An assessment of small grain winter cover crops for management of *Meloidogyne incognita* and *Rotylenchulus reniformis* in southeastern U.S. cotton production

by

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Abstract

This experiment investigates five small grain winter cover crops including barley (*Hordeum vulgare* L), oats (*Avena sativa* L.), rye (*Secale cereale* L.), triticale (x *Triticosecale* Wittmack), and wheat (*Triticum aestivum* L.) as a sustainable nematode management strategy for *Meloidogyne incognita* (root-knot nematode) and *Rotylenchulus reniformis* (reniform nematode) in cotton production in the southeastern U.S. Greenhouse (2019) and field experiments (2019-2021) evaluated these crops for nematode population reduction, forage quality, and grain yield.

Greenhouse experiments revealed that all small grains had higher average *M. incognita* egg counts than a standard corn (Zea mays L.) variety, except for one triticale cultivar, ‘Forerunner’. Overall, barley and wheat were suitable hosts (Rf>2), triticale and oat were moderate hosts (Rf=1-2), while three cultivars (‘Forerunner’ and ‘OG170039’ triticale, ‘ORO 4372’ oat) were poor hosts (Rf<1). Oat had the highest biomass and grain yield, followed by triticale, barley, rye, and wheat. Barley supported the highest population density of *M. incognita*. Oat, barley, and rye showed similar population density of *R. reniformis* and were greater than triticale and wheat. Forage quality experiments showed oat with the highest biomass, wheat with the highest crude protein, and rye and triticale leading in fiber content. Oats had the greatest total digestible nutrients and relative feed value (RFV), indicating superior digestibility. All small grains demonstrated high forage quality (RFV>100).

This experiment concludes that nematode populations did not significantly affect crop performance, with crop-specific traits playing a larger role. Cover crop selection should be based on specific management and agronomic goals. Further research on crop-specific responses and long-term effects on nematode populations and soil health is needed to optimize small grain winter cover crops in integrated pest management programs.

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ADF	Acid Detergent Fiber
CP	Crude Protein
EVS	E.V. Smith Research Center
NDF	Neutral Detergent Fiber
PBU	Plant Breeding Unit
PSRC	Plant Science Research Center
RFV	Relative Feed Value
TDN	Total Digestible Nutrients

Chapter 1: Introduction and Review of Literature

Introduction and Problem Statement

The objective of this research is to measure the winter survival of *Meloidogyne incognita* (root-knot nematode) (Kofoid and White) and *Rotylenchulus reniformis* (reniform nematode) (Linford and Oliveira) in southeastern U.S. cotton (*Gossypium hirsutum* L.) production fields. Information is lacking on additional effective management techniques to manage these nematodes during the traditional non-crop season in the Southeast where winter temperatures are generally mild. The primary objective of this research was to determine the effectiveness of small grain cover crops as an additional sustainable nematode management strategy by measuring reproduction of *M. incognita* and *R. reniformis* on fall-planted small grains in cotton production fields. Additionally, forage quality and grain yield of the small grain cultivars were analyzed to determine potential for these small grain cover crops to be utilized for livestock forage or harvested for grain.

Gossypium hirsutum

In 2024, the USDA reported approximately 11.7 million acres of upland cotton (*G. hirsutum)* planted in the U.S. cotton belt (Meyer and Dew, 2024), which is comprised of 17 southern states extending from Virginia to California (USDA, 2022b). The August 2024 cotton and wool outlook report projects U.S. cotton exports of approximately 12 million bales for the 2024/25 season projecting the U.S. to be the second largest cotton exporter in the world for 2024/25 (Meyer and Dew, 2024). Upland cotton is the most adapted and widely planted cotton species in the U.S. (Wendel et al., 1992), and accounts for approximately 97% of U.S. cotton production (USDA, 2022b). For the 2024/25 season, the USDA forecasts Upland cotton production to reach 14.6 million bales, harvested from 11.2 million acres (USDA, 2024a). Cotton is undoubtedly the single most important fiber crop in the world, which is why research and development efforts are critical for its prosperity (Starr et al., 2007).

Meloidogyne incognita

Root-knot nematodes (*Meloidogyne* spp.) are the most damaging and economically important genera of plant-parasitic nematodes (Elling, 2013). There are over 100 reported species of root-knot nematodes found throughout tropical and subtropical regions worldwide that infect a broad range of crop and weed species, of which *M. incognita*, *M. javanica*, *M. arenaria*, and *M. hapla* are considered the most damaging (Mitkowski and Abawi, 2003). More recently, reports of *M. enterolobii* infecting root-knot nematode resistant varieties of cotton and soybean in Florida (Brito et al., 2004) and North Carolina (Ye et al., 2013) and sweet potato in South Carolina have proven the resilience of *Meloidogyne* species (Rutter et al., 2019). The southern root-knot nematode, *M. incognita*, is the most reported species on cotton and is found in all cotton producing states in the U.S. (Figure 1) (Thomas and Kirkpatrick, 2001). Cotton disease loss estimates from 2023 reported approximately 455 thousand bales of cotton lost to plant-parasitic nematodes, of which an estimated 302 thousand bales were lost to *Meloidogyne* spp. (Faske and Sisson, 2024). *Meloidogyne incognita* has an extensive host range of over 2,000 species and its resiliency in southern soils makes management efforts of this pathogen challenging (Starr et al., 2007).

The root-knot nematode derives its name from the large galls or ‘knots’ that form in response to root infection (Mitkowski and Abawi, 2003). Root galling, the most diagnostic symptom of root-knot nematode damage, occurs as the result of the formation of giant cells in the root tissue where the nematode establishes its specialized feeding site (Jones et al., 2013). Root-knot nematodes feed as sedentary endoparasites, continually interrupting the passage of water and nutrients within the vascular tissue of the host plant (Lambert and Bekal, 2002). This malfunction in the root system induces the development of above-ground symptoms, such as wilting, stunting, yellowing, and an overall reduction in yield (Lawrence and Lawrence, 2020). Injury to the root system makes the host plant vulnerable to other potential soilborne pathogens, which subjects the plant to further damage (Back et al., 2002).

Root-knot nematodes overwinter in the soil as eggs and will hatch when provided adequate soil moisture and temperature (Mitkowski and Abawi, 2003). The activity threshold for root-knot nematodes to persist in the soil and infect root-tissues is 18 °C, but if infection has already occurred, this nematode can continue to develop and reproduce at 10 °C (Figure 2) (Roberts et al., 1981). During the egg phase, the root-knot nematode undergoes embryonic development and the first juvenile stage, before hatching into a vermiform second-stage juvenile (J2). The infective J2, using its stylet, will invade a host plant at the root tip near the apical meristem and migrate intercellularly in the vascular tissue in search of a permanent feeding site (Taylor and Sasser, 1978). The J2 initiates a specialized feeding site by injecting secretory proteins into giant cells, which causes the cells to expand. From these giant cells, the J2 will feed by ingesting nutrients and proteins (Jones et al., 2013). The J2 will enlarge and complete two additional molts (J3 and J4) before reaching maturation. As a mature adult female, the root-knot nematode is swollen, and her posterior may protrude through to the root surface (Taylor and Sasser, 1978). From her posterior region, the female will deposit her eggs into a protective gelatinous egg mass (Elling, 2013), which can contain between 500 to 2,000 eggs (Tyler, 1933a). When environmental conditions are sufficient, eggs will hatch and can develop into a mature nematode within 3 to 4 weeks. Depending on moisture and temperature, the root-knot nematode can complete as many as 5 to 8 generations in a single growing season (Noling, 2014).

Control measures for root-knot nematodes should be implemented when population density levels exceed a damage threshold, at which economic crop losses can be expected (Jones et al., 2013). Crop injury and economic losses can occur at population levels as low as 1 juvenile/cm^3 of soil (Jones et al., 2013). However, damage thresholds will fluctuate based on factors like soil type, soil moisture, and soil texture in combination with plant species (Monfort et al., 2007). In cotton production, when the pre-plant root-knot nematode population density exceeds 40 juveniles/100 cm^3 of soil, a 10% or greater reduction in yield can be expected. In the fall near cotton harvest when root-knot populations are typically at their peak, a 10% or greater yield loss can be expected when the root-knot nematode population density exceeds 100 juveniles/cm^3 in sand to sandy loam soil and 130 juveniles/cm^3 in clay loam soil (Mueller et al., 2012). Maintaining population density levels below the damage threshold requires implementing multiple management strategies. However, a successful integrated pest management strategy for nematode control requires correctly identifying the species of nematodes present and their population levels (Lambert and Bekal, 2002). The most effective and primary means for control of root-knot nematodes are chemical nematicides (Starr et al., 2007). Pre-plant fumigants, seed treatments, and foliar nematicides are options available to growers for chemical control (Mueller, 2020).

Rotylenchulus reniformis

The reniform nematode, *Rotylenchulus reniformis*, was first reported parasitizing cotton in Georgia in 1940 (Heald and Thames, 1982) and has been an evolving problem in the mid-south and southeastern U.S. cotton production areas (Figure 3). Of the 10 known *Rotylenchulus* species, *R. reniformis* has the most extensive host range of over 300 plant species across tropical and subtropical regions (Robinson et al., 1997). *Rotylenchulus reniformis* is more problematic in warmer regions of the U.S. cotton belt, and in soils that have higher levels of silt and clay (Kinloch and Sprenkel, 1994). In the 2023 growing season, an estimated 153 thousand bales of cotton were lost in the U.S. cotton belt to the reniform nematode (Faske and Sisson, 2024). The damage threshold for the reniform nematode fluctuates between regions based on varying temperature, moisture, and soil type. A yield reduction of 10% or greater can be expected in a cotton crop when the pre-plant reniform nematode population density exceeds 50 juveniles/100 cm^3 of soil. The same yield loss can occur near harvest when the reniform nematode population density exceeds 250 juveniles/100 cm^3 in sand to sandy loam soil and 500 juveniles/100 cm^3 in clay loam soil (Mueller et al., 2012). Visual detection of reniform nematode damage can be difficult. In the southeast, cotton plants infected by the reniform nematode will exhibit foliar symptoms, like internal yellowing, that are also characteristic of common nutritional deficiencies. In newly infested cotton fields, the reniform nematode causes patchy, irregular stunting that results from poor root development, which gives the crop canopy an uneven, jagged appearance (Lawrence and Lawrence, 2020). After several years of reniform nematode infestation, the nematodes become more evenly distributed across fields causing stunting to appear more uniform, further disguising the nematode's presence (Robinson, 2007). Root systems do not produce symptoms indicative of reniform infection, but can appear stunted with fewer, less-developed feeder roots (Lawrence and Lawrence, 2020). Additionally, reniform infestations in cotton may result in fewer and distorted bolls causing a considerable reduction in lint yield (Jones et al., 1959). The only conclusive method of diagnosing a reniform infestation is by soil and root analysis (Wrona et al., 1996).

