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# Developing Sustainable Soil Building Strategies for Tropical Fruit Groves within the South Florida Redland

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# DEVELOPING SUSTAINABLE SOIL BUILDING STRATEGIES FOR TROPICAL FRUIT GROVES WITHIN THE SOUTH FLORIDA REDLAND

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by

Ariel Freidenreich

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To: Dean Michael R. Heithaus
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This dissertation, written by Ariel Freidenreich and entitled Developing Sustainable Soil Building Strategies for Tropical Fruit Groves within the South Florida Redland, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

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The dissertation of Ariel Freidenreich is approved.

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# DEDICATION

This body of work is dedicated to the Department of Earth and Environment at Florida International University. The tremendous commitment and knowledge provided by the professors within the department, combined with the quality educational experience I received, cultivated my interest and love for the environment.

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ABSTRACT OF THE DISSERTATION

DEVELOPING SUSTAINABLE SOIL BUILDING STRATEGIES FOR TROPICAL FRUIT GROVES WITHIN THE SOUTH FLORIDA REDLAND

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Professor Krishnaswamy Jayachandran, Major Professor

Tropical fruit production has become a lucrative industry in Miami-Dade County. Consequently, developing sustainable farming practices to be applied to these systems to ensure healthy soils and economically viable fruit production is becoming increasingly important. The study is focused on the incorporation of cover cropping as a management strategy for perennial tropical fruit production and its applications for local growers. Cover crops are plants that are grown to cover soil to reduce erosion, increase soil fertility, and enhance farmland biodiversity. The project was specifically designed to test the impacts of highly prolific legumes sunn hemp (*Crotalaria juncea*) and velvet bean (*Mucuna pruriens*), intercropped with young carambola (*Averrhoa carambola*) trees on soil and plant health parameters. Sunn hemp and velvet bean were grown for two 90-day growing seasons and were left to decompose as green manure after termination. Carambola trees and surrounding soil were monitored over a 1.5-year period to quantify changes among six fertilizer treatments. Along with the field study, surveys were formulated and distributed to local growers to assess likelihood of cover crop adoption within the community. The goals of this work are threefold: 1) to understand the impact of legume cover crops on soil parameters 2) to understand the interaction between legume cover crops and carambola health/fruit production 3) to understand the perceptions of local fruit producers concerning cover cropping as a management strategy. Results indicated that sunn hemp was most successful in biomass production and providing available nitrogen to soils, while velvet bean was most stimulatory for short-term soil microbial parameters. Sunn hemp treatments were comparative to poultry manure fertilizer for contribution of soil carbon and nitrogen over the sampling period. Trees treated with sunn hemp exhibited high fruit yields and exceeded other cover crop treatments in regard to tree health parameters. Surveys conducted amongst the Miami-Dade County agriculture community revealed that farmers were interested in learning about cover cropping and attending workshops and informational sessions. Through logistic regression analysis, likelihood to cover crop was positively influenced by farm size, previous experience with cover crops, believing the practice is economically viable, and valuing cover crop importance.

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ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| AMF | Arbuscular mycorrhizal fungi |
| ANOVA | Analysis of variance |
| AOA | Ammonia oxidizing archaea |
| AOB | Ammonia oxidizing bacteria |
| B | Logistic coefficients |
| BNF | Biological nitrogen fixation |
| BMP | Best management practices |
| °C | Celsius |
| C | Carbon |
| $CaCO_3$ | Calcium carbonate |
| CC | Cover crop |
| cm | Centimeter |
| $CO_2$ | Carbon dioxide |
| Com | Compatibility |
| Comx | Complexity |
| C/N | Carbon to nitrogen |
| DIW | Deionized water |
| dw | Dry weight |
| EC | Electrical conductivity |
| EQIP | Environmental Quality Incentives Program |
| F | Fallow |
| FIU | Florida International University |

| | |
|---|---|
| FM | Fallow + poultry manure |
| g | Gram |
| $g^{-1}$ dw $h^{-1}$ | Grams dry weight per hour |
| g $kg^{-1}$ | Grams per kilogram |
| ha | Hectare |
| IFAS | Institute of Food and Agricultural Sciences |
| IR | infrared |
| K | Potassium |
| kg | Kilogram |
| kg $ha^{-1}$ | Kilograms per hectare |
| LAD | Leaf angle distribution |
| LAI | Leaf area index |
| M | Molar |
| m | Meter |
| MDC | Miami Dade County |
| Mg $ha^{-1}$ | Metric ton per hectare |
| ml | Milliliter |
| mm | Millimeter |
| MUF | 4-methylumbelliferone |
| MUFC | 4-methylumbelliferone β-D-glucoside |
| MUFN | 4-methylumbelliferone N-acetyl- β-D- glucosaminide |
| N | Nitrogen |
| Ndfa | Nitrogen derived from the atmosphere |

| | |
|---|---|
| NDVI | Normalized difference vegetation index |
| NDRE | Normalized difference red edge index |
| NIR | Near infrared |
| $NH_3$ | Ammonia |
| NRCS | National Resource Conservation Service |
| nm | Nanometers |
| $NO_2^-$ | Nitrite |
| $NO_3^-$ | Nitrate |
| $NO_X$ | Nitrate + nitrite |
| NS | Not significant |
| NT | no-till |
| Obs | Observability |
| OM | Organic matter |
| OMRI | Organic Materials Review Institute |
| pH | Power of hydrogen |
| PM | Poultry manure |
| PVC | Polyvinyl chloride |
| Q&A | Question and answer |
| RA | Relative advantage |
| RAA | Redland Agricultural Area |
| RD | Relative disadvantage |
| SE | Standard error |
| SH | Sunn hemp SHM |

| | |
|---|---|
| SHM | Sunn hemp + poultry manure |
| SOC | Soil organic carbon |
| SOM | Soil organic matter |
| SPAD | Soil Plant Analysis Development |
| TC | Total carbon |
| TFGSF | Tropical Fruit Growers of South Florida |
| TIFF | Tagged Image File Format |
| TN | Total nitrogen |
| Tri | Trialability |
| UAV | Unmanned aerial vehicle |
| UF | University of Florida |
| USDA | United States Department of Agriculture |
| VB | Velvet bean |
| VBM | Velvet bean + poultry manure |
| WFPS | Water filled pore space |
| μmol | Micromol |

# CHAPTER 1: INTRODUCTION

## 1.1 What are cover crops?

A cover crop is a plant grown for the purpose of protecting soil from erosion and nutrient loss that occurs through leaching, runoff, or volatilization (Reeves, 1994). Cover crops are grown for a period of time and then killed or terminated. After termination, cover crop residue is considered green manure and is either incorporated into soil via tillage or decomposes on the soil surface in a no-till fashion (Sharma et al. 2018). Cover crops can provide a variety of benefits including organic matter addition, soil structure improvement, weed control, nutrient management, and pollinator attraction (Scholberg et al. 2010). Implementing cover crops is considered sustainable as this practice can decrease the need for chemical herbicides and fertilizers, lessen soil erosion, protect water bodies through leaching control, and improve agricultural yields via soil enhancement (Clark, 2008). Including cover cropping as a management strategy for agricultural production settings should be easily integrated with minimal inputs and maintained with resources already on hand. As such, selecting the correct cover crop species is critical to address specific needs. The chosen species should ideally limit competition with cash crops, be easy to cultivate, and withstand adversarial environmental conditions, making the choice to implement the strategy feasible for farmers (Treadwell et al. 2008).

## 1.2 Study area

The current body of work is focused on identifying specific cover crops to be intercropped with tropical trees within South Florida. Consequently, the study takes place in South Miami within the Redland Agricultural Area (RAA, Figure 1.1). The RAA is located in plant hardiness zone 10b and has a subtropical climate (average annual extreme minimum temperature 1.6 – 4.4 °C) (USDA, 2012). South Florida has a characteristically wet summer season (May – October) and a winter dry season (November – April), with warm temperatures year-round (Duever et al. 1994). Because of these climatic patterns, warm season vegetable crops are commonly planted and cultivated fall through spring (Brown, 2012). The summer season serves as a high production period for tropical fruit crops like mango, carambola, and lychee (Crane et al. 2006). Because of increased temperature and rainfall throughout the summer months, annual vegetable crops are not commonly produced during this time, making summer an ideal season for cover cropping.

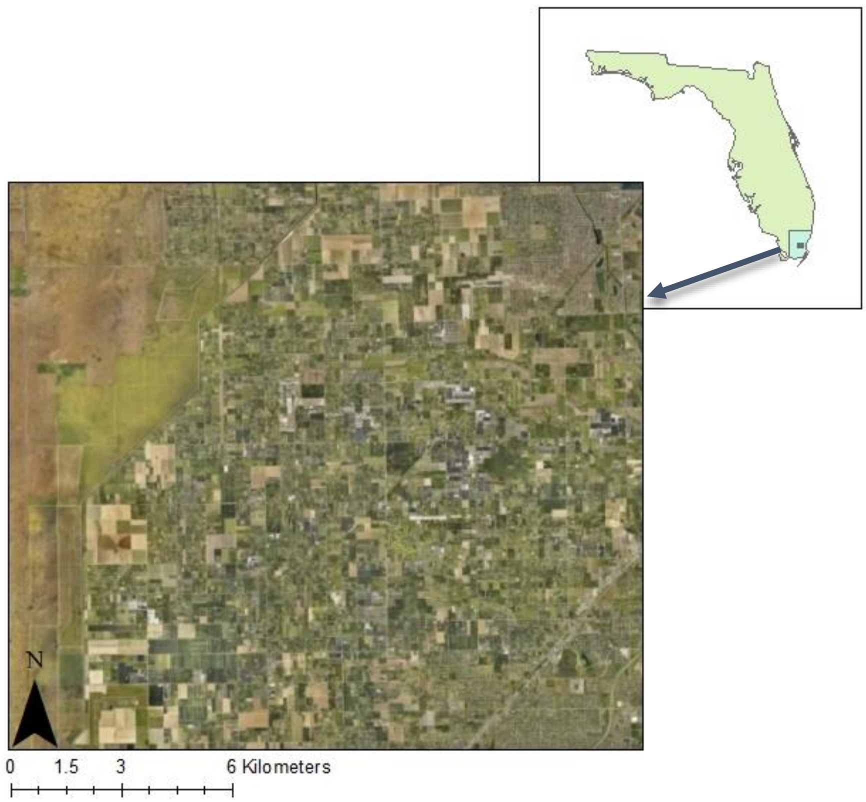


**Figure 1. 1** Location of the Redland Agricultural Area.

The soil in the RAA is categorized by the United States Department of Agriculture, National Resource Conservation Service (USDA, NRCS) as Krome Series soil. Generally, soil utilized for agricultural purposes in the RAA is rock plowed to create depth for root establishment (~15 – 20 cm) (Li, 2001). Rock plowed soils are typically gravelly in texture with many rock fragments (Zhou and Li, 2001). The limestone parent material creates a soil that has an inherently basic pH, low organic matter content, and low water holding capacity (Savabi, 2001). Given these characteristics, applying cover crops to these soils could provide substantial benefits to improving physical, chemical, and biological properties (Rich et al. 2003).

**1.3 Crop species description**

The study focuses on two cover crop species, sunn hemp (*Crotalaria juncea*) and velvet bean (*Mucuna pruriens*), to test their feasibility for intercropping with carambola trees (*Averrhoa carambola*). These species and their characteristics are described in the following sections.

*1.3.1 Sunn hemp characteristics*

Sunn hemp is a fast-growing leguminous cover crop native to India and Pakistan (Fall et al. 2020). Sunn hemp has an erect growth habit with the potential to reach heights greater than 1.8 m and branches once it reaches 60 cm (Rotar and Joy, 1983, Figure 1.2). Sunn hemp is adapted to calcareous and well-drained soil. It can thrive in a wide range of pH conditions and is drought tolerant, needing little to no external irrigation (Wang et al. 2015). When planted in late spring/ early summer, sunn hemp can produce large quantities of biomass within 60 days.

**Figure 1. 2** Sunn hemp at its mature stage.

Summer is the ideal growing season for high biomass yield of sunn hemp in South Florida because of its short-day characteristic. Since daylight hours are long throughout the summer months, sunn hemp is less likely to flower and seed than when grown during fall/winter seasons (USDA NRCS Plant Guide). For successful biomass and nitrogen production, it is recommended to inoculate seeds with cowpea type rhizobium and apply seeds at a rate of 45 - 67 kg $ha^{-1}$ for vegetable production settings (Treadwell et al. 2008; Wang et al. 2005). In South Florida, sunn hemp has been demonstrated to produce 277 - 356 kg $ha^{-1}$ of nitrogen and 9.7 - 12.5 Mg $ha^{-1}$ dry biomass within a 60-day growing period following the above recommendations (Wang et al. 2015; 2004). As an additional management strategy, Abdul-Baki et al. (2001) recommends cutting the main stem at 30-

60 cm height to induce lateral branching for ideal biomass production during the growing season.

*1.3.2 Velvet bean characteristics*

Velvet bean is a leguminous annual native to Malaysia, China, and India (Lampariello et al. 2012). Velvet bean has a vining growth habit, producing vines 3 - 18 m long with a lifecycle of 120 - 330 days (Ortiz-Ceballos et al. 2012, Figure 1.3). Velvet bean is adapted to warm and humid climates and can prosper in a wide variety of soil conditions as it is drought tolerant and can withstand soil pH ranging from 4.5 - 7.7 (Ortiz-Ceballos et al. 2012).


**Figure 1. 3** Velvet bean at its mature stage.

It is recommended to inoculate velvet bean seed with cowpea type rhizobium and apply seeds at a rate of 45 - 50 kg $ha^{-1}$ for vegetable production (Treadwell et al. 2008). In South Florida, following established seeding recommendations, velvet bean has the potential to provide 173 - 286 kg $ha^{-1}$ of nitrogen and 6.7 - 11.1 Mg $ha^{-1}$ dry biomass within a 60-day growing period (Wang et al. 2005). Like sunn hemp, velvet bean is also a short-day photoperiod crop, and is most effective in biomass production when planted in the late spring and early summer months (Hartkamp et al. 2002).

*1.3.3 Carambola characteristics*

Carambola (*Averrhoa carambola*) or starfruit, is a tropical fruit tree that originates from Southeast Asia (Saúco, 1993). Since carambola is native to tropical climates, it thrives in warm and humid conditions and has low tolerance to freezing temperatures (Manda et al. 2012). These trees are considered small to medium in size ranging from 6 - 10 m in height and produce fruit within the mid-canopy range (Knight and Crane, 2002; Crane, 2007; Crane, 2001). The carambola is an attractive fruit that is green to yellow in color, fleshy in nature, and has a unique star shape in cross section (Narain et al. 2001). The starfruit is traditionally consumed fresh or made into juice. It has a distinctive flavor and is available in both sour and sweet varieties (Gol et al. 2015).

Because of climatic limitations, Florida and Hawaii are the only states that produce carambola as a commercial crop (Crane, 2006). In its native setting, carambola can produce fruit year-round, while in Florida, the primary fruit crops mature by late summer and early winter (Morton, 1987). In South Florida, carambola typically take 60 - 75 days to reach maturity from fruit set. Fruit production of carambola tress varies by age; trees from 2-3 years old can be expected to produce 4.5 to 18 kg of fruit per year. By year 5, healthy trees produce from 45 to 68 kg per year, and at full maturity 112 – 160 kg per year (Crane, 2001). Commercial carambola production in South Florida is relatively recent, beginning in the 1970s with the development of the primary commercial cultivar 'Arkin' (Núñez-Elisea and Crane, 1998).

**Figure 1. 4** Carambola or starfruit

Carambola is fairly hearty and easy to grow with few pests and diseases that negatively affect tree and crop health (Litz and Griffis, 1989). However, carambola in South Florida have been shown exhibit some unfavorable responses to climatic variations. During the winter season, carambola can experience lack of growth, leaf chlorosis, and defoliation as a result of colder temperatures and increased cloud cover (Núñez-Elisea and Crane, 1998). These trees are also sensitive to wind, showing symptoms of wind damage via stunted growth, desiccation, and defoliation (Crane, 1994). Additionally, it has been reported that carambola is sensitive to drought stressors which adversely affect flower set and fruit production (Masri, 1995).

## 1.4 Cover crops and fruit production

Cover cropping is a management strategy that can be utilized in vegetable crop rotations or as a groundcover in perennial or orchard settings (USDA NRCS, 2008). Traditionally, cover cropping is more commonly utilized for annual vegetable production as crop rotation lends itself to easier termination and management. Orchard managers may be averse to intercropping trees with cover crops as competition for water and nutrients, along with intensive management procedures may negatively impact production (Lehmann et al. 1999). To recommend cover cropping as a management tool for fruit growers, research demonstrating benefits to production is critical to develop extension resources. There is an overall lack of peer reviewed studies in regard to cover crop incorporation and tropical fruit production systems. Steyn et al. (2014) identified a need for more detailed knowledge on cover crops and their potential in tropical fruit agroecosystems as a tool for soil building and crop protection as there are remarkably few studies that address this topic. Jannoyer et al. (2011) developed an approach for appropriate selection of cover crops to enhance orchards in tropical areas, however, little formal research has been conducted regarding specific tree and cover crop species since then.

## 1.5 Objectives

My research study was designed to encompass all aspects of introducing cover crop regimens for fruit growers in the RAA. By addressing soil and plant health aspects, along with farmers' willingness to adopt cover cropping as a practice, the study provides a holistic outlook for effectiveness and feasibility of cover cropping for tropical fruit growers. The following objectives will be addressed within the chapters to follow:

1. To test the effectiveness of sunn hemp and velvet bean as cover crops for enhancement of dynamic soil characteristics in a young carambola grove.
2. To test the effectiveness of sunn hemp and velvet bean as cover crops for enhancement of tree health and production in a young carambola grove.
3. To understand farmers perceptions of cover cropping and their willingness to adopt the practice.

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## CHAPTER 2: INFLUENCE OF LEGUMINOUS COVER CROPS ON SOIL PROPERTIES IN A NO-TILL TROPICAL FRUIT PRODUCTION SETTING

### 2.1 Abstract

South Florida's agricultural soils are traditionally low in organic matter and high in carbonate rock fragments. Thus, these calcareous soils are inherently nutrient poor and require management for successful crop production. The study focused on intercropping two highly productive leguminous cover crops, sunn hemp (*Crotalaria juncea*) and velvet bean (*Mucuna pruriens*), with juvenile carambola (*Averrhoa carambola*) trees. The intention was to test the effectiveness of these green manure crops in providing nutrients, stimulating microbial activity, and supplementing traditional fertilizer regimes (poultry manure) with sustainable soil building options. Sunn hemp and velvet bean were grown for two summer growing seasons. At the end of each 90-day growing period the cover crops were terminated and left on the soil surface to decompose in a no-till fashion. The results suggest that sunn hemp treatments produced the greatest amount of dry biomass material supplying more C and N than velvet bean. Sunn hemp treatments and the fallow + poultry manure addition added the most organic matter, total carbon, and total nitrogen to the soil. Soils treated with sunn hemp contributed the largest quantity of available N. Considering soil microbial activity, velvet bean treatments had the largest impact on soil $CO_2$ flux and sunn hemp treatments had the greatest effect on soil enzyme β-1-4-glucoside. Overall, sunn hemp treatments showed the greatest potential for supplementing soil nutrients and organic matter in a no-till fruit production setting, while velvet bean treatments had the greatest impact on short-term microbial stimulation.

## 2.2 Introduction

Cover cropping is widely known as a conservation agriculture strategy suitable for sustainable and organic food production systems. In the context of tropical fruit production, many challenges arise for land managers in warm and wet climates. Tropical climates facilitate productive growth, yet high inputs are often necessary because of quick nutrient and organic matter (OM) turnover (Seneviratne, 2000), along with heightened pest and disease pressures (Abang et al. 2014). Leguminous cover crops, specifically varieties suited for tropical climates, have great potential to act as a solution for these issues by improving soil resilience and enhancing farmland diversity (Vincent et al. 2015). Precise cover crop (CC) management has been shown to improve soil quality through increasing soil organic matter (SOM), providing nutrients to cash crops, and enhancing soil microbial activity without the addition of synthetic inputs (Garcia et al. 2013). Promotion of soil building techniques in perennial systems is critical as erosion and loss of SOM resulting from intensive agriculture practices endangers long-term soil fertility and enhances greenhouse gas emissions (Wang et al. 2010)

Organically managed farmland has grown in popularity, increasing 553% worldwide from 1999 to 2017 (Willer et al, 2019). Although organic consumables are becoming more available, sustainable production of organic commodities can be challenging. Cover cropping practices combined with standard fertilization methods utilized in organic agriculture may be an ideal combination to promote environmental and economic sustainability. Poultry manure (PM) is commonly applied as fertilizer in organic tropical fruit production systems. As over 10 billion kg of poultry litter is produced annually in the United States, composting poultry litter is a useful way to repurpose problematic waste into a nutrient source for crop production (Reddy et al. 2007). Repurposing the waste for agricultural purposes is a sustainable method of adding carbon (C) and nitrogen (N) to soils (Nyakatawa et al. 2001; Reddy et al. 2004), while reducing the risk of N leachate polluting natural systems (Kaiser et al. 2009). Utilization of CCs combined with PM fertilizer has potential as an ideal management strategy for tropical fruit orchards, although this topic has been seldomly explored.

The agricultural landscape of South Florida is one of the few regions in the contiguous United States with a subtropical climate favorable for commercial tropical fruit production. South Florida is a hotspot for agricultural industry with production of tropical fruit, winter vegetables, and ornamental plants year-round. Climate is not the only aspect that makes this area distinct. Southern Florida soils are characteristically calcareous, well drained, and high in rock fragments (Wang et al. 2005). The area has a shallow, underdeveloped, soil profile; consequently, rock plowing is a common practice in agricultural fields to create enough soil depth (10-20 cm) for root growth and establishment (Crane et al 2006). Typically, rock plowing results in a rocky or gravelly textured soil with less than 2% OM (Li, 2001). These soil characteristics make OM additions crucial to soil management in South Florida to create a productive growth medium for agricultural commodities.

Organic matter cycling and nutrient mineralization are key soil processes that maintain soil fertility and facilitate growth of plants (Tiessen et al. 1994). Soil organic carbon (SOC) content directly influences soil structure and function (Hu et al. 2014). Accordingly, incorporation of green manure residue enhances ecosystem services, like nutrient cycling, through proliferation of beneficial soil biota (Adhikari and Hartemink, 2016). Soil nutrient cycling, specifically nitrogen mineralization, is critical to crop health as plant metabolism and vital processes are fueled by uptake of N (Leghari et al. 2016). In agricultural settings, the addition of legume CCs can stimulate N cycling by the process of biological nitrogen fixation (BNF) (Kallenbach et al. 2010). Biological nitrogen fixation occurs through legume root association with diazotrophic bacteria (Xavier et al. 2017). Biological nitrogen fixation allows legumes to accumulate sufficient amounts of N for growth, which collects within their plant biomass (Parr et al. 2011). As such, when utilizing legume CCs for the purpose of green manure, residue added to the soil after termination adds N as a food source for soil organisms and ultimately subsequent crops (Dias et al. 2015). Cover crops can also excrete root exudates that stimulate/attract beneficial rhizosphere microorganisms like arbuscular mycorrhizal fungi (AMF) and N fixing bacteria, which ultimately contribute to soil and plant health (Akiyama et al. 2005; Huang et al. 2014)

Traditional CC practices involve tillage to incorporate green manure residue into soil, however, CCs can also be useful in no-till (NT) settings. Fruit orchards are traditionally NT systems once trees are planted, as mechanical tillage would cause damage to surface feeder roots that remain in the top centimeters of the soil. Therefore, soil surrounding perennial tree crops is often left unstimulated leaving trees to eventually experience reduction in productivity as crop rotation and tillage is not possible in most cases (Vukicevich et al. 2016). Perennial NT systems can significantly benefit from CC species that produce large amounts of dry biomass to achieve high C inputs to soil (Bayer et al. 2008).

Tropical leguminous CCs *Crotalaria juncea* (sunn hemp, SH) and *Mucuna pruriens* (velvet bean, VB) are fast growing nitrogen fixers that can add various benefits to (sub)tropical agricultural landscapes. As described in chapter 1, SH has been shown to produce anywhere from 277 - 356 kg $ha^{-1}$ of N and 9.7 - 12.5 Mg $ha^{-1}$ dry biomass and VB has the potential to provide 173 - 286 kg $ha^{-1}$ of N and 6.7 - 11.1 Mg $ha^{-1}$ dry biomass within a 60-day growing period in South Florida vegetable production settings (Wang et al. 2005; 2015). Previous studies found that SH and VB can significantly increase soil C and N fractions, improve soil aggregate stability, and influence the abundance of beneficial soil microbes in no-till settings (Rigon et al. 2020; Oliveira et al. 2020; Comin et al. 2018; Calonego et al. 2017). Therefore, these tropical legumes are ideal for low input systems and have great potential to enhance soil health for tropical fruit production. Sunn hemp and VB have been tested for their effectiveness in greenhouse and vegetable production studies within the South Florida agricultural climate (Wang et al. 2005; 2007; 2009; 2012; 2015). Yet, effects of CCs on soil characteristics in tropical fruit groves in South Florida has yet to be studied, particularly in young, emerging systems.

Carambola (*Averrhoa carambola*), more commonly known as starfruit, is a tropical fruit tree native to Southeast Asia (Muthu et al. 2016). Carambola is accustomed to hot, humid weather, making it ideal for growth in (sub)tropical climates (Crane et al. 2001). As such, carambola has huge potential for South Florida growers as a lucrative cash crop (Evans et al. 2017). For many years, avocado has been the staple tropical fruit crop for Miami-Dade County growers (over 2400 planted hectares, Crane and Wasielewski, 2018). However, within the last decade the aggressive emergence of a devastating fungal pathogen, commonly known as laurel wilt (*Raffaelea lauricola*), has led to the mandatory eradication of many infected avocado groves (Menocal et al. 2018; Carillo et al. 2012). Consequently, local growers are looking towards alternative tropical fruit crops to populate their groves. Carambola is a promising candidate as current individual tree value is highest for all maturity increments (1-3 years: $567, 4-6 years: $860, 7+ years: $984) as compared to avocado and other feasible alternatives (Evans et al. 2017).

To target current concerns within the Miami-Dade County agricultural scope and to explore solutions to improve management practices for sustainable production of tropical fruits worldwide, the present study was developed to test the effectiveness of SH and VB as CCs. The goal was to measure the impact of CC incorporation on dynamic soil parameters in a young carambola grove.

## 2.3 Materials and Methods

### *2.3.1 Site location and characteristics*

The two-season field experiment was conducted in a multi-use certified organic fruit orchard (6.07 ha) located in the Redland Agricultural Area (RAA) of South Florida, USA. The RAA is considered subtropical and is located in plant hardiness zone 10b (USDA, 2012). This subtropical climate is characterized by a typical wet summer season (May – October, 26.6° C average temperature, and 18 cm average annual rainfall) and a dry winter season (November – April, 21.1° C average temperature, 4.6 cm average annual rainfall) with warm weather year-around (23.6° C average temperature) (Obeysekera et al. 1999).

*2.3.2 Experimental Design*

One year before the start of the experiment, two rows of young carambola trees were planted extending 122 m long with 7 m spacing in-between rows. The trees used for this study were 'Hawaiian Super Sweet' trees grafted onto 'Golden Star' seedling rootstocks and were ~3-years-old at the start of the experiment. Carambola saplings were planted with 3.8 m between each tree resulting in 30 trees per row. Experimental sites were arranged in a completely randomized design (CRD) with 2 cover crop treatments: sunn hemp (SH) and velvet bean (VB), 2 cover crop + manure treatments: sunn hemp + poultry manure (SHM) and velvet bean + poultry manure (VBM), and 2 fallow control treatments: fallow (F) and fallow + poultry manure (FM). The design included 6 treatments with 9 replications for each treatment, a total of 54 trees (Table 2.1).

**Table 2.1** Cover crop treatments and replicates utilized throughout the experiment.

| | **Treatment** | **Replicates** |
|---|---|---|
| **F** | Fallow (no cover crop) | 9 |
| **FM** | Fallow + poultry manure | 9 |
| **SH** | Sunn hemp | 9 |
| **SHM** | Sunn hemp + poultry manure | 9 |
| **VB** | Velvet bean | 9 |
| **VBM** | Velvet bean + poultry manure | 9 |

The trees designated to receive PM were treated with an organic composted fertilizer amendment (5N-3P-2K USDA Organic Certified poultry manure).

*2.3.3 Field Methodology*

Carambola trees treated with CCs received either 33 kg $ha^{-1}$ (89g/plot) of SH *(Crotalaria juncea* L. cv. '*Tropic Sun*') seed or 25 kg $ha^{-1}$ (67g/plot) VB (*Mucuna pruriens* var. '*pruriens*') seed. Seeding rates were calculated following the Miami-Dade

County Extension recommendations for CC seeding in vegetable crop scenarios and adjusted to a 33% grove coverage rate. The CC coverage used for the study was determined using the size of trees and operation of tractor sprayer, and other machinery. Cover crop seeds were treated with OMRI certified Guard'n Seed Inoculant (Verdesian Life Sciences, Cary, NC) which contains a variety of rhizobium species (*Bradyrhizobium japonicum, Bradyrhizobium (Vigna), Rhizobium leguminorsarum biovar viceae, Rhizobium leguminosarum biovar phaseoli*), to ensure robust plants with sufficient root nodulation for N fixation.

Weeds were physically removed from each plot before the start of the experiment in preparation for cover crop seeding. The cover crop treatments were seeded directly in a circular fashion starting at the dripline (approx. 0.5 m radius from the trunk) and circling around the tree in a 1.25 m radius resulting in a planting area of 8.8 $m^2$. Sunn hemp and VB treatments were planted simultaneously. All plots were irrigated for one hour per day via sprinkler system. Sunn hemp was clipped at 60 cm above the ground at 60 days after germination to inspire lateral branching and increased biomass productivity (Abdul-Baki et al. 2001). Sunn hemp and VB were terminated 90 days after germination. Sunn hemp was terminated mechanically via hedge trimmer and VB was hand clipped, leaving root systems intact. The cover crop biomass was laid around the base of each respective tree. Following termination, fertilizer treatment (1.4 kg PM/tree) was applied every two months and green manure decomposed on the soil surface. The cover crop treatments were planted and terminated two times over the study period. Individual treatments for each tree remained the same for both years.

Composite soil samples (0-15 cm depth) were collected over the course of the experiment from the planting area of each tree. Soil samples were taken before cover crop planting, before termination, and every two months following, except for the last 4 months in which sampling occurred once per month. After initial weeding, one soil collar was installed per tree for in situ soil respiration measurements via LI-6400 XT Portable Photosynthesis Meter (Lincoln, Nebraska) with Soil $CO_2$ Flux Chamber attachment. Soil respiration (LI 6400 XT), temperature, moisture percentage, and electrical conductivity (EC) (STEVENS Hydraprobe, Portland, Oregon) was measured once per month and at corresponding soil sampling times. At 90 days after cover crop seed germination, a 40 x 40 $cm^2$ area of plant matter (cover crop and weed) was exhumed from each plot, including control plots. Aboveground CC biomass was measured to determine organic matter and nutrient additions to the soil.

*2.3.4 Physio-chemical properties of soil and plant material*

Composite soil samples were oven dried (30°C for 48 hours), sieved (2 mm), and ground to prepare for analysis of physio-chemical properties. Plant tissue samples were oven dried at 70°C for 72 hours for chemical analysis. Soil organic matter percentage was determined through the standard loss on ignition method (550°C for 4 hours; Storer, 1984). Total carbon and nitrogen (CN) of soil and plant material was measured via dry combustion utilizing a Truspec Carbon/Nitrogen Analyzer (LECO Corporation, St. Joseph, MI). Plant tissue CN was utilized to calculate TC and TN contribution from CCs to soil for each growing season.

Inorganic N was extracted using a 2M KCl extraction method. Extracts were then analyzed for nitrate ($NO_3^-$) and nitrite ($NO_2^-$) following the United States Environmental

Protection Agency's (USEPA) Nitrate-Nitrite by Automated Colorimetry Method 353.2, Revision 2.0 (1993). These same extracts were used for ammonia determination ($NH_3$) following the USEPA method 350.1, Revision 2.0 (1993). All readings were quantified with a SEAL Analytical AQ2 Discrete Auto Analyzer (Mequon, Wisconsin).

Soil moisture content was determined via gravimetric method (dried at 105˚C for 24 hours) and bulk density via cylinder method. Soil textural analysis was performed using the hydrometer method.

*2.3.5 Analyses of soil enzyme activity*

Soil enzyme analysis was conducted for determination of β-1-4-glucoside (C) and β-N-acetylglucosaminidase (N). Methodology adopted from Sinsabaugh et al. (1997), Hoppe (1993), and Chróst and Kambeck (1986) was utilized to determine soil enzyme activity using differences in concentration of fluorescent substrate released during incubation time compared with no incubation. Soil slurries with a 2:1 water to soil ratio (4g distilled deionized water to 2g wet soil) were made and pH readings were taken. Substrates were prepared using morpholinoethanesulfonic acid (MES) in combination with 4-methylumbelliferone (MUF) β-D-glucoside (MUF-C) and MUF-N-acetyl- β-D-glucosaminide (MUF-N). Soil floc was prepared at varying dilutions according to concentration. For C and N, $10^{-2}$ dilutions were analyzed using a Synergy HT Multi-Mode 96 Well Plate Reader (Biotek Inc. Winooski, Vermont).

