Chapter 15
Important Plant Parasitic Nematodes of Row Crops in Arkansas, Lousiana and Mississippi

Travis R. Faske, Charles Overstreet, Gary Lawrence, and Terry L. Kirkpatrick

15.1 Introduction

This chapter's focus is on the important plant parasitic nematodes and their management on row crops in Arkansas, Louisiana and Mississippi. This region is referred to as the Mid-South. Agronomic crops, production practices and nematode management practice are similar throughout the region.

T. R. Faske (✉)
Division of Agriculture, Lonoke Extension Center, Department of Plant Pathology, University of Arkansas, Lonoke, AR, USA
e-mail: tfaske@uaex.edu

C. Overstreet
Department of Plant Pathology and Crop Physiology, Louisiana State University AgCenter, Baton Rouge, LA, USA
e-mail: COverstreet@agcenter.lsu.edu

G. Lawrence
Department of Biochemistry, Molecular Biology, Entomology and Plant Pathology, Mississippi State University, Starkville, MS, USA
e-mail: GLawrence@endomology.msstate.edu

T. L. Kirkpatrick
Division of Agriculture, Southwest Research and Extension Center, Department of Plant Pathology, University of Arkansas, Hope, AR, USA
e-mail: tkirkpatrick@uaex.edu

S. A. Subbotin, J. J. Chitambar (eds.), *Plant Parasitic Nematodes in Sustainable Agriculture of North America*, Sustainability in Plant and Crop Protection,
https://doi.org/10.1007/978-3-319-99588-5_15

15.2 Economically Important Crops and Importance of Nematodes

The majority of row crop production in Arkansas, Louisiana and Mississippi is concentrated along the Mississippi River Delta (Fig. 15.1). Major row crops in the Mid-South include soybean (*Glycine max*), corn (*Zea mays*), cotton (*Gossypium hirsutum*), rice (*Oryza sativa*), sorghum (*Sorghum bicolor*), sweet potato (*Ipomoea batatas*) and peanut (*Arachis hypogaea*) (Table 15.1). Other areas of row crop production are concentrated near other rivers systems within each state. The total value of production of these row crops in the Mid-South is estimated at 6.9 billion dollars (Table 15.1).

Plant parasitic nematodes are major yield-limiting factors that affect row crop production in Southern United States and in the Mid-South. During the 2010–2014

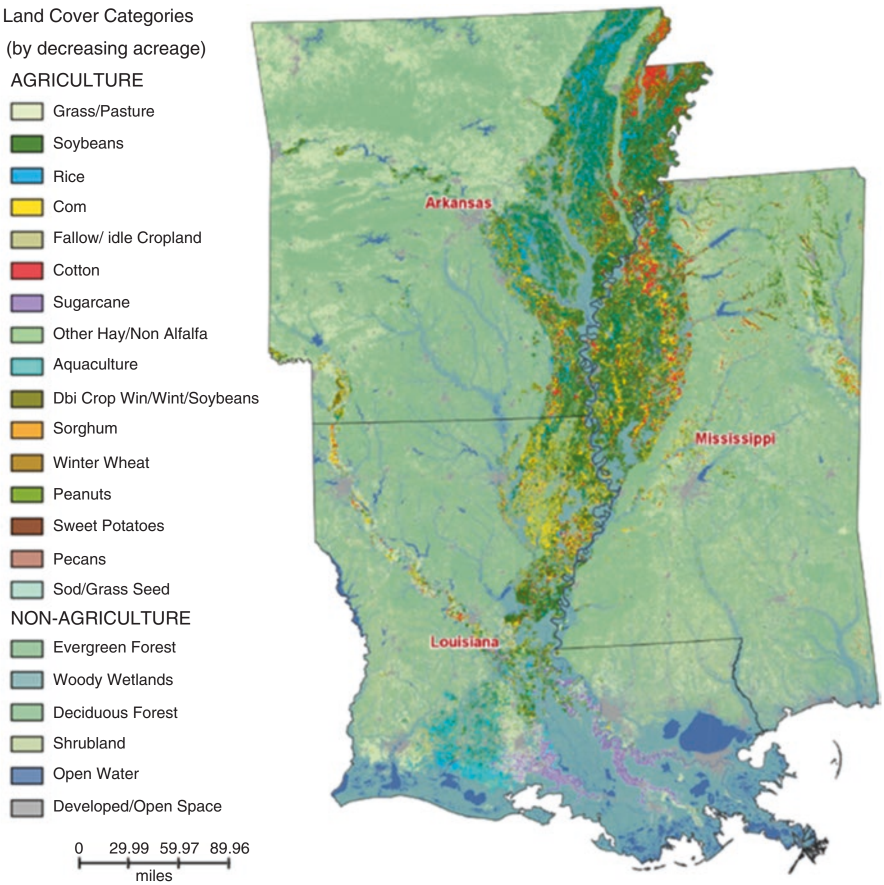

Fig. 15.1 Distribution of agricultural and non-agricultural land coverage categories in 2016 in Arkansas, Louisiana and Mississippi (USDA-NASS 2016d)

Table 15.1 Estimated hectares and crop value of the top seven row crop commodities in 2016 in Arkansas, Louisiana and Mississippi (USDA-NASS 2016a, b, c)

Commodity	Harvested hectares			Total hectares	Value of production (dollars)
	Arkansas	Louisiana	Mississippi		
Soybean	1,254,500	768,900	817,500	2,840,900	2,974,161,000
Rice	615,500	173,200	78,500	867,200	1,427,030,000
Corn	301,500	222,500	291,400	815,400	1,255,337,000
Cotton	151,700	55,400	174,000	381,100	717,802,000
Sorghum	17,800	18,600	4,400	40,800	280,070,000
Sweet potato	1,600	3,800	11,700	17,100	170,621,000
Peanut	9,300	600	15,400	25,300	47,020,000

period, soybean nematodes consistently ranked among the top soybean diseases affecting soybean production in the Southern United States (Allen et al. 2017b). For example, during the 2015 cropping season plant parasitic nematodes contributed to 320,000 ton in grain yield loss, in soybean production in the Mid-South (Allen et al. 2016). Similarly, plant parasitic nematodes were among the top three important yield-limiting factors affecting corn production from 2012 to 2015 in the Southern United States (Mueller et al. 2016). In cotton, plant parasitic nematodes continue to be one of the major yield-limiting factors in the Southern US (Lawrence et al. 2015a, 2016). Some 16,500 ton of cotton were lost in 2015 due to plant parasitic nematodes in the Mid-South (Lawrence et al. 2016). As a general rule, root knot nematodes and reniform nematodes are the most widespread and economically important nematodes on row crops in the Mid-South, although the soybean cyst nematode can also be significant in soybean production, particularly in the more northern (Arkansas, Tennessee, Missouri Bootheel) parts of the region. Research is lacking for many of the plant parasitic nematodes that are also commonly associated with row crops in the Mid-South (Table 15.2).