Reniform nematodes infect plant roots as vermiform females by partially penetrating the root and becoming stationary upon the designation of a feeding site (Wang, 2013). With her posterior positioned on the exterior surface of the root, a vermiform male in the soil will inseminate the female; although in some cases the female can reproduce parthenogenetically (Wrona et al., 1996). The female swells into a kidney-shape as she matures, eventually releasing a gelatinous egg mass of about 60 eggs or more (Linford and Oliveira, 1940). During the egg phase, the nematode will undergo embryogenesis and the first molt before emerging into the soil as a second-stage juvenile (J2). During the juvenile phases (J2-J4), the nematode is noninfective and relatively immobile (Robinson et al., 1997). Upon hatching, a young female can reach the infective stage within 1 to 2 weeks (Wang, 2013). A reniform nematode can complete its entire life cycle in 19 days when temperatures range from 25 to 29.5 °C (Rebois, 2013). In most temperate climates, the reniform nematode requires at least 25 °C (Figure 2) to reproduce; however, in more tropical regions, this nematode can reproduce at 15 °C with adequate soil moisture (Heald and Inserra, 1988).

The reniform nematode reproduces rapidly and can reach high population levels in cotton fields if not properly managed (Greer et al., 2009). Lack of resistant cultivars over the years has made control efforts challenging, forcing growers to rely chiefly on nematicides (Starr et al., 2007). Nematicides often require multiple applications to be effective, which can be expensive and toxic to the environment (Lawrence and Lawrence, 2020). End-of-season soil samples are recommended for accurately assessing population levels and field distribution (Wrona et al., 1996). Monitoring the status of this nematode’s presence in the field is essential for constructing an effective management plan (Barker and Koenning, 1998).

Management Strategies

Nematode problems can be more severe in tropical and subtropical climates, such as the southeastern U.S., where average annual temperatures typically remain within optimal ranges for

M. incognita and *R. reniformis* reproduction (Noling, 2014). Plant-parasitic nematode management is highly dependent on synthetic nematicides; however, these chemicals are highly restricted for the threat they pose to environmental and human safety, causing growers to explore alternative management options (Desaeger et al., 2020). Crop rotation, including the use of cover crops, is a cultural option to improve management of plant-parasitic nematodes (Lawrence and Lawrence, 2020). Winter-grown small grains are effective in preventing soil erosion and producing large amounts of biomass that add organic matter to the soil and provide weed suppression (Clark, 2015). Small grains are also favored for the potential profit they may provide during winter seasons for forage and/or grain (Buntin and Cunfer, 2017). The exact status of the relationship between small grains and plant-parasitic nematodes is conflicting. Johnson and Motsinger (1989) determined from a field experiment in Georgia on winter small grain cover crops, wheat (*Triticum aestivum* L.), oat (*Avena sativa* L.), rye (*Secale cereale* L.), and barley (*Hordeum vulgare* L), that *M. incognita* is capable of infecting, developing, and reproducing when soil temperatures range from 21 to 24 °C. Another field experiment conducted in the southern U.S. by Timper et al. (2006) quantified *M. incognita* reproduction on cereal rye and several leguminous cover crops to determine if winter cover crops increase *M. incognita* levels above a threshold that could be damaging to a subsequent cotton crop. Results from this experiment concluded that when a susceptible winter cover crop is coupled with a mild winter season, *M. incognita* can complete one to two generations (Timper et al., 2006). However, when comparing small grains to some leguminous cover crops, small grains have proven to be more effective in limiting nematode reproduction (Timper et al., 2006; Wang et al., 2004). In a greenhouse experiment performed in the study mentioned previously (Timper et al. 2006), it was determined that rye and vetch (*Vicia sativa* L.) had significantly lower *M. incognita* eggs per pot compared to the seven other legume cover crops tested. Another experiment by Wang et al. (2004) reported lower *M. incognita* population density in corn plots previously planted to rye or oat than lupine (*Lupinus angustifolius*) or vetch. It has been shown that *M. incognita* is not economically damaging to a small grain winter cover crop (Roberts et al., 1981); however, data does show that *M. incognita* population density can increase on a susceptible cash crop even following a poor host, like rye (Wang et al., 2004). Similarly, in studies examining *R. reniformis*, small grains, rye, wheat, and black oat (*Avena strigosa* Schreb.), support a lower population density of *R. reniformis* when compared to legume cover crop options (Jones et al., 2006). There are few studies that discuss the winter survival of *R. reniformis* on cover crops, which influenced our curiosities for including this nematode species in our research.

The integration of two or more management tactics into a nematode management program is the most sustainable and economical strategy for maintaining *M. incognita* and *R. reniformis* levels below their damage thresholds (Roberts, 1993). A single nematode management practice alone is not fully effective and is short-lived compared to a combined management program (Tyler, 1933b). Management options for plant-parasitic nematodes include methods such as proper sanitation of field equipment, crop rotation with non-hosts, alternating resistant and tolerant varieties, and utilizing nematicides (Lawrence and Lawrence, 2020). Cotton producers rely predominantly on nematicides for effective nematode management due to a lack of high-yielding cotton varieties that resist *M. incognita* and *R. reniformis* (Mueller et al., 2012). Crop rotation, a highly effective method for nematode management, is often underutilized due to growers' preference for producing cotton in a monoculture system that is traditionally seen as more profitable (Hake et al., 1991). Furthermore, to justify removing land from cotton production, the rotational crop must be economically feasible and successfully increase yield on a subsequent cotton crop (Starr et al., 2007). Nonetheless, as environmental and health concerns regarding synthetic nematicides continue to accelerate, research efforts toward sustainable nematode management have expanded (Barker and Koenning, 1998).

Crop Rotation

Crop rotation with poor or non-hosts is the most widely used cultural management tactic for managing plant-parasitic nematodes (Starr et al., 2007). Other practices include incorporating cover crops, weed removal, and field fallowing (Creech et al., 1995). Rotating with cover crops offers natural benefits for disease control that can reduce the intensive use of herbicides and pesticides (Phatak and Diaz-Perez, 2012). Cotton mono-cropping relies heavily on chemical solutions to combat the buildup of weeds and pests that occur when a single plant species is grown continuously (Thompson, 2014). Cover crops can outcompete weeds that may serve as alternate hosts for plant pathogens and create a suitable environment for soil microorganisms that can be antagonistic to soil-borne pathogens (Phatak and Diaz-Perez, 2012). The success of a cover crop in cotton for management of *M. incognita* and *R. reniformis* largely depends on the host status of the crop. Every cover crop species provides its own unique benefits to the soil ecosystem and one crop designed to reduce one species, may increase another (Lawrence and Lawrence, 2020). In no-till cotton production, legumes and small grains have proven beneficial for controlling soil erosion and enhancing soil productivity (Daniel et al., 1999). Legumes are popular for their nitrogen fixation capabilities that can provide between 70 to 100 pounds of plant available nitrogen to a subsequent cotton crop (Tyler et al., 2000). Hairy vetch (*Vicia villosa* Roth) and crimson clover (*Trifolium incarnatum* L.) are legumes well-adapted for cover crop use in the southern region of the U.S. (SARE, 2012). However, some clovers and vetches have proven to be suitable hosts for *M. incognita* (Timper et al., 2006). Small grains are desirable cover crops for the abundant surface cover they provide that can be beneficial for protecting the soil and preventing erosion (Gaskin et al., 2020). Studies show that rye, wheat, and oat support low populations of both *M. incognita* and *R. reniformis* and may be helpful for suppressing nematode populations (Brida et al., 2017; Johnson and Motsinger, 1989; Jones et al., 2006; McSorley and Gallaher, 1992; Opperman et al., 1998; Timper et al., 2006). Having a thorough understanding of the nematodes present in the soil and a rotation crop's vulnerability to a specific nematode species is important for minimizing negative outcomes (Koenning et al., 2004). Removing a field from cotton production for one year and incorporating winter grain, nematode resistant soybean, or summer fallow can reduce *M. incognita* population density for up to two years subsequent to cotton reintroduction (Hake et al., 1991). For management of *R. reniformis*, it has been shown that one year out of cotton to either corn (*Zea may*s), grain sorghum (*Sorghum bicolor*), or peanut (*Arachis hypogaea*) can help reduce *R. reniformis* population density (Lawrence and Lawrence, 2020). Despite the positive results rotational crops contribute to plant-parasitic nematode management in cotton production, growers must justify the equipment and management costs for a rotational crop to be incorporated into their production system (Koenning et al., 2004).

<u>Resistant Cultivars</u>

Utilizing resistant and tolerant cultivars is a simple nematode management tactic to implement that is cost-effective and provides protection across an entire field (Starr et al., 2007). Resistant cultivars limit nematode reproduction on cotton roots that can reduce the population density in the soil, which can potentially safeguard crops grown in subsequent years (Koenning et al., 2001). Tolerant cultivars, compared to standard non-resistant cultivars, will have minimal crop injury or yield reduction in the presence of nematodes (McSorley and Gallaher, 1995). It is recommended to alternate between resistant and tolerant varieties to avoid selecting for nematode species that can develop the capability to feed and reproduce on resistant cultivars (Lawrence and Lawrence, 2020). Breeding efforts for nematode resistance in cotton production have predominantly focused on *M. incognita* due to its detriment to cotton yields throughout all cotton producing states in the U.S. (Koenning et al., 2001). Resistant genes for both *M. incognita* and *R. reniformis* have long been studied and recognized, but the incorporation of those genes into commercial cultivars is continuously under development due to poor agronomic performance (Koenning et al., 2001). In the past, commercial cotton cultivars with resistance to *M. incognita* successfully limited nematode reproduction but did not provide the yield potential and fiber quality compared to that of a standard variety (Faske and Starr, 2009). However, newer highly resistant Phytogen® cottonseed cultivars, PHY 480 W3FE, PHY 500 W3FE, and PHY 580 W3FE, can attain average 17% higher yields compared to some susceptible cotton cultivars (Wheeler et al., 2020). Until recently, host-plant resistance in cotton for *R. reniformis* has been commercially unavailable to growers (Koenning et al., 2000). For the 2021 growing season, two PhytoGen Cottonseed varieties, PHY 443 W3FE and PHY 332 W3FE, became commercially available to growers that advertised resistance to both *M. incognita* and *R. reniformis* (PhytoGen Cottonseed, Corteva Agriscience, Wilmington, DE). Turner et al. (2021) determined, the PHY 332 W3FE cultivar displays exceptional yield potential based on a 51% increase in cotton lint yield when compared to a standard non-resistant cultivar in a reniform infested field. Advancements for high-yielding resistant cultivars for *M. incognita* and *R. reniformis* contributes to the implementation of more sustainable approaches to the management of plant-parasitic nematodes (Westphal, 2011).

Nematicides

A lack of high-performing resistant cultivars and the underutilization of crop rotation due to cotton mono-cropping has forced growers to largely depend on nematicides for effective nematode management (Mueller et al., 2012). Nematicides, both fumigants and non-fumigants, are chemically synthesized products that adversely affect nematodes, which limit the rate of nematode development and reduce population density (Hajihassani, 2018). Fumigant nematicides are formulated as liquids and applied to the soil prior to planting and are narrow-to-broad spectrum, offering protection against other soilborne pathogens beyond plant-parasitic nematodes, including fusarium, verticillium, pythium, and rhizoctonia species (Zasada et al., 2010; Martin, 2003). Fumigant nematicides are formulated with toxic, volatile compounds, like 1,3-dichloropropene, that raise environmental and human safety concerns, which causes their usage to be greatly restricted (Monfort et al., 2006). Non-fumigants, which are typically less effective than soil fumigants, are the more favored nematicides due to the regulations on fumigants (Hajihassani, 2018).