*2.3.6 Statistical analyses*

Soil data were analyzed using SPSS statistical software (IBM Corp. (1968). IBM SPSS Statistics for Windows (Version 25.0). Armonk, NY: IBM Corp.) and SAS (SAS Institute Inc. 1976. Base SAS® 9.4. Cary, NC: SAS Institute Inc.) Data were analyzed via one-way analysis of variance (ANOVA) with Tukey's posthoc to distinguish difference between treatments ($p < 0.05$). Bivariate correlation was used to determine between factor correlations and considered correlated when $p \leq 0.05$ and highly correlated when $p \leq 0.01$.

## 2.4 Results and Discussion

### *2.4.1 Soil Characteristics, climatic conditions, and cover crop contribution*

The soil present at the site was a sandy loam (73% sand, 17% clay, and 10% silt) with an average pH of 7.6, considered to be slightly alkaline (Table 2.2). In general, the soil utilized in this experiment had higher baseline nutrient content and SOM% than traditional Krome series soil. This variation in SOM can be attributed to previous soil building management strategies like nutrient and OM additions by the land manager. All tested soil parameters showed no significant difference for any of the tree areas prior to designated treatments.

**Table 2.2** Physical and chemical characteristics of soils collected before the experiment (background soil). Values (mean ± SD) presented are of composite samples from 0-15 cm of soil.

| PARAMETERS | VALUE |
|---|---|
| DEPTH | 0-15 cm |
| EC (dS/m) | 0.820 ± 0.679 |
| pH | 7.60 ± 0.07 |
| SOM (%) | 11.96 ± 0.75 |
| TC (g $kg^{-1}$) | 111.53 ± 3.02 |
| TN (g $kg^{-1}$) | 6.42 ± 0.31 |
| C/N (mol:mol) | 17.50 ± 0.51 |
| $NO_X$ (g $kg^{-1}$) | 19.62 ± 1.37 |
| $NO_3$ (g $kg^{-1}$) | 18.63 ± 1.41 |
| $NO_2$ (g $kg^{-1}$) | 0.0018 ± 0.0005 |
| $NH_3$ (g $kg^{-1}$) | 3.39 ± 0.18 |

Throughout the study period average air and soil temperatures were 26.4 °C and 28.8 °C, respectively, for summer, and 21.4 °C and 23.7 °C, respectively, for winter months (Figure 2.1). Precipitation trends were highest during July- August (18 – 23.7 cm average) in both years (Figure 2.1) as expected for South Florida given climatic trends that result in wet summers and dry winters (Kwon et al. 2009). As such, a reduction in precipitation can be observed in the beginning in the fall months (September- November) and continuing throughout the year until summer. The first-year cover crop growing season (May 18 – Aug 18) received 64% higher rainfall than the second season (May 19 – Aug 19). While relative humidity (%) remained fairly consistent with the exception of March - May 19 when increased temperature and low rainfall resulted in three lower humidity months (Figure 2.1).

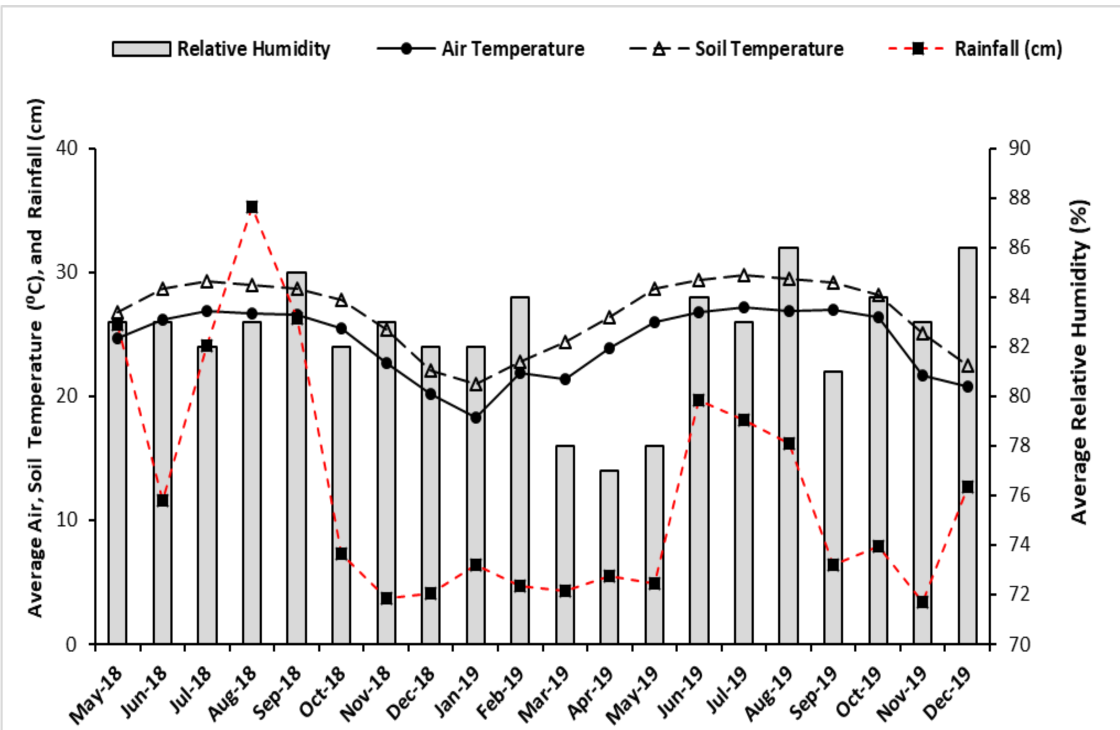


**Figure 2. 1** Climatic conditions of the sampling sites over the 1.5-year trial period. This graph represents average relative humidity (%), air temperature (°C), soil temperature (°C), and rainfall (cm).

On the basis of seeding rates augmented from field crop recommendations, results presented in Table 2.3 indicate that overall, both SH and SHM treatments produced up to 63% (season 1) and 77% (season 2) more shoot dry matter than VB treatments. Consequently, SH also produced up to 64% (season 1) and 78% (season 2) more organic C than VB treatments ($p < 0.05$) over two summer growing seasons. Biomass production rates are reflected by CC tissue C/N ratios in which VB provided consistently lower C/N green manure material (up to 50% lower for season 1 and up to 37% lower for season 2) throughout both growing seasons. When comparing total N contributed by cover crop dry matter, the SH treatment contributed ~48% (169 kg ha$^{-1}$) more N to the soil than VBM (88 kg ha$^{-1)}$ in season 1 ($p < 0.05$), while SHM (142 kg ha$^{-1}$) and VB (111 kg ha$^{-1}$) contributed similar amounts of N ($p > 0.05$). For season 2, both SH treatments produced up to 67% more N than VB treatments ($p < 0.05$). Higher amounts of N contributed by SH tissue was most likely attributed to higher overall higher biomass production.

When comparing SH and VB in a potted study within the RAA, Wang et al. (2006) found that VB produced less biomass and TC when compared to SH for two consecutive growing seasons. Because SH has a tall vertical growth habit and large stem, it has high potential for biomass production. Additionally, as a non-wood fiber crop, the SH stem can become strong and woody in its later growth stages providing higher C additions over time (Sheahan, 2012). High carbon content of SH stems is likely the cause for higher C/N ratios within the SH plant tissue material.

**Table 2.3** Displays cover crop seeding and poultry manure rates along with nitrogen contribution from two cover crop growing seasons (n = 9). Seeding rates and fertilizer rates were the same for both seasons. The 5-3-2 (N-P-K) poultry manure was applied to every plot designated for treatment (FM = fallow + manure, SHM = sunn hemp + manure, and VBM = velvet bean + manure) along with cover crop treatment or a no cover crop control (F = fallow, SH = sunn hemp, and VB = velvet bean, CC = cover crop, PM= poultry manure). Values within a column followed by different letters denote statistical difference at $p < 0.05$ within the same season.

| | **Seed Rate** | **PM N Rate** | **N (CC)** | **C (CC)** | **C/N (CC)** | **Shoot Dry Matter (CC)** | **Shoot Dry Matter (weeds)** |
|---|---|---|---|---|---|---|---|
| **Season 1** | **kg ha$^{-1}$** | **kg ha$^{-1}$** | **kg ha$^{-1}$** | **kg ha$^{-1}$** | **kg ha$^{-1}$** | **kg ha$^{-1}$** | **kg ha$^{-1}$** |
| **F** | N/A | N/A | N/A | N/A | N/A | N/A | 9475a |
| **FM** | N/A | 105 | N/A | N/A | N/A | N/A | 7802a |
| **SH** | 33 | N/A | 169a | 5855a | 34.44a | 12159a | 1778b |
| **SHM** | 33 | 105 | 142ab | 5355a | 36.54a | 11103a | 2322b |
| **VB** | 25 | N/A | 111ab | 2089b | 23.85b | 4452b | 3928b |
| **VBM** | 25 | 105 | 88b | 2028b | 18.22b | 4113b | 2384b |
| **Season 2** | | | | | | | |
| **F** | N/A | N/A | N/A | N/A | N/A | N/A | 6496a |
| **FM** | N/A | 52 | N/A | N/A | N/A | N/A | 6531a |
| **SH** | 33 | N/A | 213a | 4709a | 23.55a | 9437a | 1930b |
| **SHM** | 33 | 52 | 135ab | 2956b | 22.37a | 6028b | 3302b |
| **VB** | 25 | N/A | 88b | 1433bc | 16.21b | 2901bc | 2742b |
| **VBM** | 25 | 52 | 69b | 1029c | 14.86b | 2089c | 3156b |

In addition to cover crop biomass rates, Table 2.3 reports weed biomass in the form of shoot dry matter production. Results reveal that weed biomass was up to 81% higher in the fallow plots where cover crops were not planted (F and FM). Weed biomass quantities reflect SH and VBs ability suppress weed growth and proliferation, a common environmental benefit of CC usage (Wayman et al. 2015).

In general, CCs and weeds accumulated greater biomass in season 1 when compared to season 2 as reflected by shoot dry matter quantity (Table 2.3). Increased biomass in season 1 may have been the result of higher rainfall amounts during the seeding and germination period (May- 18) when compared to season 2 (Apr-19) and throughout growing season 1 overall (Figure 2.1).

*2.4.2 Soil electrical conductivity and pH*

On the basis of results presented in Table 2.4, CC treatments did not have any significant observable effect on measured soil EC throughout the experiment. Additions of manure and cover crop residue have been shown to have a short-term impact on altering soil EC (Eigenberg et al. 2002). Soil EC was effectively unchanged from season to season and between treatments, although it is possible that EC fluctuations occurred in the short-term when cover crops were recently terminated, however season conglomeration no effect was apparent.

**Table 2.4** Displays average soil electrical conductivity (EC) (n = 9), soil pH, soil organic matter percentage (SOM%), soil total carbon (TC), total nitrogen (TN), and C/N ratio for cover crop season 1 (Aug-18 – Apr- 19) and season 2 (n = 4). Three cover crop treatments (F = fallow, SH = sunn hemp, and VB = velvet bean) and three manure treatments (FM= fallow + poultry manure, SHM = sunn hemp + poultry manure, VBM = velvet bean + poultry manure) were analyzed for these parameters. Values within a column followed by different letters denote statistical difference at $p < 0.05$ ± denotes standard error.

| | **EC (dS/m)** | **pH** | **SOM (%)** | **TC (g kg$^{-1}$)** | **TN (g kg$^{-1}$)** | **C/N (mol:mol)** |
|---|---|---|---|---|---|---|
| **Season 1** | | | | | | |
| **F** | 0.083 (±0.007) | 8.03 (±0.05)a | 9.62 (±0.45)b | 103.66 (±2.96)b | 5.07 (± 0.18)b | 20.27 (±0.67) |
| **FM** | 0.082 (±0.005) | 7.75 (±0.07)b | 11.28 (±0.45)ab | 119.10 (±3.61)a | 6.83 (±0.41)a | 18.07 (±0.72) |
| **SH** | 0.088 (±0.007) | 7.98 (±0.06)ab | 11.45 (±0.65)ab | 113.18 (±3.44)ab | 6.03 (±0.31)ab | 19.19 (±0.67) |
| **SHM** | 0.087 (±0.007) | 7.85 (±0.06)ab | 11.87 (±0.47)a | 122.23 (±2.45)a | 6.75 (±0.35)a | 18.74 (±0.73) |
| **VB** | 0.063 (±0.004) | 7.95 (±0.07)ab | 10.45 (±0.65)ab | 116.53 (±2.93)ab | 5.91 (±0.35)ab | 20.49 (±0.88) |
| **VBM** | 0.081 (±0.006) | 7.87 (±0.04)ab | 9.58 (±0.54)b | 108.98 (±3.99)ab | 5.97 (±0.33)ab | 18.80 (±0.81) |
| **Season 2** | | | | | | |
| **F** | 0.046 (±0.061) | 8.08 (±0.04)a | 13.52 (±0.50)c | 155.53 (±4.02)bc | 7.06 (±0.31)ab | 22.56 (±0.58)ab |
| **FM** | 0.048 (±0.007) | 7.83 (±0.08)b | 16.30 (±0.45)a | 179.50 (±3.16)a | 8.31 (±0.27)a | 21.87 (±0.59)b |
| **SH** | 0.050 (±0.005) | 8.03 (±0.06)ab | 15.72 (±0.30)a | 167.74 (±3.52)ab | 7.86 (±0.25)ab | 21.58 (±0.05)b |
| **SHM** | 0.047 (±0.005) | 7.99 (±0.05)ab | 15.48 (±0.28)ab | 171.31 (±2.58)ab | 7.47 (±0.14)ab | 23.03 (±0.49)ab |
| **VB** | 0.043 (±0.004) | 7.93 (±0.05)ab | 13.93 (±0.26)bc | 167.94 (±3.68)ab | 6.81 (±0.36)b | 25.22 (±0.80)a |
| **VBM** | 0.050 (±0.005) | 7.87 (±0.07)ab | 13.98 (±0.34)bc | 150.01 (±7.40)c | 7.00 (±0.56)ab | 22.21 (±1.17)b |
| **Overall** | | | | | | |
| **F** | 0.065 (±0.005) | 8.06 (±0.03)a | 11.67 (±0.46)b | 131.03 (±5.04)ab | 6.09 (±0.24)b | 21.41 (±0.47)ab |
| **FM** | 0.070 (±0.005) | 7.79 (±0.05)c | 13.79 (±0.53)a | 150.16 (±5.69)a | 7.59 (±0.27)a | 20.02 (±0.56)a |
| **SH** | 0.070 (±0.005) | 8.01 (±0.04)ab | 13.65 (±0.50)a | 142.80 (±5.26)ab | 7.02 (±0.25)ab | 20.49 (±0.50)ab |
| **SHM** | 0.067 (±0.005) | 7.92 (±0.04)abc | 13.78 (±0.40)a | 144.05 (±4.48)ab | 7.07 (±0.21)ab | 20.65 (±0.40)ab |
| **VB** | 0.053 (±0.003) | 7.92 (±0.04)abc | 12.14 (±0.47)ab | 140.72 (±5.02)ab | 6.34 (±0.26)b | 22.72 (±0.47)b |
| **VBM** | 0.065 (±0.004) | 7.87 (±0.04)bc | 11.58 (±0.51)b | 128.29 (±5.36)b | 6.45 (±0.33)b | 20.40 (±0.51)ab |

Fallow + manure plots had significantly lower pH than all other treatments, remaining slightly alkaline throughout the experiment (7.75 – 7.83, $p < 0.05$) because PM was added directly to the soil surface without hinderance of CC debris. Conversely, the F plots had the highest pH, consistent throughout the experiment (8.03 – 8.08, $p < 0.05$, Table 2.4), which is likely attributed to the lack of OM added to the soil. All CC treatments remained similar to one another within the moderately alkaline range for both seasons fluctuating from 7.85 – 8.03 ($p > 0.05$). Organic matter addition from the CCs may have played a role in acidifying soil in the short-term but was not reflected by data grouped by season. Calcareous soils generally have a high pH buffering capacity; however, long-term fertilization can reduce calcium carbonate ($CaCO_3$) of naturally calcareous soils, ultimately lowering the buffering capacity (Zhang et al 2016). While there were not very obvious changes in soil pH throughout the study period, it is possible that over time, the loss of $CaCO_3$ and the increase of SOM may result in the acidification of soil with cover crop and manure additions.

### *2.4.3 Soil organic matter*

Within season 1, soil treated with SHM accumulated the highest SOM% (11.87%, $p < 0.05$, Table 2.4). The result aligns with high input of aboveground shoot biomass and PM additions to the soil (Table 2.3). The F (9.62%,) and VBM (9.58%) treatments had the lowest SOM% within season 1 (~19% less than SHM). Low SOM% is expected for the F treatment with no manure or CC addition and had consistently low SOM% throughout the experiment when compared to other treatments. The comparably lower SOM% within the VBM treatment throughout the experiment is likely attributed to lesser contribution of cover crop biomass (Table 2.3) along with possible high decomposition/volatilization rates resulting from no-till management (Janzen and Mcginn, 1991).

Season 2 showed varying results in SOM between treatments when compared to season 1 as FM (16.03%) and SH (15.72%) had the highest SOM% with SHM marginally lower (15.48%, $p < 0.05$, Table 2.4). As previously mentioned, it is possible that because FM plots received manure treatments without the hinderance of CC mulch, that change in SOM was more obvious in the short-term. Additionally, plots without CCs planted had a significantly higher degree of weed establishment throughout the experiment (Table 2.3). Mowing of weeds around plots occurred approximately every three months making it possible for decaying weeds to contribute to soil building and nutrition for both fallow treatments. Overall, SH and SHM (13.65% and 13.78%, respectively) contributed significantly greater amounts of OM to the soil when compared to VB, VBM, and F (12.14%, 11.58%, and 11.67%, respectively). The significant contribution of OM to the soil by SH treatments suggests that SH was effective for rapid addition of SOM, even after a short timeline of two growing seasons (~ 1.5 years). Organic matter is a vital component in soil that supplies essential nutrients, along with stimulating microbial activity, and improves water holding capacity, structure, and temperature regulation among other crucial characteristics (Nyakatawa et al. 2001). With cover crop and manure additions, SOM is expected to increase over time which was evident in this experiment.

Tropical leguminous cover crops have shown potential for supplementation of SOM in vegetable production settings in South Florida (Wang et al. 2005; 2007; 2009; 2012; 2015). Annual vegetable crops are generally grown for short time periods (months) in comparison to fruit crops, which take years to establish. As such, vegetable farmers could apply cover crops and/or other forms of crop residue at least annually, during fallow periods, to sustain SOM. For fruit growers, establishing a grove is a significant long-term investment. In perennial settings, addition of OM to ensure soil health and resilience are not as obvious or commonly practiced, yet just as crucial. Leaf litter and dropped fruit can add OM to soil, however, mature/decaying fruit can attract pests, a costly risk for growers (Atallah et al. 2014; Steck et al. 2009). This study demonstrates that SH in fruit groves successfully provide SOM in a no-till setting. This has positive implications for nutrient cycling and mineralization for sustainable fruit crop fertilization, especially for newly established groves that lack OM input from mature tree fruit and leaf drop.

*2.4.4 Soil total carbon and nitrogen*

Within season 1, SHM and FM (122.23 and 119.10 g $kg^{-1}$, respectively) had the highest TC content in the soil when compared to the other treatments ($p < 0.05$), while F plots exhibited notably lower levels of soil TC (Table 2.4). Conversely, for season 2, soils treated with VBM had the lowest TC content followed by the F treatment ($p < 0.05$). This is a result of soil treated with VBM having the least successful biomass production during season 2 (Table 2.3) with significantly lower inputs when compared to other treatments. Soil treated with FM had the highest TC content which may have been a result of high weed biomass (Table 2.3). Fallow land was advantageous for weed growth throughout the study, which may have contributed high amounts of carbon to the soil through above and belowground activities.

On the basis of the data presented in Table 2.4, the SH treatments were consistently successful in providing SOM and TC to the soil. Rosolem et al. (2016) also found that SH was effective in supplementing organic carbon within 0 - 10 cm of soil when compared to fallow and other non-leguminous cover crops. Consequently, the data within the present study did show that SH treatments are at times comparable to the standard fertilization method of PM alone (FM treatment) regarding SOM, TC, and TN.

Similar to TC results, soil TN within season 1 indicated that soil treated with F (5.07 g $kg^{-1}$) had the lowest TN. Sunn hemp + poultry manure (SHM, 6.75 g $kg^{-1}$) along with FM (6.83 g $kg^{-1}$) had the highest TN ($p < 0.05$), with all other treatments similar to one another. Within season 2, soil TN was statistically highest within soils treated with FM (8.31 g $kg^{-1}$) and lowest in those treated with VB (6.81 g $kg^{-1}$), with all other treatments similar. Again, this TN result likely a reflection of less successful biomass contribution by VB treatments during the second growing season (Table 2.3). These soil TN findings are consistent with other studies that have shown VB treatments add lower quantities of TN to soil than SH within the RAA subtropical climate (Wang et al. 2009, Wang et al. 2012).

Throughout season 1, there was no significant difference between treatments for soil C/N ratios ($p > 0.05$). Season 2 showed significantly lower C/N ratios for FM (21.87), SH (21.58), and VBM (22.21) treated soils, indicating an environment more conducive to OM breakdown and nutrient cycling by microorganisms when compared to other treatments (Eiland et al. 2001). The FM treatment had the highest contribution of TC and TN to the soil during growing season 2 (Table 2.4) which coincides with these results.

**Table 2.5** Displays bivariate correlations for all recorded parameters throughout the study.

| | NOx | $NO_3$ | $NO_2$ | $NH_3$ | Efflux | MUFC | MUFN | SOM | Soil C° | Moisture | Soil EC | TN | TC[h] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **WFPS**[a] | 0.321*[i] | 0.397** | -0.304* | 0.759** | 0.562** | 0.276* | 0.117 | -0.500** | -0.078 | 0.977** | 0.656** | -0.321* | -0.578** |
| **NOx** | | 0.493** | 0.262* | 0.260* | 0.060 | 0.049 | 0.117 | -0.014 | -0.111 | 0.357** | 0.341** | 0.107 | -0.140 |
| **$NO_3$** | | | 0.269* | 0.503** | -0.093 | 0.119 | 0.098 | 0.083 | -0.261* | 0.428** | 0.284* | 0.101 | -0.073 |
| **$NO_2$** | | | | -0.300** | -0.406** | -0.467** | -0.314* | 0.236 | 0.152 | -0.283* | -0.361** | 0.089 | 0.336** |
| **$NH_3$** | | | | | 0.445** | 0.303* | -0.018 | -0.290* | -0.207 | 0.753** | 0.531** | -0.177 | -0.468** |
| **Efflux**[b] | | | | | | 0.403** | 0.178 | -0.375** | 0.410** | 0.526** | 0.485** | -0.189 | -0.344** |
| **MUFC**[C] | | | | | | | 0.790** | 0.161 | 0.066 | 0.391** | 0.383** | 0.121 | 0.069 |
| **MUFN**[d] | | | | | | | | 0.110 | 0.165 | 0.297* | 0.284* | 0.059 | 0.041 |
| **SOM**[e] | | | | | | | | | -0.083 | -0.446** | -0.413** | 0.742** | 0.892** |
| **Soil C°** | | | | | | | | | | -0.080 | -0.110 | -0.175 | 0.060 |
| **Moisture** | | | | | | | | | | | 0.644** | -0.245 | -0.525** |
| **EC**[f] | | | | | | | | | | | | -0.198 | -0.497** |
| **TN**[g] | | | | | | | | | | | | | 0.730** |

[a] Water filled pore space
[b] $CO_2$ flux
c β-1-4-glucoside
[d] β-N-acetylglucosaminidase
[e] Soil organic matter
[f] Electrical conductivity
[g] Total nitrogen
[h] Total carbon
[i] Representing Pearson's correlation coefficient (r) significant at P ≤ 0.05 (*) or P ≤ 0.01 (**).

Throughout the study, soil TC and TN were positively correlated to SOM% ($p \leq 0.01$, Table 2.5) indicating that the increase in total nutrient concentrations is likely a direct outcome of SOM additions.

The study was conducted over a relatively short period of two CC growing seasons (~1.5 years). Changes in soil total nutrient and OM content often take years or even decades to accurately quantify impacts of conservation agriculture treatments, especially when utilizing a no-till management strategy (Baker et al. 2007). Mbuthia et al. (2015) conducted a 31- year study to quantify the long-term impact of varying CC and tillage treatments on soil health and cotton production. They concluded that implementing no-till practices combined with continuous input of legume CCs resulted in significantly enhanced soil CN storage and cycling, a result of nitrogen fixation, low soil disturbance, and OM additions. It is probable that if the current study were prolonged, more obvious differences would be observed between treatments in slower changing soil parameters such as those presented in Table 2.4. Warm and humid climatic conditions common to South Florida, have been reported to increase SOM decomposition and soil microbial activity i.e., respiration and nutrient cycling (Chen et al. 2002; Tang et al. 2005; Curiel-Yuste et al. 2007). Specifically, in no-till systems, increased dry matter production is critical as higher temperature and moisture settings are favorable for faster decomposition and volatilization rates (Rosolem et al. 2016). As such, it is likely that no-till cover cropping in the RAA may show more robust effects in total nutrient stocks, microbial communities, and other soil characteristics over additional years of continuous cover crop management to mitigate loss through green manure volatilization.

*2.4.5 Soil available nitrogen*

When considering average soil ammonia ($NH_3$) levels at each individual sampling time, regardless of treatment, Aug-18 (3.10 g $kg^{-1}$) and Oct-18 (3.02 g $kg^{-1}$) times had the highest average soil $NH_3$ content ($p < 0.05$, Figure 2.2).

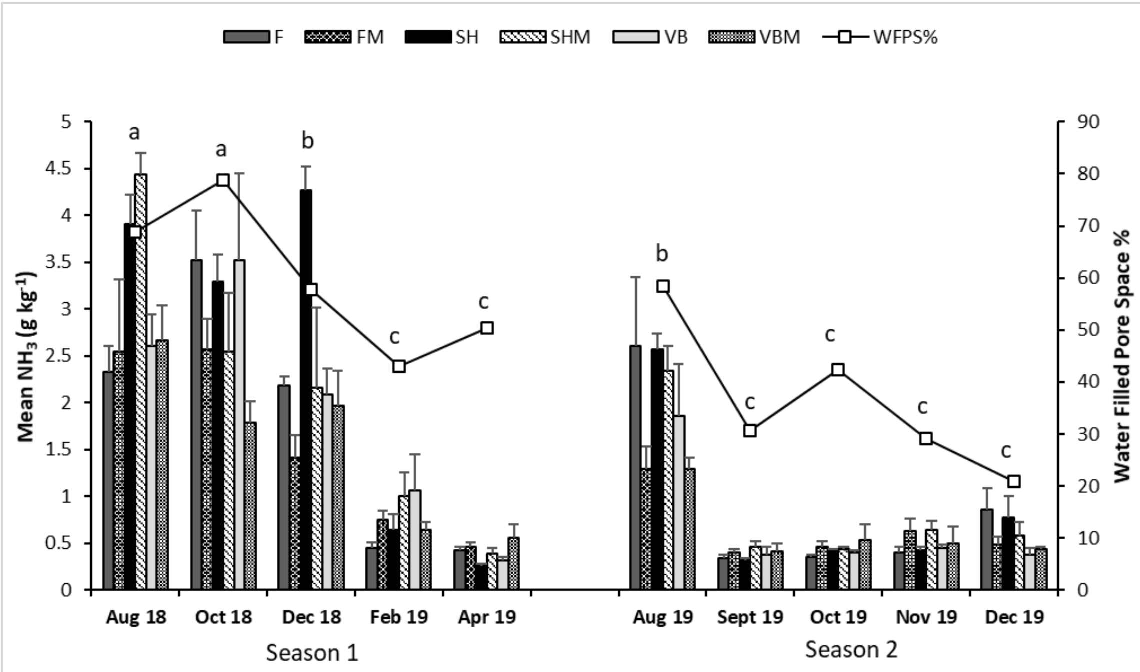


**Figure 2.2** Displays average $NH_3$ (n = 4) in soil along with its relation to water filled pore space over a two-season period after cover crop growth and termination. The bars at each sampling time represent three cover crop treatments (F = fallow, SH = sunn hemp, and VB = velvet bean) and three manure treatments (FM= fallow + poultry manure, SHM = sunn hemp + poultry manure, VBM = velvet bean + poultry manure). Different letters denote statistical difference between sampling times at $p < 0.05$, error bars denote standard error.

Additionally, there were multiple sampling times in which significant differences were observed in soil ammonia content ($NH_3$) between treatments (Figure 2.2, Table 2.6). At the Aug-18 sampling time ($1^{st}$ CC termination), soil $NH_3$ was highest for SHM treatment soils, up to ~47% higher than F treatments and ~41% higher than VB treated soils ($p < 0.05$, Figure 2.2, Table 2.6). High soil $NH_3$ was also observed at the Dec-18 sampling time (4 months after termination) within the SH (4.27 g $kg^{-1}$, $p < 0.05$) treatment compared to VB, VBM, and FM treatments (2.09, 1.96, and 1.46 g $kg^{-1}$, respectively) likely having to do with breakdown of OM from green manure addition. At the Apr-19 sampling, eight months after first CC termination, VBM treated soils were highest in $NH_3$ (0.56 g $kg^{-1}$) while SH soils (0.26 g $kg^{-1}$) were lowest ($p < 0.05$, Table 2.6).