15.3 Soybean Cyst Nematode, *Heterodera glycines*

The soybean cyst nematode (SCN) is the most important nematode pest of soybean in the United States (Riggs 1977; Allen et al. 2017b). In the Mid-South, yield losses were estimated at two million bushels in 2015 (Allen et al. 2016). *Heterodera glycines* was first reported in 1915 in Japan (Hori 1915) and in the United States in 1955, in North Carolina (Winstead et al. 1955) and now is widely distributed in most soybean-growing areas of the U.S. (Niblack and Riggs 2015). The soybean cyst nematode was first recognized as a problematic pest in 1957 in Arkansas and Mississippi, and in 1967 in Louisiana (Noel 1992). It has been detected in all major soybean-producing counties in the Mid-South (Fig. 15.2a). Dissemination of soybean cyst nematode-infested soil from Japan, as a source of rhizobia inoculum from Asia, is believed to be the source of some of the early infestations in the US.

Table 15.2 Plant parasitic nematodes associated with row crops in Arkansas, Louisiana and Mississippi

Nematode	Crop	State	Reference
Aphelenchoides besseyi	Rice	AR, LA, MS	Martin and Birchfield (1955), Birchfield and Martin (1956), Birchfield et al. (1978), and Norton et al. (1984)
Belonolaimus nortoni	Soybean	AR	Robbins (1982a) and Norton et al. (1984)
Criconemoides annulata	Soybean	LA, MS	Norton et al. (1984)
Helicotylenchus digonicus	Soybean	MS	Rebois and Golden (1978) and Norton et al. (1984)
H. dihystera	Cotton, peanut, soybean	AR, LA, MS	Rebois and Golden (1978), Robbins (1982a), and Norton et al. (1984)
H. multicinctus	Cotton, soybean	LA	Rebois and Golden (1978)
H. pseudorobustus	Soybean	AR, MS	Robbins (1982a) and Norton et al. (1984)
Hemicycliophora triangulum	Soybean	AR	Robbins (1982a)
Heterodera glycines	Soybean	AR, LA, MS	Riggs (1977), Birchfield et al. (1978), Robbins (1982a), Norton et al. (1984), and Robbins et al. (1987)
Hirschmanniella oryzae	Rice	AR, LA, MS	Hollis (1967), Norton et al. (1984), and Wehunt et al. (1989)
Hoplolaimus columbus	Cotton, soybean	LA	Astudill and Birchfield (1980)
H. galeatus	Corn, cotton, grain sorghum, peanut, soybean	AR, LA, MS	Martin and Birchfield (1955), Birchfield and Martin (1956), Birchfield et al. (1978), Rebois and Golden (1978), Robbins (1982a), and Norton et al. (1984)
H. magnistylus	Cotton, soybean	AR, MS	Riggs (1977), Robbins (1982a), Norton et al. (1984), and Robbins et al. (1987, 1989)
Meloidogyne arenaria	Peanut, soybean	MS	Norton et al. (1984)
M. hapla	Soybean	AR	Robbins (1982a)
M. incognita	Corn, cotton, grain sorghum, soybean, sweet potato	AR, LA, MS	Birchfield and Martin (1956), Fielding and Hollis (1956), Birchfield et al. (1978), Robbins (1982a), Thomas and Clark (1983), Norton et al. (1984), Robbins et al. (1989), and Lawrence and McLean (2002)
M. graminicola	Rice	LA	Birchfield et al. (1978)
Mesocriconema onoense	Rice	LA	Birchfield and Martin (1956), Hollis (1967), and Birchfield et al. (1978)
M. ornatum	Soybean	AR, LA, MS	Rebois and Golden (1978) and Robbins et al. (1987)

(continued)

Table 15.2 (continued)

Nematode	Crop	State	Reference
M. xenoplax	Grain sorghum	LA	Wenfrida et al. (1998)
Nanidorus minor	Corn, cotton, soybean	AR, LA, MS	Martin and Birchfield (1955), Fielding and Hollis (1956), Rebois and Golden (1978), and Robbins (1982a)
Paratylenchus projectus	Corn, soybean	AR	Robbins (1982a)
P. tenuicaudatus	Soybean	AR	Robbins (1982a)
Pratylenchus alleni	Soybean	AR	Robbins (1982a)
P. brachyurus	Corn, cotton, soybean, sugarcane	AR, LA, MS	Birchfield and Martin (1956), Fielding and Hollis (1956), Endo (1959), Birchfield et al. (1978), Rebois and Golden (1978), Robbins (1982a), and Robbins et al. (1989)
P. coffeae	Soybean	AR, MS	Rebois and Golden (1978), and Norton et al. (1984)
P. hexincisus	Soybean	AR	Robbins (1982a)
P. neglectus	Corn, soybean	AR	Robbins (1982a)
P. penetrans	Corn, peanut, soybean	AR, LA, MS	Dickerson et al. (1964), Rebois and Golden (1978), and Norton et al. (1984)
P. scribneri	Corn, cotton, soybean	AR, LA, MS	Fielding and Hollis (1956), Rebois and Golden (1978), Robbins (1982a), Norton et al. (1984), and Robbins et al. (1989)
P. vulnus	Soybean	AR	Robbins (1982a) and Norton et al. (1984)
P. zeae	Corn, sugarcane, rice	AR, LA, MS	Martin and Birchfield (1955), Fielding and Hollis (1956), Endo (1959), Birchfield et al. (1978), Rebois and Golden (1978), Robbins (1982a), Norton et al. (1984), Cuarezma-Teran and Trevathan (1985), and Robbins et al. (1989)
Quinisulcius acutus	Soybean	AR, LA, MS	Birchfield et al. (1978), Rebois and Golden (1978), Robbins (1982a), Norton et al. (1984), Cuarezma-Teran and Trevathan (1985), and Robbins et al. (1987)
Rotylenchulus reniformis	Cotton, soybean, sweet potato	AR, LA, MS	Birchfield and Martin (1956), Fielding and Hollis (1956), Birchfield et al. (1978), Robbins (1982a), Thomas and Clark (1983), Norton et al. (1984), Robbins et al. (1989), and Lawrence and McLean (2000)
Scutellonema brachyurus	Soybean	AR, LA	Rebois and Golden (1978) and Norton et al. (1984)
S. bradys	Soybean	AR	Robbins (1982a)
Trichodorus primitivus	Corn	MS	Norton et al. (1984)

(continued)

Table 15.2 (continued)