Seed treatments, foliar sprays, and in-furrow applications comprise the group of non-fumigant nematicides that are more economical and require little-to-no specialized equipment for application (Faske and Hurd, 2015). Nematicide seed treatments, like thiodicarb (Aeris®, Bayer CropSciences, St. Louis, MO) and fluopyram (COPeO™ Prime, BASF Agricultural, Florham Park, NJ) are easy to apply and provide root protection during plant establishment that can reduce the frequency of chemical applications that are traditionally required (Wilson et al., 2020). Fluopyram has been shown to diminish both *M. incognita* (Spinks et al., 2020) and *R. reniformis* (Groover et al., 2020) population density in cotton. Additionally, abamectin (Syngenta, Crop Protection, Greensboro, NC), another seed treatment, has also proven to support lower population levels of *M. incognita* on cotton (Monfort et al., 2006). Foliar nematicides allow the advantage of a post-emergent application that can be used in conjunction with pre-emergent nematicide treatments to further maximize protection (Faske and Starr, 2009). It has been demonstrated that oxamyl (Vydate® C-LV, Corteva, Wilmington, DE), a post-emergent nematicide, succeeding an in-furrow application of aldicarb (AgLogic™ 15G, Chapel Hill, NC) at planting ensures sufficient plant growth while reducing *M. incognita* and *R. reniformis* levels (Lawrence and McLean, 2000, 2002). Aldicarb can be utilized as in-furrow granular to diminish *R. reniformis* populations and increase seed cotton yield (Lawrence et al., 1990).

Nematicides provide growers with a variety of chemicals that can be applied prior to planting, at planting, or after planting through several different methods of application that can accommodate different production practices (Hajihassani, 2018). Nematicides remain as the most effective management strategy to minimize crop injury induced by *M. incognita* and *R. reniformis* (Lambert and Bekal, 2002). However, relying on a single management practice for plant-parasitic nematodes does not provide sufficient protection (Lawrence et al., 1990). A comprehensive approach that encompasses several control measures is recommended to achieve maximum profit (ACES, 2021). At the source of a successful nematode management plan is timely soil sampling. Early detection of specific nematodes present, their density level, and distribution throughout a field is crucial for avoiding substantial yield losses (Wrona et al., 1996).

Small Grain Cover Crops

Winter cover crops are used in rotation with summer cash crops to protect and maintain soil quality during winter months (Clark, 2015). Cover cropping was first introduced to U.S. agriculture in the 1860s and was a fundamental practice up until the formulation of synthetic fertilizers in the 1950s. The popularity of cover crops quickly declined as synthetic fertilizers gained recognition as a relatively rapid, inexpensive method for soil enhancement (White, 2014). However, as increased fertilizer and pesticide use has taken a toll on the environment, cover cropping has become a pillar for sustainable agriculture (Westphal, 2011). Additionally, research efforts dedicated to conservation-agriculture have revealed the numerous benefits provided by cover crops (Price et al., 2008), allowing them to make a comeback. A USDA farm survey over a 4-year period reported a 50-percent increase in cover crop acreage between the years of 2012 and 2017, with corn-for-silage and cotton fields having the highest adoption rates. At the conclusion of this survey in 2017, the cover crop acreage across the U.S. was recorded at 15.4 million acres. Additionally, this experiment determined that growers who implemented cover crops into their cropping systems were more likely than other growers to adopt other conservation practices, further maximizing their on-farm benefits through sustainable agricultural practices (Wallander et al., 2017).

Cover crops provide excellent coverage that protects the soil surface from wind and water erosion (Balkcom et al., 2020). Maintaining living roots in the ground year-round not only reduces erosion by protecting the soil structure, but also improves tilth and aeration that create a healthy environment for future plant growth (Magdoff and van Es, 2021). One of the greatest advantages of cover crops is their contribution to soil organic matter by increasing the quality and quantity of fresh carbon recycled to the soil (Town et al., 2022). This is particularly important to implement following low residue crops like cotton (Wallander et al., 2021). Optimal levels of soil organic matter promote soil health and fertility by enhancing aggregate stability, water infiltration, and providing nourishment for soil organisms (Gaskin et al., 2020; Town et al., 2022). Cover crops are also useful for regulating soil temperature and moisture and acting as a natural means for weed and pest suppression (Raper et al., 2009).

In the southern U.S., winter small grains are often used as cover crops before planting cotton (SARE, 2012). Wheat, rye, and oats are more commonly planted throughout the Southeast, where barley production is limited in some regions, and triticale [a hybrid of wheat and rye (x *Triticosecale* Wittmack)] is still gaining recognition as an important crop (Buntin and Cunfer, 2017). A USDA experiment that examined cover crop adoption in cropping systems over a 4-year period recorded winter wheat as the most implemented cover crop in cotton production systems in 2015 followed by rye, oats, and other (barley, etc.), respectively (Wallander et al., 2021). The fundamental purpose of a winter cover crop is to maintain living roots in the ground to protect and improve the soil during a time of the year when the soil would normally be bare (Magdoff and van Es, 2021). However, some small grains, when managed properly, can be harvested for silage, cut and baled for hay, grazed for forage (Lee et al., 2017), or harvested for grain (Tyson and Hammond, 2017), creating new sources of income for growers. Silage offers higher nutritive value in its feed compared to hay, but hay can provide a good source of dry feed (Byers, 1965). An integrated crop-livestock system combines foraging and crop production in the same field (Russelle et al., 2007). Small grains can be established in the fall and grazed during the vegetative state in late fall and spring, when nutritive value is highest (Lee et al., 2017). Furthermore, the long growing seasons and mild winters of the southern U.S. provide a suitable environment for small grains, especially wheat, to be double-cropped with cotton (SARE, 2012). Nonetheless, for a small grain cover crop to be incorporated for any of the previously mentioned purposes, careful consideration for small grain crop and cultivar selection should be taken (ACES, 2021).

Wheat is the most significant cash grain crop in the southern U.S. (Buntin and Cunfer, 2017) and has the greatest potential to be double-cropped or relay-intercropped (planting cotton into wheat) with cotton (Barber at al., 2013; Foote et al., 2014; Buntin and Cunfer, 2017). A major concern for double-cropped cotton and wheat is sub-optimal cotton lint yields that may result from delayed cotton growth and development due to later planting dates, which allow wheat to reach maturity (Stewart et al., 2007). However, the development of early maturing wheat and cotton cultivars has made double-cropping possible (Barber et al., 2013). Wheat is also widely used for grazing, providing sufficient forage later in the spring, and is commonly harvested for silage (Lee et al., 2017). Rye is another dependable small grain crop grown in the Southeast due to its greater cold tolerance and ability to produce economic yields on marginal soils. Rye is more commonly planted for livestock grazing but can also be harvested as grain for livestock feed or flour for human consumption (Bland et al., 2017). Rye also has the potential to be harvested for silage and incorporated into double-cropping systems (Lee et al., 2017). However, rye is known to release allelopathic compounds in its residue that can be antagonistic to cotton seedling emergence if not managed properly (Bauer and Reeves, 1999), which may limit its use as a double crop if time between crops is insufficient for leaching. Both wheat and rye have flexible planting dates, are considerably more winter hardy than other small grains, and have high tolerance for disease, which makes them well-adapted winter cover crops for cotton production in the southern regions of the U.S. (Tyler et al., 2000).

Oat and barley offer exceptional nutritive value in their forages for livestock, but they are highly susceptible to disease and prone to winterkill, which makes them less adapted to some regions of the Southeast (Beck et al., 2013). Oats provide the greatest forage quality for livestock but are more suited for production in central and southern regions of the U.S. where they are more likely to survive the winter months (Mask et al., 2017). Barley is an excellent grain feed for cattle, but its production is limited to the Upper Coastal Plain and northern sections of the southeastern states with less humidity and disease pressure (Cunfer and Mask, 2017). Oats are a highly palatable forage for grazing livestock and can offer high yields of good quality silage (Mask et al., 2017). Barley is not recommended for grazing in the Lower Coastal Plain due to insect and disease pressure, but in adapted regions of the Southeast, barley may be grazed as early as six weeks after planting or can be harvested for grain to be supplemented in livestock feed (Cunfer and Mask, 2017). Triticale is a winter hardy crop that is gaining recognition as an effective cover crop for soil improvement (Ayalew et al., 2018). Triticale combines the winter hardiness and abundant biomass of rye and the nutritive value and high grain yields of wheat that make it an excellent forage to be grazed, but it is more profitable being utilized for feed grain, especially in swine production (Barnett et al., 2017). Oat, barley, and triticale require more specific growth requirements, but when managed properly in well-adapted regions, they can be profitable (ACES, 2021).

Small grain cover crops allow growers the option to maximize land use by either utilizing them as forages or feed or incorporating them into a double-crop system (Lee et al., 2017; SARE, 2012). To achieve maximum benefits of a small grain cover crop used in cotton production, careful consideration for plant selection, planting date, fertilization, termination date, and termination method are crucial (Balkcom et al., 2020). In a crop-livestock integrated system, not only is it important to choose a forage that is compatible with a specific region but deciding when forage needs to be available in a system will also determine which small grain cover crop to plant (Undersander et al., 2002). For small grains to provide sufficient forage in the fall and early winter, they must be seeded earlier and at higher rates than small grains planted for grain production. Small grains intended for grain production should be seeded during optimal planting dates for the specific area to reach maximum yield potential (Bates and Burns, 1999).

The feasibility of a small grain cover crop to be harvested for forage or grain requires an in-depth evaluation of the cropping system. Nonetheless, the use of a winter cover crop is a technology that can make a difference for the management of the most important plant-parasitic nematodes in cotton, *M. incognita* and *R. reniformis*. Research efforts continue for alternative methods to manage plant-parasitic nematodes that will improve cotton yield, but also align with the core components of sustainable agriculture. Cover crops can be beneficial for management of plant-parasitic nematodes while also promoting soil quality and fertility, which supports the groundwork for sustainable agriculture. This research contributes to the use of small grain cover crops to be incorporated into a sustainable nematode management program for cotton production.