**Table 2.6** Displays average soil $NO_x$ (nitrate + nitrite), $NO_2$, $NH_3$, enzyme activity (MUFN= β-N-acetylglucosaminidase and MUFC= β-1-4-glucoside) (n=4), and soil $CO_2$ efflux (n = 9) at each sampling time throughout the two-season experiment. Three cover crop treatments (F = fallow, SH = sunn hemp, and VB = velvet bean) and three manure treatments (FM= fallow + poultry manure, SHM = sunn hemp + poultry manure, VBM = velvet bean + poultry manure) were analyzed for these parameters. Values within a column followed by different letters denote statistical difference at $p < 0.05$, ± denotes standard error.

| | **$NO_X$** **(**g $kg^{-1}$) | **$NO_2$** (g $kg^{-1}$) | **$NH_3$** (g $kg^{-1}$) | **Efflux** (mol $m^2$s) | **MUFN** (µmol $g^{-1}$ dw $h^{-2}$) | **MUFC** (µmol $g^{-1}$ dw $h^{-2}$) |
|---|---|---|---|---|---|---|
| **Aug-18** | | | | | | |
| **F** | 11.46 (±1.26) | 0.0007 (±0.0001) | 2.33 (±0.28)b | 11.30 (±0.92)bc | 0.0043 (±0.0007) | 0.0357 (±0.0013)ab |
| **FM** | 10.74 (±1.92) | 0.0012 (±0.0002) | 2.54 (±0.18)b | 10.63 (±0.83)c | 0.0027 (±0.0022) | 0.0078 (±0.0033)c |
| **SH** | 16.50 (±2.41) | 0.0010 (±0.0002) | 3.91 (±0.31)ab | 12.32 (±1.36)abc | 0.0024 (±0.0010) | 0.0175 (±0.0031)bc |
| **SHM** | 15.68 (±1.33) | 0.0009 (±0.0004) | 4.43 (±0.24)a | 10.47 (±0.54)c | 0.0033 (±0.0012) | 0.0386 (±0.0122)a |
| **VB** | 12.62 (±0.53) | 0.0009 (±0.0002) | 2.61 (±0.33)ab | 15.36 (±1.52)ab | 0.0025 (±0.0006) | 0.0174 (±0.0121)bc |
| **VBM** | 13.94 (±1.54) | 0.0008 (±0.0001) | 2.66 (±0.38)ab | 15.99 (±0.66)a | 0.0046 (±0.0018) | 0.0121 (±0.0028)c |
| **Oct-18** | | | | | | |
| **F** | 12.42 (±1.26)b | 0.0029 (±0.0003) | 3.52 (±0.53) | 9.57 (±0.74) | 0.0067 (±0.0014) | 0.0430 (±0.0035) |
| **FM** | 17.19 (±2.09)b | 0.0008 (±0.0004) | 3.05 (±0.73) | 7.73 (±0.79) | 0.0051 (±0.0010) | 0.0227 (±0.0086) |
| **SH** | 25.36 (±4.00)ab | 0.0023 (±0.0008) | 3.29 (±0.30) | 10.01 (±0.66) | 0.0064 (±0.0012) | 0.0356 (±0.0174) |
| **SHM** | 17.65 (±1.36)b | 0.0014 (±0.0011) | 3.02 (±0.64) | 9.01 (±0.37) | 0.0081 (±0.0008) | 0.0181 (±0.0024) |
| **VB** | 32.84 (±2.52)a | 0.0017 (±0.0007) | 3.52 (±0.93) | 8.52 (±0.69) | 0.0048 (±0.0003) | 0.0231 (±0.0075) |
| **VBM** | 17.26 (±2.45)b | 0.0042 (±0.0022) | 1.78 (±0.24) | 9.13 (±0.52) | 0.0045 (±0.0008) | 0.0199 (±0.0084) |
| **Dec-18** | | | | | | |
| **F** | 8.45 (±1.00) | 0.0003 (±0.0001) | 2.18 (±0.10)ab | 4.81 (±0.34)a | 0.0044 (±0.0014) | 0.0206 (±0.0064) |
| **FM** | 15.83 (±2.94) | 0.0009 (±0.0005) | 1.46 (±0.29)b | 3.60 (±0.27)c | 0.0033 (±0.0008) | 0.0102 (±0.0012) |
| **SH** | 13.62 (±3.12) | 0.0004 (±0.0002) | 4.27 (±0.26)a | 3.79 (±0.06)bc | 0.0043 (±0.0009) | 0.0117 (±0.0010) |
| **SHM** | 20.69 (±4.08) | 0.0015 (±0.0008) | 2.16 (±0.85)ab | 4.65 (±0.18)ab | 0.0029 (±0.0003) | 0.0135 (±0.0040) |
| **VB** | 13.64 (±1.36) | 0.0002 (±0.0002) | 2.09 (±0.27)b | 4.15 (±0.15)abc | 0.0040 (±0.0009) | 0.0201 (±0.0091) |
| **VBM** | 12.94 (±1.39) | 0.0005 (±0.0002) | 1.96 (±0.37)b | 4.41 (±0.25)abc | 0.0063 (±0.0010) | 0.0165 (±0.0037) |
| **Feb-19** | | | | | | |
| **F** | 6.86 (±0.90) | 0.0006 (±0.0002) | 0.45 (±0.06) | 5.80 (±0.65)ab | 0.0084 (±0.0017) | 0.0322 (±0.0131) |
| **FM** | 15.95 (±2.41) | 0.0012 (±0.0004) | 0.75 (±0.10) | 5.30 (±0.61)b | 0.0104 (±0.0023) | 0.0304 (±0.0081) |
| **SH** | 17.15 (±1.84) | 0.0007 (±0.0003) | 0.65 (±0.17) | 5.21 (±0.25)b | 0.0090 (±0.0007) | 0.0303 (±0.0123) |
| **SHM** | 13.94 (±4.98) | 0.0011 (±0.0002) | 1.01 (±0.25) | 7.14 (±0.33)ab | 0.0093 (±0.0021) | 0.0471 (±0.0153) |
| **VB** | 13.23 (±4.59) | 0.0016 (±0.0009) | 1.07 (±0.39) | 5.98 (±0.65)ab | 0.0077 (±0.0018) | 0.0379 (±0.0109) |
| **VBM** | 13.51 (±1.09) | 0.0008 (±0.0002) | 0.64 (±0.09) | 8.07 (±0.88)a | 0.0122 (±0.0014) | 0.0362 (±0.0103) |
| **Apr-19** | | | | | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| **F** | 3.79 (±0.71)c | 0.0007 (±0.0003) | 0.43 (±0.04)ab | 8.50 (±0.71)bc | 0.0057 (±0.0012) | 0.0086 (±0.0018) |
| **FM** | 6.43 (±0.11)ab | 0.0024 (±0.0006) | 0.47 (±0.05)ab | 8.09 (±0.34)bc | 0.0076 (±0.0024) | 0.0165 (±0.0055) |
| **SH** | 4.74 (±0.31)bc | 0.0007 (±0.0002) | 0.26 (±0.02)b | 7.19 (±0.54)c | 0.0035 (±0.0009) | 0.0060 (±0.0016) |
| **SHM** | 8.76 (±0.85)a | 0.0018 (±0.0002) | 0.40 (±0.05)ab | 10.24 (±0.55)ab | 0.0051 (±0.0003) | 0.0155 (±0.0039) |
| **VB** | 4.21 (±0.25)bc | 0.0010 (±0.0003) | 0.32 (±0.04)ab | 6.64 (±0.51)c | 0.0040 (±0.0009) | 0.0075 (±0.0007) |
| **VBM** | 6.08 (±0.69)ab | 0.0011 (±0.0007) | 0.56 (±0.14)a | 11.39 (±1.04)a | 0.0038 (±0.0006) | 0.0108 (±0.0034) |
| **Aug-19** | | | | | | |
| **F** | 11.38 (±0.83) | 0.0000 (±0.0000) | 2.61 (±0.74) | 12.14 (±0.55) | 0.0098 (±0.0019)ab | 0.0931 (±0.0091)ab |
| **FM** | 16.51 (±0.35) | 0.0000 (±0.0000) | 1.29 (±0.25) | 9.40 (±0.60) | 0.0096 (±0.0016)ab | 0.0617 (±0.0054)b |
| **SH** | 15.10 (±1.91) | 0.0001 (±0.0001) | 2.58 (±0.16) | 9.72 (±0.76) | 0.0085 (±0.0007)b | 0.0810 (±0.0116)b |
| **SHM** | 18.36 (±2.72) | 0.0000 (±0.0000) | 2.34 (±0.27) | 9.19 (±0.71) | 0.0169 (±0.0015)a | 0.1393 (±0.0067)a |
| **VB** | 14.24 (±1.31) | 0.0007 (±0.0004) | 1.86 (±0.55) | 10.89 (±0.86) | 0.0084 (±0.0017)b | 0.0679 (±0.0185)b |
| **VBM** | 14.58 (±4.58) | 0.0007 (±0.0007) | 1.30 (±0.12) | 12.03 (±0.77) | 0.0074 (±0.0015)b | 0.0458 (±0.0072)b |
| **Sept-19** | | | | | | |
| **F** | 2.11 (±0.25)b | 0.0002 (±0.0001) | 0.34 (±0.03) | 8.40 (±0.63) | 0.0059 (±0.0008) | 0.0269 (±0.0088) |
| **FM** | 3.48 (±0.74)ab | 0.0009 (±0.0003) | 0.40 (±0.04) | 7.76 (±0.74) | 0.0063 (±0.0010) | 0.0368 (±0.0223) |
| **SH** | 3.35 (±0.86)ab | 0.0004 (±0.0002) | 0.32 (±0.01) | 8.02 (±0.79) | 0.0055 (±0.0014) | 0.0324 (±0.0164) |
| **SHM** | 2.99 (±0.39)ab | 0.0014 (±0.0012) | 0.46 (±0.06) | 8.24 (±0.48) | 0.0059 (±0.0017) | 0.0194 (±0.0084) |
| **VB** | 2.67 (±0.14)b | 0.0006 (±0.0002) | 0.38 (±0.08) | 7.64 (±0.49) | 0.0059 (±0.0014) | 0.0194 (±0.0008) |
| **VBM** | 5.29 (±0.31)a | 0.0008 (±0.0006) | 0.42 (±0.08) | 9.80 (±1.01) | 0.0109 (±0.0043) | 0.0311 (±0.0043) |
| **Oct-19** | | | | | | |
| **F** | 11.42 (±2.63) | 0.0015 (±0.0009) | 0.35 (±0.02) | 5.88 (±0.44) | 0.0042 (±0.0008) | 0.0195 (±0.0073) |
| **FM** | 13.57 (±4.83) | 0.0030 (±0.0010) | 0.47 (±0.05) | 5.23 (±0.37) | 0.0038 (±0.0008) | 0.0082 (±0.0006) |
| **SH** | 13.16 (±1.59) | 0.0017 (±0.0006) | 0.42 (±0.02) | 5.26 (±0.52) | 0.0036 (±0.0011) | 0.0064 (±0.0023) |
| **SHM** | 13.20 (±2.08) | 0.0034 (±0.0003) | 0.44 (±0.03) | 5.97 (±0.47) | 0.0074 (±0.0009) | 0.0100 (±0.0030) |
| **VB** | 13.67 (±3.74) | 0.0020 (±0.0002) | 0.40 (±0.03) | 6.27 (±0.53) | 0.0034 (±0.0011) | 0.0066 (±0.0020) |
| **VBM** | 16.56 (±7.04) | 0.0013 (±0.0020) | 0.54 (±0.17) | 6.45 (±0.69) | 0.0051 (±0.0017) | 0.0130 (±0.0010) |
| **Nov-19** | | | | | | |
| **F** | 4.48 (±0.22)b | 0.0009 (±0.0006) | 0.40 (±0.07) | 6.16 (±0.24)a | 0.0036 (±0.0008) | 0.0111 (±0.0024) |
| **FM** | 7.66 (±1.27)ab | 0.0024 (±0.0009) | 0.63 (±0.13) | 4.26 (±0.34)b | 0.0041 (±0.0016) | 0.0106 (±0.0046) |
| **SH** | 9.24 (±0.93)ab | 0.0025 (±0.0011) | 0.42 (±0.04) | 4.68 (±0.48)ab | 0.0044 (±0.0012) | 0.0094 (±0.0013) |
| **SHM** | 12.91 (±1.65)a | 0.0024 (±0.0009) | 0.65 (±0.09) | 5.13 (±0.52)ab | 0.0049 (±0.0013) | 0.0214 (±0.0069) |
| **VB** | 9.63 (±1.63)ab | 0.0032 (±0.0016) | 0.45 (±0.04) | 5.35 (±0.50)ab | 0.0044 (±0.0011) | 0.0083 (±0.0015) |
| **VBM** | 8.92 (±1.81)ab | 0.0045 (±0.0022) | 0.50 (±0.18) | 5.50 (±0.25)ab | 0.0047(±0.0007) | 0.0180 (±0.0074) |
| **Dec-19** | | | | | | |
| **F** | 10.35 (±1.72)b | 0.0036 (±0.0005) | 0.86 (±0.23) | 2.76 (±0.11) | 0.0033 (±0.0015) | 0.0053 (±0.0012) |
| **FM** | 15.20 (±0.64)ab | 0.0038 (±0.0009) | 0.48 (±0.07) | 2.49 (±0.17) | 0.0047 (±0.0039) | 0.0078 (±0.0039) |

| | | | | | | |
|---|---|---|---|---|---|---|
| **SH** | 16.66 (±3.31)ab | 0.0027 (±0.0011) | 0.77 (±0.23) | 2.45 (±0.28) | 0.0030 (±0.0007) | 0.0040 (±0.0004) |
| **SHM** | 27.14 (±0.20)a | 0.0042 (±0.0007) | 0.59 (±0.14) | 2.62 (±0.24) | 0.0046 (±0.0007) | 0.0085 (±0.0021) |
| **VB** | 11.52 (±1.07)b | 0.0034 (±0.0010) | 0.38 (±0.06) | 3.04 (±0.31) | 0.0045 (±0.0025) | 0.0074 (±0.0020) |
| **VBM** | 17.87 (±1.13)ab | 0.0031 (±0.0010) | 0.44 (±0.02) | 3.05 (±0.30) | 0.0042 (±0.0014) | 0.0042 (±0.0010) |
| **Overall** | | | | | | |
| **F** | 8.05 (±0.72)b | 0.0010 (±0.0002) | 1.26 (±0.20) | 7.64 (±0.35)ab | 0.0056 (±0.0005) | 0.0275 (±0.0042) |
| **FM** | 12.63 (±1.07)ab | 0.0017 (±0.0002) | 1.06 (±0.16) | 6.43 (±0.32)b | 0.0058 (±0.0006) | 0.0210 (±0.0036) |
| **SH** | 14.07 (±1.27)a | 0.0013 (±0.0002) | 1.41 (±0.25) | 6.94 (±0.38)b | 0.0051 (±0.0004) | 0.0234 (±0.0044) |
| **SHM** | 15.19 (±1.26)a | 0.0018 (±0.0003) | 1.53 (±0.23) | 7.22 (±0.30)b | 0.0064 (±0.0006) | 0.0298 (±0.0037) |
| **VB** | 12.06 (±1.46)ab | 0.0015 (±0.0002) | 1.29 (±0.21) | 7.37 (±0.42)ab | 0.0050 (±0.0005) | 0.0219 (±0.0037) |
| **VBM** | 12.90 (±1.16)ab | 0.0017 (±0.0004) | 1.09 (±0.14) | 8.76 (±0.46)a | 0.0062 (±0.0008) | 0.0208 (±0.0008) |

Overall, with all times considered, the data suggests no significant difference in $NH_3$ between treatments (Table 2.6). No difference in $NH_3$ between treatments was likely a result of quick dissipation of $NH_3$ via the nitrification process, as $NH_3$ is not commonly present in soil for long periods of time (Yao et al. 2011). Because ammonification is the first key step in N cycle, this process ultimately controls the amount of available N in its mobile forms (nitrate + nitrite) (Inomura et al. 2018). It is possible that soil sampling on a bimonthly or monthly basis was not conducive to measure differences in soil ammonia between treatments, which could explain no difference between treatments within the $NH_3$ data with all times considered (overall, Table 2.6). This phenomenon also explains the higher amounts of $NO_3^-$ + $NO_2$ present in the soil when compared to $NH_3$ (Table 2.6). Nascente & Crusciol (2013) found that when applying non-legume cover crop residue to a no-till rice production system, that $NH_4^+$ was most abundant at 7 days after sowing rice, 37 days after cover crop termination, and promptly declined thereafter. With the sampling scheme utilized in the current study, quick ammonia turnover is difficult to detect and not always obvious within the data.

When comparing available N in the form of Nitrate ($NO_3^-$ ) + Nitrite ($NO_2$) (represented as $NO_x$) throughout the experiment, significant variability was observed at numerous sampling points and between treatments (Figure 2.3, Table 2.6). Soil $NO_x$ was the highest, regardless of treatment, at the Oct-18 (20.71 g $kg^{-1}$) sampling time and lowest at Sept-19 (3.25 g $kg^{-1}$, $p < 0.05$). These $NO_x$ results display a trend in which two months after cover crop termination, $NO_x$ increases which can also be observed in season 2 where $NO_x$ increases from Sept-19 to Oct-19 ($p < 0.05$). During both growing seasons, air and soil temperature remained high from Aug - Sept during termination, and throughout the first month of organic matter decomposition. These climatic conditions are characteristic of South Florida as significant rainfall and high temperatures are conducive to organic matter decomposition and N mineralization (Rao & Li, 2003). As such, the few months after CC termination are crucial for decomposition and possibly N mineralization which is apparent in the available N data when CC treatments showed significantly higher $NO_x$ (Oct-18, Sept -19, Nov -19, and Dec- 19).

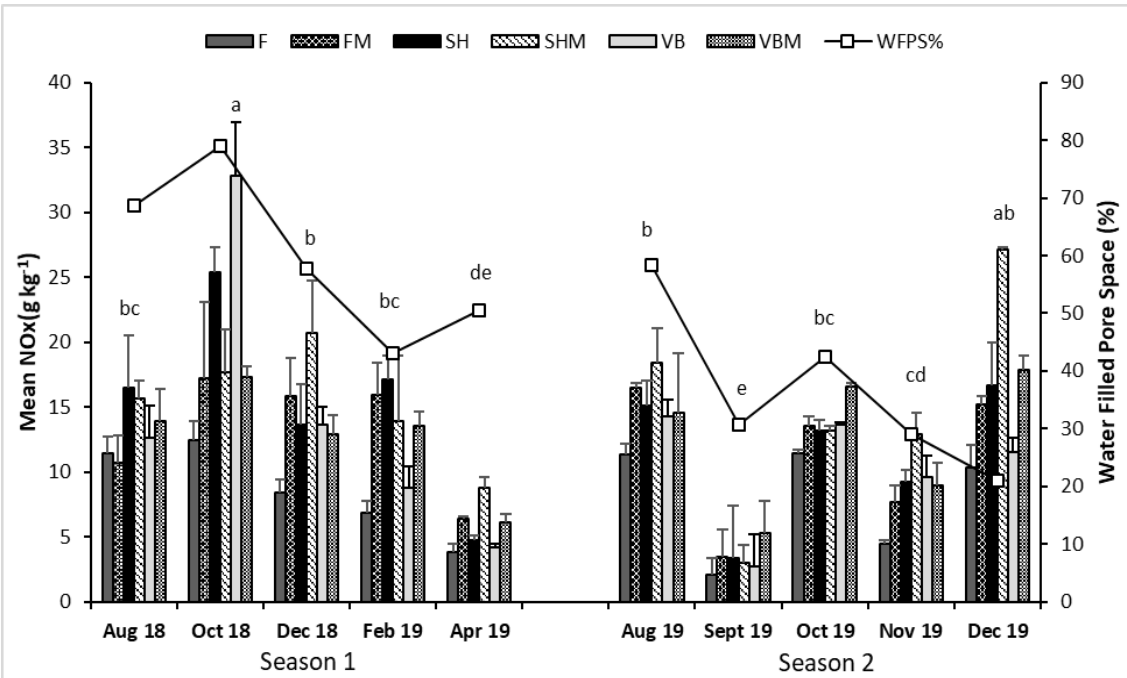


**Figure 2. 3** Displays average NOx (nitrate + nitrite, n=4) in soil along with its relation to water filled pore space over a two- season period after cover crop growth and termination. The bars at each sampling time represent three cover crop treatments (F = fallow, SH = sunn hemp, and VB = velvet bean) and three manure treatments (FM= fallow + poultry manure, SHM = sunn hemp + poultry manure, VBM = velvet bean + poultry manure). Different letters denote statistical difference between sampling times at $p < 0.05$, error bars denote standard error.

At the Sept-19 sampling period (1 month after second CC termination), average $NO_x$ was low, corresponding with lower water filled pore space (WFPS)% as compared to other sampling periods. Conversely, high concentrations of $NH_3$ were observed during both cover crop termination times (Aug- 18 and Aug-19) which coincided with high

WFPS (Figure 2.2). Water filled pore space played a significant role in the N mineralization process throughout the experiment as it was statistically correlated to all available N parameters ($NO_2$, $NO_3$, $NO_x$, and $NH_3$) (Table 2.5). In general, it was observed that as WFPS% increases so does available N content and vice versa (Figure 2.2 and 2.3). Soils under no-till management are typically less aerobic and can have higher WFPS than those that undergo traditional tillage (Linn and Doran, 1984b). As such, tillage practices have a large influence on $N_2O$ emission which are generally higher in soil under no-till practice as anaerobic conditions are more common (Ball et al. 2008). Water holding capacity around 60% is the threshold for maximum aerobic activity ideal for ammonification and nitrification (Linn and Doran, 1984a). In the experiment, N became more plant available as WFPS increased. Plant available N can be compared with WFPS as previous studies have shown a link between WFPS, soil moisture, and $N_2O$ emission (Clagnan et al. 2019, Liu et al. 2007, Dobbie and Smith, 2001). Results indicated that $NO_x$ content was high even when WFPS surpassed the 60% threshold at the Oct-18 time, although generally, high $NO_x$ was observed with WFPS at ~60%, ideal conditions for this parameter. This finding suggests that anerobic bacteria may have played a role in nutrient cycling throughout the study when WFPS% was high.

There are two groups of organisms responsible for N transformations in soils, ammonia oxidizing bacteria (AOB) and ammonia oxidizing archaea (AOA) (Daims et al. 2015; Carey et al. 2016). The population size and response of AOA and AOB are highly related to soil type and management strategies. Traditionally it has been found that AOB are more likely to contribute N additions in agricultural soils as their populations are generally more elevated when N supply is higher, enhancing nitrification potential, while

AOA are more commonly dominant in soils from more natural or diverse ecosystems (Gao et al. 2020). Shen et al. (2008) compared abundance of AOB and AOA communities in an alkaline sandy loam (similar to the tested soil type) with various fertilizer treatments. They found significantly higher communities of AOB in soils treated with traditional N fertilizer when compared to organic manure treatments which is possibly explained by competition with heterotrophic bacteria, commonly present in soils amended with carbon (green or organic manures) (Shi and Norton, 2000). It is possible that increased presence of AOA contributed significantly to N cycling in the present experiment as these organisms are highly adaptable to extreme environmental conditions like low oxygen levels and are more common in diversified soils (Yin et al. 2018). Because additions of OM to soil are favorable for microbial diversity it is likely that the combination of CC inputs, paired with occasional anerobic soil conditions, created a diversified microbial environment that facilitated N fixation and mobilization.

Besides WFPS, it is possible that BNF played a role in soil available N content. At both termination times (Aug-18 and Aug-19) cover crop treatments had numerically higher $NO_x$ than the F treatments ($p > 0.05$), and significantly higher $NH_3$ ($p < 0.05$, Table 2.6). The Aug-18 time is specifically interesting as this was before any PM fertilizer was applied, indicating successful N fixation of the legume treatments. Legume symbiosis with rhizobium bacteria works to reduce $N_2$ to $NH_4^+$ and $NH_3$ in ideal climatic soil conditions (Hungria and Kaschuk, 2014). Biological nitrogen fixation is dependent on many factors and can vary by species and effectiveness of rhizobium type/inoculation success (Enrico et al. 2020). Nezomba et al. (2008) found that *Crotalaria* spp. had high potential to fix N in sandy soil. Specifically, *Crotalaria juncea* (SH) was estimated to have a 90% N fixation rate resulting, in 58 kg $ha^{-1}$ N provided to soil. Within the current experiment, both SH and VB seeds were inoculated with the recommended cowpea type rhizobium before planting to encourage nodulation. Genus *Crotalaria* (SH) has been shown to create symbiotic relationships with many strains of rhizobium bacteria resulting in high potential for N fixation and biomass accumulation (Allen and Allen, 1981). Conversely, much less is known about the genus *Mucuna* (VB) and its rhizobial-host-plant interactions. Cowpea type rhizobium is compatible with genus *Mucuna;* however, successful nodulation has not been shown with a wide variety of rhizobium species (Allen and Allen, 1981). These factors may have had an impact on the differences in N content in soil between the SH and VB treatments, specifically during and directly after the CC growing seasons (Aug-18 and Aug-19) in which SH showed more success in providing available N.

When considering individual sampling times, there were significant differences in soil $NO_x$ between treatments at multiple periods. At Oct-18, 2 months after cover crop termination, VB had significantly higher $NO_x$ (32.84 g $kg^{-1}$) followed by SH with all other treatments significantly lower in soil $NO_x$ ($p < 0.05$, Table 2.6). Interestingly, plots treated with PM (FM, SHM, and VBM) were significantly lower than plots that did not receive manure at this sampling time. It is likely that PM dissipated over the two-month timespan and plant available nutrients were utilized by the carambola tree as they were readily available. Remarkably, eight months post CC termination at the Apr-19 time, the SHM treatment had the highest soil $NO_x$ content (8.76 g $kg^{-1}$), followed by marginally lower VBM (6.08 g $kg^{-1}$) and FM (6.43 g $kg^{-1}$). Consequently, eight months after termination, SHM was the ideal treatment for supplying carambola trees with nutrients.

At the Sept-19 period (one month after the second termination) the VBM (5.29 g $kg^{-1}$) treatment had the highest soil $NO_x$ content, ~60% higher than the F plots, but only marginally higher than FM, SHM, and SH (Table 2.6). As such, VB treatments are likely more efficient in providing plant available N in the short-term, while SH treatments have a longer decomposition period and are more effective in $NO_x$ contribution overall. Rao and Li (2003) found that SH treatments exhibited highest nitrate mineralization rates when comparing leachate over a 20-week period than VB, an indication of the long-term potential of soil N additions by SH as a green manure crop. By the conclusion of our experiment (Nov-19 and Dec-19), soils treated with SHM had the highest NOx content when compared to all other treatments ($p < 0.05$, Table 2.6).

*2.4.6 Soil biological properties*

Soil microbial biomass is very sensitive to changes in SOM and can have a distinct relationship with soil physical characteristics and overall quality. Low soil disturbance combined with OM inputs results in enhanced soil biota dynamics (Castellanos-Navarrete et al. 2012). Soil $CO_2$ flux is an indicator for decomposition of SOM and can be used as a tool for understanding organic carbon turnover rates (Chen et al. 2002).

Figure 2.4 shows a trend between soil efflux and average soil temperature over time as soil $CO_2$ emission follows a similar trend with soil average temperature. All treatments considered, Aug-18 had significantly higher soil efflux than all other sampling periods with Aug-19 having the second highest overall average. Both these sampling times exhibited high corresponding average soil temperatures (Figure 2.4). Conversely, sampling times with cooler soil temperatures generally exhibited significantly lower soil efflux rates.

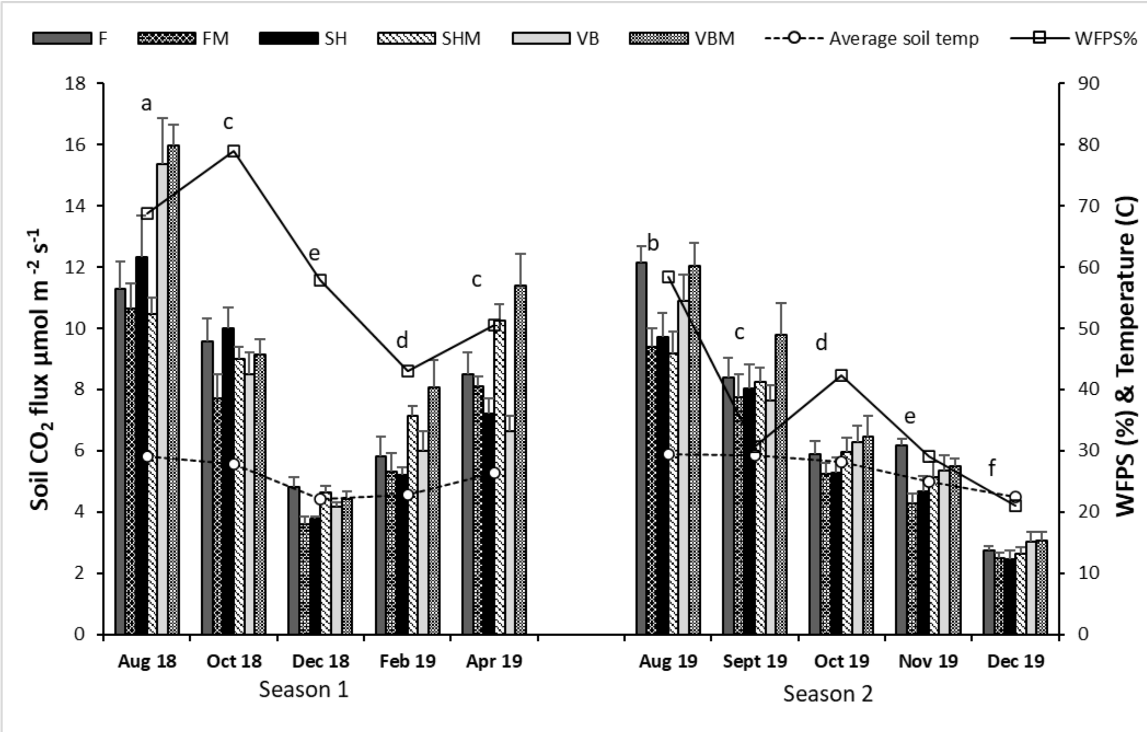


**Figure 2. 4** Displays average soil $CO_2$ efflux (n = 9) rates with ambient soil temperature and moisture over a two-season period after cover crop growth and termination. The bars at each sampling time represent three cover crop treatments (F = fallow, SH = sunn hemp, and VB = velvet bean) and three manure treatments (FM= fallow + poultry manure, SHM = sunn hemp + poultry manure, VBM = velvet bean + poultry manure). Different letters denote statistical difference between sampling times at p < 0.05, error bars denote standard error.

At the first sampling time (Aug-18) right before cover crop termination, plots treated with VBM (15.99 µmol $m^{2}s$) and VB (15.36 µmol $m^{2}s$) had up to ~34% higher soil efflux rates than all other treatments ($p < 0.05$). High soil efflux was also observed at the Feb-19 date for VBM (8.07), six months after first termination and two fertilizer applications, and at the Apr- 19 date (11.38), eight months after termination and three fertilizer applications ($p < 0.05$, Table 2.6). Overall, the VBM treatment had the highest soil $CO_2$ flux (8.70 µmol $m^{2}s$) which was the general trend observed at most sampling times with significant differences between treatments (Table 2.6, Figure 2.4). Higher soil

$CO_2$ flux could be reflective of additions of PM fertilizer along with VB organic matter decomposition as soil $CO_2$ flux was most impacted for treatments with fertilizer application. Roberson et al. (2008) found that poultry manure application showed higher $CO_2$ flux in no-till systems than application of standard ammonium nitrate fertilizer, which can be seen in our results when comparing VBM treatments to all others. It is possible that VB treatments were more likely to volatilize and decompose more quickly than SH. This is also reflected in available N data as VB treated soil generally had lower available N overall and at most sampling times with significant differences (Table 2.6).

Cover crops have the potential to increase $CO_2$ emissions by increasing soil C, which potentially enhances respiration via rhizosphere metabolic activity increase (Sanz-Cobena et al. 2015). In fact, $CO_2$ emissions can even be heightened with the use of legume CCs (Alluvione et al. 2010). Muhammad et al. (2019) found that application of legume cover crops increased $CO_2$ emissions, however, $CO_2$ flux decreased with increased C/N ratio of green manure material. Within the current study, SH CC material consistently contributed higher C/N ratio than VB, and as a result, lower $CO_2$ flux. Conversely, VB material was lower in plant tissue C/N and higher in soil efflux, possibly providing a more degradable food source for microorganisms. When comparing phytomass decomposition rates of cover crops in a tropical area of Brazil, Xavier et al. (2017) categorized SH as a cover crop with great resistance to decomposition, while VB was categorized as intermediate resistance. This difference in decomposition rates may have implications for VB being more useful as OM stock in the short-term and SH being more suitable for long-term carbon storage.

Soil β-1-4-glucoside rates differed over time and between treatments (Figure 2.5, Table 2.6). Throughout the sampling times, with all treatments considered, the Aug-19 time (second CC termination) had the highest rates of β-1-4-glucoside, corresponding with high soil temperatures and WFPS%, a trend that can be seen throughout the data parameters. There was no significant difference between treatments at individual sampling times except for the Aug- 18 (the end of cover crop growing season 1, right before termination) and Aug-19 (the end of cover crop growing season 2, right before termination) sampling times. At both August times the SHM treatment had the highest β-1-4-glucoside (0.0386 and 0.1393 μmol $m^{2}$s, respectively) with all other treatments significantly lower ($p < 0.05$, Table 2.6), which may be indicative of SHM excreting carbon into the rhizosphere, enhancing overall microbial diversity. Overall, soils treated with SHM reflected the highest numeric β-1-4-glucoside, although no significant difference was discernable ($p > 0.05$, Table 2.6).

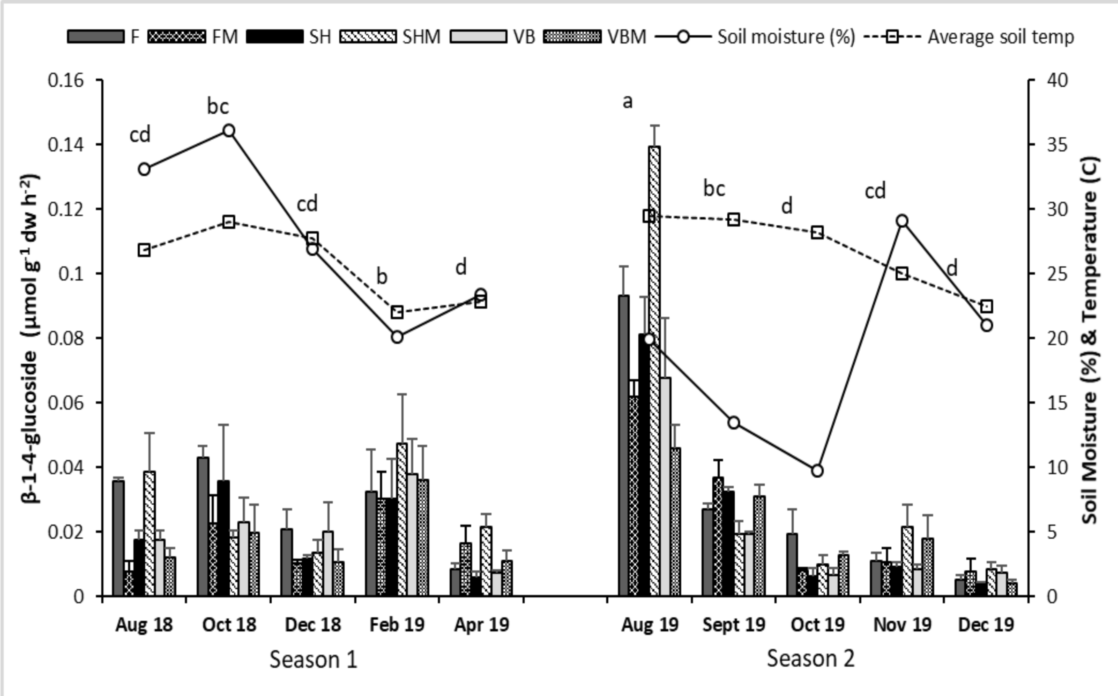


**Figure 2. 5** Displays average soil β-1-4-glucoside rates (n = 4) with ambient soil temperature and WFPS over a two-season period after cover crop growth and termination. The bars at each sampling time represent three cover crop treatments (F = fallow, SH = sunn hemp, and VB = velvet bean) and three manure treatments (FM= fallow + poultry manure, SHM = sunn hemp + poultry manure, VBM = velvet bean + poultry manure). Different letters denote statistical difference between sampling times at $p < 0.05$, error bars denote standard error.