Nematode	Crop	State	Reference
Tylenchorhynchus annulatus	Corn, grain sorghum, rice, soybean, sugarcane	AR, LA, MS	Fielding and Hollis (1956), Birchfield et al. (1978), Rebois and Golden (1978), Robbins (1982a), Norton et al. (1984), Robbins et al. (1987), Wenfrida et al. (1998), and Bae et al. (2009)
T. canalis	Soybean	AR	Robbins et al. (1987)
T. claytoni	Corn, cotton, soybean	LA, MS	Martin and Birchfield (1955), Rebois and Golden (1978), and Norton et al. (1984)
T. cylindricus	Corn, cotton, soybean	MS	Rebois and Golden (1978) and Norton et al. (1984)
T. ewingi	Soybean	AR	Robbins (1982a) and Robbins et al. (1987)
T. goffarti	Soybean	AR	Robbins (1982a) and Robbins et al. (1987)
T. nudus	Corn, soybean	MS	Rebois and Golden (1978) and Norton et al. (1984)
Xiphinema americanum	Corn, cotton, soybean, sugarcane	AR, LA, MS	Martin and Birchfield (1955), Birchfield et al. (1978), Rebois and Golden (1978), Robbins (1982a), Norton et al. (1984), and Robbins et al. (1987)
X. chambersi	Soybean	AR	Robbins (1982a) and Robbins et al. (1987)
X. rivesi	Soybean	AR	Robbins (1982a) and Robbins et al. (1987)

[*]Names of the states are represented by two letter abbreviations: AR Arkansas, LA Louisiana, MS Mississippi

Heterodora glycines has a host range that includes several genera in the Fabaceae family and a few species outside that family (Riggs 1992). Of the major row crops grown in the Mid-South, soybean is the only crop affected by the soybean cyst nematode. Although soybean cyst nematode was widely distributed in Louisiana in the past, over the past 20 years the nematode has become difficult to find in most fields. This decline is likely related to pathogens or parasites of the nematode in the soil, rather than management practices using host resistance or crop rotation. Since soil temperatures remain fairly warm year-round in Louisiana, microorganisms in the soil could be active all the time.

Populations of soybean cyst nematode differ in their ability to parasitize resistant soybean cultivars. To classify these genetic variants a race classification scheme was developed based on the female ability to develop on four soybean lines; Pickett, Peking, PI 88788 and PI 909763 compared to that of the susceptible standard, cv. Lee (Riggs and Schmitt 1988). Based on the four differential lines, sixteen races are theoretically possible to exist. Race designations are used in the Mid-South with several of the 16 races being reported from field surveys. Races 2–9 and 14 were detected in 1994 in Mississippi, while races 1–5, 9, 10 and 15 were reported in 1988 in Arkansas (Riggs and Schmitt 1988). In a more recent survey in Arkansas, the majority of the soybean cyst nematode populations from the results of a 2015 survey were races 2, 5 and 6, which was similar to the races 2, 4 and 5 reported in 1988 (Riggs and Schmitt 1988; Kirkpatrick 2017). Because a population of soybean

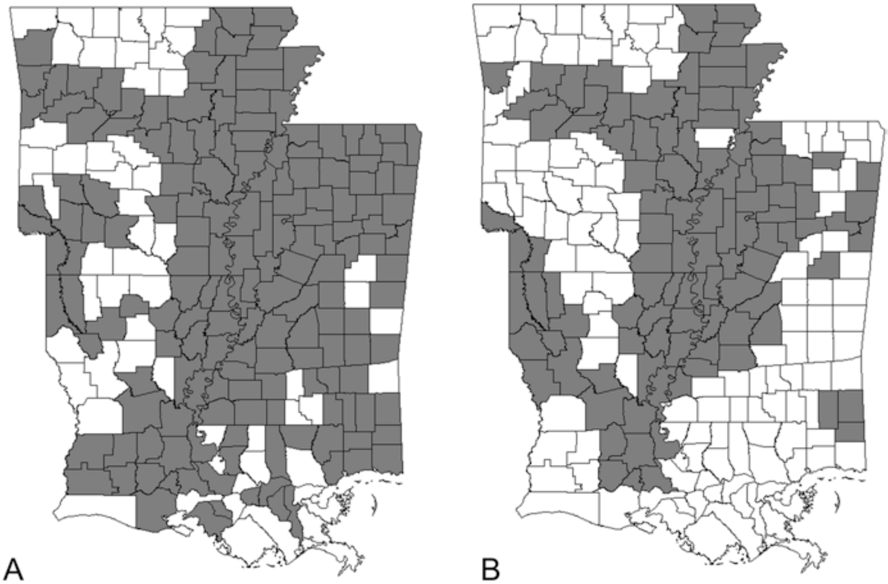

Fig. 15.2 (**a**) Counties (highlighted gray) where *Heterodera glycines* has been detected on soybean in Arkansas, Louisiana, and Mississippi. (**b**) Counties (highlighted gray) where *Meloidogyne incognita* has been detected on row crops in Arkansas, Louisiana, and Mississippi

cyst nematode in a field can vary in genetic diversity, a newer mechanism for describing pathogenic variability, referred to as the HG type scheme, has been adopted (Niblack et al. 2002). As with the race scheme, populations are distinguished based on their ability to reproduce on a set of indicator lines (PI 548402 (Peking), PI 88788, PI 90763, PI 437654, PI 209332, PI 89772 and PI 548316 (Cloud), that represent the major sources of resistance used in the US to develop resistant soybean cultivars.

The soybean cyst nematode occurs across a wide range of temperatures and soil types, but is most problematic in course textured, sandy soils. Crops growing in sandy soils are stressed by low water-holding capacity, plus the stress caused by soybean cyst nematode results in a greater damage potential compared to those growing in finer-textured, clay soils.

15.3.1 Symptoms

Foliar symptoms of infection range from undetectable to stunted, chlorotic plants that may occur in roughly circular or elliptical patterns in a field. Symptomology often depends on the severity of the problem as it relates to the nematode population's ability to reproduce on a soybean cultivar. In general, symptoms are often confused with nutrient deficiencies, although the nematodes are relatively easy to detect visibly without magnification in a field, as white, yellow or brown lemon-shaped females on infected roots. Though damage thresholds vary with soil type, a population density of 500 nematodes/100 cm^3 soil can cause yield loss in the Mid-South.

15.3.2 Management Strategies

Management of the soybean cyst nematode requires several tactics that include cultural practices, the use of resistant cultivars and in some situations, the application of nematicides. Growing crops that are non-hosts to the nematode in rotation with soybean can be an effective means to lower nematode population densities and maintain the nematode densities below an economic threshold (Wrather et al. 1992). Corn, cotton, grain sorghum or peanut are non-host crops and therefore, are a good rotation crop option for the Mid-South. Growing a non-host crop for 2–3 years on a nematode-infested field may be required before a susceptible soybean cultivar can be grown to achieve its full yield potential. The inclusion of a race- or HG-type-specific resistant soybean cultivar is also an economical method for nematode management (Lawrence and McGuire 1987; Wrather et al. 1992) if the appropriate resistance is available in an adapted cultivar. However, the continuous or frequent use of a resistant cultivar may increase the population of individual nematodes that can overcome the host resistance and lead to a “race shift” that eventually renders the resistant cultivar useless. Given that most of the commercially available soybean cultivars adapted to the Mid-South are not resistant to the race or HG types in the region, the use of non-host crops is the best option in soybean cyst nematode management.

