and soil incorporation on decomposition rate of sunn hemp in Krome very gravelly loam soil.

In the first experiment, there was no strong effects of incorporating sunn hemp into Krome very gravelly loam soil on soil N or OM contents, or leaf gas exchange, leaf chlorophyll content, growth, flowering or fruit yield of papaya plants. In the second experiment, plant age at the time of mowing sunn hemp, prior to incorporating combined stem and leaf tissues into Krome very gravelly loam soil, affected the decomposition rate of the buried sunn hemp tissues. Prior to burying the plant tissues, there was a significant difference among treatments in tissue fresh weight, with the one-month-old treatment having the highest fresh weight, followed by the two-months-old treatment, with the 3-months-old treatment having the lowest fresh weight. Nitrogen content of the excavated, buried sunn hemp tissue was significantly higher in the one-month-old treatment than the other treatments on most measurement dates.

For all sunn hemp treatments, there was a rapid reduction in plant dry weight during the first 14 days after tissues were buried and after that time there was a large reduction in the rate of decrease of tissue dry weight over time. Also, the three-months-old sunn hemp treatment had a higher fiber (NDF and ADF) content than the one-month-old treatment on all but one sampling date. The typical practice of allowing sunn hemp to reach more than 2 meters high prior to mowing consequently may reduce the effectiveness of sunn hemp incorporation into the soil on increasing soil N and organic matter contents. A better approach may be to mow the sunn hemp at an earlier growth stage (younger age) when stems are less lignified which may hasten decomposition and yield of nitrogen from the sunn hemp incorporated into the soil.

The results of the decomposition study indicated that the age of sunn hemp at the time of mowing and burying stem and leaf tissues into Krome very gravelly loam soil affected the decomposition rate of the buried plant tissues. For all sunn hemp treatments, there was a rapid decrease in dry weight of the plant tissues during the first 14 days after burying tissues in the soil, followed by a very slow gradual decrease over the rest of the study period. Also throughout the experiment, the one-month-old treatment generally had higher N content and lower fiber contents (NDF and ADF) than the two- or three-months-old treatments. The slower breakdown of the two- and three-months old plant tissue compared to the one-month-old tissue was most likely due to the larger, more fibrous stems of the older plants. Other studies showed that sunn hemp decomposes slowly in the soil and provides suitable cover and added N for the cash crop planted after the sunn hemp is mowed and incorporated into the soil (Mansoer et al. 1997; Balkcom and Reeves, 2005; Cherr et al. 2006b). Additionally, Cherr et al. (2006b) observed that during the early growth stages, sunn hemp leaf dry matter and N content ranged from 50 to 60% of the total plant dry matter. Another study indicated that in south Florida, 'Tropic Sun' sunn hemp yielded more than 0.8 Mg ha-1 of biomass and approximately 150 kg N ha-1 when grown for 12 weeks in summer and then incorporated into the soil (Cherr et al. 2006b).

Various studies have shown that N from a cover crop incorporation into the soil commonly involves quick immobilization and extended mineralization of N (Aulakh et al. 1991; Maskina et al. 1993; McKenney et al. 1995; Mansoer et al. 1997; Medhdi et al. 1999). Consequently, planting dates after cover crop are incorporated into the soil must be planned to maximize the use of nutrients released from the cover crop residue. The present sunn hemp decomposition study showed that mowing and soil incorporation of sunn-hemp at a younger age (one-month-old) in summer, as opposed to the typical practice of mowing and soil incorporation at three- to four-months old, results in a quicker breakdown of plant fiber and a longer retention of N in the plant tissue for a longer and slower release of N to the soil. Future studies should investigate how higher sunn hemp planting density, compared to those of this study, prior to mowing and soil incorporation effects soil N and OM content over time. In addition, in this study bags containing sunn hemp tissues were all buried at the same depth in the soil. This may not be an accurate representation of what happens when sunn hemp is incorporated into the soil by the standard agricultural practice of rototilling and therefore is mixed throughout the soil. Therefore, additional studies using bags containing sunn hemp at several different soil depths instead of a single depth may change the rate of sunn hemp tissue decomposition. Additionally, the rate of sunn hemp tissue decomposition is presumably related to soil temperature and soil moisture content. Thus, studies relating different soil temperatures and soil water contents to the rate of sunn hemp tissue decomposition in the soil would be worth investigating. Finally, the present decomposition study was conducted in pots buried in the soil so that the soil volume among sunn hemp treatments would be similar. However, burying the sunn hemp tissues directly in the field soil may render different results than those observed in pots.

In contrast to observations with other crops where incorporating sunn hemp into Krome very gravelly loam soil increased crop growth and yield (Wang, et al. 2006,2009; Seaman, 2004; Hooks et al. 2007), there was little effect of soil incorporation of sunn hemp on physiology, yield and growth of papaya. Because of this, it was difficult to discern any differences in age of mowing and soil incorporation on papaya plant physiology, growth or yield. The reasons for lack of effect of soil incorporation of sunn hemp on papaya may be due to the relatively rapid initial breakdown of sunn hemp tissue (during the first 14 days of soil incorporation) shown in the decomposition study, relative to the slow growth rate of papaya compared to vegetable crops such as tomato (Wang et al. 2009), okra (Wang et al. 2006), cucumber (Hooks et al. 2007) that were previously studied. Thus, for vegetable crops, the rapid growth rate may have allowed them to take advantage of the rapid breakdown of a good portion of sunn hemp tissue in the soil soon after planting. In contrast, during much of the growth period of papaya, the majority of sunn hemp tissue in the soil was probably already broken down and most N from sunn hemp was already released into the soil for all sunn hemp treatments, regardless of age.

Moreover, this study suggests, that instead of the standard practice of mowing and incorporating sunn hemp into the soil when it is approximately three months old, mowing and incorporating it into the soil at an earlier age (one-month-old) will facilitate breakdown of the plant material and also provide a longer lasting source of slow-release N from a high planting density sunn hemp cover crop. Future studies with papaya should investigate the efficiency of increasing sunn hemp planting density, which may effectively increase the incorporation N and OM into the soil. Perhaps, mixing sunn hemp with other slow decomposing grasses or legumes may help develop a successful cover crop combination capable of supplying immediate and slow release N along different growing stages of papaya plant. Future studies with papaya should also investigate the effects of multiple cropping seasons in rotation sunn hemp. This would not only increase the amount of sunn hemp residue in the soil, but would also give a better indication of sunn hemp growth and yield. In addition, this would prevent unforeseen negative climatic factors, such as heavy rains and flooding in the case of this study, from obfuscating the results.

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BIOGRAPHICAL SKETCH

Abdulhakeem Baitsaid was born in Salalah, Oman. He received a Bachelor of Science degree in Crop Sciences from the Sultan Qaboos University, Oman, in October 2005. After graduation, he started working as a Horticulturist at Muscat Overseas Agri. Group, focusing on organic farming and protected agriculture. In 2007, he joined the Royal Court Affairs (Mango Encyclopedia Project) as a Horticulturist, where he developed experience in classification, modeling, and mapping species distributions. Over the last five years, he has worked on the Project Desert Beauty Farm, in the Empty Quarter. In 2015, he began his Master of Science degree program in the Horticultural Sciences Department at the University of Florida. His advisor is Dr. Bruce Schaffer at the Tropical Research & Education Center in Homestead, and the other members of his graduate committee are Dr. Yuncong Li and Dr. Guodong Liu.