Correlation results reveal that soil $CO_2$ flux was negatively correlated with TC and SOM, indicating that as $CO_2$ flux increased, TC and SOM decreased (Table 2.5); an expected result, as high rates of soil $CO_2$ flux are generally indicative of reduction in storage of soil C (Rayment and Jarvis, 2000). Efflux was positively correlated with β-1-4-glucoside activity, soil temperature, WFPS%, and moisture (Table 2.5) indicating that as SOM decomposition was occurring, β-1-4-glucoside activity increased, and ultimately responded to soil temperature and moisture conditions (Figure 2.5). Soil β-glucosidase is a significant driver of the terrestrial carbon cycle (Ekenler and Tabatabai, 2002). Soil β-glucosidase enzyme works to catalyze the formation of glucose, a crucial reaction in supplying energy for microbial biomass (Hai-Ming et al. 2014). As such, positive correlation of β-glucosidase and soil efflux is indicative of OM breakdown (Adetunji et al. 2017).

Enzyme β-N-acetylglucosaminidase reflects N cycling by microbial biomass and overall breakdown of OM (Chung et al. 2007). Soil β-N-acetylglucosaminidase results indicated change over time, regardless of treatment. Like β-1-4-glucoside, the highest occurrences were at the Aug-19 (0.0094 μmol m $^{2}$s), at the second CC termination (Figure 2.6). There was no significant difference of β-N-acetylglucosaminidase between treatments at any of the individual sampling times except for Aug-19. At the Aug-19 time, soils treated with SHM (0.0169 μmol m $^{2}$s) showed significantly higher β-N-acetylglucosaminidase activity than the rest of the treatments (Table 2.6, Figure 2.6).

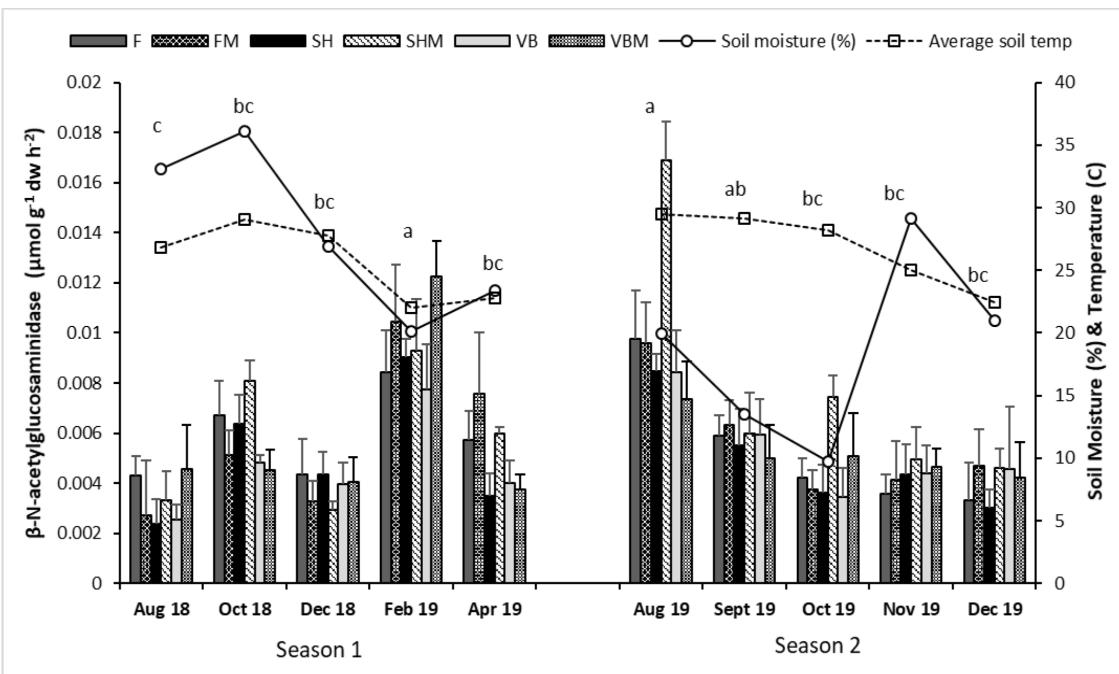


**Figure 2. 6** Displays average β-N-acetylglucosaminidase rates (n = 4) in soil with ambient soil temperature and moisture over a two-season period after cover crop growth and termination. The bars at each sampling time represent three cover crop treatments (F = fallow, SH = sunn hemp, and VB = velvet bean) and three manure treatments (FM= fallow + poultry manure, SHM = sunn hemp + poultry manure, VBM = velvet bean + poultry manure). Different letters denote statistical difference between sampling times at $p < 0.05$, error bars denote standard error.

These enzyme activity results can be reflective of two processes. After the 90 days of the second growing season, it appears that the SHM treatment was effective in providing belowground stimulation to soil and as such, breakdown of glucose and transformation of N occurred as shown by increased enzyme activity at this sampling period (Aug -19). Although not statistically significant, these results coincide with higher concentrations of $NO_x$ and $NH_3$ at the corresponding sampling period. A study conducted by Maltais-Landry (2014) concluded that legume CCs had high β−glucosidase activity in the rhizosphere by the end of their growing season when compared to non-legumes, which was especially apparent when compared to legume cover crops that also had a composted poultry manure component added. Our study shows that this is true in a no-till field setting for SH treated with PM (SHM). Shoot and root contributions supplied by cover crops are specifically important in no-till systems as root exudates added during the growing season and organic material added after termination stimulate soil microbial communities (Henry et al. 2008).

**2.5 Conclusions**

Cover crops have rarely been explored as a soil management method for tropical fruits. The results of this study show that tropical leguminous cover crops have potential as beneficial soil amendments to add OM, nutrients, and promote nutrient cycling by stimulating microbial activity.

This experiment was conducted in an organic production farm where cover crops were intercropped with young carambola trees. Juvenile carambola trees require ~ 90 - 270 N kg ha-1 per year. With the seeding rate utilized in this experiment, SH treatments consistently provided sufficient amounts of total dry matter N to supply carambola trees with the necessary nutrients that they require. Poultry manure, the traditional amendment for organic fruit production, combined with sunn hemp (SHM) was the most successful cover crop treatment in terms of SOM and plant available nutrient contribution. Comparatively, soil treated with poultry manure without cover crop addition (FM) had quantifiable benefits to soil throughout the two-season study. This is likely a result of poultry manure added directly to the soil surface having more immediate impact on the measured parameters. Based on the nature of organic matter breakdown processes, it is likely that over a longer period of consistent cover cropping, soil treated with cover crop amendments would reflect even greater positive outcomes for soil health parameters that would outweigh fallow treatments.

With all results considered, sunn hemp and velvet bean both have potential to act as soil enhancers for fruit production in tropical and subtropical settings. When applying this to tropical fruit production, these cover crops can provide chemical and biological benefits to enhance soil for the successful growth of tropical fruit trees. These cover crops can be utilized in combination with poultry manure or other organic fertilizers for ideal crop growth and soil improvement. It is expected that with a longer experimental time frame, cover crop treatments would have great impacts for soil health. With the growing issue of soil erosion and organic matter depletion, it is imperative that farmers consider these matters and incorporate management strategies that ensure the long-term sustainable productivity of their land.

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# CHAPTER 3: TROPICAL LEGUMINOUS COVER CROPS AS A FERTILIZATION STRATEGY FOR *AVERRHOA CARAMBOLA*

## 3.1 Abstract

This study tests the effectiveness of two tropical leguminous cover crops sunn hemp (*Crotalaria juncea*) and velvet bean (*Mucuna pruriens*) as fertilization methods for young carambola (*Averrhoa carambola*) trees. Sunn hemp and velvet bean were grown and left to decompose on the soil surface (no-till) twice over a 1.5-year time period. Poultry manure treatments were included to replicate standard organic fertilization practices. Non-destructive sensors, along with traditional leaf tissue analysis and fruit yield measurements were used to distinguish N differences in carambola trees treated with various cover crop and poultry manure treatments. Multispectral remote sensing data was obtained via UAV flights to extract NDVI and NDRE readings of carambola trees every two months throughout the experiment, while a SPAD sensor was used on the ground to take chlorophyll measurements. Sensor readings were compared to leaf tissue total carbon and nitrogen of carambola leaves. Results of this study reveal that during the first growing season, NDVI and NDRE did not distinguish difference between treatments, while carambola leaf tissue N% was highest in trees treated with sunn hemp + poultry manure, corresponding with low C/N ratio and high fruit yield. Throughout the second growing season SPAD results indicated the highest readings for the sunn hemp treatment, corresponding with high NDRE readings. Average fruit yield within season two was highest for fallow + poultry manure and sunn hemp treated trees. Overall, sunn hemp has proven to be an effective cover crop for carambola tree fertilization when compared to velvet bean and is on par with traditional manure fertilization methods.

### 3.2 Introduction

Nitrogen (N) management for crop production has become an increasingly important matter based on need for food production on a global scale. The discovery of the Haber–Bosch process in the early 20th century facilitated a transition to heavy use of synthetic nitrogen fertilizers for agriculture and landscape management purposes (Erisman et al. 2008). Nitrogen is a critical macronutrient that is essential for plant productivity. Due to nutrient cycling, soil-plant dynamics, and loss via runoff or volatilization, N is rarely plant available season after season without consistent fertilization (Dong et al. 2020). In the face of intensified agriculture practices, there is a heightened need for exploration of environmentally conscious approaches to maintain productive arable land.

Cover cropping is an inherently sustainable practice that can prove beneficial for a variety of environmental and agricultural needs. Generally, cover crops (CC) are grown during fallow seasons, after cash crops, for the purpose of providing ground cover to mediate soil erosion (Abdalla et al. 2019). In most cases, CCs are applied to vegetable production settings as they can be easily planted, grown, and terminated on a large scale with few barriers for management. However, when properly applied and managed, cover cropping has potential for success in fruit orchards to enhance soil quality and crop health, although few studies have been conducted to confirm this. Cover cropping has been utilized and applied to orchards in the Mediterranean with positive results. Cover crops added to olive groves utilizing no-till (NT) practices resulted in a significant increase in carbon storage and fixation in just one year when compared to a traditional tillage system (Nieto et al. 2012). This practice can not only provide carbon for increased soil and crop health, but also can be seen as a suitable strategy to mitigate elevated atmospheric $CO_2$ when practiced on a large scale. Research utilizing leguminous CCs for the purpose of providing N in an olive orchard setting resulted in increased olive yields and tree crop growth when compared to unfertilized trees surrounded by natural vegetation (Rodrigues et al. 2013). Trees treated with leguminous CC species showed even higher N concentration in leaf tissue and fruit (Rodrigues et al. 2013). Green manure treatments have also been shown to increase soil nutrients, microbial enzyme activity and aggregate stability, improving overall soil health in Mediterranean almond orchards (Ramos et al. 2010). Because of the limited number of studies that address cover cropping practices, a significant knowledge gap exists for the effectiveness of leguminous CCs for commercial fruit production within the (sub)tropics.

For optimal results using CC species for soil enhancement, the intended use must be clearly identified. Non-leguminous CCs can be used in heavily fertilized agricultural systems to reduce nitrate ($NO_3^-$) leaching as a strategy to prevent eutrophication in aquatic habitats (Thapa et al. 2018). Conversely, legume CCs add N through the production of high-quality green manure residue and belowground N fixation during the growing process (Snapp et al. 2005). While organic N sources (animal or green manure) are preferred as an environmentally conscious option, they can prove difficult to manage. The quantity and timing of N availability may be highly variable depending on decomposition rates, soil environmental conditions, and C/N ratios of decomposing organic matter (Zak et al. 1999; Qian and Schoenau, 2002).

Selection of green manure crops for specific land management goals requires careful consideration of both above and belowground growth habits. The role of roots is especially important in NT systems because soil compaction often occurs in the top layers where CC roots are likely to be present (Garcia et al. 2013). In intercropped systems with trees, the potential for root competition for water and nutrients should be carefully evaluated. For this study, two CCs with opposite above and belowground growth habits were selected in an attempt to test their feasibility in aspects of biomass production, N fertilization, and resource competition for use with tree crops.

For the present study, two tropical leguminous CCs, *Crotolaria juncea* L (sunn hemp) and *Mucuna pruriens* L. DC. (velvet bean) were grown in an *Averrhoa carambola* (carambola or starfruit) orchard to identify if these cover crops are sufficient in providing N to trees to satisfy their nitrogen demands. These legume cover crops were grown for two seasons, cut, and allowed to decompose on the soil surface in a NT fashion. Sunn hemp (SH) has an erect growth habit ranging from 1-3 m in height with a long taproot that produces strong lateral roots (Baligar and Fageria, 2007). Following recommended seeding rates, in South Florida, SH has been shown to produce anywhere from 277 - 356 kg $ha^{-1}$of N and 9.7 - 12.5 Mg $ha^{-1}$ dry biomass within a 60-day growing period (Wang et al. 2005; 2015). Velvet bean (VB), another annual tropical legume, can produce large quantities of biomass through its vining growth habit and spreading surface roots (Baligar and Fageria, 2007). Like SH, VB can flourish in a wide variety of soils. Following established seeding recommendations, VB has the potential to provide 173 to 286 kg $ha^{-1}$of N and 6.7 to 11.1 Mg $ha^{-1}$ dry biomass within a 60-day growing period in a subtropical setting (Wang et al. 2005; 2015).

Sunn hemp and VB proved to be successful when grown in South Florida as a green manure supplement for vegetable production in soils that are inherently calcareous with low organic matter (OM) and plant available nutrient content (Wang et al. 2005; 2007a; 2009; 2012; 2015). While the use of these CCs has shown promising benefits for nutrient cycling and mineralization of SOM in (sub)tropical settings, these studies have been conducted solely in pots or vegetable fields. No studies have been conducted on the effects of intercropping SH and VB with tropical fruit trees within South Florida. For this study, the aforementioned CCs were intercropped with carambola, a tropical fruit tree that is cultivated commercially in South Florida.

Carambola trees, indigenous to Southeast Asia, are highly adapted to hot and humid tropical climates but are able to flourish in subtropical climates like in South Florida. They are adapted to well-drained soil types that are inherent in Miami-Dade County. Carambola trees are capable of concurrent vegetative and reproductive growth, and in ideal conditions continually grow vegetatively and reproductively year-round (Núñez-Elisea and Crane, 1998). Carambola is most successful in growth, flowering, and fruiting in conditions with ambient temperatures between 18 - 43°C and soil temperatures from 20 - 30°C (optimal shoot growth 20 - 35°C and optimal root growth 20 - 30 °C) (George et al. 2002). With optimal flowering range for fruit set and development at > ~18 °C (George et al. 2000). The carambola fruit development period ranges from 8-12 weeks during spring/summer months and 10-16 weeks through fall/winter months, which can be dependent on cultivar and temperature conditions (Núñez-Elisea and Crane, 1998). Carambola is a highly productive fruit bearing crop (>150kg/tree in mature trees 7+ years old; Núñez-Elisea and Crane, 1998). In South Florida, star fruit is considered to be a minor tropical fruit crop with an estimated 60 hectares planted in the state, only 16 hectares of which are situated in Miami-Dade County (Crane and Wasielewski, 2018).

While carambola is currently considered a minor crop, it has potential to expand as a lucrative alternative to other popularly produced fruit commodities. Within the last few decades, disease has hindered the production of major cash crops like citrus and avocado. Avocado, Miami-Dade County's most prominently produced tropical fruit crop (over 2400 planted hectares; Crane and Wasielewski, 2018), has been decimated by the fungal disease, laurel wilt (*Raffaelea lauricola*). With limited strategies for treating this disease, tree removal is the common approach to reduce disease spread once signs of infection become apparent. Laurel wilt was first documented in Florida in 2007 (Mayfield et al. 2008) and has since resulted in the loss of over 120,000 trees in Miami-Dade County (Wasielewski, 2020). Carambola production is an alternative option to increase profitability for farmers looking to invest in crops to replace avocado groves, as carambola trees are highly productive and begin producing fruit at a young age. Reported tree value for carambola is highest compared to other alternative crop options (1-3 years: $567, 4-6 years: $860, 7+ years: $984; Evans et al. 2017) with potential for gross revenue of over $24,000/acre/year (Ballen et al. 2020). With the possible expansion of carambola production for Miami-Dade County, determination of successful sustainable fertilization options in an attempt to provide low-cost and environmentally sound solutions for farmers is crucial.

This study was developed in an effort to test CCs SH and VB for their effectiveness as a fertilization strategy for young carambola trees. As such, carambola response to CC treatment was monitored using various methods including non-destructive optical sensor technology. A greater understanding of plant vigor and its relation to spectral signatures has led to the development of sensor technology to be utilized for determination of vegetation indices. Recently, this technology has become commercially available to agricultural land managers to provide quick insight on plant stress and nutrient levels. Optical sensing is a useful tool for monitoring crop status through spectral reflection indicators, which have been shown to correlate with chlorophyll content within green vegetation (Freidenreich et al. 2019). Leaf chlorophyll content is an important health indicator for plant stress, nutritional state, and photosynthetic activity (Pavlović et al. 2015). Green plants with higher chlorophyll content per leaf unit area are expected to perform better when compared to plants that are chlorotic. As such, chlorophyll content can be used as a parameter to identify crop stressors like nutrient or water deficiencies (Zarco-Tejada et al. 2004).

With the advancement of remote sensing technology, various vegetation indices have been studied for use as indicators of plant vigor. It has been well established that reflectance of vegetative plant material is highest in the near infrared (NIR) range and low at the blue and red range of the visible spectrum (Jorge et al. 2019). Normalized Difference Vegetation Index (NDVI) and Normalized Difference Red Edge Index (NDRE) have been developed as important indices for estimating leaf area index (LAI), biomass, and N levels (Hassan et al. 2019). NDVI values are calculated utilizing reflectance of the NIR and red-light spectrum (Tucker, 1979), and has become a successful gauge for predicting field crop yield (Magney et al. 2016; Wall et al. 2008). As such, NDVI has been the most consistently used vegetation index for determining plant status, and therefore has become popular and widespread for use in agricultural settings. NDRE is an alternative to NDVI as the red edge sensitivity to crop chlorophyll absorbance is much higher and can therefore avoid saturation issues (Li et al. 2014). In fruit crop or orchard settings, NDRE has proven to be useful for visualizing tree health and crop inhomogeneities in a low cost and non-destructive fashion (Jorge et al. 2019; Syafiqah et al. 2019). This study utilizes these vegetation indices, along with traditional leaf tissue CN analysis, and fruit yield data to determine if the selected CCs are optimal to supply N needs for commercial carambola production in South Florida.

## 3.3 Materials and Methods

### *3.3.1 Carambola plant material*

This study was conducted from May 2018 through December 2019 in a commercial, organically managed tropical fruit orchard (6.07 ha) located in Redland Agricultural Area (RAA) of Homestead, FL. The trees used for this study were ~three-year-old 'Hawaiian Super Sweet' trees grafted onto 'Golden Star' seedling rootstocks. Sixty trees were planted in two 122 m long rows (30 trees/row) with 7 m between rows and 3.8 m between each tree. Experimental sites were arranged in a completely randomized design (CRD) with 2 cover crop treatments: sunn hemp (SH); and velvet bean (VB), 2 cover crop + fertilizer treatments: sunn hemp + poultry manure (SHM); and velvet bean + poultry manure (VBM), and 2 fallow control treatments: fallow (F); and fallow + poultry manure (FM), resulting in 6 treatments with 9 replications for each treatment. The trees designated to receive poultry manure were treated with an organic composted fertilizer amendment (5N-3P-2K USDA Organic Certified poultry manure).

### *3.3.2 Cover crop treatments*

To establish experimental plots, a 0.5m radius was marked from the center of each tree in which no treatment was applied to ensure adequate space and no cover crop interreference in the center canopy area. From this 0.5m radius point, a 1.25m radius area was established around each tree creating a circular CC planting area of 8.8 $m^2$. At the start of the experiment, weeds were physically removed from planting areas and soil was hand tilled to ensure minimal carambola root disturbance in preparation for cover crop seeding. Trees that were treated with cover crops received either 33 kg $ha^{-1}$ (89g/plot) of SH or 25 kg $ha^{-1}$ (67g/plot) VB. Seeding rates were calculated using a 33% grove coverage. Cover crop seeds were treated with OMRI certified Guard'n Seed Inoculant (Verdesian Life Sciences, Cary, NC) which contains a variety of *rhizobium* species (*Bradyrhizobium japonicum, Bradyrhizobium sp. (Vigna), Rhizobium leguminorsarum biovar viceae, Rhizobium leguminosarum biovar phaseoli*), to inspire root development and nodulation. Both SH and VB were planted simultaneously and grown for 90 days after initial germination. Sunn hemp was clipped at 60 cm above the ground at 60 days after germination to inspire lateral branching and increased biomass productivity (Abdul-Baki et al. 2001). Sunn hemp was terminated via motorized hedge trimmer and VB by mechanical clipping. Following termination, cover crop biomass was laid within the sampling area of its respective carambola tree to decompose as green manure on the soil surface, a common NT practice; both SH and VB roots were left intact for decomposition. Trees randomly selected for poultry manure (PM) treatment received their first application at cover crop termination (1.4 kg poultry manure/ tree), and then every two months following until the end of the experimental period. Cover crop treatments were grown and terminated twice over 1.5-year study period (grown in the summer season from May – August 2018 and 2019). Individual treatments for each tree remained the same for both years to facilitate compounding effects by individual treatments over time.

*3.3.3 Biomass estimation and fruit yield*

At 90 days after CC seed germination, a 40 x 40 $cm^2$ square of PVC pipe was thrown randomly in each plot area to collect 1600 $cm^2$ of plant matter (cover crop and weed). Above ground biomass (leaves and stems) was measured for dry weight to determine contribution of dry matter and nutrient additions.

Carambola marketable fruit yield was measured for one complete calendar year (beginning in January 2019 and extending through December 2019). Every two weeks during the production period, marketable fruits were harvested, and wet weight was recorded.

*3.3.4 Plant tissue sampling and analysis*

Leaf samples from carambola trees were taken once every two months after the first cover crop growing season and termination. Five mature sun leaves were randomly selected for collection from the mid-canopy area. At cover crop termination, cover crop matter was collected for tissue analysis from sampled biomass.

Plant tissue samples were dried at 70°C for 72 hours, weighed, and ground for analysis of TC and TN via dry combustion utilizing a Truspec Carbon/Nitrogen analyzer (LECO Corporation, St. Joseph, MI).

*3.3.5 SPAD measurements*

A Soil Plant Analysis Development (SPAD)-502 Plus Chlorophyll Meter (Konica Minolta Sensing Americas, Inc. Ramsey, New Jersey) was used as a noninvasive, non-destructive tool to estimate leaf chlorophyll content in carambola trees. Every two months, five mature sun-leaves were selected at random from the middle canopy region of each tree. SPAD readings were taken three times in the same spot of each leaf (avoiding midrib and margins), and the average value was recorded. If leaf readings were highly variable, the SPAD was recalibrated and/or a new leaf was selected for measurement.

*3.3.6 Remote sensing measurements*

To detect differences in tree vigor between carambola treated with various fertilizers images were collected from a multispectral RedEdge-M sensor (RedEdge-M by MicaSense, Seattle, Washington). This sensor has various spectral ranges of five bands including Blue (455- 495nm), Green (540-580nm), Red (658-678nm), Near IR (800-880 nm), and Red Edge (707-727nm). An unmanned aerial vehicle (UAV) (Draganflyer Commander, Saskatoon, Saskatchewan) with the attached sensor was flown over the research site at the beginning of the experiment, at termination, and every ~two months following (corresponding with SPAD sampling times) until the conclusion of the experiment.

*3.3.7 Data collection and image processing*

Prior to data collection, the sensor was calibrated using a calibration plate for the purpose of calibrating each band during image processing. To cover the entire study area, ~200 images were taken per flight for each band, resulting in 3 cm resolution images.

Photogrammetric processing was performed using Pix4D software (Pix4D SA, Lausanne, Switzerland). Images were calibrated and stitched together via aerial triangulation to generate accurate and high-resolution orthomosaics. The five bands were stacked into one TIFF-format image for each flight. The stacked images were georeferenced in ArcGIS ArcMap ver. 10.7.1 (Esri, Redlands, California). A 1-m diameter circle was generated from manually identified centroids for each tree for all processed images. Average NDVI and NDRE values were extracted from each tree 1-m centroid buffer for all flight dates.

*3.3.8 Statistical analyses*

Vegetation data was analyzed using SPSS statistical software (IBM Corp. (1968). IBM SPSS Statistics for Windows (Version 25.0). Armonk, NY: IBM Corp.). A one-way ANOVA with Tukey's posthoc analysis established differences between treatments at each sampling time and between seasons for each individual measured variable ($p <$ 0.05). Bivariate correlation was used to determine between factor correlations by sampling time, season, and overall, throughout the entire study. Parameters were considered correlated when $p \leq 0.05$ and highly correlated when $p \leq 0.01$.

Carambola health status was determined using a variety of indicators including non-destructive sensors, leaf tissue analysis, and fruit yield. Results were statistically analyzed through two types of grouping: 1) grouped by season 2) grouped by each individual sampling time period. Season 1 consists of data compiled from the first CC termination time (Aug-18) through the sampling time before the second CC planting (Feb-19). Season 2 consists of data compiled from May 19 ($2^{nd}$ CC seeding) to Dec-19, the end of the experimental data collection. The "overall" category reflects all data collected throughout the experiment for each individual treatment and parameter.

## 3.4 Results

### *3.4.1 Climatic conditions*

Climatic conditions throughout the study were standard for South Florida's climate history. Average soil and air temperatures coincided with seasonality as warmer temperatures were observed in the summer months and lower temperatures in the winter months (Figure 3.1).

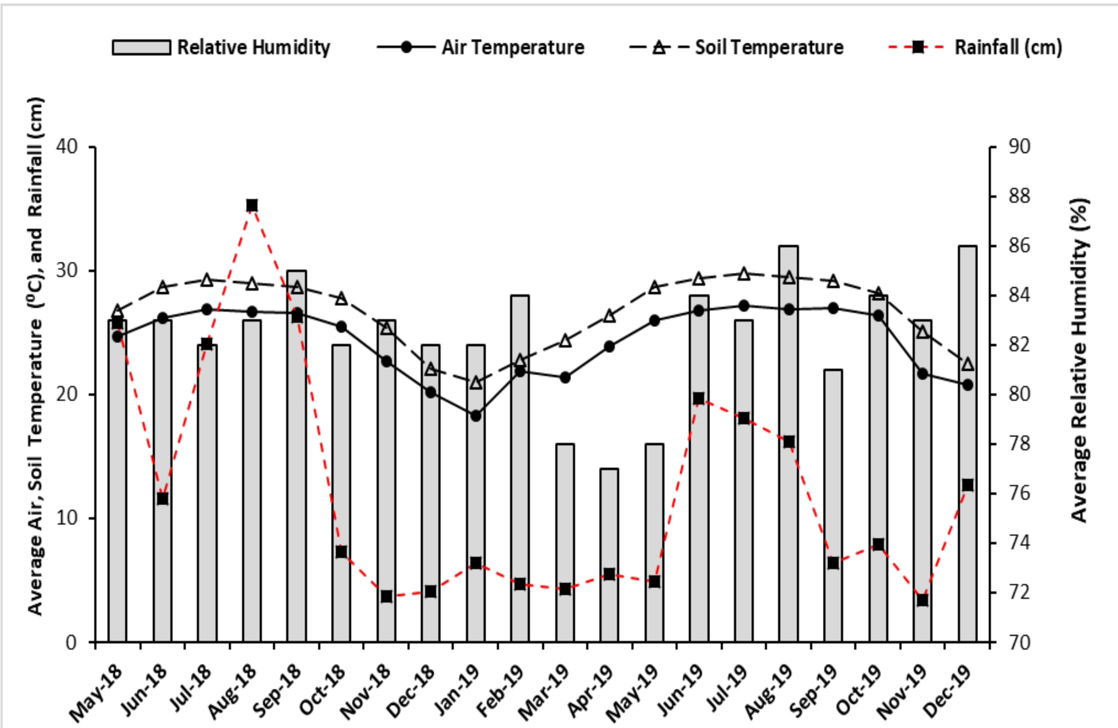


**Figure 3. 1** Climatic conditions of the sampling sites over the 1.5-year trial period. This graph represents average relative humidity (%), air temperature (°C), soil temperature (°C), and rainfall (cm).

Throughout growing season 1, average monthly rainfall from May-18 – Sept-18 was much higher than the following months. Similarly, June-19 – Aug-19 (CC growing season 2) showed an uptick in average monthly rainfall when compared to the preceding months. This aligns with South Florida climate in which the wet season spans from May - October and the dry season from November - April (Obeysekera et al. 1999). Average monthly rainfall was generally higher throughout the season 1 CC growing period (May-18 – Aug- 18) than season 2 (May-19 - Aug-19, Figure 3.1).

*3.4.2 Cover crop biomass and nutrient contribution*

Cover crop biomass and accumulated nutrients within CC plant tissue differed by growing season. Table 3.1 quantifies the contribution of CC biomass, nutrients, and PM added to the soil for both seasons.

**Table 3.1** Displays cover crop seeding and poultry manure rates along with nitrogen contribution from two cover crop growing seasons (n = 9). Seeding rates and fertilizer rates were the same for both years. The 5-3-2 (N-P-K) poultry manure was applied to every plot designated for treatment (FM, SHM, and VBM) along with cover crop treatment or a no cover crop control (CC = cover crop, PM= poultry manure). Three cover crop treatments (F = fallow, SH = sunn hemp, and VB = velvet bean) and three fertilizer w/ cover crop treatments (FM= fallow + chicken manure fertilizer, SHF = sunn hemp + chicken manure fertilizer, VBF = velvet bean + chicken manure fertilizer) were analyzed for these parameters. Values within a column followed by different letters denote statistical difference at $p < 0.05$ within the same season.

| | **Seed Rate** | **PM N Rate** | **N (CC)** | **C (CC)** | **C/N (CC)** | **Shoot Dry Matter (CC)** | **Shoot Dry Matter (weeds)** |
|---|---|---|---|---|---|---|---|
| **Season 1** | **kg ha$^{-1}$** | **kg ha$^{-1}$** | **kg ha$^{-1}$** | **kg ha$^{-1}$** | **kg ha$^{-1}$** | **kg ha$^{-1}$** | **kg ha$^{-1}$** |
| **F** | N/A | N/A | N/A | N/A | N/A | N/A | 9475a |
| **FM** | N/A | 105 | N/A | N/A | N/A | N/A | 7802a |
| **SH** | 33 | N/A | 169a | 5855a | 34.44a | 12159a | 1778b |
| **SHM** | 33 | 105 | 142ab | 5355a | 36.54a | 11103a | 2322b |
| **VB** | 25 | N/A | 111ab | 2089b | 23.85b | 4452b | 3928b |
| **VBM** | 25 | 105 | 88b | 2028b | 18.22b | 4113b | 2384b |
| **Season 2** | | | | | | | |
| **F** | N/A | N/A | N/A | N/A | N/A | N/A | 6496a |
| **FM** | N/A | 52 | N/A | N/A | N/A | N/A | 6531a |
| **SH** | 33 | N/A | 213a | 4709a | 23.55a | 9437a | 1930b |
| **SHM** | 33 | 52 | 135ab | 2956b | 22.37a | 6028b | 3302b |
| **VB** | 25 | N/A | 88b | 1433bc | 16.21b | 2901bc | 2742b |
| **VBM** | 25 | 52 | 69b | 1029c | 14.86b | 2089c | 3156b |

Growing season 1 was ultimately more successful for CC biomass production of shoot dry matter. Within season 1, SH treatments produced up to 63% more shoot dry matter than the VB treatments ($p < 0.05$). Consequently, the SH treatment had the highest N contribution during season 1 (169 kg ha $^{-1}$), while the VBM treatment had the lowest (88 kg ha $^{-1}$, $p < 0.05$), and both SHM and VB were similar in value ($p > 0.05$). Although SH treatments resulted in greater biomass production, VB had similar N contribution in season 1 when compared to SHM (111 and 142 kg ha $^{-1}$, respectively, $p > 0.05$). An interesting result as SHM had numerically greater (NS) shoot dry matter production than SH and significantly higher than VB. Both SH and SHM treatments produced significantly more TC, and as a result, SH plant material had higher C/N ratios than VB treatments during season 1 ($p < 0.05$). The data presented in Table 3.1 for CC C/N ratios is a composite calculation of stem + leaf biomass production. Therefore, with SH stem incorporated into the calculation, C/N ratios for SH green manure were consistently higher than VB for both growing seasons. Although, without averaging SH leaf and stem material, SH leaf tissue had a C/N ~10.8 and stem ~37.1, indicating that woody stems contributed a large amount of C.