Planting early before nematode eggs hatch and juveniles become active in the soil, also known as avoidance, has been suggested as a management tactic. The eggs will not hatch until soil temperatures reach 20 °C (Ross 1988). Early planting before soil temperatures warm-up, allow sufficient time for a soybean plant to become established without nematode damage to its developing root system. In a planting date study in Arkansas, reproduction by SCN was lower on early planted (April) soybeans than late planted (June or July), but grain yield was similar between planting dates (Riggs et al. 2000).

The use of nematicides is another management tactic for soybean cyst nematode management. Fumigant nematicides, including 1, 3 dichloropropene (Telone® II), metam potassium (K-PAM® HL™) and metam sodium (VAPAM® HL), are labeled for use, but are not commonly used in the Mid-South due to cost, the need for special application equipment and rather stringent environmental restrictions. Currently, the vast majority of nematicides used in the Mid-South are applied as seed treatment and are divided between chemical and biological agents. Chemical agents include abamectin (Avicta® 500 FS) and fluopyram (ILeVO® 600 FS), while *Bacillus firmus* (VOTiVO®) and *Pasturia nischizawae* (Clariva® *pn*) are biological agents. Seed-applied nematicides may provide some protection of the developing seedling, but do not provide season-long nematode control. They are more beneficial when paired with moderately resistant cultivars or where there is more than one population of plant parasitic nematode in the field. The decision to use a nematicide should be based on nematode population density, level of cultivar resistance and expected yield benefit.

15.4 Root Knot Nematode, *Meloidogyne incognita*

The southern root knot nematode (*Meloidogyne incognita*) is one of the most important plant parasitic nematode affecting row crop production in the Mid-South and United States. Root knot nematodes were first described on cucumber in 1855 in England (Berkeley 1855) and in 1889 in the Southern U. S. (Neal 1889). Although root knot nematodes are now considered to be indigenous and widely distributed in the U.S. (Chitwood 1949), they were not referenced until 1911 in the Mid-South (Bessey 1911). *Meloidogyne incognita* has a broad host range comprised of thousands of plant species, which include many weed species and row crops. This root knot nematode species attacks most of the major row crops produced in the Mid-South including cotton, corn, grain sorghum, soybean and sweet potato (Fig. 15.2b). *Meloidogyne incognita* Race 3 is the most common biotype, which is probably due to the history of cotton production in the Mid-South (Baker et al. 1985).

Distribution of root knot nematodes within a field is frequently uneven and scattered, particularly in coarse textured, sandy soil. Within these areas, *M. incognita* population density can increase and cause significant damage and symptom development on a susceptible host crop (Thomas and Kirkpatrick 2001). Crops within these areas often suffer the greatest yield losses due to enhanced water stress from nematode infection and the low water holding capacity of sandy soils.

The overwinter survival stage of the root knot nematode is primarily eggs. As a general rule, the total population density of root knot nematode is greatest near harvest in annual row crops. Initially, eggs in the soil or on roots make up the greatest proportion of the total fall population density, but as J2 hatch, the proportion of the population shifts toward J2. Second-stage juvenile survival is short-lived in the absence of a host and the majority die during the winter, so there is a general decline in the total nematode population density. In many cases, the early spring population density is often less than 10% of the total fall population of root knot nematode. In some parts of the Mid-South and in some years, root knot nematodes may survive on some winter weeds or cover crops (Timper et al. 2006). The soil temperature thresholds for J2 infection and female reproduction are 18 °C and 10 °C, respectively (Ploeg and Maris 1999).

15.4.1 Cotton

Meloidogyne incognita is one of the most important, yield-limiting plant parasitic nematode that affects cotton production in the Mid-South. During the 2015 cropping season, yield loss estimates of cotton lint averaged 2.2% in the Mid-South (Lawrence et al. 2016). Over the past 10 years, the estimated yield losses of cotton lint due to *M. incognita* ranged from 2.0% to 2.6% per year for a total lint yield loss of 214,700 ton (NCCB 2017).

15.4.1.1 Symptoms

The degree of symptom development on cotton is positively related to nematode population density. Severely infected cotton plants are stunted, wilt during the heat of the day and may show signs of drought stress or nutrient deficiencies even in the presence of adequate soil moisture and nutrients. The presence of root galls on secondary roots is the best diagnostic symptom (Fig. 15.3a). These galls are visible as early as 45 days after planting on a susceptible cultivar. Root galls are a good indication of nematode presence, but soil sample are better suited to monitor nematode

Fig. 15.3 (**a**) Galls caused by *Meloidogyne incognita* on cotton root system; (**b**) Stunted and yellow plants as a result of a moderate to high population density of *M. incognita*; (**c**) Severely galled soybean root system caused by *M. incognita*; (**d**) Corn root system with clustered and stunted root caused by stubby root nematode. (Photos by T. R. Faske)

population densities and determine if an economic threshold is present. The damage threshold in cotton for *M. incognita* in the Mid-South is 50–100 J2/100 cm^3 soil from soil samples collected in the fall (Robinson 2008).

15.4.1.2 Management Strategies

For the past 20 years, nematode management in cotton has relied heavily on an integrated approach that includes the use of nematicides, host plant resistance (on a very limited basis) and crop rotation. During much of this time, commercially available cotton cultivars, with a suitable level of both nematode resistance and yield potential, were lacking. Thus, the most common nematicides used in the Mid-South were 1, 3-dichloroporpene (Telone® II), aldicarb (Temik® 15G) and oxamyl (Vydate® C-LV). As a general rule, Telone® II was more effective than the non-fumigant nematicides, but they were more expensive and required special equipment for application. Aldicarb provided systemic protection from both early-season insects and nematodes on developing cotton seedlings. Aldicarb was once the most widely used nematicide in the Mid-South, but the use of aldicarb decreased as supplies became limited, because the manufacturer stopped the production of Temik® 15G that was to be phased out by 2018. Recently, however, there has been a renewed interest in the use of aldicarb by cotton producers in the Mid-South, and in 2016, AgLogic™ 15GG was registered for use with the EPA. Currently, the most common nematicides used are those that are applied on the seed coat. There are two groups of seed-applied nematicides: chemical and biological control agents. Abamectin (Avicta® 500 FS) was registered in 2006 as the first chemical seed-applied nematicide in cotton. Abamectin provides some early-season control of *M. incognita* on developing cotton seedlings (Monfort et al. 2006), but seedling protection is limited to a few centimeters from the treated seed as only a small portion of abamectin is transferred along the developing root system (Faske and Starr 2007). Fluopyram is an succinate dehydrogenase inhibitor fungicide that was recently shown to affect *M. incognita* motility and ability to infect tomato seedlings (Faske and Hurd 2015). Fluopyram (COPeO™ Prime) was registered in 2014 for use as a seed-applied nematicide in cotton. Additionally, a formulation of fluopyram + imidacloprid (Velum® Total) was registered in 2015 as a liquid in-seed-furrow spray for use against insects and nematodes in cotton. In field trials, Velum® Total generally provided better suppression of *M. incognita* than other seed-applied nematicides applied on cotton. Fluopyram as COPeO™ Prime preformed similarly to other seed applied nematicides (Lawrence et al. 2015b; Faske et al. 2017). Tioxazafen (NemaStrike™) is currently being evaluated as a seed-applied nematicide and will be marketed for use on cotton.