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Figure 1: Geographic distribution of *Meloidogyne incognita* infestation in field crops across the United States (Adapted from Faske et al., 2023)

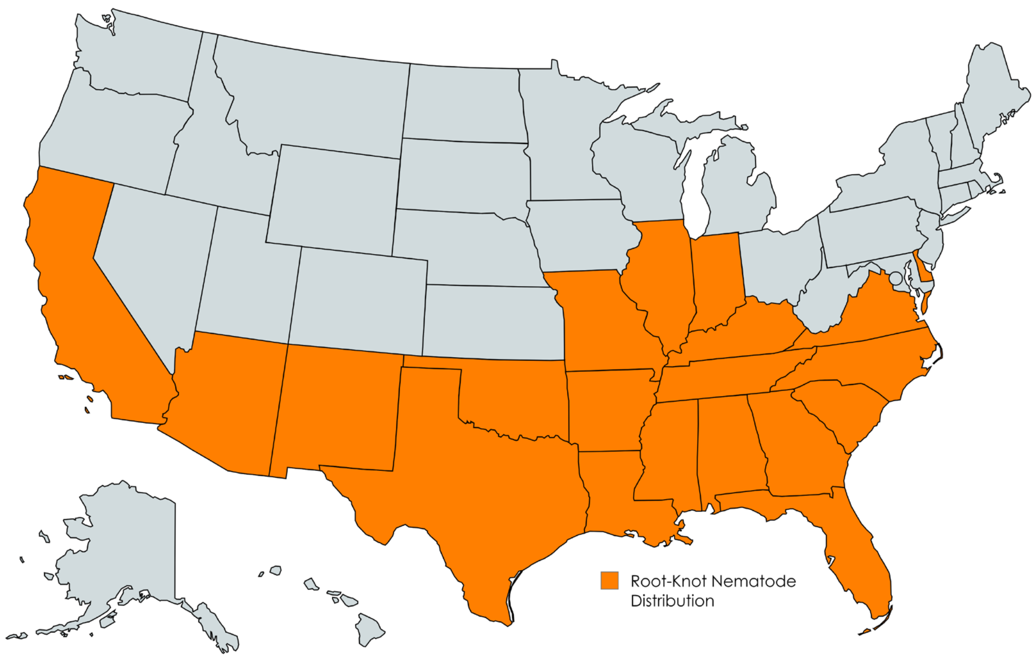


Figure 2. Average daily temperatures near Shorter, AL from monthly climatological summary at E. V. Smith Research Center in Shorter, AL. The dashed line indicates the base developmental threshold (10 °C) for *Meloidogyne incognita*. The solid line indicates the base developmental threshold (25 °C) for *Rotylenchulus reniformis*.

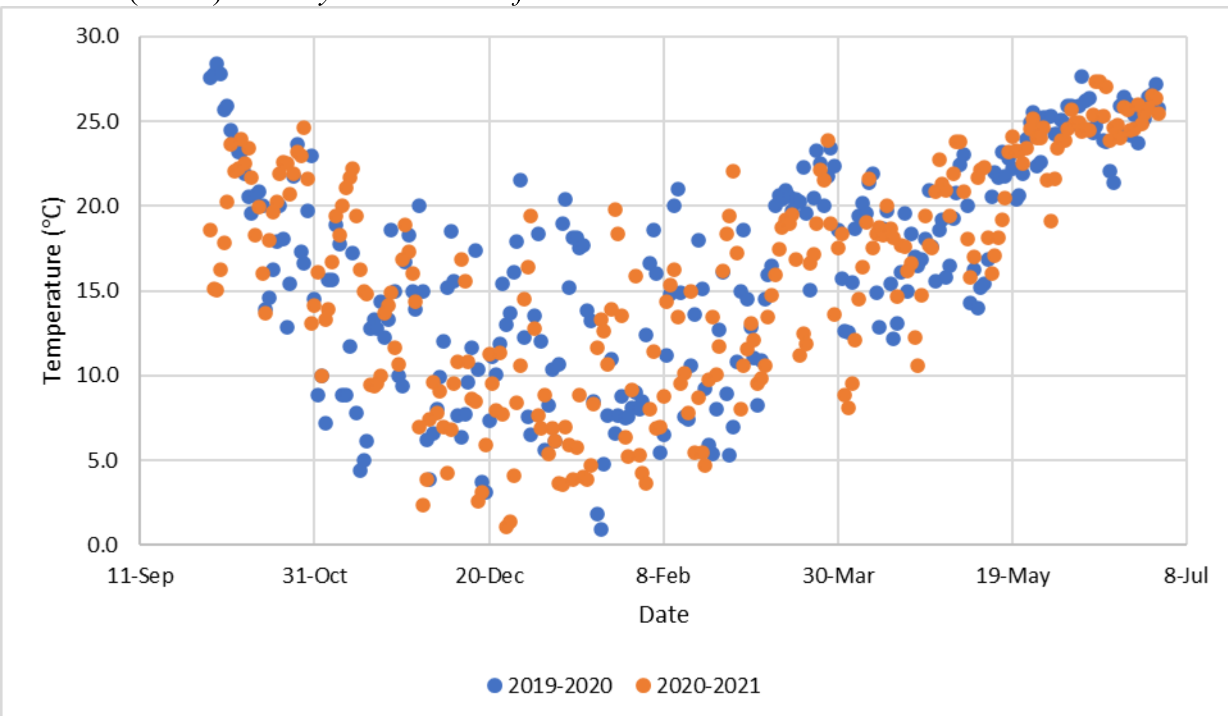
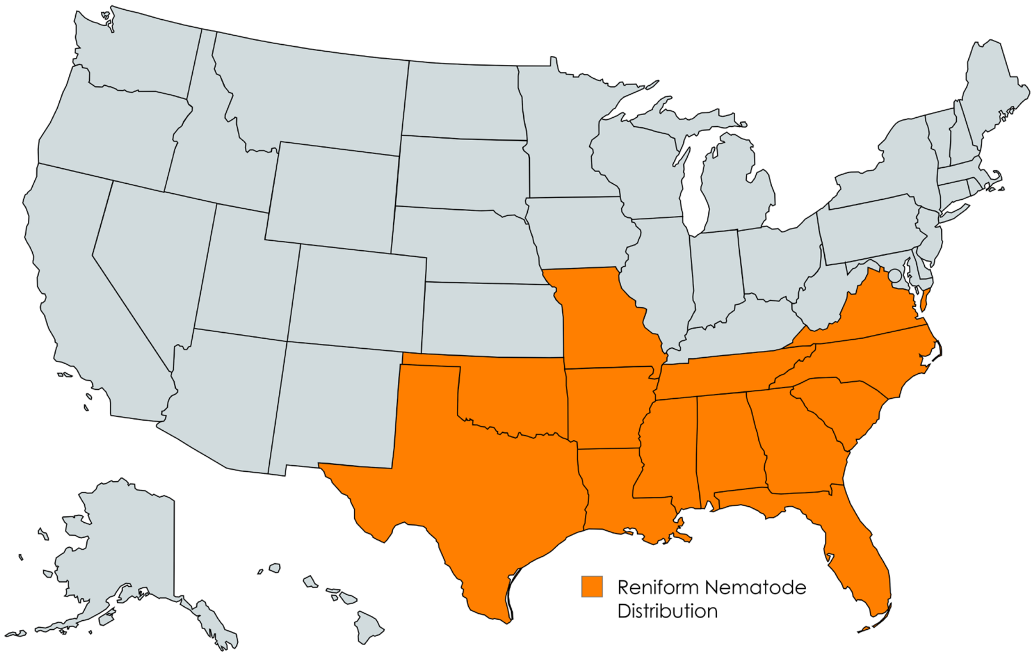


Figure 3: Geographic distribution of *Rotylenchulus reniformis* infestation in field crops across the United States (Adapted from Faske et al., 2024)



Chapter 2: Evaluation of small grain cover crops as a sustainable nematode management strategy for *Meloidogyne incognita* and *Rotylenchulus reniformis* on *Gossypium hirsutum* in the southeastern U.S.

Introduction

In southeastern U.S. cotton production, there is a need for more sustainable management strategies for *M. incognita* and *R. reniformis* that effectively reduce nematode populations while supporting optimal plant growth and yield. Crop rotations with cover crops are effective in naturally disrupting disease cycles for plant-parasitic nematodes that may reduce the intensive use of herbicides and pesticides (Phatak and Diaz-Perez, 2012). Studies quantifying *M. incognita* reproduction levels on small grain and legume cover crops in cotton production fields determined that small grains are more effective in limiting *M. incognita* reproduction (Timper et al., 2006; Wang et al., 2004). Similarly, research shows that small grain cover crops (rye, wheat, and black oat) support lower population density of *R. reniformis* compared to some legume cover crops (Jones et al., 2006). Strategically incorporating small grain cover crops into an integrated nematode management plan is an environmentally conscious strategy for maintaining *M. incognita* and *R. reniformis* level below their damage thresholds (Roberts, 1993). Furthermore, small grains can be used for livestock grazing or harvested for grain that may allow growers to maximize their land use and create new sources of income (Lee et al., 2017; Tyson and Hammond, 2017).

Meloidogyne incognita [(Kofoid and White) Chitwood] is a major pest of cotton and is found in all cotton producing states in the U.S. (Thomas and Kirkpatrick, 2001). It feeds as a sedentary endoparasite, blocking the passage of water and nutrients within the vascular tissue of the host plant (Lambert and Bekal, 2002). Root infection by *M. incognita* results in the formation of large galls on the plant's root system, which is the most diagnostic symptom of *M. incognita* damage (Jones et al., 2013). Reduced water and nutrient uptake contribute to the development of above-ground symptoms, such as wilting, stunting, yellowing and yield reduction (Lawrence and Lawrence, 2020). *Meloidogyne incognita* requires at least 18 °C to remain active in the soil but can develop and reproduce at temperatures as low as 10 °C if root infection has already taken place (Roberts et al., 1981). It has an extensive host range of over 2,000 plant species among important agronomic and horticultural crops and various weed species, which makes management efforts challenging (Starr et al., 2007). Effective management of *M. incognita* is largely dependent on synthetic nematicides, which constitutes a threat for environmental and human safety. The integration of cover crops may be an alternative for managing plant-parasitic nematodes that may alleviate the exhaustive use of nematicides.

Rotylenchulus reniformis (Linford and Oliveira) is increasingly problematic throughout the U.S. cotton belt. It is well-adapted to tropical and subtropical regions and soils with high silt and clay concentrations (Kinloch and Sprenkel, 1994). *Rotylenchulus reniformis* feeds on plant roots as a semi-endoparasite that causes injury to cotton plants producing symptoms, such as irregular and stunted plant growth, limited root development, and reduced boll size and yield (Lawrence and Lawrence, 2020). In most temperate climates, *R. reniformis* requires at least 25 °C to reproduce; however, in more tropical regions, it can reproduce at 15 °C with adequate soil moisture (Heald and Inserra, 1988). Under optimal conditions, *R. reniformis* can complete its life cycle within 25 to 30 days (Birchfield, 1962). Its rapid reproduction rate can cause *R. reniformis* to be a severe a problem for growers if not properly managed (Greer et al., 2009). Growers rely heavily on nematicides to reduce *R. reniformis* population levels in cotton production fields (Starr et al., 2007). There is a need for alternative management strategies that are less of a risk for sustainable agriculture but allow growers to maintain their current production levels.

Crop rotation with cover crops is a critical management tool that can help reduce nematode population levels by outcompeting weeds that may serve as alternate hosts for plant-parasitic nematodes and creating a suitable environment for soil microorganisms that can be antagonistic to these soil-borne pathogens (Phatak and Diaz-Perez, 2012). Furthermore, there are numerous benefits provided by cover crops beyond nematode management that can improve the physical characteristics of the soil (Price et al., 2008; Town et al., 2022). Small grain cover crops are favored in the Southeast compared to other cover crop options due to their greater cold tolerance and abundant above-ground biomass that protects the soil structure and improves soil quality (SARE, 2012).

Cover crops are primarily defined by their use for soil health benefits. The USDA specifically defines cover crops as being used primarily for erosion control, soil health improvement, and water quality enhancement (USDA-NRCS 2019). This distinction is crucial, as cover crops are not considered 'crops' for insurance purposes (Wallander et al., 2021). The adoption of cover crops has been substantially driven by financial incentive programs offered at both the federal and state levels. In 2018, approximately one-third of the acreage planted with cover crops received financial assistance payments from various programs (Wallender et al., 2021). Between 2011 and 2015, the total acreage enrolled in the USDA's Conservation Stewardship Program (CSP) for cover crop practices increased from approximately 350,000 acres to more than 2 million acres (Wallander et al., 2021). Additionally, state-level incentive programs supported over 1 million acres of cover crops in 2018 across at least 22 states (Wallander et al., 2021).