Similar to growing season 1, season 2 resulted in SH treatments producing greater shoot dry matter (SH: 9437 kg ha $^{-1}$, SHM: 6028 kg ha $^{-1}$), when compared to VB (2901 kg ha $^{-1}$) and VBM (2089 kg ha $^{-1}$, $p < 0.05$). All treatments produced less biomass in season 2 than the previous growing season. Sunn hemp plots had ~22% less produced biomass, while SHM (~45%), VB (~34%) and VBM (~49%) treatments had larger reductions. Cover crop leaf tissue N production during season 2 was highest for the SH plots (213 kg ha$^{-1}$, $p < 0.05$), which also produced the greatest quantity of dry matter, and lowest for the VBM treatment (69 kg $ha^{-1}$, $p < 0.05$) which produced the lowest quantity dry matter. Both the SH treatments contributed significantly more C and N content via green manure biomass than VB treatments for season 2, which can be attributed to higher dry matter production. Like season 1, C/N ratios were lower for both VB treatments when compared to SH treatments ($p < 0.05$).

Weed density was also measured for all plots at both CC termination times. The data reflects that aboveground weed biomass was up to ~81% higher in season 1 and up to ~70% higher in season 2 for plots where no CCs were present than those in which CCs were planted ($p < 0.05$, Table 3.1).

*3.4.3 Carambola plant health indicators*

Carambola health status was determined throughout the study using non-destructive sensors, leaf tissue nutrient analysis, and fruit yield. To understand the relationship between factors, correlations were conducted to compare each parameter to one another. For season 1, there was no correlation between leaf N% and NDVI, while NDRE was negatively correlated ($p \leq 0.01$) to leaf N% readings. This indicates that as leaf tissue N increased, NDRE values decreased (Table 3.2). Fruit yield values for season 1 were positively correlated to both NDVI and NDRE, along with leaf tissue N%, and negatively correlated to leaf C/N ratio.

**Table 3.2** Bivariate correlation of recorded parameters grouped by season**.**

| | NDVI[a] | NDRE[b] | Leaf N (%)[c] | Leaf C/N[d] | Fruit Yield |
|---|---|---|---|---|---|
| **Season 1[e]** | | | | | |
| **SPAD[f]** | 0.189*[g] | 0.115 | -0.034 | -0.045 | 0.094 |
| **NDVI** | | 0.548** | 0.134 | -0.152 | 0.536** |
| **NDRE** | | | -0.346** | 0.093 | 0.518** |
| **Leaf N (%)** | | | | -0.951** | 0.464* |
| **Leaf C/N** | | | | | -0.484* |
| **Season 2** | | | | | |
| **SPAD** | 0.081 | 0.406** | 0.181 | -0.176 | 0.137 |
| **NDVI** | | 0.339** | -0.169 | 0.177 | 0.321** |
| **NDRE** | | | 0.269* | -0.2688 | 0.501** |
| **Leaf N (%)** | | | | -0.987** | 0.250 |
| **Leaf C/N** | | | | | -0.183 |
| **Overall** | | | | | |
| **SPAD** | 0.072 | 0.315** | 0.197* | -0.200* | -0.001* |
| **NDVI** | | 0.411** | -0.015 | 0.032 | 0.216* |
| **NDRE** | | | -0.081 | -0.099 | 0.261** |
| **Leaf N (%)** | | | | -0.959** | 0.274 |
| **Leaf C/N** | | | | | -0.246 |

[a] Normalized Difference Vegetation Index
[b] Normalized Difference Red Edge Index
c Carambola leaf total N %
[d] Carambola leaf C/N ratio
[e] Time period
[f] Soil Plant Analysis Development
[g] Representing Pearson's correlation coefficient (r) significant at $p \leq 0.05$ (*) or $p \leq 0.01$ (**)

For season 2, NDRE was positively correlated to leaf tissue N% ($p \leq 0.05$), a result that was not observed in season 1. It is possible that this result is indicative of delayed effects of tree response to fertilization treatments. NDVI and NDRE were correlated to each other and to fruit yield throughout the experiment. With all data and times considered (overall), NDVI and NDRE were not significantly correlated to leaf tissue N% ($p > 0.05$), while SPAD readings were ($p \leq 0.05$). SPAD readings varied in correlation to the remotely sensed data as readings were significantly correlated to NDVI in season 1 and NDRE in season 2. With overall data considered, SPAD was positively correlated to NDRE, carambola leaf tissue N%, and negatively correlated to fruit yield and leaf tissue C/N ratios.

Correlations conducted at each individual sampling time (Table 3.3) reveal that NDVI and NDRE were correlated to each other at each individual sampling period, for both seasons, and overall ($p \leq 0.01$, Tables 3.2 and 3.3), yet SPAD had varying correlations to indices. SPAD was significantly correlated to both NDRE and NDVI at only 2 sampling times (Feb-10 and May-19).

**Table 3.3** Bivariate correlation of recorded parameters at each sampling time.

| | NDVI [a] | NDRE [b] | Leaf N (%)[c] | Leaf C/N [d] |
|---|---|---|---|---|
| **Aug-18 [e]** | | | | |
| **SPAD [f]** | 0.288*[g] | 0.218 | 0.203 | -0.153 |
| **NDVI** | | 0.624** | 0.409 | -0.360 |
| **NDRE** | | | 0.394 | -0.341 |
| **Leaf N (%)** | | | | -0.933** |
| **Oct-18** | | | | |
| **SPAD** | 0.215 | 0.463** | -0.374 | 0.348 |
| **NDVI** | | 0.744** | 0.098 | -0.011 |
| **NDRE** | | | -0.083 | 0.056 |
| **Leaf N (%)** | | | | -0.973** |
| **Dec-18** | | | | |
| **SPAD** | 0.595** | 0.296 | 0.319 | -0.434 |
| **NDVI** | | 0.463** | 0.523* | -0.649** |
| **NDRE** | | | 0.458* | -0.491* |
| **Leaf N (%)** | | | | -0.978** |
| **Feb-19** | | | | |
| **SPAD** | 0.634** | 0.400* | 0.271 | -0.261 |
| **NDVI** | | 0.816** | 0.223 | -0.052 |
| **NDRE** | | | -0.204 | 0.150 |
| **Leaf N (%)** | | | | -0.968** |
| **May-19** | | | | |
| **SPAD** | 0.446** | 0.472** | 0.576* | -0.562* |
| **NDVI** | | 0.790** | 0.667** | -0.711** |
| **NDRE** | | | 0.579** | -0.631** |
| **Leaf N (%)** | | | | -0.993** |
| **Sept-19** | | | | |
| **SPAD** | 0.190 | 0.348* | -0.166 | 0.146 |
| **NDVI** | | 0.740** | 0.301 | -0.303 |
| **NDRE** | | | -0.231 | 0.239 |
| **Leaf N (%)** | | | | -0.989** |
| **Dec-19** | | | | |
| **SPAD** | 0.236 | 0.342* | 0.047 | -0.105 |
| **NDVI** | | 0.847** | -0.434 | 0.339 |
| **NDRE** | | | -0.353 | 0.315 |
| **Leaf N (%)** | | | | 0.990** |

[a] Normalized Difference Vegetation Index
[b] Normalized Difference Red Edge Index
c Carambola leaf total N %
[d] Carambola leaf C/N ratio
[e] Time period
[f] Soil Plant Analysis Development
[g] Representing Pearson's correlation coefficient (r) significant at $p \leq 0.05$ (*) or $p \leq 0.01$ (**)

SPAD readings were also rarely significantly correlated with leaf N% with the exception of the May-19 sampling time, and when considering all data collected overall (Tables 3.2 and 3.3). Carambola leaf tissue N% was correlated to NDVI/NDRE at only two sampling periods (Dec-18 and May-19).

*3.4.4 Carambola leaf nitrogen and carbon content*

Growing season 1 resulted in differences between treatments for carambola leaf tissue N% (Table 3.4). On average, trees treated with SHM had the highest leaf tissue N (2.08%) and the F treatment had the lowest leaf N content (1.77%, $p < 0.05$), with all other treatments similar to one another. For season 2, no significant difference in carambola leaf tissue N% was observed.

**Table 3. 4** Displays average SPAD, NDVI, NDRE, fruit yield (n = 9), carambola leaf tissue N% and C/N ratios (n = 4) for cover crop season 1 and season 2. Three cover crop treatments (F = fallow, SH = sunn hemp, and VB = velvet bean) and three fertilizer w/ cover crop treatments (FM= fallow + poultry manure fertilizer, SHM = sunn hemp + poultry manure fertilizer, VBM = velvet bean + poultry manure fertilizer) were analyzed for these parameters. Lowercase letter denotes difference between treatments within the same season at ($p < 0.05$), ± denotes standard error.

| | **SPAD** | **NDVI** | **NDRE** | **Leaf N (%)** | **Leaf C/N** | **Fruit Yield (kg)** |
|---|---|---|---|---|---|---|
| **Season 1** | | | | | | |
| **F** | 49.83 (±0.76) | 0.8857 (±0.059) | 0.4433 (±0.0113) | 1.77 (±0.04)b | 28.47 (± 0.79)a | 4.40 (±0.93)b |
| **FM** | 50.25 (±0.82) | 0.8920 (±0.0346) | 0.4685 (±0.0118) | 1.96 (±0.06)ab | 26.10 (±0.71)ab | 6.85 (±0.49)ab |
| **SH** | 51.16 (±0.78) | 0.8982 (±0.0042) | 0.4743 (±0.0119) | 2.01 (±0.06)ab | 24.85 (±0.56)b | 8.81 (±0.76)a |
| **SHM** | 50.49 (±0.86) | 0.8921 (±0.0044) | 0.4557 (±0.0110) | 2.08 (±0.09)a | 24.35 (±0.93)b | 6.29 (±0.78)ab |
| **VB** | 52.56 (±0.69) | 0.8925 (±0.0062) | 0.4903(±0.0179) | 1.91 (±0.05)ab | 26.60 (±0.62)ab | 5.46 (±0.62)b |
| **VBM** | 51.87 (±0.76) | 0.8962 (±0.0052) | 0.4886 (±0.0145) | 2.01 (±0.06)ab | 24.77 (±0.58)b | 9.51 (±0.87)a |
| **Season 2** | | | | | | |
| **F** | 42.45 (±1.24)c | 0.8981 (±0.0041) | 0.4038 (±0.0062)b | 1.82 (±0.09) | 27.18 (±1.28) | 8.45 (±1.75)bc |
| **FM** | 45.69 (±0.87)abc | 0.9015 (±0.0042) | 0.4243 (±0.0049)ab | 1.86 (±0.09) | 27.11 (±1.50) | 14.70 (±0.68)a |
| **SH** | 49.69 (±1.32)a | 0.9073 (±0.0035) | 0.4362 (±0.0060)a | 1.79 (±0.05) | 27.31 (±0.80) | 13.91 (±1.33)ab |
| **SHM** | 45.49 (±1.04)abc | 0.8984 (±0.0049) | 0.4236 (±0.0087)ab | 1.77 (±0.09) | 27.54 (±1.51) | 8.73 (±1.49)bc |
| **VB** | 44.92 (±1.19)bc | 0.8895 (±0.0062) | 0.4151 (±0.0073)ab | 1.73 (±0.06) | 29.23 (±0.85) | 5.16 (±1.11)c |
| **VBM** | 47.27 (±0.91)ab | 0.8966 (±0.0057) | 0.4106 (±0.0087)ab | 2.01 (±0.53) | 24.58 (±0.66) | 8.16 (±1.42)c |
| **Overall** | | | | | | |
| **F** | 46.70 (±0.83)b | 0.8909 (±0.0039) | 0.4264 (±0.0074) | 1.79 (±0.04)b | 27.88 (±0.72)a | 7.10 (±1.26)b |
| **FM** | 48.43 (±0.67)ab | 0.8960 (±0.0038) | 0.4508 (±0.0078) | 1.91 (±0.05)ab | 26.58 (±0.80)ab | 12.46 (±0.94)a |
| **SH** | 50.54 (±0.72)a | 0.9022 (±0.0029) | 0.4566 (±0.0074) | 1.93 (±0.05)ab | 25.88 (±0.52)ab | 12.30 (±1.08)a |
| **SHM** | 48.55 (±0.74)ab | 0.8946 (±0.0033) | 0.4427 (±0.0077) | 1.95 (±0.07)ab | 25.68 (±0.87)ab | 7.83 (±1.00)b |
| **VB** | 49.11 (±0.84)ab | 0.8912 (±0.0044) | 0.4574 (±0.0118) | 1.84 (±0.04)ab | 27.63 (±0.56)a | 5.27 (±0.72)b |
| **VBM** | 50.09 (±0.65)a | 0.8964 (±0.0038) | 0.4577 (±0.0107) | 2.01 (±0.04)a | 24.69 (±0.43)b | 8.76 (±0.87)ab |

When considering individual sampling dates, carambola leaf tissue N % was significantly different between treatments during three sampling times (Figure 3.2, Table 3.5). At the Aug-18 time (1st CC termination), trees treated with SH had the highest average leaf tissue N% (2.26%) while the F treatment had the lowest (1.85%, $p < 0.05$), with all other treatments similar to one another ($p > 0.05$).

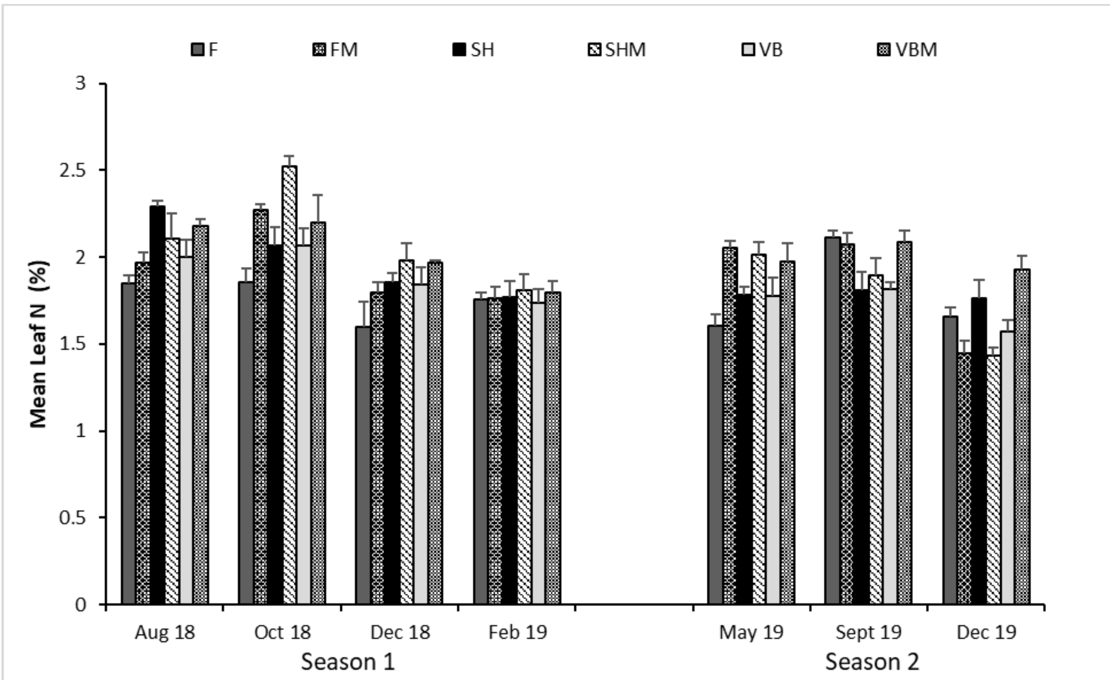


**Figure 3. 2** Displays average carambola leaf tissue N% over a 2-season period after cover crop growth and termination (n = 4). The bars at each sampling time represent three cover crop treatments (F = fallow, SH = sunn hemp, and VB = velvet bean) and three fertilizer w/ cover crop treatments (FM= fallow + poultry manure fertilizer, SHM = sunn hemp + poultry manure fertilizer, VBM = velvet bean + poultry manure fertilizer) that were analyzed for these parameters. Error bars represent the standard error of the mean.

The Oct-18 (2 months after 1st CC termination) time showed that average leaf tissue N% was highest for the SHM treatment (2.52%) and lowest for F and VB (1.85% and 2.07%, respectively, $p < 0.05$), with all other treatments similar in leaf tissue N%. At the May-19 sampling time, right after CCs were seeded for season 2, FM and SHM (2.05% and 2.01%, respectively) had the highest average leaf tissue N%, while F trees had the lowest average (1.60%, $p < 0.05$). All other treatments were similar in the mid-range (Table 3.5).

**Table 3.5** Displays average SPAD, NDVI, NDRE (n = 9), carambola leaf N and C/N ratios (n = 4) at each sampling time throughout the experiment. Three cover crop treatments (F = fallow, SH = sunn hemp, and VB = velvet bean) and three fertilizer w/ cover crop treatments (FM= fallow + poultry manure fertilizer, SHM = sunn hemp + poultry manure fertilizer, VBM = velvet bean + poultry manure fertilizer) were analyzed for these parameters. Lowercase letter denotes difference between treatments at each sampling time at ($p < 0.05$), ± denotes standard error.

| | SPAD | NDVI | NDRE | Leaf N (%) | Leaf C/N |
|---|---|---|---|---|---|
| **Aug-18** | | | | | |
| **F** | 50.55 (±1.01)ab | 0.8450 (±0.0101) | 0.3695 (±0.0078)b | 1.85 (±0.04)b | 27.86 (±0.77)a |
| **FM** | 50.12 (±1.04)b | 0.8470 (±0.0114) | 0.3798 (±0.0069)ab | 1.97 (±0.05)ab | 26.41 (±0.91)ab |
| **SH** | 52.50 (±0.99)ab | 0.8849 (±0.0069) | 0.4067 (±0. 0078)a | 2.26 (±0.04)a | 22.76 (±0.71)b |
| **SHM** | 52.61 (±0.64)ab | 0.8716 (±0.0079) | 0.3884 (±0.0071)ab | 2.11 (±0.14)ab | 24.64 (±1.72)ab |
| **VB** | 55.44 (±1.38)a | 0.8654 (±0.0092) | 0.3987 (±0.0102)ab | 1.96 (±0.09)ab | 27.36 (±0.82)ab |
| **VBM** | 51.61 (±1.59)ab | 0.8615 (±0.0106) | 0.3996 (±0.0082)ab | 2.18 (±0.04)ab | 23.25 (±0.34)ab |
| **Oct-18** | | | | | |
| **F** | 49.66 (±1.56) | 0.9107 (±0.0074) | 0.4675 (±0.0127) | 1.85 (±0.08)b | 27.42 (±1.35)a |
| **FM** | 46.08 (±1.51) | 0.9185 (±0.0022) | 0.4633 (±0.0084) | 2.27 (±0.03)ab | 22.89 (±0.39)bc |
| **SH** | 51.16 (±0.84) | 0.9144 (±0.0049) | 0.4861 (±0.0105) | 2.07 (±0.10)b | 24.68 (±0.93)ab |
| **SHM** | 46.33 (±1.05) | 0.9054 (±0.0046) | 0.4514 (±0.0099) | 2.52 (±0.06)a | 20.09 (±0.42)b |
| **VB** | 50.15 (±0.37) | 0.9057 (±0.0105) | 0.4679 (±0.0192) | 2.07 (±0.10)b | 24.04 (±0.87)abc |
| **VBM** | 50.64 (±1.40) | 0.9100 (±0.0045) | 0.4792 (±0.0143) | 2.20 (±0.16)ab | 22.77 (±0.1.44)bc |
| **Dec-18** | | | | | |
| **F** | 49.68 (±1.73) | 0.9018 (±0.0054) | 0.4360 (±0.0127) | 1.60 (±0.15) | 31.52 (±2.46) |
| **FM** | 53.45 (±1.40) | 0.9127 (±0.0035) | 0.4791 (±0.0124) | 1.79 (±0.06) | 27.82 (±0.88) |
| **SH** | 49.91 (±2.14) | 0.9105 (±0.0039) | 0.4633 (±0.0154) | 1.85 (±0.06) | 26.80 (±0.84) |
| **SHM** | 51.26 (±2.10) | 0.9075 (±0.0052) | 0.4660 (±0.0061) | 1.98 (±0.10) | 26.63 (±1.84) |
| **VB** | 53.55 (±1.07) | 0.9021 (±0.0058) | 0.4826 (±0.0238) | 1.86 (±0.08) | 27.58 (±1.59) |
| **VBM** | 52.48 (±0.70) | 0.9144 (±0.0047) | 0.4849 (±0.1141) | 1.97 (±0.01) | 25.64 (±0.18) |
| **Feb-19** | | | | | |
| **F** | 49.33 (±1.97) | 0.8873 (±0.0088) | 0.5273 (±0.0109) | 1.76 (±0.04) | 27.43 (±0.09) |
| **FM** | 51.90 (±1.39) | 0.8897 (±0.0063) | 0.5518 (±0.0172) | 1.76 (±0.07) | 28.37 (±0.60) |
| **SH** | 51.09 (±2.20) | 0.8870 (±0.0101) | 0.5691 (±0.0158) | 1.77 (±0.09) | 25.93 (±0.91) |
| **SHM** | 51.53 (±2.10) | 0.8846 (±0.0108) | 0.5511 (±0.0123) | 1.81 (±0.09) | 25.18 (±0.62) |
| **VB** | 50.73 (±1.22) | 0.8924 (±0.0148) | 0.6111 (±0.0241) | 1.74 (±0.08) | 26.85 (±0.58) |
| **VBM** | 52.62 (±1.76) | 0.9009 (±0.0088) | 0.5790 (±0.0264) | 1.79 (±0.07) | 26.53 (±1.05) |
| **May-19** | | | | | |
| **F** | 41.17 (±1.40) | 0.9055 (±0.0067) | 0.4028 (±0.0082) | 1.60 (±0.07)b | 30.70 (±1.29) |

| | | | | | |
|---|---|---|---|---|---|
| **FM** | 46.19 (±1.32) | 0.9064 (±0.0072) | 0.4131 (±0.0085) | 2.05 (±0.04)a | 23.88 (±0.42) |
| **SH** | 46.71 (±2.37) | 0.9140 (±0.0046) | 0.4196 (±0.0099) | 1.78 (±0.04)ab | 26.72 (±1.15) |
| **SHM** | 44.72 (±2.37) | 0.9214 (±0.0019) | 0.4306 (±0.0082) | 2.01 (±0.07)a | 24.44 (±0.96) |
| **VB** | 46.86 (±1.25) | 0.9061 (±0.0064) | 0.4239 (±0.0143) | 1.78 (±0.10)ab | 29.35 (±0.60) |
| **VBM** | 46.45 (±1.26) | 0.9211 (±0.0056) | 0.4415 (±0.0121) | 1.97 (±0.11)ab | 25.27 (±1.44) |
| **Sept-19** | | | | | |
| **F** | 41.28 (±2.05)c | 0.8826 (±0.0065)ab | 0.4238 (±0.0102)ab | 2.11 (±0.05) | 23.06 (±0.54) |
| **FM** | 48.43 (±1.91)abc | 0.8836 (±0.0059)a | 0.4340 (±0.0090)ab | 2.07 (±0.07) | 23.67 (±0.80) |
| **SH** | 55.45 (±1.44)a | 0.8907 (±0.0049)a | 0.4572 (±0.0075)a | 1.81 (±0.11) | 27.34 (±1.58) |
| **SHM** | 46.93 (±0.95)abc | 0.8793 (±0.0059)ab | 0.4539 (±0.0063)a | 1.90 (±0.05) | 25.96 (±0.60) |
| **VB** | 43.78 (±2.68)bc | 0.8565 (±0.0066)b | 0.4225 (±0.0114)ab | 1.82 (±0.07) | 27.14 (±0.79) |
| **VBM** | 51.02 (±1.22)ab | 0.8720 (±0.0075)ab | 0.4120 (±0.0121)b | 2.09 (±0.07) | 23.53 (±0.75) |
| **Dec-19** | | | | | |
| **F** | 44.63 (±2.58) | 0.9052 (±0.0056) | 0.3848 (±0.0101)bc | 1.66 (±0.14) | 28.66 (±2.08) |
| **FM** | 43.13 (±0.90) | 0.9145 (±0.0047) | 0.4247 (±0.0056)ab | 1.45 (±0.06) | 33.77 (±1.30) |
| **SH** | 47.75 (±1.37) | 0.9184 (±0.0034) | 0.4313 (±0.0103)a | 1.76 (±0.13) | 28.44 (±1.98) |
| **SHM** | 47.75 (±1.77) | 0.8998 (±0.0077) | 0.3863 (±0.0158)bc | 1.44 (±0.12) | 33.24 (±2.84) |
| **VB** | 44.03 (±1.41) | 0.9060 (±0.0035) | 0.3948 (±0.0088)abc | 1.57 (±0.10) | 31.20 (±1.91) |
| **VBM** | 45.40 (±1.43) | 0.9003 (±0.0059) | 0.3727 (±0.0078)c | 1.93 (±0.03) | 25.31 (±0.28) |

When comparing carambola leaf tissue C/N ratios, season 1 data revealed that the F leaf tissue had the highest average C/N ratio (28.47) while the SH, SHM, and VBM treated trees had significantly lower C/N (24.85, 24.35, and 24.77 respectively, $p < 0.05$). While season 2 carambola leaf tissue C/N showed no significant differences between treatment averages.

Like carambola leaf N%, C/N results were significantly different between treatments at the first two sampling dates. At Aug-18 (1$^{st}$ CC termination time), carambola leaf tissue C/N ratios were highest within the F treatment (27.86) compared to the lowest average value in the SH treatment (22.76, $p < 0.05$). All other treatments showed no significant difference in value (Table 3.5). At the Oct-18 sampling time (two months post CC termination), plant tissue collected from the F treatment had the highest C/N (27.42) compared to the SHM treatment (20.09) which displayed the lowest ($p < 0.05$). All other sampling times showed no significant difference between treatments for leaf tissue C/N ratios. Comparing carambola leaf tissue N% throughout the study indicates a trend in which trees that received SH treatments were more likely to have higher N content in their leaves.

*3.4.5 SPAD readings*

SPAD readings for season 1 indicated no difference between carambola trees treated with various fertilizer regimens. Variations between treatments were slight, ranging from 49.83 to 52.56 ($p > 0.05$, Table 3.4). On average, throughout season 2, trees treated with SH had the highest average SPAD value (49.69) which was 14.5% higher than the lowest average value from trees within the F treatment (42.45, $p > 0.05$). The FM and SHM treatments were similar in value ($p > 0.05$, while the VBM treatment had the second highest SPAD reading (47.27, $p < 0.05$) and the VB treatment had the second lowest average reading (44.92, $p < 0.05$). Considering the overall data (all sampling times), a similar trend can be observed in which SH trees resulted in the highest SPAD readings and F trees had the lowest ($p < 0.05$, Table 3.4).

When examining individual sampling times, SPAD readings for the carambola trees were similar between treatments throughout the study with the exception of the Aug-18 sampling time (at season 1 CC termination) and at the Sept-19 sampling time (1 month after season 2 CC termination) (Table 3.5). At the Aug-18 time, SPAD readings were highest in the VB treated trees (55.44) and lowest for the FM treatment (50.12, $p < 0.05$), with all other treatments similar (Table 3.5). This is a contrast when compared to the Sept-19 sampling time, as trees treated with SH had the highest average SPAD reading (55.45), 25% higher than F trees (41.28, $p < 0.05$) at this sampling period. Trees treated with VBM had the second highest SPAD readings (51.02, $p < 0.05$) with VB resulting in the second lowest (43.78, $p < 0.05$). Both FM and SHM treatments were similar within the midrange ($p > 0.05$) at Sept-19 (Table 3.5).

*3.4.6 Normalized difference vegetation index*

When considering NDVI grouped by season (Table 3.4), readings were similar for all treatments over both season 1 and 2 ($p > 0.05$). NDVI data at individual sampling times (Table 3.4) showed no significant differences between treatments at any sampling time with the exception of Sept-19 (1-month post season 2 CC termination). At this sampling time, NDVI values were highest for the FM and SH treated trees (0.8836 and 0.8907, respectively, $p < 0.05$). Trees treated with VB had the lowest average NDVI reading at the Sept-19 time period (0.8565, $p < 0.05$), with all other treatments similar in value.

*3.4.7 Normalized difference red edge index*

NDRE readings for each treatment were similar for season 1 (NS), while differences were distinguished within in season 2 and within the overall data (Table 3.4). In season 2, NDRE readings were highest for trees treated with the SH treatment (0.4362) and lowest for the F treated trees (0.4038, $p < 0.05$), with all other treatments similar to one another within the midrange (Table 3.4). With all data combined (overall) there was no difference between treatments in NDRE readings. For specific sampling times, there were differences in average NDRE readings between treatments throughout the study (Table 3.5). This aligns with other tested parameters in which variance was shown at the end of both cover crop growing seasons. At the Aug-18 sampling period (1$^{st}$ CC termination), NDRE readings were highest in trees treated with SH (0.4067), and lowest for the F treatment (0.3695, $p < 0.05$), with all other treatments similar in value to one another ($p > 0.05$). At the Sept-19 sampling period (1 month after 2$^{nd}$ CC termination), SH and SHM treatments were highest in NDRE average value compared to other treatments (0.4572 and 0.4539, respectively $p < 0.05$), while the VBM treated trees had the lowest average reading (0.4120, $p < 0.05$), and all other treatments similar in value. At the last sampling time of the experiment (Dec-19), NDRE values were again highest for trees treated with SH (0.4313, $p < 0.05$), with second highest average readings observed for the FM treatment (0.4247, $p < 0.05$) and the lowest average reading was recorded from trees treated with VBM (0.3727, $p < 0.05$). At sampling periods where NDRE did show difference between treatments, trees treated with SH and SHM showed consistently higher values than others.

*3.4.8 Fruit yield*

There were differences in average fruit yield values between treatments for both seasons individually and overall, throughout the study (Table 3.4). Season 1 fruit yield averages revealed that trees treated with SH and VBM treatments had the highest fruit yields (8.81kg and 9.51 kg, respectively), while F and VB treatments had significantly lower values (4.40 kg and 5.56 kg, respectively, $p < 0.05$). In season 2, FM had highest fruit yield (14.70 kg), followed by SH (13.91 kg), while both VB and VBM had the lowest fruit yield (5.16 kg and 8.16 kg, respectively, $p < 0.05$). Overall, FM and SH treatments (12.46 kg and 12.30 kg, respectively) performed the best in regard to fruit yield with highest average fruit yields compared to the other treatments ($p < 0.05$).

## 3.5 Discussion

*3.5.1 Carambola phenology and temperature response*

Carambola phenology in South Florida is indicative of climatic patterns. Generally, these tropical trees have reduced vegetative growth and development starting in October and running through March, which are typically cooler, drier, months. Around April, trees begin a vegetative flush that boosts growth and leaf production through September, while root flush begins around March and runs through October (Figure 3.3, Núñez-Elisea and Crane, 1998).

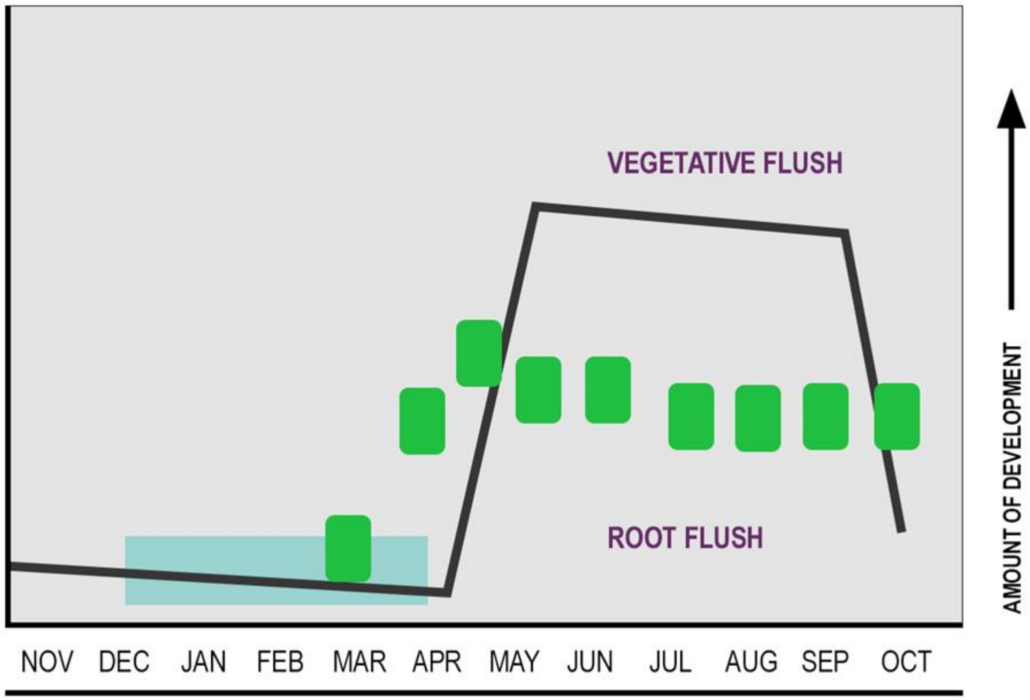


**Figure 3.3** Carambola phenology in South Florida as adopted from Núñez-Elisea and Crane, 1998. The black line represents vegetative flush patterns, the green boxes represent root flush patterns, and the blue box represents leaf chlorosis and drop.