Of the biological control agents registered for suppression of nematodes, *Bacillus firmus* has been widely used as a seed treatment biological nematicide and is marketed in combination with clothianidin as Poncho®/VOTiVO® for seedling protection against insects and nematodes. Recently, heat-killed *Burkholderia* spp. (BioST® Nematicide 100) has been marketed as a seed treatment for suppression of nematode damage. Although the use of seed-applied nematicides is increasing, all appear to be most effective when used in fields with low nematode population densities, particularly if they are paired with a moderately resistant cultivar.

Nematicides increase production costs and may not be necessary field-wide. Distribution varies both vertically and horizontally within the soil profile (Baker and Campbell 1981). The root knot nematode is most commonly associated with coarse-textured soils, which are often the areas of a field that also suffer the greatest moisture deficit stress and yield loss (Wrather et al. 2002; Monfort et al. 2007). Emerging precision technology now allows soil texture to be estimated and mapped in a field based on apparent electrical conductivity (EC_a), measured with equipment like the Veris 3100 Soil EC Mapping System. Recent studies have shown that areas within the field with the lowest EC_a values, indicating the highest sand content, are high risk zones where nematicide use can have the greatest impact on protecting cotton yield potential (Ortiz et al. 2012; Overstreet et al. 2014). As the use of precision technology including yield monitors, remote sensing, soil EC mapping, etc. increases, so will the opportunities to incorporate site-specific nematicide application as a nematode management tool.

The use of host plant resistance is the most economical and sustainable option for managing plant parasitic nematodes. Resistance suppresses nematode reproduction, which results in a lower nematode population density for the subsequent crop. Pioneering and recent studies have identified a rich source of resistant breeding lines in the germplasm of various *Gossypium* spp. (Robinson and Percival 1997; Robinson et al. 2001). The breeding line Auburn 623 RNR, that was developed from the cross between two moderately resistant parents, Clevewilt 6 and Wild Mexican Jack Jones (Shepherd 1974), was highly resistant to root knot nematodes. This breeding line was later crossed with the recurrent parent cultivar Auburn 56 to develop Auburn 634 RNR (Shepherd 1982), which was back crossed into various recurrent parents with acceptable agronomic characteristics to develop the M-series of breeding lines (e.g. M-120, M-240, M-315) (Shepherd et al. 1996). The mechanisms of resistance in Auburn 623 RNR sources of resistance are not well understood, but resistance is based on both reduced root galling in the host and lower egg production by the nematode (Creech et al. 1995; Jenkins et al. 1995). Studies investigating the inheritance of resistance in Clevewilt 6 indicate that a single recessive gene is involved (Bezawada et al. 2003). A two-gene model for resistance in M-315 was proposed that included a dominant gene from Wild Mexican Jack Jones and an additive gene from Clevewilt 6 (McPherson et al. 2004). The molecular aspects of these genes in M-120 and M-240 were characterized in several studies (Shen et al. 2006; Ynturi et al. 2006; Gutierrez et al. 2010; He et al. 2014). Based on their work, a gene on chromosome 11 (*Mi*-C11) that was present in Clevewilt 6 was primarily responsible for reduction in nematode galling, while a gene on chromosome 14 (*Mi*-C14), present in Wild Mexican Jack Jones was primarily responsible for suppression of nematode reproduction. Five additional sources of resistance were identified from the Yucatan region of Mexico (Robinson and Percival 1997). Though these accessions are not as resistant to *M. incognita* as Auburn 623 RNR, based on nematode biology (reproduction and development), two accession (TX-1174 and

TX-2079) may have genes for resistance that differ from Clevewilt 6 and Wild Mexican Jack Jones (Faske and Starr 2009).

One of the main challenges in breeding for resistance had been integrating resistance from these resistant sources into elite cotton cultivars – a long and slow process. During the mid-1990s resistance to root knot nematode in cotton was moderate at best, with most commercial cultivars containing one resistant gene. By about 2010, some cotton cultivars exhibited much better resistance with a two-gene system. Current commercially available root knot nematode resistant cultivars such as Deltapine DPL1558NR B2RF and Phytogen PHY 427 WRF, are marketed as having two genes and a high level of resistance, while PHY 487 WRF and Stoneville ST 4946 GLB2 have one gene and a moderate level of resistance. It is likely that future resistant cultivars will play a vital role in the management of root knot nematode in cotton.

Crop rotation with a non-host or poor host can be effective at reducing the nematode population density below a damage threshold. Rotation has been used effectively in the Mid-South to manage root knot nematode in cotton. Peanut is a relatively new to the Mid-South production system and is a non-host to the southern root knot nematode, making it a great option as a rotational crop (Kirkpatrick and Sasser 1984). Peanut production has increased in Arkansas and Mississippi, but is still of limited potential in the region due to soil type variability and the relatively low acreage of peanut in relation to that of cotton. Rice is good option as a rotational crop (Bridge 1996) because flooding is an effective tool in nematode control. Unfortunately, most cotton fields are not suitable for rice production because it is so difficult and expensive to maintain adequate flooding levels due to the soil type. Grain sorghum has been recognized as useful rotation crop to manage the southern root knot nematode. Recent studies in the Mid-South have indicated that there is a wide range in host suitability among grain sorghum hybrids (Hurd and Faske 2017), so some grain sorghum hybrids may sustain or possibly increase populations of root knot nematode for the subsequent row crop. Corn is commonly grown in the Mid-South and it too has a wide range in host suitability to root knot nematode. Most corn hybrids are susceptible to root knot nematodes (Davis and Timper 2000). Soybean is a common rotational crop with cotton in the Mid-South. While some soybean cultivars are root knot nematode resistant, most cultivars in all of the maturity groups grown in the Mid-South have little or no resistance (Kirkpatrick et al. 2016).

15.4.2 Soybean

The southern root knot nematode is the most important plant parasitic nematode affecting soybean production in the Mid-South. During the 2015 cropping season, the southern root knot nematode accounted for an estimated average yield loss of 2.0% in Louisiana and Mississippi and 3.6% in Arkansas for a total grain yield loss of 9.4 million bushels (Allen et al. 2016).