While cover crops are primarily grown for soil health benefits, there is potential for dual-purpose use with small grain cover crops. According to USDA-NRCS (2019) guidelines, cover crops may be grazed or harvested as hay or silage, unless prohibited by specific crop insurance policy provisions. However, they cannot be harvest for grain or seed under these programs (USDA-NRCS 2019). For growers not participating in financial assistance programs, there may be opportunities to optimize small grain cover crops for grain. This flexibility could provide additional economic benefits to growers while still maintaining the soil health advantages of cover cropping. By carefully selecting varieties, adjusting planting dates, and managing fertility, growers can potentially harvest a marketable grain crop while preserving the soil-improving qualities of cover crops. This strategy can diversify income streams and make more efficient use of land throughout the year (Schipanski et al., 2014).

The purpose of this experiment was to assess the capability of small grain cover crops to reduce *M. incognita* and *R. reniformis* population density in environments in the Southeast that traditionally experience warm winter temperatures, which may support nematode reproduction on these winter cover crops. The objectives of this research were 1) to determine the effectiveness of small grain cover crops as an additional sustainable nematode management strategy by measuring reproduction of *M. incognita* and *R. reniformis* on fall-planted small grains in cotton production fields; and 2) analyze the forage quality and quantify the grain yield of the small grain cultivars to assess their potential as dual-purpose crops.

Materials and Methods

Greenhouse experiments were used to measure the reproductive potential of *M. incognita* on some small grain cover crops and field experiments were conducted to measure reproductive potential of *M. incognita* and *R. reniformis* on small grain cover crops in cotton (*Gossypium hirsutum*) production fields in Alabama.

<u>Greenhouse Experiments</u>

In 2019, greenhouse experiments were conducted at the Plant Science Research Center (PSRC) in Auburn, AL. A Kalmia loamy sand soil (80% sand, 10% silt, 10% clay), acquired from the Plant Breeding Unit of the E.V. Smith Research Center near Tallassee, AL, was used for all experiments. The soil was steam pasteurized at 80 °C for 90 minutes and cooled for 24 hours; the process was repeated once more to prevent the regeneration of potential plant pathogens. The pasteurized soil was mixed with sand to a combined ratio of 60:40 soil: sand. Prior to use, fertilizer and lime were added to the soil according to recommendations specified by the Auburn University soil, forage, & water testing laboratory. All tests were performed in 150 cm^3 plastic cone-tainers (Stuewe & Sons, Inc., Tangent, OR). Advanced breeding lines from OreGro Seeds, INC. (Albany, OR) and commercial varieties across four small grain crop groups were tested with *M. incognita* to determine the host susceptibility of the small grain cover crops. The four small grain groups tested included eight triticale (X *Triticosecale* Wittmack), five barley (*Hordeum vulgare*), four wheat (*Triticum aestivum*), and three oat (*Avena sativa*) cultivars in comparison to DEKALB DKC68-26 corn (*Zea mays*) for *M. incognita* host susceptibility. Four seeds of each variety of small grain and two seeds of DKC68-26 corn were planted 1 cm deep in each cone-tainer. Small grain plants were thinned to two plants per cone after germination. Tests were planted in the fall with greenhouse temperatures ranging from 24 °C to 35 °C, and supplemental lighting was supplied via 1000-watt halide bulbs producing 110,000 lumens at a rate of 14 hours per day. Plants were watered as needed to maintain soil moisture between 40% and 60%. All plants were inoculated with *M. incognita* eggs 7 days after emergence (DAE).

Nematode Inoculum

Inoculum was prepared at the PSRC from stock cultures of *M. incognita* maintained on DEKALB DKC68-26 corn in 500 cm^3 polystyrene pots in the greenhouse. *Meloidogyne incognita* eggs were extracted from the corn roots by agitating the root systems in a 0.625% NaOCl solution on a Barnstead Lab Line Max Q 5000 E class shaker for 4 min at 120 rpm (Conquer Scientific: San Diego, CA) (Hussey and Barker, 1973). Roots were then washed under tap water and eggs were collected on a 25-µm pore sieve. The contents collected from the 25-µm pore sieve were processed by sucrose centrifugation-flotation at 240 g-forces for 1 minute (Jenkins, 1964). An inverted TS100 Nikon® microscope was used at 40x magnification to confirm the presence of *M. incognita* and enumerate eggs to a standardized 2,000 eggs/ml where 1 ml was pipetted into each cone-tainer 7 DAE of small grain and corn plants in the greenhouse.

Data Collection

Two greenhouse experiments with *M. incognita* were conducted. The small grain cultivars were tested in a randomized complete block design (RCBD) with five replications. Both greenhouse experiments were terminated 42 days after planting. Timing of germination was not recorded. Plant height and root fresh weight were collected for each experiment. When *M. incognita* was present, total nematode eggs per cone-tainer and eggs per gram of root were also recorded. *Meloidogyne incognita* eggs were extracted from small grain and corn roots and enumerated as previously described. Reproduction factor was determined as Rf = Pf (final population)/Pi (initial population) as specified by Oostenbrink (1966). The Rf values were grouped into four categories as follows: Rf=0-0.09, nonhost; Rf=0.1-0.9, poor host; Rf=1-2, moderate host; Rf>2, suitable host (Oostenbrink, 1966).

<u>Field Experiments</u>

Nematode Field Experiments

Field experiments examining small grain winter cover crops were conducted from 2019 to 2021 under *M. incognita* stress at the Plant Breeding Unit (PBU) in Tallassee, AL (Figure 4) and under *R. reniformis* stress at the E.V. Smith Research Center (EVS) in Shorter, AL (Figure 5). These experiments analyzed a larger selection of small grain cover crops than what was tested in the greenhouse including, 14 triticale, 5 barley, 5 oat, 4 wheat, and 3 rye (*Secale cereale* L.) cultivars. The small grain cultivars were a combination of advanced breeding lines from OreGro Seeds, INC. (Albany, OR) and additional commercial cultivars. Both field experiments were maintained by research station personnel throughout the winter growing season. Small grain winter cover crop experiments were established in fields previously grown in cotton. PBU is naturally infested with *M. incognita* and has a Kalmia loamy sand soil (80% sand, 10% silt, 10% clay) classification. At EVS, fields are naturally infested with *R. reniformis,* and the soil is a Compass loamy sand (76% sand, 13.6% silt, 10.4% clay). In all field experiments, the small grain cultivars were organized within their respective crop group and were arranged in a RCBD with 5 replications. Prior to planting, the seedbed was prepared with a KMC field cultivator and a Lely roterra tiller. The small grain cover crops were drilled at 100 grams of seed per plot with a Hege field plot grain drill (Hege Equipment Inc., Colwich, KS) at 19.1 cm row spacing. Individual plots were 6.1 m in length and 1.2 m in width with 3 m alleys in between replications. The 31 small grain cultivars were sown in fields with *M. incognita* at PBU on November 20, 2019, and November 13, 2020. The same small grain cultivars were established at EVS in fields with *R. reniformis* on October 3, 2019, and November 16, 2020. Fertility management in both years at both locations included an application of 17-17-17 at 14 kg/ha on the same day as planting prior to drill-seeding. A broadcast application of 33-0-0 was applied in mid-February in both years at PBU. At EVS, 33-0-0 was broadcasted in late January during the 2019-2020 growing season and in mid-February during the 2020-2021 growing season. Grain was harvested using an ALMACO R1 rotary single plot combine (Nevada, Iowa). In the 2019-2020 growing season, grain was harvested on June 12, 2020, at PBU and on May 21, 2020, at EVS. In the 2020-2021 growing season, grain was harvested on June 17, 2021, at both locations.

Nematode Field Data Collection

The population density of *M. incognita* and *R. reniformis* on the small grain cover crops near harvest were determined by collecting four random plant samples representative of each plot. In the first trial year, plant and root samples were collected from both PBU and EVS on May 11, 2020. In the second trial year, plant and root samples were collected from PBU on May 6, 2021, and from EVS on May 18, 2021. The four random plant samples were manually dug with a shovel from each plot. From these plant and root samples, measurements including, plant height, root fresh weight, and nematode eggs per gram of root were recorded. Plant and root samples were processed for nematodes as described in the greenhouse experiments. To compare the biomass yield between the small grain winter cover crops, a 30 cm square was randomly placed in each plot and the above-ground biomass was collected, leaving an 8 cm stubble, and then weighed. Biomass samples were not dried before weighing. In the 2019-2020 growing season at both locations, above-ground biomass cuttings were taken near harvest on May 11, 2020. In the 2020-2021 growing season, above-ground biomass cuttings were taken on May 6, 2021, at PBU and on May 18, 2021, at EVS.

<u>Forage Quality Field Experiments</u>

Field experiments were established at an on-farm location near Germanton, NC (Figure 6) in a region of the Southeast that is more adapted for cool-season annual grain production. The same 31 small grain cultivars tested in the nematode field experiments were planted in North

Carolina on October 19, 2019, and November 25, 2020, in a field that was previously sown in tall fescue. These small grains were measured for plant height, biomass yield, and forage quality. The experiments were managed by the grower at the on-farm site. Prior to planting in the 2019-2020 growing season, 3.36 kg/ha of glyphosate was applied to the field trial site to eliminate the established tall fescue crop, and the seedbed was then prepared with a Krause 2800 disk chisel followed by a Taylor-Way 590 Tandem Disc Harrow and Brillion Cultipacker. In both years, a pre-plant application of 17-17-17 and then a mid-season topdressing of 46-0-0 in late February were applied. The soil classification at this on-farm site is a Codorus loam (25% clay, 30% sand, 45% silt). In both experiments, the small grain cultivars were organized within their respective crop group and were arranged in a RCBD with 5 replications. The field experiments were seeded with a Clean Seeder AP 2-line push planter (Sutton Ag Enterprises, Salinas, CA) at 15.2 cm row spacing. Individual plots were 6.1 m in length and 1.2 m in width with 1.5 m alleys in between replications.

Forage Quality Data Collection

The grazing potential of these small grains was measured by biomass yield and forage quality analyses. Forage samples were collected by placing, randomly, a 30 cm square in each plot and cutting the biomass within the square leaving an 8 cm stubble. For each small grain cultivar, the biomass cuttings from all replications were combined for a representative sample and weighed. Biomass samples were not dried before weighing. One pound of the composite sample was packaged in a plastic bag and frozen before being shipped to the Dairy One Forage Lab (Ithaca, NY) for forage quality analysis. The forage quality of these small grain cover crops during the vegetative state was analyzed on April 15 and May 22 in 2020 and on April 15 and May 14 in 2021, and compared based on crude protein, acid detergent fiber, neutral detergent fiber, total digestible nutrients, and relative feed value. These criteria were used to evaluate the overall nutritive value of the small grains.