Leaf chlorosis and defoliation may occur from December to April, before vegetative flush (Núñez-Elisea and Crane, 1998). Cover crops were planted at the end of April/beginning of May during both CC growing seasons. Root flush for carambola begins to pick up in April and reaches its peak during May (Figure 3.3). At this time, CC seeds were germinating and only beginning to sprout. While carambola is going through its vegetative flush stage, they also typically flower April-June (Núñez-Elisea and Crane, 2000). Therefore, CCs were planted during a time when nutrients are critical for the carambola tree. Flowering and fruit development occurred throughout the summer months, with fruit harvesting time July - October, and a prominent harvest in August. These times coincide with CC planting, growth, and termination. As such, it is possible that the CCs could have inspired stress, competition, or possibly facilitated growth and/or crop production.

To better understand measured parameters that indicate phenological change, Table 3.6 shows differences in the recorded plant health indicators taken throughout the study in regard to sampling period (regardless of treatment).

**Table 3.6** Displays average SPAD, NDVI, NDRE, carambola leaf N and C/N ratios for all treatments at each sampling time, regardless of treatment. Lowercase letter denotes difference between times ($p < 0.05$).

| | SPAD | NDVI | NDRE | Leaf N (%) | Leaf C/N |
|---|---|---|---|---|---|
| **Time** | | | | | |
| **Aug-18** | 52.09a | 0.8624c | 0.3899e | 2.06ab | 25.32bc |
| **Oct-18** | 48.89bc | 0.9109a | 0.4691b | 2.16a | 23.66a |
| **Dec-18** | 51.68ab | 0.9084a | 0.4682b | 1.85cd | 27.51b |
| **Feb-19** | 51.23ab | 0.8904b | 0.5660a | 1.77de | 26.74b |
| **May-19** | 45.40d | 0.9118a | 0.4213cd | 1.88bcd | 26.43b |
| **Sept-19** | 47.06cd | 0.8783b | 0.4342c | 1.98bc | 24.98bc |
| **Dec-19** | 44.98d | 0.9079a | 0.4003de | 1.59e | 30.59a |

Following the classically observed phenology of carambola patterns in South Florida (Figure 3.3), leaf N% may be the most indicative parameter to reflect phenological change in carambola when considering seasonality. Carambola average leaf tissue N% was lowest during the winter months at the Dec-19 sampling time, followed by Feb-19 and Dec-18, all months in which temperature drops and leaf chlorosis and senescence is expected. Leaf tissue N% was the only parameter that consistently indicated this pattern (Table 3.6).

Nitrogen is known as a mobile nutrient and as such, vascular plants have the ability to reallocate nutrients from older leaves to younger leaves (Tanoi and Kobayashi, 2015). This phenomenon results in tree N deficiencies becoming most apparent in older leaves compared to younger ones. Little work has been conducted to determine ideal nutrient levels for leaf tissue in carambola trees grown in the subtropical climate of South Florida. However, preliminary nutrient data collected in South Florida by Tropical Fruit Crop Extension Agents reveal that ideal leaf tissue N% for mature trees ranges from 1.7 - 2.60% (Crane and Thomas, 2011, unpublished data). Throughout this study, there were multiple occasions that treated trees fell below the 1.7% threshold. Collectively, winter sampling times had lower overall N% for all treatments (Dec-18, Feb-19, Dec-19, Table 3.5). Average monthly temperatures never dropped below the optimal range during the study period with the lowest recorded air and soil temperatures occurring in Jan-19 (18.32°C and 20.97°C, respectively, Figure 3.1). Temperature should not have been a substantial confounding factor for leaf greenness. However, while these temperatures are still within optimal range, it is possible that within the month of Jan-19 there were several occasions where temperatures dropped below the 18°C threshold. Consequently, if there were days below optimal temperatures, it may have induced chlorosis and eventual leaf abscission. It has been observed in the winter months that carambola in South Florida exhibit unfavorable patterns including defoliation and general lack of growth which guides phenological responses (Figure 3.1). Besides lower temperatures, increased cloud cover over winter months could be the possible cause of chlorophyll oxidation, resulting in leaf chlorosis (George et al. 2000). The combination of these factors could have resulted in lower leaf N concentrations observed in Dec-18 and Feb-19 sampling times (Figure 3.2, Table 3.5).

All of the sampling times where carambola leaf N% fell below 1.7% were during winter months. The first-time being Dec-18 where F treatment readings were recorded at 1.60% ($p > 0.05$). Although N% values were not significantly different at this sampling period, it is possible that remaining cover crop residue may have acted as an insulation buffer for carambola roots during cold snaps. Soil temperature can have huge impacts on water and nutrient absorption, growth rates, and metabolic processes for tropical woody fruit tree species (George et al. 2001). George et al. (2000) found that when comparing mulched carambola trees to non-mulched trees in South Florida, that leaf chlorosis and abscission were consistently higher for the non-mulched group, and that fruit yields were 16-50% greater for trees that received mulching treatment. It is probable that by Dec-18/19 (4 months after CC termination) CC residue was highly degraded. However, remaining residue may have played a role in soil/root insulation, especially for trees treated with SH as woody stems take a longer time to fully decompose when grown past 42 days (Baitsaid et al. 2018). Trees treated with CC residue showed higher leaf tissue N% numerically at Dec-18 (NS, $p > 0.05$, Table 3.5) than both F and FM treatments. This result may have been a combination of nutrient additions and insulation via green manure residue.

*3.5.2 Green manure material*

Carbon to nitrogen ratios in organic amendments are highly important for nutrient mineralization in soil (Rodrigues et al. 2006). Results presented in Table 3.1 show that the VB CC provided green manure material with consistently lower C/N ratios than SH. This is due to differences in species and growth habit of the CCs utilized for this study. Velvet bean produces vines up to 14 m in length with an abundance of green forage (Buckles, 1995). The vegetative growth of VB is distinctly high in leaf production and its leguminous nature results in high N content and ultimately, low C/N ratio of plant material (Zasada et al. 2006), ideal for microbial decomposition (Wang et al. 2007b).

Sunn hemp has an opposite growth habit in which it produces rigid stems that are fibrous in nature, with leaves arranged along a tall stalk (Wang et al. 2015). Both SH and SHM treatments added significantly more TC, and as a result, SH plant material had significantly higher C/N ratios when leaf and stem tissue are averaged together than VB treatments within both seasons (Table 3.1). Sunn hemp green manure residue has low C/N ratio within the leaf tissue (~10.8) and high C/N ratios within the stem tissue (~37.1), making leaf material more readily decomposable in the short-term and stem material decomposable over the long-term (Xuluc-Tolosa et al. 2003).

In (sub)tropical climates with high temperature and moisture conditions, litter decomposition and nutrient release rates are generally faster, and can potentially be a reliable substitute for inorganic fertilizers in tropical crop settings (Seneviratne et al. 2000). This could explain differences in N% and C/N ratios within the carambola leaf tissue just two months after CCs were terminated (Oct-18, Table 3.5). At this sampling time, trees treated with SHM had the highest leaf tissue N% and lowest C/N ratio while VBM and FM showed second lowest tissue N% and higher C/N ratios. Fast decomposition rates of SH material coupled with PM addition had significant impacts on carambola tree nutrient status two months after green manure and first PM application. All trees without PM application had significantly lower N% at the Oct-18 sampling time. This result shows that boosts in leaf tissue N% were highly attributed to a combination of CC decomposition and nutrient additions from PM two months after first application and cover crop termination. This result coincides with Rodrigues et al. (2006) who found that N content of leaf tissue from olive trees treated with legume CCs in a

Mediterranean climate had significantly higher N than other non-legume treatments starting at two months after CC termination.

The last sampling time in which carambola leaf tissue N% showed significant differences was at the May-19 sampling time (Table 3.5). At this sampling time (second CC seeding, season 2), leaf N% results revealed that FM and SHM (2.05% and 2.01%, respectively) had the highest averages ($p < 0.05$), while F trees had the lowest average (1.60%, $p < 0.05$, Table 3.4). At this time, it had been one complete calendar year since the first round of cover crops were planted, and ~9 months after the first round of cover crops were terminated. Trees with PM additions every two months were sustaining higher nitrogen content ($p < 0.05$) within their leaves and lower C/N ratios ($p < 0.05$). It is apparent that lack of fertilization was negatively effecting N content of carambola that did not receive CC or PM as re-foliation and vegetative flush should have been occurring at that specific sampling period resulting in prospectively higher leaf chlorophyll content.

*3.5.3 Belowground interactions*

Carambola trees had a 0.5 m radius circle starting at the trunk that was left undisturbed and was not seeded with CCs. From there, a 1.25 m radius circle around the tree was planted with CC. Because of South Florida's inherently shallow soil profile and limestone parent material (Migliaccio et al. 2010), the land was trenched (~46-61 cm deep and ~41-46 cm wide) before carambola trees were planted; a common management strategy for tree crop producers in Miami-Dade County (Crane et al. 2006). Therefore, the trees sampled in this study likely developed strong support roots within the trenched area. Besides trenching, rock-plowing ~10-20 cm is common practice to create enough soil depth for root establishment for farms within South Florida (Li et al. 2001). It is probable that beyond the trenched area, sampled carambola trees had extensive surface feeder roots. As such, CC roots and carambola roots likely inhabited the same area throughout the CC growing season creating opportunity for rhizosphere interactions between the trees and CCs.

Significant differences in carambola leaf tissue N% were recorded the Aug-18 sampling time ($1^{st}$ CC termination). Trees treated with SH had the highest average leaf tissue N content (2.26%, $p < 0.05$) and F had the lowest (1.85%, $p < 0.05$, Figure 3.2, Table 3.5). Initial differences at termination time could be attributed to biological nitrogen fixation (BNF) by the legume cover crops, as the trees treated with SH had the highest carambola leaf N% and lowest leaf C/N ratio when compared to other treatments (Table 3.5). Sunn hemp cover crops provided the highest CC N contribution for season 1 (Table 3.1), which shows success in biomass production and possibly BNF.

Because of their leguminous nature, both SH and VB had significant potential to acquire N through BNF (Parr et al. 2011), especially since seeds were inoculated with a rhizobium mix before planting. Symbiotic relationships between legume species and rhizobia through nodule formation have potential to accumulate large amounts of N derived from the atmosphere (Ndfa). It has been reported that green manure legumes have higher potential to accumulate N when compared to food legumes and often surpass 80% Ndfa (Ladha and Reddy, 2003). Like decomposition rates and nutrient cycling as a whole, BNF (specifically rhizobial interaction and nitrogenase enzyme activity) is directly influenced by soil environmental factors, specifically water availability and high temperatures (27 - 40 °C, Drinkwater et al. 2017), which were present throughout this experiment (Figure 3.1).

Besides BNF, root exudates from CCs may have played a significant role in supplying carbon and attracting beneficial organisms to facilitate cycling and exchange as plants have been shown to expel exudates that increase micronutrient availability through metal chelation via amino and organic acids (Bais et al. 2006). Organic compounds produced via rhizodeposition (release of carbon compounds from roots) can also facilitate stimulation of nutrient cycling microorganisms (Jones et al. 2004). When terminating CCs, belowground root systems were left intact to decompose and provide additional carbon and nutrients to carambola rhizosphere soil, which may have impacted tree and crop health in trees treated with CC (Kavdir and Smucker, 2004).

Since it has been established that leguminous CCs have potential for high Ndfa in ideal soil environments, if CCs utilized BNF to obtain N for their own growth, there would be little to no competition for N between the CC and the carambola tree. Nitrogen derived from the atmosphere by legumes is also dependent on existing plant available N content (Kermah et al. 2018). Legumes planted in soils with low N content are more likely to rely on N fixation for nutrients than those in N rich settings as BNF is a resource intensive process (Büchi et al. 2015). This could be a reason for no significant difference in carambola leaf tissue N% after the second growing season (Sept-19, Table 3.5) as soils may have already had sufficient N content for CC growth. It is also possible that temperature and moisture conditions during the season 1 CC growing period were more conducive for successful BNF and biomass production than season 2 CC growing period, which experienced less rainfall during May-19 - Aug-19 and slightly higher soil and air temperatures (Figure 3.1). Because CCs produced less biomass in season 2, it is likely that there was less root biomass, carbon input via root exudates, and BNF. This is a possible explanation for no differences between treatments in carambola tissue N % for season 2 overall (Table 3.4).

*3.5.4 Optical sensor readings*

In this study, three types of optical sensor readings were utilized. The SPAD readings were taken on the ground from each individual tree, while NDVI and NDRE readings were taken via UAV flights. Generally, SPAD, NDVI, and NDRE readings are considered indicators of plant health or stress through detecting leaf greenness, and therefore chlorophyll content. Leaf chlorophyll content is a key factor for photosynthesis rates and overall plant productivity (Ghosh et al. 2004). Chlorophyll can be estimated via sensor technology because chlorophylls show characteristically strong reflectance within the red wavelength region with absorbance between 660nm and 680nm (Wu et al. 2010). Because N is a key component of the chlorophyll molecule, N nutrient status can theoretically be estimated based upon spectral reflectance (Rorie et al. 2011). As such, leaf/canopy reflectance has been proven to be a useful and reliable tool for assessing physiological stress and overall plant health status (Agarwal and Gupta, 2018).

When considering correlation results, SPAD, NDRE, and NDVI were rarely correlated to carambola leaf tissue N% (Table 3.2 and 3.3) which could be related to a variety of factors. For tree crops, canopy chlorophyll content estimation through remote sensing can prove challenging as results are influenced by more than just leaf reflectance and transmittance. Many other factors influence the reliability of canopy sensing including, but not limited to, leaf area, chlorophyll distribution, canopy structure, and leaf orientation (Wu et al. 2010). The carambola tree has a distinct and relatively uncommon growth habit that could have impact on readings from remotely sensed data when comparing to actual leaf N%. These trees grow upright at first, fruit, then branches orient laterally downward after fruiting (results in plagiotropic branches) (Fisher and Stevenson, 1981). This growth habit causes overlapping branching and a spreading growth pattern. The interior canopy becomes shaded and defoliates forming non-productive empty space in the interior (Crane et al. 1992). Nitrogen status monitoring can be strongly influenced by the plant growth stage based on background noise from soil and weeds (Zheng et al. 2020). For this study, data was extracted via manual selection of tree center points in ArcGIS software with a 0.5 m radius; a suitable area to cover tree center points without including areas outside of the canopy. However, at the beginning of the experiment, carambola trees were relatively young and somewhat sparse, meaning the canopy may not have been fully developed. This, along with defoliation of the interior, may have introduced background noise to the data at the beginning of the experiment and could have impacted correlation between remotely sensed data and carambola leaf N% for season 1 (Table 3.2).

Other plant growth characteristics could also influence data collected with UAV remote sensing equipment. Carambola leaves are pinnately compound with leaflets varying from 2-11 in number, ranging from 2.5-7.5 cm long and 1-4 cm wide (Paull and Duarte, 2011). The leaves are mobile and change in orientation as a result of varying factors. When trees are stressed, the leaves change their orientation from horizontal to vertical (George et al. 2002). Marler et al. 1994 found that varying light levels impacted growth morphology and leaf physiology in young carambola trees. In their study carambola grown in full sunlight (100%) began each photoperiod (daylight) with leaves in horizontal orientation, and by mid-morning on days without cloud cover, leaflets changed to vertical orientation and continued that way for the remainder of the photoperiod. They also found that carambola exposed to 100% sunlight had ~47% less chlorophyll content and a ~29% less midday chlorophyll fluorescence ratio ($F_v/F_m$), indicating decline in photochemical efficiency during typical bright and sunny days. As such, this could have caused varying results in NDVI and NDRE readings. While UAV flights generally took place around the same time each flight period (11:00 am – 1:00pm), it is possible that weather may have had an impactful role on these readings. The data was atmospherically corrected within the Pix4D software through calibration images taken before and after each UAV flight. However, this does not account for change in carambola leaf orientation impacted by cloudy or sunny days. Leaf orientation is known in remote sensing as leaf angle distribution (LAD) and can be an important limiting factor for accuracy of remotely sensed vegetation data. This indicator can be utilized as a canopy structural parameter because it impacts light transmission and other biophysical processes within the canopy (Kuo et al. 2019). Since carambola can change their LAD with environmental conditions, effectiveness of multispectral data collected throughout this experiment may have been impacted as it correlates to leaf N% (Tables 3.2 and 3.3)

NDVI has been associated with various structural and functional traits of vegetation including LAI, biomass, absorbed photosynthetic active radiation, and aerial net primary productivity (Di Bella et al. 2004). When considering overall data (Table 3.2), SPAD readings were positively correlated with NDRE ($p \leq 0.01$), leaf N% ($p \leq 0.05$), and negatively correlated with leaf C/N ($p \leq 0.05$). Change in carambola leaf orientation may be a factor when considering correlation of NDVI and NDRE to SPAD readings. Correlations conducted at each individual sampling time (Table 3.3) reveal that SPAD was significantly correlated to both NDRE and NDVI at only 2 sampling times (Feb-10 and May-19). An interesting result considering SPAD has a similar mode of optical sensing as NDVI and NDRE indices. SPAD works by utilizing transmittance of infrared (940 nm) and red (650 nm) and to calculate a meter reading value that corresponds to leaf chlorophyll content (Uddling et al. 2007).

$$\boldsymbol{NDVI = \frac{NIR - Red}{NIR + Red}}$$

**Eq 3.1** NDVI equation

In this study, NDVI data was calculated utilizing NIR (800-880 nm) and red (658-678nm) bands (Equation 3.1), while NDRE was calculated utilizing NIR (800-880 nm) and Red Edge bands (707-727nm) (Equation 3.2).

$$\boldsymbol{NDRE = \frac{NIR - RE}{NIR + RE}}$$

**Eq 3.2** NDRE equation

Therefore, while calculations are based off of similar transmittance wavelengths, these readings have potential to show varying indicators for plant health. It is possible that changes in leaf orientation could be the reason why SPAD readings were not often correlated with NDVI and NDRE. This is because SPAD readings are collected on the ground by clipping individual leaves, and therefore, leaf orientation is not a factor. NDVI and NDRE were significantly correlated $p \leq 0.01$ at each individual sampling period, for both seasons, and overall (Tables 3.2 and 3.3), yet SPAD had varying correlations to indices. SPAD readings were also rarely significantly correlated with leaf N% with the exception of the May-19 sampling time, and when considering all data collected overall (Table 3.2). In this study, SPAD readings are only representative of five sampled leaves while NDVI and NDRE values are representative of the entire canopy which also introduced variation to correlation results between remotely sensed data and SPAD data.

Like all plants, carambola need a diverse assortment of nutrients to thrive. In most cases, plants require macronutrients, like N, in large quantities (Lipson and Näsholm, 2001). However, lack of micronutrients can be a significantly limiting factor and result in leaf chlorosis and senescence (Schaffer et al. 2006). Soil micronutrient availability is influenced by many factors, and in this study soil pH may have played an important role. Carambola trees were planted in calcareous soils with pH ranging from 7.60 - 8.08 throughout the study (slightly to moderately alkaline). Calcareous soils that are alkaline in nature often exhibit micronutrient deficiency, a problematic limiting factor for plant growth (Najafi-Ghiri et al. 2013). Carambola trees are sensitive to micronutrient deficiency, particularly iron (Fe), zinc (Zn), and manganese (Mn) (Crane, 2001). Thus, it is recommended to South Florida growers that these micronutrients be supplemented in the form of foliar spray application to carambola trees 4 - 8 times per year based on visual symptoms (Crane, 2001). Micronutrient deficiency in carambola is visually apparent through interveinal chlorosis, a symptom that has shown to be detectable in carambola through SPAD readings (Crane et al. 2007). In this study, carambola trees did not receive micronutrient spray or any method of application throughout the entire 1.5-year period. It is highly possible that carambola may have been impacted by micronutrient deficiencies at some point throughout the study. Because micronutrient deficiencies induce chlorosis in leaves, it is probable that SPAD, NDVI, and NDRE readings were influenced by this phenomenon and are potential indicators for this type of nutrient stress. This could be the cause of conflicting results between optical sensor readings and leaf N%, as N is not the only factor that inspires leaves to become chlorotic in carambola.

When reexamining the data for season 2 there are significant differences between treatments for SPAD and NDRE readings (Table 3.4), with no significant differences for season 1. On average for season 2, trees treated with SH showed the highest SPAD reading of 49.69 ($p$ <0 .05) which is 14.5% higher than the lowest reading average readings from the F treated trees (42.45, $p < 0.05$). Overall, a similar trend can be seen with season 2 NDRE data in which SH trees resulted in the highest readings treatment (0.4362) and the F treatment the lowest (0.4038, $p < 0.05$, Table 3.4). This may be an indication that trees treated with SH were less deficient in micronutrients than other treatments.

Sensor reading results were opposite of leaf tissue N% and C/N ratios in which no significant differences were apparent in season 2, and prominent differences apparent for season 1 (Table 3.4). These sensor results may have been indicative of plant stress or nutrient deficiencies other than plant available N. If this is the case, this is a limitation for application of optical sensors to pinpoint specific nutrient deficiencies for carambola, as a variety of plant stress factors can be linked to chlorosis and, in turn, a loss of chlorophyll content in leaves (Carter and Knapp, 2001). Therefore, these readings are better suited to determine overall tree stress rather than being compared to actual specific leaf nutrient values. Although, it is possible that with further experimentation, specific mineral deficiencies can be identified through targeted wavelengths to identify precise pigment distribution within each individual tree (Rustioni et al. 2018). To truly assess the accuracy of vegetation indices, they must be compared to plant-truth data collected in-situ, including biomass, LAI, actual chlorophyll content, and leaf water potential (Gago et al. 2015). Therefore, it is probable that spectral reflectance can be utilized as a tool in this regard with further analysis of carambola leaf nutrients, identification of suitable spectral signatures, and other plant-truth data indicators.

When considering NDVI, there was only one sampling time in which differences were seen between treatments within this study. As previously mentioned, although NDVI has been proven as a successful vegetation index, it can be easily saturated or lose sensitivity when crops reach mature growth stages with high canopy cover conditions (Gnyp et al. 2014). The data reflects this in both average NDVI values grouped by season (NS throughout season 1 or 2, Table 3.4), and at individual sampling times (Table 3.5). Conversely, there were multiple sampling times in which NDRE values detected treatment differences. NDRE was also correlated to actual leaf tissue N% when data was grouped by season (Table 3.2). As such, NDRE is a more reliable and useful index for this study to identify plant stress/beneficial reactions at varying sampling times. If major stress occurred throughout the study, it should be apparent through NDRE readings taken at the end of each CC growing season and through fruit yield.

There were three sampling times in which NDRE average values showed significant differences between treatments. At the first CC termination time (Aug-18), average NDRE was highest in trees treated with SH (0.4067, $p < 0.05$), and lowest for the F treatment (0.3695, $p < 0.05$). Which as explained prior, may have been an indicator of highly efficient BNF in trees treated with SH, and also a possible benefit of shading throughout the CC growing period. At the Sept-19 sampling period (1 month after 2nd CC termination), SH and SHM treatments were highest in value (0.4572 and 0.4539, respectively $p < 0.05$), with the VBM treated trees showing the lowest average reading (0.4120, $p < 0.05$). Trees treated with SH and SHM again, may have been reflecting these same benefits as the first termination time (Aug-18). At the last sampling time of the experiment (Dec-19), NDRE values were highest for trees treated with SH (0.4313, $p < 0.05$), with second highest average readings observed for the FM treatment (0.4247, $p < 0.05$) and the lowest average reading was recorded from trees treated with VBM (0.3727, $p < 0.05$) (Table 3.5). From these results, it can be inferred that VBM treated trees were the most stressed by the conclusion of the experiment and SH trees the least stressed on the basis of NDRE results. Various factors may have played a role here. Velvet bean is a vigorous and aggressive vining annual legume (Zasada et al. 2006; Buckles, 1995) that can easily overgrow and use trees as a trellis. Throughout the CC growing period, VB that climbed sample trees was clipped every two weeks, however, vining overgrowth may have been an additional source of stress during the carambola flowering and fruiting period for VB treated trees. Trees treated with VB may have exhibited competition stress throughout the CC growing season including root restriction, drought, and physical coverage/strangling of trees by vining VB vegetation. Trees treated with SH had the opposite result, and with accordance to NDRE data, were seemingly the most robust by the last sampling period of the study.

Carambola are highly sensitive to wind and drought stress. Wind and drought stress reactions are similar and manifest visually through leaf abscission, stem/limb dieback, reduced yield, and limb breakage (Paull and Duarte, 2011). Trees planted with VB may have incurred greater wind or drought stress than SH treated trees throughout the CC growing period. Because the area was trenched before saplings were planted, carambola roots had opportunity to grow deeper with greater potential for water scavenging and hydraulic redistribution (Yu and D'Odorico, 2014). Drought stress should not have been hugely impactful as there was fairly consistent rainfall throughout the summer months (Figure 3.1) and each tree was equally irrigated via sprinkler system for 30 minutes per day. However, with shared root space, competition for water resources could have been a possibility for trees treated with VB. Sunn hemp and VB have opposite root structures as SH develops tap roots and VB develops spreading surface roots (Calonego et al. 2017; Buckles, 1995). Velvet beans spreading root growth may have hindered water uptake, causing impactful differences in carambola tree health. Alternatively, cover crops with tap roots have been shown to lessen the impact of soil compaction in NT systems by creating channels after decomposition (Williams and Weil, 2004), another possible benefit SH may have provided to carambola trees.

Because of wind sensitivity, it is recommended that windbreaks be utilized around carambola plantings. At the start of the experiment, treated trees were small at ~3 years in age. Cover crops were planted in a dense and uniform fashion around the carambola trees. Since SH has a tall, vertical growth habit, it is likely that trees treated with SH benefited as they were partially shielded from winds during the summer CC growing period. As summer months are prominent for fruit growth, this may have been crucial for fruit set and development. Carambola trees are also moderately adapted to shade up to ~30% and can efficiently acclimate to varying light intensities (Marler et al. 1994). Trees treated with SH may have benefits from partial shading and wind protection throughout the CC growing period, which may have been reflected through NDRE data.

Although pinpointing specific nutrient or other stressors may not be possible via NDVI and NDRE readings alone, these indices showed promising results in utilization to predict health status in the form of carambola fruit yield. The correlation results reveal that both NDVI and NDRE were positively correlated to fruit yield for season 1 and season 2 ($p \leq 0.01$, Table 3.2). Overall, when considering all values collected at every sampling time, NDVI ($p \leq 0.05$) and NDRE ($p \leq 0.01$) were again positively correlated (Table 3.3). This has great implications for the use of multispectral sensing as a tool to measure fruit yield success, specifically for carambola. Yield estimation can prove a tedious task that involves counting and weighing of marketable fruits. Especially for carambola, a tree that continuously flowers and bears large quantities of fruit year-round. This is explicitly true for large scale commercial production where counting methods are often inefficient, expensive, and potentially inaccurate, especially when high variability is a factor (Bargoti and Underwood, 2017).

Accurate crop yield modeling has become a growing necessity for orchard managers, as yield estimations are crucial in stakeholder decision making processes (Apolo-Apolo et al. 2020). With these correlation results (Tables 3.2 and 3.3), this opens the door for crop modeling with remotely sensed data to better understand carambola tree vigor through the utilization of 3D point clouds to estimate plant biomass and tree structure characterization (height, volume, and crown area) (Sarron et al. 2018). Sarron et al.

(2018) found that quickly and accurately assessing fruit production for specific mango cultivars utilizing tree structural parameters is possible. Although, this would entail extensive calibration parameters and assessment of various cultivars, which would be feasible and useful if Miami-Dade County sees an increase in carambola production. These calibrations can be executed utilizing tree structure characterization and flower density combined with tree vigor indices (Sarron et al. 2018; Aggelopoulou et al. 2011; Modica et al. 2020).  In this study, these plant vigor variables are indicators that can be used to distinguish carambola yield status between various fertilization treatments. Vigor indicators have been used in past studies to estimate yield in various types of field crops (Li et al. 2014; Magney et al. 2015; Hassan et al. 2019). But for fruit crops, NDVI/NDRE readings are just one aspect of modeling. Yield models based on tree species can incorporate phenology, aboveground biomass, actual fruit yield, carbon/dry matter ratio, and dry/wet biomass ratios, along with canopy structure indicators, all of which must be compared to in situ reference data for accuracy (Maselli et al. 2012). Maselli et al. (2012) found that utilizing a C-fix model that incorporates NDVI readings, that it is possible to provide accurate simulations for fruit biomass in Mediterranean olive groves. C-Fix is a parametric point model that simulates carbon exchange via relationship between Fraction of Absorbed Photosynthetically Active Radiation (fAPAR) and NDVI (Veroustraete et al. 2002); a potentially useful approach to be considered for further yield estimations for fruit trees in South Florida. The remotely sensed data recorded throughout this experiment has prospects for future modeling uses for the tropical fruit industry if desired by the farming community.

*3.5. 5 Fruit yield*

In regard to fruit yield data (Table 3.4), season 1 had highest average yield results for VBM and SH treatments (8.81 kg and 9.51 kg, respectively), while F and VB treatments had the lowest values (4.40 kg and 5.56 kg, respectively, ($p < 0.05$)). For season 2, FM had the highest fruit average yield (14.70 kg, $p < 0.05$), followed by SH (13.91 kg, $p < 0.05$), and both VB and VBM resulted in the lowest fruit yield (5.16 kg and 8.16 kg, respectively, $p < 0.05$). Cover crop establishment was generally higher for both SH and VB treatments in season 1 than in season 2 considering dry biomass production (Table 3.1). The SH CC treatment in season 1 and season 2 provided the greatest amount of CC N ($p > 0$ .05), which may explain success in fruit production for trees treated with SH over both seasons because these trees may had greater potential N uptake resulting from CC additions and decomposition within the soil.

As previously discussed, carambola benefit from wind protection. Sunn hemp acting as a wind barrier may have resulted in higher fruit field than VB treatments during season 2. Higher yield was only observed in the SH treatment and not the SHM, which may be explained by lesser dry matter produced by SHM than SH in season 2 (Table 3.1). Additionally, carambola flowering can be induced by stress including drought stress or root restriction (Paull and Duarte, 2011). Therefore, it is possible that throughout the study, cover crop growth during spring/summer flowering periods may have caused stress/competition for trees treated with CC, resulting in higher flowering rates and therefore greater fruit production. It is also likely that tree age may have played a role in fruit production. Trees are considered past the juvenile age at 5 years old and increase in fruit production each year until fully matured past age 7. In this study, trees were three years during season 1 and four years old during season 2, which is impactful for fruit yield and explains the increase in average yield from season 1 to 2 (Table 3.4)

There is a universal lack of literature conducted on soil-plant macronutrient status and their relation to carambola root uptake, flowering, and fruit production. However, when considering N use and uptake in fruit trees across the board, there is a good scientific understanding of N utilization. Nitrogen in trees is translocated to various organs through the xylem and occurs through three methods via root uptake from soil, phloem-xylem recycling, and remobilization of internally stored N reserves (Dambrine et al. 1995). These processes, specifically remobilization and root uptake of N, depend on a variety of factors including tree age. When trees are growing rapidly (juvenile stages), like in this study, N demand for the shoots is high. This need for N in the shoots prioritizes uptake by roots for translocation to shoots with low translocation back to roots for root development (Grassi et al. 2003). Conversely, when shoots are growing less rapidly, there is a low demand for shoot N, which reduces root uptake (Grassi et al. 2003). Nitrogen is not always utilized right away in woody plants. Because N is mobile, trees can build up an N reserve to use when necessary for vegetative flush and bud break during times where N root uptake is not ideal (Menino et al. 2007).

Carambola are considered to be a fleshy fruit, and generally, in the beginning stages of fleshy fruit development, N concentration is higher. From there, throughout further stages of development, N concentration decreases till maturity due to dilution effect (fruit becoming larger) and lower uptake rates (Brunetto et al. 2015). Though, this phenomenon is highly dependent on species (including grafting combination of cultivar and rootstock) and environmental conditions (Carranca et al. 2018). Nitrogen availability for trees with developing fruit is most crucial during the beginning stages of fruit development. In this study, peak flowering time in May resulted in harvest August/October and then again in September with harvest in December/January (Núñez-Elisea and Crane, 1998, Figure 3.3). Therefore, the most crucial periods for N distribution to fruits is likely from May-June and September-October. Based on Table 3.5, it is probable that overall SPAD readings are indicative of these nutrient changes resulting from fruit production as they line up with established phenological patterns.