15.4.2.1 Symptoms

Above ground symptoms are dependent on nematode population density and crop maturity. Stunted seedlings can be observed at high population densities, while stunted and chlorotic plants are common at mid to late reproductive growth stages where moderate to high population densities occur (Fig. 15.3b). These plants may senesce earlier than non-infected soybean plants. Galls on infected roots are the most diagnostic feature of root knot nematode on soybean. Galling severity depends on population density. Small galls can be observed on soybean at early vegetative stages of growth, but large galls that are easier to identify occur at early and mid-reproductive growth stages (Fig. 15.3c). Severely infected roots may have several galls that coalesce causing the entire root system to appear galled. With this level of severity, many times entire root systems become discolored and necrotic, leaving only a portion of a taproot intact with very few to no secondary roots remaining on the root system. Severely infected plants produce fewer pods and smaller seed per pod, which contributes to lower gain yield. The damage threshold for southern root knot nematode is 60 J2/100 cm^3 soil for soil samples collected in the fall.

15.4.2.2 Management Strategies

The use of resistant cultivars is the most efficient tactic to manage root knot nematodes, because resistant cultivars not only perform better, but may actually lower the overall population density of the nematode (Cook and Evans 1987). The sources of resistances to *M. incognita* in germplasm and breeding lines that are most commonly used to develop resistant cultivars includes Avery, which is a maturity group (MG IV) cultivar, Forrest (MG V), D83-3349 (MG VI), G93-9009 (MG VI), PI 417444 (MG VI), PI 96354 (MG VI) and Gordon (MG VII) (Hartwig and Epps 1973; Boerma et al. 1985; Luzzi et al. 1987; Anand and Shannon 1988; Hartwig et al. 1996; Luzzi et al. 1996). These lines range in resistance to *M. incognita* from partially to highly resistant, with most of the highly resistant germplasm in later soybean maturity groups (MG VI and VII). The inheritance of resistance to *M. incognita* in the cultivar Forrest was reported to be conditioned by a single additive gene (*RMi*1) that confers partial resistance to root galling (Luzzi et al. 1994b); however, horizontal resistance is more common in soybean. A high level of resistance to *M. incognita* in PI 417444 and PI 96354 are conditioned by a few genes that differ from those of Forrest (Luzzi et al. 1994a). The mechanism of resistance in PI 96354 is associated with the inability of J2 to establish a feeding site, or slower development of those individuals that do establish a feeding site. Fewer eggs were produced by survivors on this line than on the susceptible cultivar Bossier (Herman et al. 1991; Moura et al. 1993). Although these PI lines possess unique resistant genes, integrating resistance from these sources into high-yielding cultivars has been a slow process, especially in the early maturity groups (III – V) that are popular in the Mid-South (Kirkpatrick et al. 2016). The majority of the maturity groups grown in the Mid-South are MG IV, followed by MG V and MG III. The availability of elite cultivars with nematode resistance is further complicated by the use of different herbicide resistance traits across the Mid-South.

Due to the lack of available cultivars with good yield potential and a high level of resistance to *M. incognita*, nematode management requires an integrated approach in the Mid-South. Rice is a commonly used in crop rotation in the Mid-South, which is a good option for root knot nematode management as flooded conditions for rice production are unfavorable for nematode survival in the soil. Peanut is a non-host for *M. incognita* and offers an excellent option in fields that are suitable for peanut production. Corn and grain sorghum can increase or sustain a population of root knot nematode depending on host suitability of the cultivar (Davis and Timper 2000; Hurd and Faske 2017). Other cultural practices include subsoil tillage in areas where soil compaction may limit root development (Minton and Parker 1987). Though fumigant nematicides are effective they are generally too expensive to be economically practical in soybean production. Abamectin, fluopyram and *B. firmus*-treated seed provide some suppression of root knot nematode infection on seedling root systems. In general, this suppression of nematode infection is limited with variable responses to yield protection (Hurd et al. 2015, 2017a, b; Jackson et al. 2017). These seed-applied nematicide are best used in fields with a low population density of root knot nematode and paired with at least a moderately resistant cultivar (Jackson et al. 2017). Tioxazafen (NemaStrike™), heat-killed *Burkholderia rinojensis* (BioST® Nematicide 100) and *Bacillus amyloliquefaciens* (AVEO™ EZ Nematicide) are being evaluated as a seed-applied nematicide and field efficacy trials are ongoing to determine the impact of these chemical and biological agents in soybean.

15.4.3 Sweet Potato

The southern root knot nematode (*Meloidogyne incognita*) is one of the most important and widespread plant parasitic nematodes affecting sweet potato production in the Mid-South and worldwide (Overstreet 2013a). Damage from root knot nematode affects both sweet potato quality and yield.

15.4.3.1 Symptoms

The most diagnostic symptom is galls, which appear as spindle-shaped swellings on the fibrous root of sweet potato. Gall size and severity is reflective of nematode population density, but can vary among cultivars. On storage roots, small bumps or blisters can be observed on the root surface. Mature females with egg masses can be detected beneath these raised areas. Cracking on storage roots can be caused both by root knot nematode and fluctuations in soil moisture (Thomas and Clark 1983; Lawrence et al. 1986; Overstreet 2013a).

Sweet potato cultivars with resistance to *M. incognita* are available and provide the most economical approach to management (Overstreet 2013a). Reproduction by *M. incognita* can increase with increasing soil temperatures on resistant cultivars, but not to the same magnitude as that of a susceptible cultivar (Jatalla and Russell

1972). Fumigant nematicides (1,3 dichloropropene and metam sodium) are effective tools and the non-fumigant granular nematicide ethroprop is also registered for use in sweet potato production. Because sweet potato is vegetatively propagated it is important to propagate slips in a root knot nematode-free bed. Infected slips (those with adventitious roots) could transport and distribute root knot nematodes into a new field. Propagation with cuttings would eliminate the risk of root knot nematode infected slips. Other cultural practices including rotation with peanut or some grain sorghum hybrids, may reduce nematode population densities, (Johnson et al. 1996) as well as some fungal diseases (Jenkins et al. 1995).

15.5 Other Root Knot Nematode Species, *Meloidogyne* spp.

Though several other species of *Meloidogyne* affect row crop production in the United States, *M. incognita* is the most common species found on row crops in the Mid-South. Other species have been reported on non-cultivated land or in a field or two in a specific state. In Arkansas, *M. arenaria* and *M. javanica* have been reported on non-cultivated land, while *M. hapla* has been reported on non-cultivated land and on soybean (Robbins 1982b). In Louisiana, *M. javanica* has been detected in a few soybean fields but is not considered a common pest. *Meloidogyne javanica* was found in association with *M. incognita* in some Louisiana soybean fields and the complex contributed to a failure of soybean varieties with resistance to *M. incognita* (E. C. McGawley, pers. comm.). In Mississippi, *M. arenaria* Race 2 has been detected in soybean and *M. arenaria* Race 1 in peanut, but neither species is a common pest. *Meloidogyne javanica* has been detected on vegetables in the southern part of the state, but its impact has not been investigated.

15.6 Stubby Root Nematodes, *Paratrichodorus* spp. and *Trichodorus* spp.

Stubby root nematodes are widespread throughout the U.S. and they are common on row crops in the Mid-South. They have a broad host range that includes hundreds of plant species, but are most damaging to species in the grass family Poaceae.