Statistical Analysis

Data collected from the greenhouse and field experiments were analyzed in SAS 9.4 (SAS Institute, Cary, NC) using the PROC GLIMMIX procedure. LS means were compared between individual cultivars and small grain crops using ANOVA and Tukey-Kramer multiple pair wise comparison at a significance level of $P \leq 0.05$. Dependent variables included plant height, root fresh weight, *M. incognita* and *R. reniformis* eggs per gram of root, biomass yield (kg/ha), and grain yield (kg/ha). Random effects included replication.

Results

Greenhouse Experiments

The greenhouse experiments demonstrated that the average *M. incognita* eggs per gram of root were greater in cone-tainers containing the small grains (triticale, wheat, oat, and barley) compared to the DK68-26 corn variety, with the exception of triticale cultivar, 'Forerunner' (Table 1). The average Rf values for cultivars of oat and triticale were 1.13 and 1.86, respectively, which were considered to be moderate hosts of *M. incognita* in the greenhouse setting. Barley and wheat cultivars averaged Rf values of 2.44 and 2.99, respectively, measuring to be suitable hosts in the greenhouse (Table 1). Three small grain cultivars, 'Forerunner' and 'OG170039' triticale and 'ORO 4372' oat, had Rf less than one indicating these specific cultivars were poor hosts for *M. incognita* (Table 1). All other cultivars tested among the small grain crops were determined to be either moderate or suitable hosts (Table 1).

Field Experiments

Meloidogyne incognita Field 2019-2020 and 2020-2021

In samples taken near harvest in the *M. incognita* field, rye cultivars had the greatest plant height of the small grain crops tested, followed by oat and triticale cultivars, respectively (Table 2). Barley and wheat cultivars, on average, were shorter than rye, oat, and triticale cultivars (Table 2). 'Abruzzi' rye was the tallest of the rye cultivars followed by 'Goku' and 'Elbon', respectively (Table 2). 'Shooter' oat, had the greatest plant height of the oat cultivars and was significantly greater than 'Intimidator', 'OG6285', and 'Buck Forage', respectively, of which had statistically similar plant heights to each other (Table 2). 'TAMO 411' was the shortest plant of the oat cultivars (Table 2). For triticale cultivars, the plant height measurements near harvest were statistically similar except for '158 EP', which was significantly shorter (Table 2). 'OG140760' was the tallest barley cultivar but was statistically comparable to 'OG140797' and 'Verdant', respectively (Table 2). 'Alba' and 'OG140789' barley cultivars had statistically similar plant heights but were significantly the shortest of the barley cultivars (Table 2). The tallest wheat cultivars were 'KGAL' and 'Willow Creek', respectively, followed by 'OG9484' and 'Summit 515', respectively, which were significantly shorter than 'KGAL' and 'Willow Creek' (Table 2).

For all small grain cultivars, biomass yield near harvest ranged from 3,257 to 47,559 kg/ha (Table 2). Biomass yield was numerically greater in the oat cultivars followed by rye, barley, triticale, and wheat cultivars respectively (Table 2).

Overall, oat cultivars had significantly greater yields compared to all other small grain cultivars, followed by triticale, barley, rye, and wheat, respectively (Table 2). Grain yield for all small grain cultivars ranged from 787 to 6,192 kg/ha (Table 2). All oat cultivars yielded statistically similar kg/ha with 'Buck Forage' supporting the greatest yield (Table 2). Within triticale, 'Doublet' yielded the greatest kg/ha followed by '158 EP', 'OG8783', and 'OG8782', respectively (Table 2). The remaining triticale cultivars had statistically similar yields to each other and were comparable to ‘158 EP’, ‘OG8783’, and ‘OG170039’, but yielded significantly less kg/ha than ‘Doublet’ (Table 2). The barley cultivars had statistically similar yields with ‘Alba’ supporting the greatest yield followed by ‘OG140760’, ‘OG140797’, ‘Verdant’, and ‘OG140789’ (Table 2). ‘Abruzzi’ had the greatest yield of the rye cultivars followed by ‘Goku’ and ‘Elbon’, respectively, and all rye cultivars had statistically similar yields (Table 2). All rye cultivars, ‘Abruzzi’, ‘Goku’, and ‘Elbon’, respectively, yielded statistically similar kg/ha (Table 2). Within wheat, ‘OG9484’ yielded the greatest kg/ha followed by ‘KGAL’ (Table 2). The remaining wheat cultivars, ‘Summit 515’ and ‘Willow Creek’, respectively, had statistically similar yields to each other and ‘KGAL’, but were significantly shorter than ‘OG9484’ (Table 2).

The total seasonal *Meloidogyne incognita* numbers per gram of root were statistically similar between the cultivars in each small grain group (Table 2). Barley cultivars supported the greatest total seasonal *M. incognita* per gram of root followed by oat, wheat, triticale, and rye, respectively (Table 2).

Rotylenchulus reniformis Field 2019-2020 and 2020-2021

In the *Rotylenchulus reniformis* field experiment, rye cultivars had the greatest plant height followed by oat, triticale, barley, and wheat, respectively (Table 3). ‘Abruzzi’ was the tallest rye cultivar followed by ‘Goku’ and ‘Elbon’, respectively, and all rye cultivars had statistically similar plant height (Table 3). Within the oat cultivars, ‘Shooter’ was the tallest on average followed by ‘Buck Forage’ and ‘OG6285’, respectfully, which were statistically similar to each other, but significantly taller than ‘Intimidator’ and ‘TAMO 11’, respectfully (Table 3). All triticale cultivars had statistically comparable plant height, except for ‘OG8782’ and ‘158 EP’, respectively, which were significantly shorter (Table 3). For barley, ‘OG140760’ had the greatest plant height of the barley cultivars followed by ‘Alba’, ‘OG140797’, and ‘Verdant’, respectively (Table 3). ‘OG140789’ was significantly shorter on average than all other barley cultivars (Table 3). Within the wheat cultivars, ‘KGAL’ and ‘OG9484’, respectively, had the greatest plant height followed by ‘Willow Creek’ (Table 3). ‘Summit 515’ had statistically similar plant height to ‘Willow Creek’ but was significantly shorter than ‘KGAL’ and ‘OG6285’ (Table 3).

For all small grain cultivars, biomass yield near harvest ranged from 4,659 to 23,228 kg/ha (Table 3). Biomass yield was numerically greater in the oat cultivars followed by triticale, rye, wheat, and barley, respectively (Table 3).

Barley cultivars supported the greatest grain yield followed by rye, oat, wheat, and triticale cultivars, respectively (Table 3). ‘Alba’ barley yielded the greatest kg/ha followed by ‘OG140760’, ‘OG140797’, and ‘OG140789’, respectively, and were statistically similar to ‘Alba’ (Table 3). ‘Verdant’ yielded the lowest kg/ha and was significantly shorter than ‘Alba’, but statistically similar to all other barley cultivars (Table 3). ‘Abruzzi’ had the greatest grain yield for rye cultivars followed by ‘Elbon’ and ‘Goku’, respectively, which had statistically similar yields (Table 3). Within the oat cultivars, ‘TAMO 411’ had significantly greater yield of all oat cultivars followed by ‘OG6285’, ‘Buck Forage’, ‘Shooter’ and ‘Intimidator’, respectfully. There was no significant difference in grain yield for cultivars of wheat and triticale (Table 3).

The total seasonal *R. reniformis* numbers per gram of root were statistically similar between the cultivars in each small grain group (Table 3). Oat, barley, and rye cultivars supported equal and the greatest total seasonal *R. reniformis* per gram of root followed by triticale and wheat, respectively (Table 3).

North Carolina Forage Quality 2019-2020 and 2020-2021

In the forage quality experiments in North Carolina, rye cultivars were the tallest small grain followed by oat, triticale, barley, and wheat, respectively (Table 4). There were no significant differences in plant height within the cultivars of rye and of oat (Table 4). All triticale cultivars had statistically similar plant height except for ‘OG8782’ and ‘158 EP’, respectively, which were significantly shorter (Table 4). Within the barley cultivars, ‘OG140760’ had the greatest plant height and was statistically similar to ‘OG140797’ and ‘Verdant’ but was significantly greater than ‘Alba’ and ‘OG140789’ (Table 4). ‘OG140789’ was significantly the shortest of all barley cultivars (Table 4). For wheat, ‘Willow Creek’ supported the greatest plant height followed by ‘KGAL’, which had statistically similar plant height (Table 4). ‘OG9484’ and ‘Summit 515’, respectively, had statistically similar plant height to ‘KGAL’ but were significantly shorter than ‘Willow Creek’ (Table 4).

For all small grain cultivars, biomass yield in the vegetative phase ranged from 3,048 to 7,128 kg/ha (Table 3). Biomass yield in the vegetative phase was numerically greater in the oat cultivars followed by triticale, rye, wheat, and barley, respectively (Table 3). Overall, crude protein (CP) concentrations of the small grain crops ranged from 17.8 to 28.1 % (Table 4). The highest CP concentrations were supported by wheat cultivars, followed by triticale, oat, barley, and rye, respectively (Table 4). Percent acid detergent fiber (ADF) for all small grain crops ranged from 23.2 to 31.4 % (Table 4). Rye and triticale cultivars had the highest and almost equal percent ADF followed by wheat, barley, and oat, respectively (Table 4). Percent neutral detergent fiber (NDF) for all small grain crops ranged from 39.3 to 53.1 % with the highest NDF concentrations supported by rye cultivars followed by triticale, wheat, barley, and oat, respectively (Table 4). Percent total digestible nutrients (TDN) for all small grain crops ranged from 64 to 71 % (Table 4). Oat cultivars had the greatest % TDN followed by barley, rye, triticale, and wheat, respectively (Table 4). The relative feed value (RFV) index for all small grain crops ranged from 116 to 168 (Table 4). The highest RFV indices were supported by oat cultivars followed by barley, wheat, triticale, and rye, respectively (Table 4).

Discussion

Greenhouse Experiment

All small grain cultivars evaluated in the greenhouse showed higher average *M. incognita* eggs per gram of root compared to the standard DK68-26 corn variety that was included in the tests as a standard comparison. The Rf values revealed varying levels of host suitability for *M. incognita* among the small grain cultivars. Overall, barley and wheat demonstrated high suitability as host plants, while triticale and oat exhibited moderate host potential. Notably, two triticale cultivars, 'Forerunner' and 'OG170039' and one oat cultivar, 'ORO 4372' stood out as poor hosts, exhibiting Rf less than one indicating the *M. incognita* population was not sustained. A similar greenhouse experiment by Ibrahim et al. (1993) also revealed variation in host suitability among cultivars of barley, corn, oat, rye, sorghum, triticale, and wheat. However, in this greenhouse experiment, corn was more susceptible to *M. incognita* infection than the small grains tested except for barley. Barley was the most suitable host of *M. incognita* (Ibrahim et al., 1993). These findings from 20 years ago are similar to our experiment indicating potential variability in the nematode suppressive capabilities of different small grain cultivars.