Carambola is an evergreen tree, and while little information exists on N mobilization for carambola specifically, it can be compared to other evergreen fruit species, like orange trees. Roccuzzo et al. (2017) found that developing shoots, followed by fruits, are the greatest N sinks in orange trees. Therefore, fruit development potentially has a large impact on N reserves in the leaves. In the current study, fruit yield was correlated with carambola leaf N% only for season 1, while season 2 and overall data showed no N% correlation (Table 3.2). It is possible that available N was not the only factor playing a role in carambola fruit production. Thus, fruit yield may be a better parameter for tree health as opposed to leaf N rates when considering temporal fertilization success via green manure and other organic fertilizers. The fruit yield data indicates that the SH treatment consistently provided high fruit yield compared to other treatments. The exception can be seen in season 2, where FM had the highest yield ($p < 0.05$, Table 3.4). Because these trees were not competing with cover crops and receiving a constant supply of stable fertilization, it is possible that this was reflected in the fruit yield data for season 2. Interestingly, yield data for trees treated with VBM is conflicting from season 1 to 2. (Table 3.4) For season 1, VBM had the highest fruit yield numerically and statistically was in the highest yield category, while for season 2, VBM was in the lowest category for yield (Table 3.4). When comparing to other parameters, numerically, VBM had the highest leaf N% and lowest leaf C/N ratio (NS). It seems that trees treated with VBM were allocating more resources to vegetative growth rather than fruit production throughout the season 2 sampling period. When considering overall fruit yield, F, SHM, and VB treatments were least successful in enhancing production, while SH and FM treatments were most successful.

**3.6 Conclusions**

This experiment was conducted for the purpose of establishing sustainable, effective, and executable fertilization protocols for tropical fruit. Rarely have cover crops been studied for their effectiveness in enhancing tree health and fruit production in orchard settings, especially when applying this strategy to tropical fruit crops and tropical leguminous cover crops. This project is particularly unique as it targets an understudied and undervalued minor crop that has great potential to be lucrative for farmers in MDC and South Florida as a whole. Not only does this project address a unique crop, study area, and sustainable strategy, it incorporates a remote sensing aspect that has never been tested before for its effectiveness in monitoring carambola trees.

Overall, with our implemented cover crop coverage and no-till strategy, the data presented suggests that sunn hemp is a good candidate for intercropping with juvenile carambola trees for the purpose of enhancing tree vigor and fruit production. Sunn hemp produced large amounts of dry biomass adding large quantities of C and N for soil enhancement and nutrient availability for carambola trees. Sunn hemp is a good candidate for intercropping as it can act as a windbreak and provide partial shade to young, establishing trees that require this type of management strategy. These benefits were reflected in carambola leaf tissue N%, C/N ratios, and fruit yield throughout the study. This project was conducted over a short period of time with only two cover crop growing seasons. With consistent yearly green manure additions, it is probable that tree health and resilience would be even greater as organic matter decomposition and other soil processes can take years to become apparent through crop success.

Although sunn hemp seems to be an effective cover crop, there is much room for further investigation to confirm its effectiveness for fertilization and its potential negative effects regarding resource competition. Better understanding of carambola macro/micro-nutrient dynamics are pertinent for gaining a clearer understanding of cover crop interactions and carambola success. Moreover, to gain a greater understanding of tree vigor, fruit yield, and relationship to optical sensor readings, this project would benefit from additional analysis of spectral signaling and capacity for modeling. Developing models for this study could be a successful way to estimate fruit yield for farmers in an accurate and non-destructive fashion. This opens the door for further investigation of tropical leguminous green manure species and their compatibility with tropical fruit trees to provide sustainable supplementation to enhance grove health and fruit production.

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# CHAPTER 4: ADOPTION AND PERCEPTION OF COVER CROP IMPLEMENTATION FOR SOUTH FLORIDA TROPICAL FRUIT GROWERS

## 4.1 Abstract

Cover cropping is a sustainable strategy for increasing soil nutrients, organic matter, and improving overall soil health. This practice is heavily promoted for annual vegetable growers, however, there is less widespread acknowledgment for cover crops as a management strategy in perennial settings. Research is limited in this field, specifically when considering cover cropping for tropical fruit groves. This study analyzes data from surveys distributed to Miami-Dade County tropical fruit producers to quantify their perceptions on incorporating cover crops in their fruit production systems. Two surveys were formulated and distributed: the first was developed to understand farmer familiarity and interest, and the second survey presented results of the field study conducted in the previous chapters to quantify change in perception and likelihood of cover crop adoption. Logistic regression analysis of cover crop adoption revealed that having previous experience with cover crops, valuing cover crop importance, perceiving the practice as economically viable, and farm acreage were all positive predictors. Negative predictors of cover crop adoption included familiarity with cover crop benefits and farmer education level. When questioned about specific species, sunn hemp and velvet bean, farmers expressed greater interest in incorporating sunn hemp into their production systems. Qualitative data revealed that farmers were highly interested in learning more about cover crops and attending demonstrative workshops to discern if implementing cover crops would be right for their operation. Overall, the findings suggest that Miami-Dade County

fruit producers are interested in incorporating cover cropping practices within their production systems.

### 4.2 Introduction

As environmental and public health issues associated with agricultural production become apparent, Americans are more conscious of where food comes from and how it is produced. As a result, organic agricultural operations have increased in popularity throughout the United States. Organically produced products are becoming gradually mainstream as greater than 50% of organic food products are being marketed and sold by conventional grocery store chains and as such, the United States is responsible for nearly 72% of certified organic operations worldwide (Haumann, 2016). As the paradigm shifts, it becomes exponentially more important for farmers to adopt environmentally sustainable practices that can be applied to organic food production.

Within the agricultural sciences community, cover crops are well known to effectively reduce nutrient runoff and erosion while improving soil health when incorporated as green manure (Hartwig et al. 2002). This practice has been shown to have short- and long-term benefits for continued arable land preservation, and as such, the United States Department of Agriculture, National Resource Conservation Service (USDA, NRCS) has consistently supported the implementation of cover crops nationwide. The NRCS updates guidelines and fact sheets annually to assist farmers in understanding appropriate cover crop species for their farms, sample planting schemes, and planting/termination timing (USDA, 2019). In fact, the USDA offers monetary incentives for farmers who utilize cover cropping, among a variety of other sustainable practices, through the Environmental Quality Incentives Program (EQIP) and

Conservation Stewardship Program (CSP), voluntary conservation programs that provide technical and financial assistance to target natural resource issues and to improve ecosystem services. The EQIP was established under the 1996 Farm Bill and has since been growing to further the NRCS' goal of supporting productive farmland with a focus on maintaining and restoring environmental health (EQIP Programmatic Environmental Assessment, 2009). Similarly, CSP was established under the 2008 Farm Bill to provide farmers with financial and technical assistance for promoting conservation practices including cover crops (CSP Programmatic Environmental Assessment, 2019).

While effort is being put forth by federal agencies to reward farmers for implementing sustainable practices, the US 2017 Census of Agriculture reveals that cover crops were planted on only 4% of US cropland. This is a slight increase from the 2012 estimation of 3%, however, there is opportunity for a large quantity of fallow land to be planted with ground cover during the off-season. In Florida specifically, cover crops were planted on 1.5% of total cropland in 2017, a slight increase of 0.1% from the 2012 statistic (1.4% total cropland). Cover cropping should be especially promoted in Florida where concerns are mounting regarding the impact of agriculture on aquatic natural resources and Everglades conservation. Within the last century, urban development and agricultural production have been the primary driver of degradation to Florida's natural resources (Aillery et al. 2001). In an effort to mitigate these impacts, a Comprehensive Everglades Restoration Plan has been enacted to restore flow and biological infrastructure to these preserved lands (Perry, 2004). With Everglades conservation and restoration at the forefront, action has been taken to explore solutions and best management practices (BPMs) for involved entities, with a specific focus on the agricultural industry. Thus, cover cropping has been identified as a BPM to minimize the movement of sediment and particulate matter from the Everglades Agricultural Area in Central Florida into the designated protected area in order to reduce environmental impact of increased nutrient loads (Daroub et al. 2011).

Although cover cropping is becoming a more widely known practice, there is a lack of peer reviewed cover crop adoption studies, specifically in niche commodity production communities. In a study conducted to target the Iowa corn industry Arbuckle Jr. and Roesch-McNally (2015) found that local farmers perceived cover crops as a beneficial practice to reduce nutrient loss and soil erosion while enhancing productivity. This belief in the positive attributes of cover cropping ultimately influenced adoption decisions by many farmers represented in that study. While the targeted community did see benefits to incorporating this practice, it was found that participating farmers perceived multiple risks including successful establishment/termination and negative yield impacts, ultimately hindering the probability of adoption (Arbuckle Jr. and Roesch-McNally, 2015). For large scale field crop producers, many note disincentives to growing cover crops which may include costs associated with management problems like losses from delayed planting, competition, or substitution (Snapp et al. 2005). Benefits of cover cropping are not always obvious in the short term, which can be a problem for implementation and as such, it is essential that land managers have access to clear information in order to make informed decisions (Snapp et al. 2005).

Adoption and diffusion are two common concepts that are used to estimate technological adoption over time. Adoption is the choice to begin using a new technology, while diffusion is the process by which technology is spread (Rogers, 2010).

The decision to adopt new agricultural technologies is heavily based upon various factors including farmer education, extension influence, cost of acquiring technology, profitability of incorporating technology, and education of the decision maker (Ugochukwu and Phillips, 2018). With this understanding, these factors can be applied to gain insight on farmer perception of cover cropping and its adoption.

This study is focused in Miami-Dade County (MDC), Florida, primarily in the Redland Agricultural Area (RAA) of South Miami. The RAA is unique because it is located in the subtropical climate of South Florida. This climate is conducive to growth and commercial production of tropical fruits, one of the few areas in the US where this is possible. The MDC agricultural area is also interesting because it consists of primarily small, family owned, production operations with 95% family owned and 73% of farm size within the range of 1-9 acres (Ag Census, 2017). Local fruit growers in the RAA are part of an active, tightknit community, that is interested in farmer education via extension resources and opportunity. As such, the MDC Agriculture Extension office holds monthly forums to address needs and concerns of growers, along with providing educational sessions and trainings. The local farmers of the RAA have bound together to create their own local group, the Tropical Fruit Growers of South Florida (TFGSF), organized in 1987, in order to *"form an organization to support the "minor" crop industry"* (TFGSF, 2020). This group is supported by the MDC local agriculture extension office and holds its public board meetings after each monthly forum. With openness and interest from the local community, informing producers of cover cropping technology via extension and public workshops is a potentially effective method to inspire adoption. However, smaller scale farmers may be apprehensive of trying new practices if they pose risk to profitability, especially to those who have already slim margins.

Cover crops can be beneficial for a variety of environmental services including erosion control, nutrient leaching, nitrogen fixation, and overall soil health improvement, and with careful species selection, can further enhance specific management goals (Fageria et al. 2007). While cover crops have been proven to provide benefits in vegetable production settings in South Florida (Wang et al. 2005; 2009; 2012; 2015), little is known about the effectiveness of tropical leguminous cover crops and their interactions with tropical tree crops. Implementation of legume species is an effective strategy to reduce synthetic fertilizer use (Kaye and Quemada, 2017). Reducing synthetic inputs is a primary goal of this study, which could result in impactful changes for South Florida agriculture in regard to sustainability and eco-stewardship. Moreover, we aim to understand the perceptions of local land managers regarding the applicability of applying cover crops to commercial tropical fruit production, and their willingness to adopt this practice. The objective of this research is to determine local MDC RAA fruit growers' willingness to adopt cover cropping practices supported by opinions of perceived feasibility, economic viability, and sustainability characteristics.

## 4.3 Materials and Methods

### *4.3.1 Conceptual framework*

Adoption is fundamentally the decision to utilize a technology or practice on a regular basis. Technological adoption is classically based on Rogers's "Diffusion of Innovations" theory. As such, Rogers (2010) describes five characteristics of innovation that apply to agricultural adoption technology: 1) *Relative advantage*, or to what degree the new technology is perceived to be beneficial over the existing practice, 2) *Compatibility*, or how a new technology coincides with needs and existing values of potential adopters, 3) *Complexity*, or the degree to which the practice or technology is difficult to use or understand, 4) *Trialability*, or the degree to which the technology can be attempted on a small scale, and 5) *Observability*, or how effective the results of the technology are found to be. In the case of this study, these characteristics are viewed in the perspective of sustainable technology adoption. Relative advantage is generally considered as financial gain by the business or adopter. While relative advantage is economical, in this study it can also encompass the benefits of environmental sustainability. Compatibility is considered to be how the presented cover cropping practice would be implementable within the farmer's existing production system. Cover cropping is essentially a simple practice; however, complexity arises when educating on ecological benefits and how they coincide with profitability in the long run. In this case, trialability is related to small-scale implementation of cover cropping in a production system. Lastly, observability is the visible outcome of cover cropping benefits which may not be as obvious like in conventional agricultural practices such as the application of synthetic chemicals. These five attributes cover a large scope of adoption factors; however, an individual's assessment and overall adoption of a new technology can be complicated as opinions are subjective and may change over time as a result of new information (Caswell et al. 2001). Therefore, to cover a wide scope of farmer perceptions, a conceptual framework was developed to incorporate additional aspects to most accurately grasp farmers willingness to adopt cover cropping practices in a tropical fruit production setting.

Fishbein and Ajzen (2011) expanded and developed upon adoption theory in the form of the Reasoned Action Approach. This approach was formulated to understand individual's adoption behavior based on their 'intent to adopt'. These intentions are influenced by 3 driving forces: 1) the potential adopter's attitude towards the behavior, 2) social norms (descriptive and subjective), and 3) perceived behavioral control. There are many influences that make up an individual's beliefs, and therefore, adoption decisions. This stems from a variety of sources including formal education, media, and personal experiences, while individual differences such as demographics and personality characteristics also play a large role (Fishbein and Ajzen, 2011). Generally, an individual develops either a positive or negative belief towards a behavior which is outwardly expressed through driving forces, the first one being 1) attitude (generally expressed as positive or negative). People also have the tendency to form beliefs resulting from their surrounding environment and the approval of their peers or loved ones making driving force 2) social norms, an important adoption factor. Lastly, environmental and personal factors can influence adoption by facilitating or inhibiting adoption and is recognized as 3) perceived behavioral control. With all these factors in mind, an additional characteristic of risk was incorporated into the study. The risk attribute was introduced by Cary et al. (2001) when considering adoption of sustainable farming practices. This concept is defined as uncertainty which ultimately affects an individual's welfare (Bodie and Merton, 1998). Risk is already a major influence within the agricultural industry. There are many uncontrollable factors such as pest infestation, unpredictable weather, disease, etc., that may impact financial returns. As such, farmers are inherently risk averse and may be difficult to convince with regards to new ideas or technologies

(Harwood et al. 1999). In this study, risk is considered uncertainty of introduced practice effectiveness and economic impact of implementing the practice.

Two survey questionnaires were designed to incorporate the aforementioned five characteristics, two driving forces (attitude and behavioral control), and the concept of risk. A conceptual model was reconstructed from Reimer et al. (2012) and Arbuckle Jr. & Roesch-McNally (2015) to better relate and predict behavior of potential adopters to this study (Figure 4.1). The initial questionnaire was developed with the intention to understand if Redland farmers are familiar with cover cropping practices, and if so, how willing or interested they are in incorporating these practices into their tropical fruit production systems. The follow-up questionnaire presented results of the field study presented in chapters two and three in a clear and comprehensible manner. Respondents were then asked a series of questions regarding their perceptions of cover cropping practices and how it pertains to them.

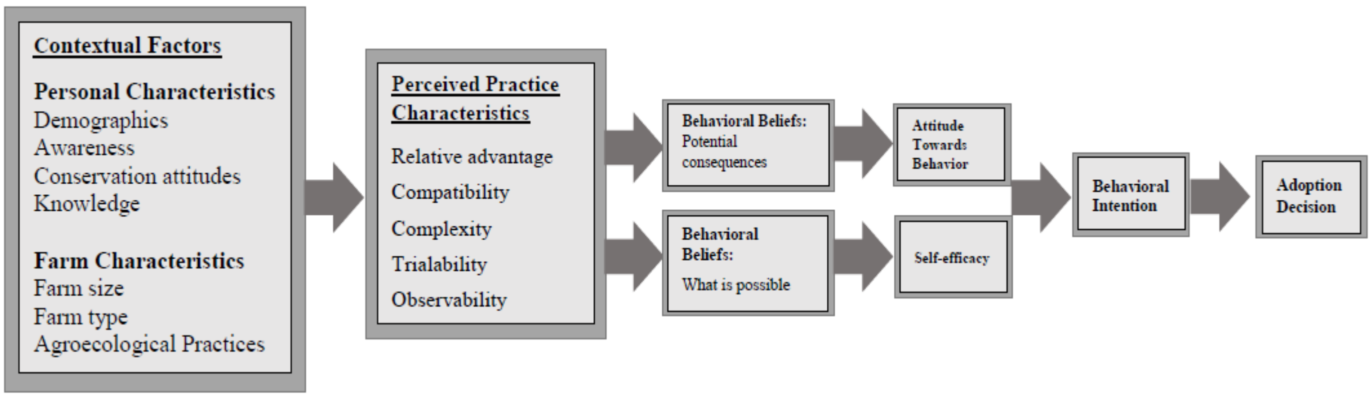


**Figure 4.1** A conceptual framework modified from Reimer et al. (2012) and Arbuckle Jr. & Roesch-McNally (2015) utilized to formulate two surveys to understand willingness to adopt cover cropping practices of tropical fruit growers in MDC.

*4.3.2 Studied practices*

This study focused on the willingness of local MDC growers to incorporate cover crops into their tropical fruit production management strategies. Cover cropping is a relatively uncommon practice for orchard managers, even though the use of green manure has great potential for productivity and sustainability. Consequently, a 1.5-year field trial was conducted to test the effectiveness of two species of tropical leguminous cover crops commonly known as sunn hemp (*Crotolaria juncea* L.) and velvet bean (*Mucuna pruriens* L. DC.). The survey questionnaires inquired about general use of cover cropping practices and targeted use of sunn hemp and velvet bean species.

*4.3.3 Survey design, data, and collection*

Quantitative and qualitative data for this study was compiled through the Tropical Fruit Growers of South Florida Cover Crop Implementation online surveys (part 1 and 2) constructed using the Qualtrics platform. Qualitative data was gathered in the first and second survey via short answer questions that required a typed response. Quantitative data was acquired through a variety of question styles including yes or no, scale bar (1-10), select all that apply, and Likert scale. The initial questionnaire was distributed in the summer of 2018 with the intention of evaluating cover cropping experience and interest of local MDC tropical fruit growers. The follow-up survey was distributed in the fall of 2020. The second survey described the results of the field study presented in Chapters two and three, then, inquired about farmers perceptions of cover cropping after receiving this information. These surveys were distributed through three email listservs to target MDC tropical fruit producers: 1) the University of Florida Institute of Food and Agricultural Sciences (UF-IFAS) MDC extension office via the Commercial Tropical

Fruit Extension Agent 2) the UF-IFAS Tropical Research and Education Center via the Tropical Fruit Specialist 3) the Tropical Fruit Growers of South Florida organization. In total, survey 1 and survey 2 were distributed to 490 recipients. We received 30 complete responses for survey 1 and 20 complete responses for survey 2, totaling 50 complete responses ($n$ = 50, 10% response rate). Of the 50 responses, 41 were one-time respondents and 9 were repeat respondents.

*4.3.4 Descriptive statistics analysis*

Data analysis was conducted through multiple methods. First, demographic information provided by participants was compared to the 2017 US Census of Agriculture results for MDC to better understand participant perceptions and bias. From there, responses from similar questions derived from both surveys were compared to gain insight on overall farmer perceptions. Likert scale responses from the second survey were analyzed utilizing response percentages and Cronbach's α to ensure reliability. The surveyed variables were grouped into three measuring scales adapted from Arbuckle Jr. and Roesch-McNally (2015) which assessed the "perceived benefits" and "perceived risks" of incorporating cover crops, along with "potential facilitators" that make cover crop implementation more viable. These three scales incorporated the characteristics of innovation along with behavioral beliefs and attitudes. The perceived benefits were formulated to encompass relative advantage, compatibility, and a behavioral component (belief/attitude). The perceived risks incorporated questions that measured compatibility, complexity, and trialability. Potential facilitator questions were designed to measure self-efficacy. To better quantify Likert scale responses, values were assigned to each answer i.e. strongly disagree = 1, disagree = 2, uncertain =3, agree = 4, and strongly agree = 5.

From there, mean and standard deviation was calculated for each individual question and every question group.

To analyze qualitative data from both surveys, expressed characteristics were summarized from both surveys and grouped them into two categories: 1) motivations that positively influence adoption and 2) limitations that negatively influence adoption. Next, survey responses were categorized employing the 5 characteristics of innovation (relative advantage, compatibility, observability, trialability, complexity) plus the risk aspect, relative disadvantage, and grouped into positive response and negative response (adapted from Reimer et al. 2012). Themes were examined from survey response data and quoted responses were incorporated from qualitative data for a comprehensive understanding of the answers.

*4.3.5 Assessing Miami-Dade County fruit producers' likelihood to cover crop*

Data utilized for binary logistic regression was collected from both surveys. Survey 1 and 2 had a series of overlapping questions that were utilized as variables for a logistic model. Participants who responded to both surveys were only counted once in the logistic model. Therefore, the nine repeat responses for survey two were excluded resulting in $n = 41$ for responses analyzed with in the logistical model. At the beginning of each survey, a short description of cover crops was presented, from there, farmers were asked to respond to a series of questions regarding cover crops.

The dependent variable in the binary model is a measure based on the respondents' likelihood to cover crop. This was determined by two questions: 1) *"Have you used cover cropping practices in your fruit grove?"* (yes or no) and 2) *"If you were not already implementing cover cropping practices, how likely would you be to do so?"*

(indicate level of likelihood, 1-10 scale). Likelihood to cover crop = 1 (for the adopter) if respondents replied yes to question 1 or > 5 for question 2. Likelihood to cover crop = 0 (for the non-adopter) if respondents replied no to question 1 and ≤ 5 for question 2.

The independent variables were derived from a set of various questions. The first question *"Have you used sunn hemp or velvet bean as a cover crop?"* (Yes = 1 and No = 0). The second question utilized in the model was *"Prior to this survey, were you familiar with the potential benefits cover crops can provide when implemented into fruit groves/orchards?"* (Yes = 1 and No = 0). The third aspect of the model was calculated by responses to a scale question *"On a scale of 1-10 how important are these aspects to you in regard to cover cropping: weed suppression, pest suppression, soil building, pollinator attraction, nutrient leaching prevention, soil erosion control, and windbreak"*. Scores were summed to create an "importance score" up to 70 points (summated rating scale). Economic viability was also considered as such, *"Do you feel as though implementing cover cropping into your farming regimen would be economically viable?"* (Yes = 1 and No = 0). Respondents provided their education level by category: less than high school education = 0, High school diploma/GED = 1, some college = 2, college degree = 3, and professional/graduate degree = 4. Lastly, respondents were asked to provide information on farm size (acres) as a predictor variable within the regression model.

To conduct analysis on cover crop adoption likelihood, a binary logistic regression model was utilized to understand the relationship between adoption probability and the factors that determine it. This model is founded on maximizing utility function, in other words, it was assumed that the participant (farmer/decision-maker) is an individual with the goal of profit maximization in combination with choosing optimal resource allocation (De Graaff, 1993). As such, the decision-maker is predicted to utilize practices that offer the largest net gain or expected utility, which can be formulated into a probability function where the decision to adopt cover cropping (A) by an individual farmer (*i*) ($A_i$ = 1) or not ($A_i$ =0). The following equations are modified from Zbinden and Lee (2005) and Miassi and Dossa (2018):

Adoption: $A_i = 1$ if $U_i^0 \leq U_i^1$

**Eq. 4.1** Probability of adoption

Non-adoption: $A_i = 0$ if $U_i^0 > U_i^1$

**Eq. 4.2** Probability of non-adoption

This function assumes that the farmer would adopt cover cropping practices if the expected utility gained from adoption ($U_i^1$) exceeds that of non-adoption ($U_i^0$).

The utility of the $i^{th}$ farmer is described below:

$$U_i = B_0 + B_1X_{i1} + B_2X_{i2} + B_3X_{i3} + B_4X_{i4} + B_5X_{i5} + B_6X_{i6}$$

**Eq. 4.3** Adoption utility equation

In which $X_{i1}$, $X_{i2}$,..., $X_{i6}$ are 6 independent variables representing farmer perceptions and demographic information, and $B_0$, $B_1$,...,$B_6$ are the model parameters. With the application of this above utility function, the probability that a farmer may adopt cover cropping as a practice $A_i$ (YES), can be modeled with the logistic equation below:

$$Prob(Ai = 1) = \mathrm{e}^{Ui} / 1 + \mathrm{e}^{Ui}$$

**Eq 4.4** Adoption logistic equation

With this, the adoption is a binary variable with the value 1 assigned if the participant is likely to adopt and value 0 if the participant is not likely to adopt. It is known that $P(A_i)$ is the probability that the farmer adopts cover cropping, therefore, the probability that the same farmer does not adopt cover cropping $1 - P(A_i)$. Using these two probabilities, we can construct the following odds ratio:

$$\frac{P(A_i)}{1 - P(A_i)} = \frac{e^{U_i}/(1 + e^{U_i})}{1 - [e^{U_i}/(1 + e^{U_i})]} = e^{U_i}$$

**Eq. 4.5** Odds ratio of probability of adoption to probability of non-adoption

Taking the natural log of both sides of the above equation results in the following estimating equation:

$$ln[\, P(A_i)/(1 - P(A_i))] = U_i$$

$$= B_0 + B_0 + B_1X_{i1} + B_2X_{i2} + B_3X_{i3} + B_4X_{i4} + B_5X_{i5} + B_6X_{i6}$$

**Eq. 4.6** Natural log of the adoption equation

Additionally, Table 4.1 displays the independent variables utilized in the model and their expected model outcomes.

**Table 4.1** Independent variables for assessing farmers' willingness to implement cover cropping practices.

| Independent variable | Definition | Expected effect on adoption |
|---|---|---|
| Utilization of cover crops | Have you used sunn hemp or velvet bean (yes=1) | Positive |
| Familiar with benefits | Educated on the benefits that cover crops could provide to fruit groves (yes =1) | Positive |
| Cover crop importance score | A composite score based on how important benefits of cover crops are to the respondent | Positive |
| Economic viability | 1 = if the respondent finds the practice economically viable<br>0= if the respondent does not find the practice economically viable | Positive |
| Farmer education level | 0= less than high school education<br>1= high school diploma/GED<br>2= some college<br>3= college degree<br>4= professional/graduate degree | Positive |
| Farm size (acres) | Land area of the participants farming operation | Positive |

Table 4.1 indicates that it is expected that all independent variables will have a positive effect on farmer likelihood to cover crop.

*4.3.6 Statistical analysis*

All formal statistics were conducted using SPSS statistical software (IBM Corp. (1968). IBM SPSS Statistics for Windows (Version 25.0). Armonk, NY: IBM Corp.). Cronbach's α was considered reliable at $\alpha \geq 0.70$. Binary logistic regression results were considered significant when $p \leq 0.10$. We recognize that this study utilized a small sample of farmers. Readers may view the work as an exploratory study which was undertaken to provide quick, yet information useful for designing farmers' educational program. Results are encouraging and merit further refinement.

## 4.4 Results and Discussion

### *4.4.1 Farmer demographics*

Demographic data was collected from all survey respondents to compare to the 2017 Census of Agriculture statistics for MDC. The 2017 census data is representative of all types of producers including vegetable, grain, and fruit crops, along with nursery production of ornamentals and livestock/poultry. Of the $837,734,000.00 market product value, $43,573,000.00 was attributed to the "fruits, tree nuts, berries category" (~5%). Therefore, it can be assumed that the targeted respondents of our questionnaire make up a small percentage of the total MDC agricultural community. Although fruit producers in MDC are a relatively small community, the surveyed respondents are somewhat representative of the overall census results (Table 4.2).

**Table 4.2** Farm size and producer characteristics from survey sample size compared to the 2017 US Agriculture Census.

| | MDC Ag Census (2017) | Survey Sample 1 (2018) | Survey Sample 2 (2020) | Overall Response |
|---|---|---|---|---|
| **Farm Size (acres)** | | | | |
| 1-9 | 73% | 59% | 55% | 61% |
| 10-49 | 21% | 26% | 30% | 27% |
| 50-179 | 4% | 6% | 5% | 5% |
| 180-499 | 1% | 3% | 0% | 2% |
| 500-999 | 1% | 0% | 0% | 0% |
| 1000+ | <1% | 6% | 10% | 5% |
| **Producer sex** | | | | |
| Male | 62% | 84% | 75% | 80% |
| Female | 38% | 16% | 25% | 20% |
| **Producer age** | | | | |
| <35 | 7% | 0% | 6% | 2% |
| 35-64 | 61% | 31% | 25% | 30% |
| 65+ | 37% | 69% | 69% | 68% |
| **Producer education** | | | | |
| < High School | N/A | 0% | 0% | 0% |
| High School/GRE | N/A | 6% | 0% | 5% |
| Some College | N/A | 23% | 10% | 20% |
| College Degree | N/A | 26% | 35% | 29% |
| Graduate Degree | N/A | 45% | 55% | 46% |

Based on Table 4.2 results, farm size of the survey respondents was similar to the MDC agricultural census. Farmers in MDC typically have smaller sized operations and as such, 63% of MDC growers operate on farms 1-9 acres in size, similarly, 61% of survey respondents claimed farms of this size. When considering the other land size categories, all were similar with the exception of 1000+ acres, in which 5% of the survey respondents claimed large commercial production, while MDC overall showed less than 1% in this category. Therefore, this survey covers an interesting and rare demographic for MDC given the response from large commercial producers. When comparing producer sex, the survey responses are biased towards male producers (80%) when compared to overall MDC farmers (62%). The farmers who responded to the surveys were also skewed towards a higher age range when compared with the census with 68% being 65+ compared to 37% for all MDC producers. This shows that generally, fruit growers are older than the typical farming population reflected by the census. The majority of MDC growers (61%) are within the 35 - 64 age range, while the survey sample only reflected 30% of respondents in the midrange for age. Besides farm size, sex, and age, this survey inquired about producer education level. It was found that 46% of the respondents were highly educated with having completed some a graduate/professional degree, 29% received a college degree, and 20% participated in some college courses, for a total of 95% of respondents that received some degree of formal college education.

*4.4.2 Descriptive statistics*

While survey one and two differed in content, there were several questions that were the same across both questionnaires. Table 4.3 displays the results of all similar questions across the two surveys in the form of all first-time respondents (survey one and two), survey sample one respondents, and those who responded to both surveys (survey sample two). This comparison was made to quantify if there was any change in perception between survey time periods.

Overall, ~83% of farmers claimed to be familiar with the term cover cropping prior to taking the survey, which encompasses a large majority of the respondents. However, when asked about familiarity with the benefits cover crops could provide when implemented into fruit production practices, ~63% responded yes. This shows that while the surveyed farmers were familiar with the term, 20% of respondents were not educated about benefits that cover crops could have for their operation. When considering change in awareness by the farmers that responded to both surveys, ~26% more respondents were familiar with the benefits at the second survey response time. Nearly 90% of farmers that responded to both surveys claimed to understand cover cropping benefits for fruit production. This indicates that these respondents showed interest in educating themselves about the practice, whether it be from introduction by the first survey or through their own learning experiences.

**Table 4.3** Shows the responses to questions asked in both survey 1 and survey 2 (first response only) and change in response from survey 1 to survey 2 for those who responded to both. Change was not significant from survey 1 to survey 2 within any of the categories ($p < 0.05$).

| Category | Overall response (first time responders) n=41 | Survey Sample 1 n=30 | Survey Sample 2 n=9 | Change |
|---|---|---|---|---|
| **Familiar w/ CC** | | | | |
| Yes | 82.9% | 83.3% | 88.9% | + 5.6% |
| No | 17.1% | 16.7% | 11.1% | - 5.6% |
| **Familiar CC w/ benefits** | | | | |
| Yes | 63.4% | 63.3% | 88.9% | + 25.6% |
| No | 36.6% | 36.7% | 11.1% | - 25.6% |
| **Familiar w/ SH** | | | | |
| Yes | 34.1% | 40% | 66.7% | + 26.7% |
| No | 65.9% | 60% | 33.3% | - 26.7% |
| **Used SH** | | | | |
| Yes | 12.2% | 13.3% | 11.1% | + 2.2% |
| No | 87.8% | 86.7% | 88.9% | - 2.2% |
| **Familiar with VB** | | | | |
| Yes | 23.3% | 23.3% | 44.4% | + 21.1% |
| No | 76.7% | 76.7% | 55.6% | - 21.1% |
| **Used VB** | | | | |
| Yes | 4.9% | 3.3% | 22.2% | + 18.9% |
| No | 95.1% | 96.7% | 77.8% | - 18.9% |
| **Economically Viable** | | | | |
| Yes | 66.7% | 67.9% | 87.5% | + 19.6% |
| No | 33.3% | 32.1% | 12.5% | - 19.6% |
| **Beneficial to Your Practice** | | | | |
| Yes | 87.2% | 89.3% | 87.5% | - 1.8% |
| No | 12.8% | 10.7% | 12.5% | + 1.8% |
| **Importance Score** | | | | |
| | 43.05 | 40.43 | 46.25 | + 5.82 |
| **Likely to CC** | | | | |

| | | | | |
|---|---|---|---|---|
| Yes | 62.2% | 65.4% | 77.8% | + 12.4% |
| No | 37.8% | 34.6% | 22.2% | - 12.4% |

When considering the questions involving the field-tested cover crops, the majority of farmers were not familiar with sunn hemp (~66%) or velvet bean (~77%). Even less of the respondents had experience using these cover crops, with only ~12% having had experience planting sunn hemp and ~5% velvet bean. It is likely that because the respondents are primarily fruit growers, they have little experience with this practice. As a result, there is a lack of available resources for MDC fruit growers in regard to recommendations for cover cropping. Therefore, it can be expected that fruit producers are less likely to be familiar with species options for their operations. Even though there is limited information available to fruit producers about our specific tested species, familiarity did increase for sunn hemp (+ ~27%) and velvet bean (+ ~21%) from survey one to survey two. Respondents were asked if they felt that implementing cover crops as a management strategy would be beneficial to the overall health of their fruit grove. Approximately 87% agreed that cover cropping would be beneficial. When asked if they believed that incorporating cover crops into their farming regimen would be economically viable, ~67% responded favorably. While the majority of the farmers associated cover cropping with benefits to their production (~87%), ~ 20% less believed that incorporating cover cropping would be feasible cost-wise, although this statistic did increase by those who responded to both surveys (+ ~20%).