Population densities of stubby root nematodes within a field are scattered and irregular, both vertically and horizontally. Stubby root nematodes are commonly found in sandy and sandy-loam soils and often occur deeper (*ca*. 30 cm) in the soil profile than other plant parasitic nematodes because they are very sensitive to low soil moisture and mechanical disturbance from tillage. Stubby-root nematode population densities can change quickly during the season with adequate moisture in the root zone. Additionally, population densities can also decrease quickly, making diagnosis difficult without the use of root symptomology.

15.6.1 Symptoms

Stubby root nematodes are ecotoparasitic nematodes. They feed on the meristematic cells of root tips causing root growth to slow and eventually stop, hence the "stubby root" symptom. Unlike other plant parasitic nematodes, stubby root nematodes have an onchiostyle which is a curved, solid stylet. The nematode uses the stylet to puncture the meristem cells, where it secretes salivary materials that are used to construct a feeding tube. The nematode uses the feeding tube to extract nutrients and cellular components before migrating to another cell, leaving the feeding tube behind. As new roots emerge near the root tip they are parasitized by the nematode causing a proliferation of secondary roots near the root tips (Fig. 15.3d). Affected root systems have small, stunted root systems with fewer and shorter secondary roots. Seedlings are especially sensitive to stubby root nematode feeding. On dicots, root symptoms are less obvious and appear as a reduced root system, in contrast to the stubby roots that occur in a grass crop. Foliar symptoms of affected plants are severely stunted and yellow, but continue to develop through reproductive stages of growth.

15.6.2 Management Strategies

Stubby root nematodes have been associated with stunted corn in the Mid-South (Koenning et al. 1999; Faske and Kirkpatrick 2015). Corn is highly susceptible with some variation in host suitability among hybrids (Timper et al. 2007). Given the broad host range of stubby root nematodes, which includes soybean and cotton, nematode population densities are often maintained with the use of these common rotation crops in the Mid-South. Soil tillage can be an effective strategy to reduce nematode population density (Todd 2016). Though nematicides can be effective, they are not always economically beneficial to the farmer. Nematicides registered for use in corn production include fumigants (1,3 dichloropropene), non-fumigant granular nematicides (terbufos) and chemicals applied as a seed treatment; abamectin and *Bacillus firmus*. In general, nematicides applied as a seed treatment are most effective at low population densities of nematodes in the soil.

15.7 Lesion Nematodes, *Pratylenchus* spp.

Several species of *Pratylenchus* have been identified in the Mid-South, but in general, *P. brachyurus* and *P. zeae* are among the most common, especially in corn. Lesion nematodes are migratory endoparasitic nematodes, so a portion of the total viable population in a field may be present in the roots rather than in the soil. Therefore, both a root and a soil sample are needed to determine the total population density of lesion nematode in a field. Lesion nematodes can be found in a range of soil types depending on the species. *Pratylenchus brachyurus* and *P. zeae* were reported to reproduce at a greater rate in silt loam soils than loam or clay soils (Endo 1959).

15.7.1 Symptoms

Symptom development is dependent on nematode species, population density and environmental conditions (soil temperature and moisture). All lesion nematodes cause dark brown lesions on roots, but root lesions vary in size depending on nematode species. Lesion nematode distribution is often aggregated in the field, thus foliar symptoms may occur in irregular patches in the field. Foliar symptoms are non-specific with stunted and yellow plants being the most common descriptions.

15.7.2 Management Strategies

The usefulness of crop rotation in the management of lesion nematodes is species specific. Corn, foxtail millet (*Setaria italica*), grain sorghum, cereal rye (*Secale cereale*), soybean and sudangrass (*Sorghum drummondi*) were good hosts for *P. zeae*, while barley (*Hordium vulgare*), oat (*Avena sativa*) and watermelon (*Citrullus lanatus*) were reported as poor hosts (Endo 1959). Corn, cotton, potato (*Solanum tuberosum*), watermelon and sudangrass, have been reported as good hosts for *P. brachyurus*, while soybean, oat, sweet potato, cereal rye and pearl millet (*Pennisetum glaucum*) are relatively poor hosts (Endo 1959; Timper and Hanna 2005). So, species identification is an important factor when recommending a rotational crop for lesion nematode in the Mid-South. Cover crops resistant to some species of lesion nematode have been effective at reducing nematode population densities, but cover crops resistant to one species of *Pratylenchus* may be susceptible to another, so monitoring nematode population densities is a good practice when using cover crops. Currently, there is no information on the susceptibility of commercially available corn hybrids to lesion nematodes.

15.8 Reniform Nematode, *Rotylenchulus reniformis*

The reniform nematode is recognized as one of the most important plant parasitic nematodes affecting cotton production in the Southern United States. Cotton lint losses in the 2016 cropping season, from three Mid-South states, were estimated at 17,500 ton (Lawrence et al. 2017).

The reniform nematode has become a pathogen of major importance during the past 40 years in the Mid-South. The nematode was first reported in Hawaii in 1940

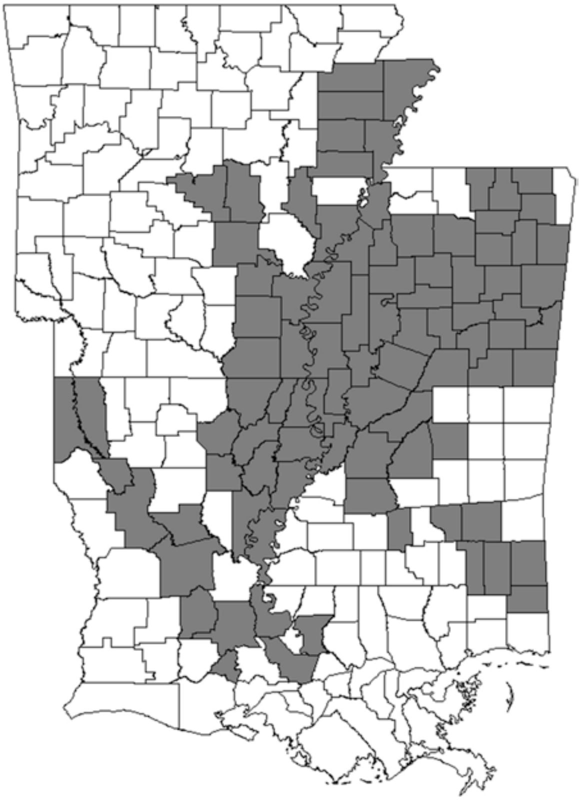

Fig. 15.4 Counties (highlighted gray) where *Rotylenchulus reniformis* has been detected on row crops in Arkansas, Louisiana, and Mississippi

(Linford and Oliveira 1940) and in the Mid-South in Baton Rouge, Louisiana in 1941 (Smith and Taylor 1941). The first occurrence of this nematode in Mississippi was in 1968 and in Arkansas in 1979 (R. T. Robbins, University of Arkansas, pers. comm.). In Louisiana, this nematode was considered as only a minor problem in the 1960s as it was only associated with 800–1000 ha of cotton in two counties (Birchfield and Jones 1961). Reniform nematodes have spread rapidly in the Mid-South since they were first detected. A survey of cotton fields conducted in Louisiana during 1994 and 1995 (Overstreet et al. 2008) indicated that over 200,000 ha were infested with the reniform nematode. McLean and Lawrence (2000) found that reniform nematodes were present in 67% of the fields in Northeast Louisiana. Reniform nematodes are also widely distributed through Mississippi and parts of Arkansas. The distribution of the reniform nematode as of 2017 includes many of the major row crop producing counties or parishes in the Mid-South (Fig. 15.4).