Field Experiments

Meloidogyne incognita Field 2019-2020 and 2020-2021

Despite variations in plant growth and grain yield across the small grains, nematode populations did not vary significantly. Total seasonal nematode numbers per gram of root were statistically similar between the cultivars within their respective small grain group. Observed differences in plant height and grain yield were likely due to attributes that were crop-specific rather than to *M. incognita* infection. In an experiment by Roberts et al., (1981) where the effects of *M. incognita* on winter wheat grain yield and the influence of soil temperature and planting date on *M. incognita* development, reproduction, and winter survival determined that *M. incognita* is capable of infecting autumn-sown wheat plants and completing one generation during the winter season. This experiment saw comparable results to our findings in our field experiments where there was no significant difference in grain yield between infested and non-infested plots (Roberts et al., 1981). Furthermore, the experiment also demonstrated there were no visible differences in top growth, plant height, leaf color, and amount of tillering in November and December between young *M. incognita* infected and non-infected plants (Roberts et al., 1981). In our experiment, in the *M. incognita* field in both years, rye cultivars consistently exhibited the greatest plant height, followed by oat and triticale, while barley and wheat cultivars were shorter on average. Johnson et al. (1981) observed this same superiority in shoot growth of rye cover crops reporting four times more shoot growth in winter rye than spring oats that were grown in the fall and then winter-killed. Rye is known to be taller and quicker growing of the cereal crops, but it also the hardiest, being widely adapted across most climate zones (SARE, 2012). Oats are another widely adapted cover crop recognized for its tall, upright growth reaching heights 1 meter and greater (SARE, 2012). Triticale is not only a tall crop but offers a large canopy cover and performs well in less optimal environments (Ayalew et al., 2018). The tall stature of some rye, oat, and triticale cultivars can form a canopy that blocks sunlight from reaching weeds, allowing these cereal crops to outcompete weeds and enhance overall crop performance (Teasdale and Mohler, 2000). Allelopathic compounds are also known to be present in oat and rye roots that can naturally inhibit weed growth (Shirley et al., 1998) and nematode reproduction (Halbrendt, 1996). An experiment by Timper (2017) suggests that in addition to seeing improvements in soil structure, moisture retention, and weed control, growers may benefit from lower populations of *M. incognita* following a high-residue rye winter cover crop. Biomass yield near harvest ranged widely among the small grain cultivars, with oat cultivars yielding the greatest biomass followed by rye, barley, triticale, and wheat, respectively. Raper et al. (2008) demonstrated that high-residue small grains integrated into a conservative cotton production system, can be rolled when mature prior to cotton planting to conserve soil moisture. Oats are known to provide quick, weed-suppressing biomass that can provide sufficient ground cover as a mulch before low-till or no-till crops (Shirley et al., 1998). Additionally, oat cultivars had greater grain yields compared to all other small grain cultivars, followed by triticale, barley, rye, and wheat, respectively. Oats can be harvested for grain but require a longer growing season in the southeastern U.S. to optimize yield. In general, small grains planted too late are subject to winter damage that negatively effects yield (Mask et al., 2017). Wheat is widely grown in the winter as a cash grain in addition to its cover crop benefits, however, for wheat to be a successful grain crop it must be managed as such by selecting the right variety, timely planting, and monitoring soil fertility (SARE, 2012). Developmental variety, 'OG9484' wheat produced significantly greater grain yield compared to the other three wheat cultivars analyzed. It may be the 'OG9484' cultivar is more adaptive to the southeast region. These results highlight the intricate interplay between nematode management and agronomic performance in small grain cover crops. This knowledge is essential for developing tailored strategies that optimize both nematode control and crop productivity. Although there were no significant differences in total seasonal *M. incognita* egg population amongst the small grain cover crops, barley cultivars could potentially act as favorable hosts for *M. incognita* in the southeast, suggesting a need for careful consideration when selecting cover crops based on specific nematode management objectives.

Rotylenchulus reniformis Field 2019-2020 and 2020-2021

The same superiority in shoot growth of rye, oat, and triticale cultivars, respectively, that was observed in the *M. incognita* field was also observed in the *R. reniformis* field. Barley and wheat cultivars, on average, were the shortest of the winter small grain crops, which was also consistent with observations from the *M. incognita* field. Barley cultivars, although not advantageous in shoot growth or biomass production in the *R. reniformis* field, outperformed all other small grain crops in grain yield. Barley cultivars, along with oat and rye, also had the highest total seasonal *R. reniformis* eggs per gram of root. Overall, grain yield was low in the *R. reniformis* field compared to results from the *M. incognita* field, which may be due to poor field conditions following unseasonable weather that was observed in the second trial year, which submerged the plots on several occasions. There was little variability in grain yield between cultivars within their respective crop groups, with two notable exceptions. 'TAMO 411' oat and 'Abruzzi' rye demonstrated significantly higher grain yields compared to other oat and rye cultivars tested. Oat cultivars overall were the top producers of biomass, which was also noted in the *M. incognita* field. These results further confirm the premise that nematode populations may not influence crop performance of winter small grains, but more importantly as suitable hosts, may affect nematode levels that a subsequent cotton crop may be exposed to. Jones et al. (2006) determined in a cover crop field experiment utilizing wheat and rye in addition to leguminous cover crops that no increase in *R. reniformis* populations was observed over two consecutive cover cropping seasons under natural field conditions. However, when these cover crops were observed in rotation with cotton, there was a substantial increase in *R. reniformis* population density 120 days after emergence of cotton plants (Jones et al., 2006). In contrast, some studies show that cover crops like rye did not affect reniform nematode populations but did reduce cotton yields in certain regions (Molin and Stetina, 2013). More research is needed on the host suitability of winter small grain cover crops to *R. reniformis* to determine the best choice of a useful rotation crop in southeastern cotton production.

North Carolina Forage Quality Experiments 2019-2020 and 2020-2021

The forage quality experiments provided valuable insights into the nutritional value of the small grains tested. Plant height trends were consistent with findings in the nematode field experiments, with rye, oat, and triticale cultivars being taller than barley and wheat. In terms of forage quality, plant height serves as an important indicator of forage biomass and potential grazing or hay yield (Sollenberger and Cherney, 1995). The fresh biomass weights collected in these experiments were collected during each crop's vegetative stage when samples were required to be collected for forage quality analysis versus collecting fresh biomass weights near harvest in the nematode experiments. Rye cultivars showed superior biomass production during the vegetative stage. Nonetheless, in terms of forage production, the suitability of a cover crop to be utilized as a forage is reliant upon its forage quality (Snapp et al., 2005). Oat, barley, and rye cultivars had optimal crude protein concentrations for the fall and winter seasons (Ditsch and Bitzer (n.d.)). Triticale and wheat cultivars averaged slightly outside of the optimal range, which indicates potential for these crops to cause digestive issues if crude protein concentrations become too high (National Research Council, 2000). The acid detergent fiber (ADF) and neutral detergent fiber (NDF) concentrations for all small grains during the vegetative stage indicated potential for high fiber content and high digestibility values close to 30% and 40%, respectively (Rocateli, A. and Zhang, H. (n.d.)) with averages ranging between 25 to 27 % for ADF and 43 to

48 % for NDF. These small grains offer a well-rounded nutritional profile, providing sufficient fiber, digestibility, and available energy measured by their total digestible nutrients (TDN) (Rodehutscord et al., 2016). While high TDN levels are generally desirable for meeting energy needs of grazing animals, it's crucial to maintain a balanced approach. Excessively high TDN levels, without considering other nutritional factors could potentially lead to digestive issues (Owens et al., 1998). As plants mature, their TDN levels tend to decrease, further highlighting the importance of proper forage management and timing to ensure optimal forage quality and animal health (Rocateli, A. and Zhang, H. (n.d.)). Among the small grains, oats stand out as the most digestive-friendly option due to their high fiber content, minimizing the risk of gastrointestinal disturbances (Dhuyvetter, J. (n.d.)). Rye is generally less palatable compared to other small grains, while wheat should be consumed in moderation to reduce potential digestive issues (Dhuyvetter, J. (n.d.)). Our research has shown variations in fiber content among these small grains, with rye and triticale cultivars exhibiting the highest levels, followed by wheat and barley, while oat cultivars had the lowest fiber content. Barley and triticale forages are known for their superior nutrient profile and enhanced digestibility compared to oats and wheat (Khorasani et al., 1997). These differences in fiber and nutrient composition highlight the importance of carefully selecting and incorporating the appropriate small grains into livestock diets to ensure optimal digestive health and overall animal performance. Percent ADF is combined with percent NDF to produce the Relative Feed Value (RFV) index, which is used to compare forages to the standard forage quality found in full bloom alfalfa hay (Undersander et al., 2010). Alfalfa hay at full bloom has approximately 53 percent ADF and 41 percent NDF that establishes a baseline RFV of 100 (Moore and Undersander, 2002). This baseline is a popular metric used by both buyers and sellers to determine the best dollar value for quality hay. Forages possessing RFV

indices above 100 are considered to be of superior quality. (Rocateli, A. and Zhang, H. (n.d.)). All small grains sampled in the vegetative phase for forage analysis had RFV indices above 100, indicating superior quality compared to the alfalfa hay standard.

Conclusion

This comprehensive experiment provides crucial insights into the complex relationships between small grain cover crops, nematode populations, and agronomic performance. Through a combination of greenhouse and field experiments, this research revealed varying host suitability across the small grain cultivars for *M. incognita*, with some triticale and oat varieties demonstrating potential as poor hosts. Notably, field experiments for both *M. incognita* and *R. reniformis* indicated that nematode populations did not significantly impact crop performance, suggesting that crop-specific attributes play a more substantial role in determining plant height, biomass, and grain yield. Each small grain crop exhibited distinct advantages: oats demonstrated versatility in nematode management and high yields; rye excelled in height and biomass production, potentially enhancing weed suppression (Teasdale and Mohler, 2000); triticale offered balanced performance; barley showed high grain yield potential, particularly in *R. reniformis*-infested fields; and wheat provided superior crude protein content for forage. Forage quality analysis overall revealed that all small grains offer superior nutritional value compared to the alfalfa hay standard, with each crop presenting unique nutritional profiles. These diverse attributes underscore the importance of selecting cover crops based on specific management goals, including nematode suppression, biomass production, forage quality, and overall soil health improvement.

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Table 1. Host susceptibility of *Meloidogyne incognita* on commercial cultivars and developmental lines of winter small grains tested under greenhouse conditions at the Plant Science Research Center in Auburn, AL measured by average number of eggs per gram of root and reproductive factors.

Plant Science Research Center				
Cultivar	***M. incognita***			
	Eggs/g Root		**Rf Value[v]**	**Host Suitability**
Triticale (x *Triticosecale* Wittmack)				
Doublet[y]	2015	c	2.02	Suitable Host
Forerunner[y]	183	g	0.38	Poor Host
EST 2640	2473	b	2.89	Suitable Host
EST 2767	628	e	1.35	Moderate Host
EST 2824	2606	c	1.5	Moderate Host
ORO 4370	2420	d	3.01	Suitable Host
ORO 4371	4366	a	2.95	Suitable Host
OG170039	393	f	0.75	Poor Host
Crop Average	***1886***		***1.86***	
Wheat (*Triticum aestivum*)				
KGAL[y]	3579	a	3.68	Suitable Host
Summit 515[y]	3761	a	2.86	Suitable Host
Willow Creek[y]	1038	b	1.48	Moderate Host
ORO 4373	8773	a	3.93	Suitable Host
Crop Average	***4288***		***2.99***	
Oat (*Avena sativa*)				
Intimidator[y]	682	b	1.08	Moderate Host
Shooter[y]	1021	a	1.42	Moderate Host
ORO 4372	1666	c	0.89	Poor Host
Crop Average	***1123***		***1.13***	
Barley (*Hordeum vulgare*)				
Alba[y]	476	d	1.61	Moderate Host
Verdant[y]	403	e	1.11	Moderate Host
OG140760	5513	a	3.53	Suitable Host
OG140789	2155	b	2.84	Suitable Host
OG140797	1760	c	3.10	Suitable Host
Crop Average	***2061***		***2.44***	
Corn (*Zea mays*)				
DKC68-26	187		1.76	Moderate Host

[z]LS-means followed by the same letter are not significantly different at $P \leq 0.05$ as determined by the Tukey-Kramer method. Data is from two test combined for a total of 10 replications per small grain.
[y]Indicates commercial small grain cultivar.
[x]Rf= final population/initial population of *M. incognita.*
[w]Small grain cultivars were statistically analyzed within their respective crops.
[v]Rf values are grouped as follows: Rf=0-0.09, nonhost; Rf=0.1-0.9, poor host; Rf=1-2, moderate host; Rf>2, suitable host

Table 2. Plant height, dry matter, grain yield, and total seasonal *Meloidogyne incognita* population numbers on small grain cover crops planted on 20 November 2019 and 13 November 2020 at the Plant Breeding Unit in Tallassee, AL.