To accompany the previous questions, respondents were asked about seven characteristics and their importance level in regard to cover crop benefits. The seven categories were soil building, pollinator visitation/diversity, weed control, pest control, nutrient leaching control, soil erosion control, and wind break. These benefits each received an individual score on a scale from 1 -10. Then, an importance score was calculated based on these seven categories by summing the responses by each farmer for a possible 70 points. The average importance score overall was 43.05 out of 70, which gained a slight increase of ~6 points from respondents who answered both surveys. Individual importance score average values for each category is reported in Table 4.4.

**Table 4.4** Importance score averages for each inquired category (first time response only).

| Category | Score |
|---|---|
| Soil building<br>*n* = 41 | 7.6 |
| Pollinator visitation<br>*n* = 36 | 6.97 |
| Weed control<br>*n* = 40 | 8.3 |
| Pest control<br>n= 37 | 6.84 |
| Nutrient leaching control<br>*n* = 41 | 7.02 |
| Soil erosion control<br>*n* = 36 | 5.31 |
| Windbreak<br>*n* = 33 | 4.18 |

As per the farmers responses, weed control and soil building are the most important expected benefit of cover crops for fruit growers, while windbreak and erosion control are the least. In the case of cover crop implementation, soil building through organic matter additions and nutrient stock may take several years to become observable to farmers (Mbuthia et al. 2015). However, other advantages like weed/pest suppression could have obvious economic benefits in the short-term via reduction of traditional pesticides. This information is valuable for cover crop species selection for future studies and educational workshops or extension information.

The last factor that was considered across both surveys was likelihood of implementing cover cropping practices. Overall, ~62% of respondents agreed that they were likely to implement, while ~38% responded that they were not likely to implement the practice. For the group of people that responded to the first survey, ~65% were likely to cover crop, while ~35% were not likely to cover crop. With this in mind, a second survey was formulated to gain a more in-depth understanding about factors that could influence the adoption decision.

Tables 4.5 and 4.6 present Likert scale questions utilized in the second survey to specifically target the respondents perceived benefits, perceived risks, potential facilitators, and awareness and concern when considering cover cropping for their operation. To gain insight on perceived benefits (Table 4.5), questions were asked specifically about the field trial cover crops sunn hemp and velvet bean. Cronbach's α for perceived benefits of both sunn hemp (α = 0.831) and velvet bean (α = 0.826) was sufficient to ensure reliability (Taber, 2017). The sunn hemp perceived benefits score mean was 3.74 while the velvet bean perceived benefits score mean was 3.62. This indicated that farmers perceived sunn hemp to be more beneficial than velvet bean as a cover crop. This also shows that farmers agreed that both sunn hemp and velvet bean were beneficial overall on a 1-5 scale, leaning more towards agreement (4) and strong agreement (5). Respondents felt most confident in sunn hemp and velvet bean's ability to improve soil productivity (mean scores 3.90 and 3.79, respectively), as 70% agreed with regards to sunn hemp and 55% agreed for velvet bean. Farmers were least confident that the use of sunn hemp would improve fruit yield as 47.4% agreed and 52.6% were uncertain (mean score 3.53). For velvet bean, they showed least confidence in its ability to suppress weeds with 55% uncertain and 45% in agreement (mean score 3.55). When asked if respondents were interested in trying the cover crops, farmers were more interested in trying sunn hemp (mean score 3.70) than velvet bean (3.50) within their operation based on mean score, however both species received the same agreement rate at 60%. Ten percent of farmers were not interested in trying velvet bean as a cover crop for their operation, resulting in a lower mean score.

**Table 4.5** Means and percentage distributions for perceived cover crop benefits.

| | Mean | SD | Strongly disagree (%) | Disagree (%) | Uncertain (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|---|---|
| Perceived benefits SH α = 0.831 | 3.74 | 0.113 | | | | | |
| SH can add sufficient N for fruit trees (n=20) | 3.80 | 0.834 | 0.0 | 0 | 45.0 | 30.0 | 25.0 |
| SH can add sufficient OM for fruit trees (n=19) | 3.79 | 0.631 | 0.0 | 0 | 31.6 | 57.9 | 10.5 |
| SH can reduce soil erosion (n=20) | 3.80 | 0.894 | 0.0 | 5.0 | 35.0 | 35.0 | 25.0 |
| SH can improve overall soil productivity (n=20) | 3.90 | 0.718 | 0.0 | 0.0 | 30.0 | 50.0 | 20.0 |
| SH helps to suppress weeds (n=20) | 3.65 | 0.671 | 0.0 | 0.0 | 45.0 | 45.0 | 10.0 |
| SH can improve fruit yield (n=19) | 3.53 | 0.612 | 0.0 | 0.0 | 52.6 | 42.1 | 5.3 |
| I am interested in trying SH (n=20) | 3.70 | 0.801 | 0.0 | 5.0 | 35.0 | 45.0 | 15.0 |
| Perceived benefits VB α = 0.826 | 3.62 | 0.085 | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| VB can add sufficient N for fruit trees (n=20) | 3.65 | 0.671 | 0.0 | 0.0 | 45.0 | 45.0 | 10.0 |
| VB can add sufficient OM for fruit trees (n=20) | 3.60 | 0.681 | 0.0 | 0.0 | 50.0 | 40.0 | 10.0 |
| VB can reduce soil erosion (n=20) | 3.65 | 0.745 | 0.0 | 0.0 | 50.0 | 35.0 | 15.0 |
| VB can improve overall soil productivity (n=19) | 3.79 | 0.787 | 0.0 | 0.0 | 40.0 | 35.0 | 20.0 |
| VB helps to suppress weeds (n=20) | 3.55 | 0.686 | 0.0 | 0.0 | 55.0 | 35.0 | 10.0 |
| VB can improve fruit yield (n=20) | 3.60 | 0.598 | 0.0 | 0.0 | 45.0 | 50.0 | 5.0 |
| I am interested in trying VB (n=20) | 3.50 | 0.889 | 5.0 | 5.0 | 30.0 | 55.0 | 5.0 |

Overall, when considering mean scores and agreement percentages, farmers believe that sunn hemp would be more compatible for their fruit production systems. Because results of the field study were presented in the survey before asking questions about the individual cover crop species, it is probable that this impacted the perspective of the respondents since only ~12% had experience using sunn hemp and ~5% using velvet bean (Table 4.3). In the information section presented prior to inquiring about the perceived benefits, it was reported that sunn hemp provided greater benefits in the form of nitrogen and dry matter additions to the soil; a likely explanation for why farmers perceived sunn hemp to be more beneficial than velvet bean. Additionally, respondents expressed greater interest in trying sunn hemp when compared to velvet bean as well. The more confident farmers are in regard to a specific cover crop species, the more interested and likely they are to conduct a trial for that species or cultivar. This is an important point for research implications and further studies.

Table 4.6 reports the data regarding perceived risk questions. The mean score for the 5 perceived risk questions was 3.13 out of 5 which shows that there was strong uncertainty and a lower level of agreement for this group of questions when compared to the perceived benefits scale. Additionally, Cronbach's α was 0.654 or < 0.70 indicating some response inconsistency and less reliability than the other Likert scale groups. The highest mean score out of all the questions on the risk scale was 3.50 for the statement *"Cover crops are too labor intensive to incorporate into a tropical fruit production setting",* in which 30% agreed, 25% were uncertain, and 45% disagreed. This shows that the majority of the respondents were either unsure or did not think that cover cropping in their grove would require too much labor to manage. Farmers are more inclined to adopt labor saving practices to reduce overhead costs (Gallardo and Sauer, 2018), and as such, additional labor required to manage cover crops may be a negative factor influencing the adoption decision. Moreover, farmers were concerned with cover crops competing for nutrients (50% agree) and water resources (45% agree), yet overall, they were most uncertain and least in agreement with cover crops negatively impacting fruit yield. *"Cover crops can reduce cash crop yield of tropical fruit trees"* garnered an interesting response as only 10% agreed with this statement and the majority were uncertain (60%). Farmers were much more in agreement that cover crops would cause nutrient and water resource competition, but the majority were uncertain about the negative impact on fruit yield. This may indicate that the respondents believe that the benefits outweigh the risks as far as fruit production is concerned. While the most obvious and observable cover crop benefit may be an increase in fruit yield, this may not be the reason for adoption. A case study conducted by Michler et al. (2018) regarding technology adoption for Ethiopian farmers found that although there was very low yield increase resulting from implementation of an improved chickpea variety, there was a very high adoption rate by local farmers. They found that adoption of the practice resulted in significant reductions in overall production costs which resulted in significant profit increases. Traditionally, it has been assumed that farmers who try a practice and experience low net returns (i.e. yield) would not adopt that specific technology (Suri, 2011), however for conservation practices with various benefits, this may not be the case.

**Table 4.6** Means and percentage distributions for perceived cover crop risks, facilitators, and ecological awareness/concern.

| | Mean | SD | Strongly disagree (%) | Disagree (%) | Uncertain (%) | Agree (%) | Strongly Agree (%) |
|---|---|---|---|---|---|---|---|
| Perceived risks α = 0.654 | 3.13 | 0.397 | | | | | |
| Cover crops compete w/ trees for water (n=20) | 3.35 | 0.671 | 0.0 | 10.0 | 45.0 | 45.0 | 0.0 |
| Cover crops compete w/ trees for nutrients (n=20) | 3.30 | 0.801 | 0.0 | 20.0 | 30.0 | 50.0 | 0.0 |
| Cover crops can reduce yield (n=20) | 2.65 | 1.040 | 20.0 | 10.0 | 60.0 | 5.0 | 5.0 |
| Cover crops are too labor intensive (n=20) | 3.50 | 0.688 | 20.0 | 25.0 | 25.0 | 30.0 | 0.0 |
| I am not convinced cover crops would be useful (n=20) | 2.65 | 1.137 | 20.0 | 25.0 | 25.0 | 30.0 | 0.0 |
| Potential facilitators α = 0.783 | 3.97 | 0.155 | | | | | |
| I would like to learn more about cover crops (n=20) | 4.10 | 0.553 | 0.0 | 0.0 | 10.0 | 70.0 | 20.0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| If cover crop seeds were available and affordable, I would purchase them (n=20) | 3.75 | 0.967 | 5.0 | 0.0 | 30.0 | 45.0 | 20.0 |
| I would be interested in attending a workshop about cover crops (n=20) | 4.05 | 0.605 | 0.0 | 0.0 | 15.0 | 65.0 | 20.0 |
| Awareness and concern α = 0.925 | 4.1 | 0.05 | | | | | |
| MDC farmers can do more to reduce fertilizer usage (n=20) | 4.15 | 1.089 | 5.0 | 5.0 | 5.0 | 40.0 | 45.0 |
| I would like to improve conservation practices on my land (n=20) | 4.05 | 0.999 | 5.0 | 0.0 | 15.0 | 45.0 | 35.0 |

Based on perceived risks and benefits scale responses, it is clear that much uncertainty is present amongst the targeted fruit growing community of MDC in regard to cover crop adoption. However, considering the potential facilitators scale (Table 4.6), the mean score was 3.97 with a reliable $\alpha = 0.783$. This mean score indicates high interest in facilitators that make cover crop implementation easier for farmers (more compatible and less complex). Ninety percent of respondents claimed they were interested in learning more about cover crops, while 85% were interested in attending a demonstration workshop focused on cover crop management for fruit groves. This response indicates a clear need for educational resources to facilitate knowledge spread of cover cropping as a practice for the MDC fruit growing community. Education in the form of demonstrative workshops, Q&A sessions, and extension documentation is critical for the widespread adoption of cover cropping within this community. Not only could these educational resources help interested farmers to gain insight on how to use cover crops for the benefit of their operation, they could also act as informational sessions for farmers to learn about monetary benefits they may receive from the USDA-NRCS for incorporating this practice.

The last set of Likert scale questions was used to quantify awareness and concern of local growers when it comes to sustainable practices (Table 4.6). This category received the highest mean score of 4.1 and $\alpha = 0.925$. This high mean score was the result of agreement amongst growers who believed that MDC farmers can do more to reduce usage of chemical fertilizers (85% agree) and those who claimed they would like to improve conservation practices on their land (80% agree). This result indicates that the population of surveyed farmers are interested in sustainability and natural resource preservation. This aligns with questions presented at the beginning of the survey in which 75% of respondents claimed to utilize conservation practices on their land. When asked if participants believed that conservation practices were beneficial to their operation, 40% indicated that conservation practices are useful in the long-term, 5% in the short-term, 50% felt that conservation practices are beneficial in both the long and short-term, while only 5% claimed that conservation practices were not beneficial to their operation. These statistics indicate that the participants were highly conscious of conservation practices and felt that incorporating them could be useful or beneficial. Therefore, it is probable that these insights had an impact on perceptions of benefits and willingness learning more about cover cropping.

*4.4.3 Logistic regression*

To determine the respondents likelihood to employ cover cropping practices, a binary logistic regression model was utilized to compare a dependent variable, “likelihood to cover crop”, to 6 independent variables. A binary logistic regression approach was employed based on the dichotomous measure of those likely to adopt cover cropping (1) and those not likely to adopt cover cropping (0). To determine goodness of fit, the Hosmer and Lemeshow test statistic was utilized, resulting in a value of 3.488 ($p$ = 0.836, Table 4.7), indicating a good model fit based on a non-significant result (Archer and Lemeshow, 2006). Additionally, the model predicted 80.6% of correctly classified likelihood, demonstrating good model accuracy. Utilizing listwise deletion, cases with missing values from at least one variable had an effect on sample size reducing the $n$ from 41 to 36.

**Table 4.7** Logistic regression results: likelihood to utilize cover crops in a tropical fruit production setting (Yes=1).

| Predictor variables | B | SE | Exp(B) |
|---|---|---|---|
| Constant | -4.500 | 2.923 | 0.011 |
| Have used SH or VB (Yes=1) | 7.277* | 5.165 | 1446.750 |
| Familiar with cover crop benefits (Yes=1) | -3.098** | 1.496 | 0.045 |
| Cover crop importance score | 0.147** | 0.067 | 1.158 |
| Implementing cover crops is economically viable (Yes=1) | 3.080* | 1.773 | 21.763 |
| Farmer education level | -1.586* | 0.965 | 0.205 |
| Farm size (acres) | 0.334* | 0.192 | 1.369 |
| n | 36 | | * $p \leq 0.10$ |
| Percentage correctly classified | 80.6% | | ** $p \leq 0.05$ |
| Hosmer and Lemeshow | $p = 0.836$ | | *** $p \leq 0.01$ |
| Model $\chi^2$, *df* 6 | 24.728**** | | **** $p \leq 0.001$ |

The relationship between the dependent variable, likelihood to cover crop, and the independent covariates differed from the expected results presented in Table 4.1. The results of the logistic regression are reported in Table 4.7, where the statistical significance of variables in the model are represented by *. Logistic coefficients (B) represent values in which a score > 0 indicates a positive relationship and a score < 0 indicates a negative relationship. All of the tested independent variables were significant indicators of adoption ($p \leq 0.10$), yet familiarity with cover crops and cover crop importance score were the most significant predictors ($p \leq 0.05$).

Having previous experience with using sunn hemp and/or velvet bean as a cover crop was a strongly positive predictor for adoption as expected ($p \leq 0.10$, Table 4.7). Farmers who have planted cover crops would be likely to revisit the practice as they already have experience with implementation, management, and have the infrastructure to implement. Also, if they tried the cover crop and found it to be effective or satisfactory to their needs, it would be logically likely for them to revisit the practice. Perceived level of benefits that cover crops may provide (importance score) was also positively related to cover crop adoption ($p \leq 0.05$). This was an expected result as those who value the benefits of cover crops would naturally be more inclined to utilize them for enhancement of orchard success and sustainability. Furthermore, economic viability was another strong positive predictor for likelihood of adoption ($p \leq 0.10$). Respondents who viewed cover cropping to be an economically viable practice for their operation would be more likely to adopt than those who did not. This category could encompass a variety of variables including seed and labor costs, along with monetary benefits like decreasing pesticide usage and fruit yield increase. The last positive predictor for adoption was farm size in acreage ($p \leq 0.10$), which can be related to overall production. Farm size as a positive predictor was expected because larger operations generally have greater resources and more economic opportunity to try new practices as these operations have more acreage to implement trial runs than smaller farms. This has been observed in previous studies where adoption rates of conservation practices were higher with farmers who had greater sales and overall capital (Saltiel et al. 1994). The degree of farmer specialization can also impact their perceptions due to greater understanding of technological complexity. All of the positive predictor results were indicative of the research expectations. Farmers who had experience using cover crops or understood the level of trialability were likely to adopt. Along with this point, those who understood relative advantage in the form of cover crop importance score were also more likely to implement the practice. Compatibility was represented by perception of economic viability and farm size, which were also expected positive predictors.

Conversely, there were two unexpected negative predictors, previous familiarity with cover crop benefits and farmer education level (Table 4.7). Respondents were asked *"Prior to this survey were you familiar with the term cover cropping?"* in order to gauge previous knowledge about the practice. Based on the logistic regression results, being previously familiar with cover cropping practices was a negative predictor to adoption likelihood ($p \leq 0.05$). This may indicate that farmers with previous knowledge of the practice had already made up their mind as to whether or not cover cropping is right for their operation, a possible result of their behavioral beliefs or attitudes. Farmer education level was also a significant negative predictor ($p \leq 0.10$), signifying that higher formal education is not a positive aspect for cover crop adoption likelihood. This was a surprising result; however, it is possible that producers with higher education may have spent most of their lives in other career ventures. The demographics showed that 68% of our respondents were over the age of 65, therefore, it is possible that respondents have taken up farming at the end of their careers and into retirement. If this were the case, these farmers may have less experience in cultivating crops and farming practices overall. These highly educated respondents may be hobbyist farmers who have less time or desire to add additional management practices to their operations than those who grow tropical fruit as their main source of income. Alternatively, since the majority of farmers were within an older age range and formally educated, it is possible that long-term experience may have played a role in perceptions of cover cropping and overall likelihood of adoption.

*4.4.4 Important characteristics/long response results*

Long response questions help to interpret quantitative data by providing further insight into participant ideas about cover cropping. All long responses were based off of two questions: 1) *"What are some of the primary reasons you are not in favor of cover cropping?"* 2) *"What are some of the primary reasons you are in favor of cover cropping"*. These responses were split into two categories to better understand motivations that positively influence adoption and limitations that negatively influence adoption. These factors are presented by Table 4.8, in which each element has been further characterized into six categories which relate back to the conceptual framework (Figure 4.1): 1) relative advantage (RA), 2) relative disadvantage (RD), 3) compatibility (Com), 4) observability (Obs), 5) complexity (Comx), and 6) trialability (Tri).

**Table 4.8** Summarization of important characteristics for fruit growers to adopt cover cropping based on qualitative responses (adapted from Reimer et al. 2012).

| Motivations (positively influence adoption) | Limitations (negatively influence adoption) |
|---|---|
| Soil aeration (RA) | Uncertainty (Comx) |
| Nitrogen fixation (RA) | Cost (RD) |
| Pest control (RA) | Labor inputs (RD) |
| Reduce nutrient leaching (RA) | Difficult to terminate (RD) |
| Soil building (RA) | Adverse effects for tree roots (RD) |
| Weed suppression (RA) | Unkempt appearance (RD) |
| Erosion control (RA) | Ground cover not practical for diverse tree plantings (Com) |
| Wind break (RA) | Interreference with picking (Com) |
| Utilizing unused space (Com) | Issues with government agencies (Com) |
| Soil acidification (RA) | Utilizing open space for other plants (Com) |
| Promotes sustainability (RA) | Non-familiar with the practice (Comx) |
| Pollinator attraction (RA) | Competition (RD) |
| Soil nutrient retention (RA) | Insufficient trial information (Tri) |
| Saving money (RA) | Attract pests (RD) |
| Have seen the effect of cover crops on soil borne pathogen defense (Obs) | Grass already planted between rows that is easily managed (Com) |
| Eliminating herbicide use (RA) | Not useful/ no perceived need (Com) |
| Can be utilized for certified organic operations (Com) | Reduce fruit yield (RD) |
| Soil nitrogen enhancement (RA) | Water resource competition (RD) |
| Organic matter addition (RA) | Nutrient resource competition (RD) |
| Readily available and affordable seeds (Com) | Not economically viable (Com) |
| Interested in learning more (Comx) | |
| Have used cover crop practices (Tri) | |
| Beneficial to overall orchard health (RA) | |
| Economically viable (Com) | |
| Ground cover (RA) | |
| Environmental improvement for honeybees (RA) | |

Note abbreviations: RA: Relative advantage; RD: Relative disadvantage; Com: Compatibility; Obs: Observability; Comx: Complexity; Tri: Trialability

Based on results from Table 4.8, it is clear that respondents were able to discern a variety of relative advantages that cover cropping could provide for their production practices. Some responses were alike to previously presented advantages within the structured questions sections, while other responses were unique due to perception and experience. The results of the regression analysis show that experience using cover crops, level of benefit importance (importance score), and economic viability are all positive predictors for likelihood of cover crop adoption (Table 4.7). These themes were also prevalent when considering long response answers. Respondents claiming > 5 on the likelihood to cover crop scale noted a variety of relative advantages or benefits to cover cropping. One respondent listed *"aeration of the soil, fixing nitrogen, and assisting in control of pests"* as benefits, while others mentioned cover crops may be valuable for utilizing unused space in between rows and many other relative advantages (Table 4.8). A lychee grower responded that *"building a more acidic humus soil with organic mass and green mulches"* was a priority for their operation. Soil pH is a major concern for South Florida growers, as the limestone parent material makes for inherently alkaline soil. This is especially concerning for tree species that thrive in acidic soils, like lychee (Crane et al. 2005).

The grower with the largest operation (1200+ acres) noted their personal experience: *"I have seen [for] myself the effects of cover crops on soil borne pathogen management and improvement [of] soil condition"*, an observable benefit to cover crop implementation. All of the respondents who claimed large acreage (100+ acres) were highly in favor of cover cropping as a management strategy as per their long answer responses. This result is in alignment with the regression analysis which revealed that increasing acreage is a positive predictor regarding cover crop adoption for tropical fruit producers. Additionally, multiple farmers noted economic benefits. One farmer expressed that they could save money by eliminating or reducing herbicide usage. Other respondents noted that cover cropping is *"a good agriculture practice with minimum cost"*, and that there are *"multiple benefits from one procedure [that is] not terribly expensive"*. All of these responses coincide with regression results suggesting that believing cover cropping is an economically viable practice positively predicts likelihood of adoption.

Based on growers who responded ≤ 5 when asked how likely they were to implement cover cropping practices, there were a variety of limitations or characteristics that could negatively influence adoption (Table 4.8). Some farmers were concerned about adverse effects of cover crops for their overall cash crop production and grove health. One individual noted an issue of compatibility in which *"planting in fruit groves can be difficult and adversely affect tree roots"*. Other farmers felt that the utilization of tall growing cover crops, like sunn hemp, could allow for the attraction of insects and other pests. Respondents also identified that utilizing cover crops could hinder grove management. One farmer felt that because they have a highly diversified tree planting, not typical of common commercial growers, that ground covers are not always practical for varying harvest procedures. Another shared that their grove is managed by a larger company and that *"sunn hemp would interfere with movement in and around the trees for picking, pruning and vine management"*. This comment aligned with some of the other respondents who felt that the extra management of mowing cover crops would be too labor intensive.

The RAA of MDC is unique due to its proximity to a largely developed urban area with high population. The RAA is a desirable place for homeowners to escape urban Miami without being too far removed from metropolitan conveniences. As such, it is not uncommon that fruit growers live on their property, and in many cases, cultivators are hobbyist that have taken up the practice as a leisure or post retirement activity (not their main source of income). As previously pointed out, this may have been a reason for higher education as a negative predictor variable for cover crop adoption when considering logistic regression results (Table 4.7). This was communicated by multiple growers that may find the practice of cover cropping incompatible for their specific purpose of growing tropical fruits primarily as a leisurely activity. Multiple growers expressed concerns about the unkempt appearance of cover crops, especially those that lived in more residential type areas of the RAA. One respondent provided some detailed insight on the issue saying that *"Many growers live among their groves and having a "weedy" looking grove attached to a manicured lawn will be problematic for some (my husband) growers. To overcome that issue, I would think that the science of planting a cover crop would have to strongly show the benefits. Many growers now have grass in between the rows, and it is easy to maintain. It is easy to walk down the rows to scout for pests, irrigation problems, and any other potential issues".* This response again reiterates the need for educational workshops and extension documents to further explain the ecological and overall production benefits that cover crops could potentially add to production systems. This also brings light to an issue of observability, as cover crop benefits may not be obvious in the short-term, as previously mentioned.

It is clear from results of Tables 4.5 and 4.6 that respondents expressed uncertainty when asked about perceived benefits, a result that is supported through qualitative responses. One respondent replied *"[I] need to learn more about benefits of cover crops. [I am] hesitant to implement due to additional workload and expense"*. This individual expressed a desire to learn more about cover cropping for fruit production, which aligned with 90% of growers who agreed that they wanted to learn more about cover crops, and 85% who agreed they would be interested in attending a cover cropping workshop (Table 4.6). Other growers also articulated uncertainty claiming they did not fully understand the practice and/or how it could benefit their specific crop type. This was voiced by respondents who felt there was insufficient information for studies conducted on commercial lands. One farmer responded *"The evidence is unclear that cover crops contribute significantly to productivity. The labor and cost in planting might better be served in mowing the weeds".* This example, along with other statements made by survey respondents illustrates a clear need for further research to be conducted to make better recommendations for cover crop incorporation in fruit groves. Identification of specific cover crop species that are compatible with individual fruit crops would be a tremendously effective tool for communicating to farmers a clear and easy guide to facilitate cover crop implementation.

**4.5 Conclusions**

This study provides perspective on local MDC tropical fruit producers and their ideas about implementing cover cropping as a practice suitable for their production systems. By incorporating a variety of strategies to better understand farmer insight and awareness on the topic, multiple conclusions can be made. When considering Likert scale mean scores, adoption was most heavily driven by awareness and concern for the environment, along with potential facilitators that, if available, would make the practice more accessible and compatible for the community. Perceived benefits of sunn hemp were greater than velvet bean indicating a stronger likelihood for trialability of sunn hemp as a cover crop for the targeted growers. As per the regression results, experience with the use of cover crops, holding value for cover crop benefits, farm size, and perceiving the practice as economically viable were all positive predictors for adoption. Based on response rate, ~68% of respondents felt that cover cropping would be economically viable for their operations, which ultimately aligned with the respondents who claimed they would be likely to adopt the practice (~65%).

Qualitative data responses revealed that relative advantage was the most important motivator to positively influence adoption, while relative disadvantage and compatibility issues were the most significant limitations that negatively influence adoption decisions. In regard to adoption motivations, respondents were mainly driven by sustainability and soil building incentives. Fruit yield increase, a benefit that directly influences monetary gain, was not explicitly mentioned by respondents. However, it is apparent that benefit to overall orchard health and environmental sustainability were essential factors. Producers expressed concerns which limit adoptability of the practice, many of which were seeded in compatibility issues that would make harvest and management more complicated. Moreover, respondents expressed uncertainty as to whether the benefits of the practice were worth the additional expense and changes in management strategies.

The traditional adoption standard is that technological practices that do not provide observable financial gain (incurring net financial cost) are seldom adopted on a large scale (Barr and Cary, 1992). Adoption of new sustainable practices is often an ongoing and fluctuating process that depends on farmer assessment. The adoption of sustainable practices is unique when compared to other technological strategies which may solve problems quickly and have high effective observability for the adopter. Sustainable practice adoption is much more complicated as education is a large component in which farmers must be convinced of the long-term benefits. These issues were apparent within this study as uncertainty was clearly expressed by the tropical fruit growing community of MDC. While uncertainty and risk were identified by qualitative and quantitative responses, most participants acknowledged and agreed that cover cropping does come with a number of both long-term and short-term benefits. Thus, there was an overwhelming consensus that local farmers were interested in learning more about cover crops and attending interactive workshops to expand their knowledge on the practice. This is key to the widespread adoption of cover cropping as a practice in the MDC RAA. Based on logistic regression analysis it was found that perception of cover crop importance and economically viability are both strong predictors of cover crop adoption. Both of these facets would be easily presentable in online/in-person sessions and would fit nicely into classes offered by the MDC agriculture extension office. In an effort to increase awareness and knowledge about cover cropping as a practice for MDC fruit growers, it is evident that further field trial research is necessary to create reliable recommendations for specific cover crop species and strategies for implementation.

Lastly, while information gathered from this study was incredibly valuable to understanding the perception of local MDC fruit growers, there were some limitations that may have impacted the results and conclusion of this chapter. When considering farmer demographics, the surveyed fruit growers were clearly skewed towards the older age range. This may have impacted responses based on degree of formal agricultural education, extensive farming experience, or preconceived notions regarding sustainable practices. Additionally, the survey response rate resulted in a relatively small sample size. With greater a greater sample size, data analysis and conclusions of this study may have differed as a result of alteration of adoption likelihood factors.

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# CHAPTER 5: CONCLUSIONS

This research project was formulated with the intention of thoroughly addressing the systematic process of incorporating cover crops as a management strategy for tropical fruit production within the Redland Agricultural Area of South Miami. Two cover crop species, sunn hemp and velvet bean, were chosen based on their previous successful characteristics when tested for effectiveness as green manure in vegetable crop settings in Miami-Dade County. The cash crop, carambola, was selected as a model species based on its economic potential as a transitional crop for avocado growers.

The previous chapters focused on a field study that explored a variety of targeted parameters to better understand the impact these cover crops had on the surrounding soil and cash crop health. In addition to the field study, a social study was conducted to gain a better understanding about perceptions of local growers and their willingness to adopt cover cropping as a practice within their fruit groves. This strategy was formulated to incorporate the applied science of agroecology and its principals, including input reduction, recycling of resources, biodiversity enhancement, land and resource preservation, along with the social aspect of knowledge sharing and participation.

Based on the findings it can be concluded that tropical leguminous cover crops have potential as an effective amendment for juvenile carambola trees. More specifically, sunn hemp was shown to be effective on its own and when combined with poultry manure fertilizer to stimulate plant available nutrients, tree health, and crop production. While this result has promising implications, it should be noted that there is much room for experimentation and expansion of this project as this study had various limitations. It is possible that with an extended study period, results may have been more obviously conclusive, especially when considering long-term soil cycling processes. Space and sample size was limited for the field portion of the project which also may have impacted the results recorded throughout the two seasons. Based on visual analysis, cover crops that do not have vining growth habit would possibly prove more successful for intercropping with trees. Vertical growth habit cover crops are also likely more appealing to farmers who prefer reduced management and labor. As such, this project could be expanded upon utilizing various cover crops, cover crop mixes, termination times, and fruit tree species to further quantify interactions and solidify conclusions. Additionally, when considering the social aspect, the sample size of surveyed farmers was relatively small (10% response rate). The survey results could have benefited from a larger sample size which may have limited skewness of the demographics and provided more conclusive insight to MDC farmer's likelihood to implement cover cropping.

As made apparent by the results of chapter four, the local farming community is overwhelmingly interested in learning more about how cover cropping could be useful for tropical fruit tree production and management. The information gathered from expanding research that builds upon this study is essential to creating extension resources in the form of recommendations, documentation, and demonstrative workshops to educate the local fruit growing community. With greater scientific knowledge and access to educational resources, the widespread adoption of cover cropping as a practice within the Miami-Dade County agriculture community could be possible. Sustainable practices that facilitate economic prosperity and protect ecosystem services could be key to improving the environmental landscape in and around the Redland Agricultural Area, which could have positive implications for the Everglades and other natural systems that lie within close proximity.

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