Plant Breeding Unit 2019-2021						
Cultivar	**Plant Height (cm)**		**Fresh Biomass Weight (kg/ha)**	**Grain Yield (kg/ha)**		**Total Seasonal *M. incognita* (eggs/g root)**
Triticale (x *Triticosecale* Wittmack)						
Doublet[y]	110	dc	21774	4516	a	5
Forerunner[y]	125	abc	16436	1547	b	3
Round Table[y]	113	bcd	10572	1586	b	1
158 EP[y]	75	e	4947	3028	ab	2
OG8782	96	de	6500	2250	b	3
OG8783	135	ab	17008	2781	b	4
OG170004	132	abc	20387	1827	b	2
OG170012	146	a	19879	1942	b	2
OG170023	129	abc	24542	2146	b	3
OG170035	138	a	22057	2070	b	1
OG170036	132	abc	22037	2110	b	5
OG170039	128	abc	17457	2235	b	2
OG170040	134	ab	22564	1928	b	2
OG170043	131	abc	16744	1966	b	1
Crop Average	***123***		***17350***	***2281***		***3***
Wheat (*Triticum aestivum*)						
KGAL[y]	92	a	23670	2117	ab	2
Summit 515[y]	65	c	3257	829	b	3
Willow Creek[y]	92	a	14612	787	b	3
OG9484	79	b	12457	3077	a	4
Crop Average	***82***		***13499***	***1702***		***3***
Oat (*Avena sativa*)						
Buck Forage[y]	129	b	15917	6192		6
Intimidator[y]	135	b	30606	1293		4
Shooter[y]	153	a	47559	2667		2
TAMO 411[y]	106	c	30147	4707		3
OG6285	130	b	25244	1992		5
Crop Average	***131***		***29895***	***3370***		***4***
Barley (*Hordeum vulgare*)						
Alba[y]	69	b	14629	2816		6
Verdant[y]	82	a	17129	2007		10
OG140760	89	a	17735	2456		18
OG140789	64	b	20879	1881		10
OG140797	83	a	20733	2231		6
Crop Average	***77***		***18221***	***2278***		***10***
Rye (*Secale cereale*)						
Abruzzi[y]	174		35830	2464		1
Elbon[y]	154		26665	1797		3
Goku[y]	161		23154	2303		3
Crop Average	***163***		***28550***	***2188***		***2***

[z]LS-means followed by the same letter are not significantly different at $P \leq 0.05$ as determined by the Tukey-Kramer method.
[y]Indicates commercial small grain cultivar.
[x]Small grain cultivars were statistically analyzed within their respective crop.

Table 3. Plant height, dry matter, grain yield, and total seasonal *Rotylenchulus reniformis* population numbers on small grain cover crops planted on 3 October 2019 and 16 November 2020 at E.V. Smith Research Center in Shorter, AL.

E.V. Smith Research Center 2019-2021						
Cultivar	**Plant Height (cm)**		**Fresh Biomass Weight (kg/ha)**	**Grain Yield (kg/ha)**		**Total Seasonal *R. reniformis* (eggs/g root)**
Triticale (x *Triticosecale* Wittmack)						
Doublet[y]	101	b	18790	1979		4
Forerunner[y]	116	ab	14307	1010		12
Round Table[y]	100	b	13668	748		5
158 EP[y]	69	c	8243	1381		5
OG8782	77	c	7618	1627		4
OG8783	117	ab	17677	1633		4
OG170004	119	a	14234	1069		2
OG170012	127	a	23228	1324		6
OG170023	120	a	14449	1037		7
OG170035	125	a	18912	1364		6
OG170036	119	a	18340	1239		3
OG170039	120	a	16876	1331		7
OG170040	119	a	17862	1061		6
OG170043	117	ab	17310	1346		5
Crop Average	***110***		***15822***	***1296***		***5***
Wheat (*Triticum aestivum*)						
KGAL[y]	85	a	19826	1154		3
Summit 515[y]	51	b	4659	755		5
Willow Creek[y]	65	ab	12621	1304		2
OG9484	84	a	11836	2126		3
Crop Average	***71***		***12235***	***1335***		***3***
Oat (*Avena sativa*)						
Buck Forage[y]	135	a	20768	1248	b	6
Intimidator[y]	114	b	21105	861	b	7
Shooter[y]	142	a	22853	984	b	8
TAMO 411[y]	110	b	19386	3151	a	3
OG6285	132	a	13839	1359	b	5
Crop Average	***127***		***19590***	***1521***		***6***
Barley (*Hordeum vulgare*)						
Alba[y]	74	b	9669	2171	a	10
Verdant[y]	71	b	9518	1256	b	6
OG140760	85	a	9801	1887	ab	4
OG140789	57	c	11866	1412	ab	7
OG140797	72	b	11612	1657	ab	5
Crop Average	***72***		***10493***	***1677***		***6***
Rye (*Secale cereale*)						
Abruzzi[y]	149		17467	2281	a	7
Elbon[y]	140		11905	1405	b	7
Goku[y]	145		10099	1178	b	4
Crop Average	***144***		***13157***	***1621***		***6***

[z]LS-means followed by the same letter are not significantly different at $P \leq 0.05$ as determined by the Tukey-Kramer method.
[y]Indicates commercial small grain cultivar.
[x]Small grain cultivars were statistically analyzed within their respective crop.

Table 4. Plant height and dry matter yield near harvest of small grain cover crops in the on-farm forage trial in Germanton, NC in the cool seasons of 2019-2020 and 2020-2021.

Cultivar	Plant Height (cm)		Fresh Biomass Weight (kg/ha)	% CP	% ADF	% NDF	%TDN	RFV
Triticale (x Triticosecale Wittmack)								
Doublet[z]	118	bc	4060	20.85	27.75	48.15	68.50	131
Forerunner[z]	125	bc	4283	24.30	26.30	45.90	67.50	140
Round Table[z]	116	bc	3477	20.35	28.40	50.95	67.00	123
158 EP[z]	82	d	3893	20.40	28.55	47.95	67.00	135
OG8782	97	d	5730	18.15	31.40	53.10	65.00	116
OG8783	143	ab	6350	21.70	28.30	48.40	68.50	132
OG170004	142	ab	5499	23.75	26.00	44.55	67.50	143
OG170012	157	a	5386	22.50	26.30	45.30	68.00	141
OG170023	141	ab	3923	23.05	25.65	41.45	69.50	155
OG170035	132	ab	4422	25.45	25.70	45.10	68.00	142
OG170036	135	ab	4379	22.35	26.60	44.55	69.50	143
OG170039	140	ab	5416	24.40	25.35	42.35	68.00	152
OG170040	136	ab	4828	25.85	27.35	42.05	66.00	150
OG170043	131	ab	4474	22.80	24.80	42.65	68.50	152
Crop Average	***128***		***4723***	***22.56***	***27.03***	***45.89***	***67.75***	***139***
Wheat (*Triticum aestivum*)								
KGAL[z]	100	ab	3578	23.75	24.55	41.45	68.50	158
Summit 515[z]	75	b	3983	19.50	30.65	52.90	64.00	119
Willow Creek[z]	119	a	3077	28.10	25.90	43.45	66.00	147
OG9484	86	b	3048	22.70	26.05	43.30	66.00	148
Crop Average	***95***		***3421***	***23.51***	***26.79***	***45.28***	***66.13***	***143***
Oat (*Avena sativa*)								
Buck Forage[z]	134		5535	22.65	24.85	42.65	70.00	152
Intimidator[z]	134		4915	18.20	25.65	43.80	71.00	148
Shooter[z]	139		6066	18.85	25.85	45.20	70.50	142
TAMO 411[z]	111		7128	19.85	25.10	43.90	70.50	148
OG6285	131		5048	19.70	23.20	39.30	70.50	168
Crop Average	***130***		***5738***	***19.85***	***24.93***	***42.97***	***70.50***	***151***
Barley (*Hordeum vulgare*)								
Alba[z]	102	b	5474	18.15	25.50	44.10	69.50	146
Verdant[z]	108	ab	5311	18.05	25.70	44.65	70.00	144
OG140760	113	a	4895	17.80	23.90	42.70	71.00	153
OG140789	91	c	4496	18.85	24.10	42.70	70.00	153
OG140797	109	ab	4378	19.45	25.80	43.85	70.00	146
Crop Average	***104***		***4911***	***18.46***	***25.00***	***43.60***	***69.70***	***148***
Rye (*Secale cereale*)								
Abruzzi[z]	166		9117	18.20	2720	49.30	68.50	128
Elbon[z]	166		8656	19.20	25.75	46.00	67.50	141
Goku[z]	169		8042	16.70	28.25	48.50	69.50	130
Crop Average	***167***		***8605***	***18.03***	***27.07***	***47.93***	***68.50***	***133***

[z]Indicates commercial small grain cultivar.

[y]% CP refers to percent crude protein and is measured by nitrogen content. % CP of cool-season grasses varies between 8-23 %.

[x]% ADF refers to percent acid detergent fiber. Lower % ADF indicates better digestibility. Depending on plant maturity, most forages have % ADF between 24-51 %.

[w]% NDF refers to percent neutral detergent fiber. Lower % NDF indicates higher intake. Depending on plant maturity, most forages have % NDF between 29-66 %.

[v]% TDN refers to percent total digestible nutrients. Cool-season grasses should have TDN values between 55-68%.

[u]RFV refers to relative feed value and is an index that ranks quality from prime (highest) through grade 5 (lowest); Prime:>151, Grade 1:125-151, Grade 2:103-124, Grade 3:87-102; Grade 4:75-86; Grade 5:<75.

Figure 4: 31 winter small grain cultivars arranged in a randomized complete block design, photographed on 4 May 2021 in the *Meloidogyne incognita* field at the Plant Breeding Unit in Tallassee, Alabama.

Figure 5: 31 winter small grain cultivars arranged in a randomized complete block design, photographed on 6 May 2021 in the *Rotylenchulus reniformis* field at the E.V. Smith Research Center in Shorter, Alabama.

Figure 6: 31 winter small grain cultivars arranged in a randomized complete block design, photographed on 4 April 2020 in the non-nematode field in Germanton, North Carolina