15.8.1 Field Introduction and Distribution

The reniform nematode is very easy to introduce into a production field because of its unique ability to survive in an anhydrobiotic stage (Lawrence and McLean 2001). This is one of the few nematodes that can withstand desiccation for several years, then rehydrate and become active again. Reniform nematodes that are in this dried state can easily be transmitted to fields on any type of farm equipment. Reniform nematodes can spread quickly within fields (Monfort et al. 2008; Xavier et al. 2012a). Once the nematode has entered a field, it can quickly spread through water movement (rainfall events or flood irrigation) or equipment (Overstreet et al. 2008). The spread has been associated with the direction of rows within a field, caused by the general tillage practices in that field (Monfort et al. 2008). In both of these reports, reniform nematode went from a small isolated area to quickly being present over a much greater area of the field.

Although reniform nematodes sometimes appear to be uniformly distributed within a field, populations are in reality described as being a non-clustered horizontal distribution (Lee et al. 2015). Densities are much higher in some locations in a field than others, likely due to a number of factors (Overstreet et al. 2011b). Population densities are strongly influenced by soil texture (Monfort et al. 2008; Xavier et al. 2014) and the nematode is often found in soils with significant silt or clay content. In Louisiana, the highest densities occurred when clay content was between 10% and 20% with lower populations below and above this clay percentage (Xavier et al. 2012c). Monfort et al. (2008) reported that the greatest populations of the reniform nematode occurred when silt content of the soil was between 54% and 60%.

Of particular concern is the distribution of reniform nematode vertically in the soil profile. Reniform nematodes can occur to greater depths in the soil than most other nematode species (Robinson et al. 2005; Robinson et al. 2006). In some cases very low populations can be detected in the upper surface (15–20 cm depth) but very high populations may be present below that depth (Xavier et al. 2012a, b). Rotation with corn or fall or spring tillage contribute to the decline of the nematode at the surface, and since soil samples for nematode analysis are usually taken at this depth, results can sometimes be misleading. Reniform populations deep in the soil profile may quickly rebound when a susceptible crop is grown.

15.8.2 Biology and Hosts

The reniform nematode has a short life cycle requiring only 17–23 days, depending on soil temperature (McGawley and Overstreet 2015). Egg masses typically contain 50–75 eggs and a number of generations of the nematode can develop in a single crop (Overstreet et al. 2009). Reniform nematodes also have a fairly wide host range that includes many broad-leaf weeds (Carter et al. 1995; Robinson et al. 1997). This can make it difficult to reduce or eliminate the nematode once established in a field, since there may be alternative hosts present. Weeds in combination with cotton or soybean have also been found to influence the reniform nematode and may actually suppress population development of this pathogen (Pontif and McGawley 2007, 2008). Common weed species that have been identified as excellent hosts of the reniform nematode include sicklepod (*Senna obtusifolia*), spurred anoda (*Anoda cristata*), entireleaf morning glory (*Ipomoea nil*) and velvetleaf (*Abutilon theophrasti*) which potentially could lead to increased populations (Molin and Stetina 2016).

In the past several years in the Mid-South, a number of researchers have reported that populations of reniform nematodes may not always respond similarly to the same crops or cultivars (Agudelo et al. 2005; Arias et al. 2009; McGawley et al. 2010, 2011). A number of populations have shown differences in how well they reproduce on the same cultivars, and some populations are more pathogenic than others (Xavier et al. 2014; Bhandari et al. 2015). These differences in how the nematode impacts plants from one location to another have serious implications on the use of resistant varieties as a management tool (Agudelo et al. 2005).

15.8.3 Crop Losses

Of the row crops produced in the Mid-South, the reniform nematode is most often associated with cotton (Kirkpatrick and Thomas 2007). Lint loss estimates from reniform nematode to cotton have been reported as high as 50–60% in individual fields (Birchfield and Jones 1961), although based on nematicide trials over the past 40 years, losses are typically more in the 15–30% range (Overstreet 1996). Because reniform nematode may be spread throughout a field, subtle or even serious damage from reniform nematode may go undetected when hot spots are not visible (Lawrence and McLean 2001).

15.8.4 Symptoms and Damage

Typical symptoms of reniform nematode damage on cotton include stunting, delayed flowering and fruit set, uneven plant heights (Fig. 15.5a) and low yield (Lawrence and McLean 2001; Overstreet et al. 2008). Reniform nematode populations vary within a field and shortly after the initial introduction into a field, hots spots or severely stunted areas may be visible. One of the most distinct symptoms of reniform nematode infestation, during the first few years following their initial introduction in a field, is unevenness in plant height (Overstreet et al. 2008). These wavy patterns in plant height are associated with changing populations in the field. Once the reniform nematode has been present in a field for some time, damage may be more uniform, making it more difficult to recognize (Lawrence and McLean 2001). The damage threshold for this nematode varies somewhat between states but levels from 250 to 5000 per 500 cm^3 of soil are considered high enough to cause injury (Greer et al. 2009; Mueller et al. 2012). Factors that impact the level of damage that plants are likely to experience include soil texture, cultivar selection, soil moisture and possibly fertility. Although reniform nematodes can develop in a wide range of soil textures, some soils are much more prone to show damage symptoms (Robinson et al. 1997). Coarse-textured soils will likely sustain the greatest amount of damage and damage may occur with lower population levels of the nematode (Monfort et al. 2008; Overstreet et al. 2011b, 2014). Fine-textured soils with higher

Fig. 15.5 (**a**) Stunted and uneven stand of cotton as result of *Rotylenchulus reniformis* (Overstreet); (**b**) Stunted and uneven stand of cotton as result of a mixed field population of *R. reniformis* and *Meloidogyne incognita*; (**c**) Non-fumigant (left) *vs*. fumigated (right) treated rows in a field with a damaging population of *R. reniformis*; (**d**) Unthrifty soybean growth due to high population density of *R. reniformis*; (**e**) Cracking symptoms of sweet potato storage roots due to early infection by *R. reniformis*; (**f**) Egg masses of *R. reniformis* on sweet potato root system. (Photos by C. Overstreet)

silt or clay content may not be as prone to damage and require higher populations of the nematode to cause injury. Recent studies with site-specific applications of nematicides indicate that soil texture in a field may be much more important than actual nematode populations in determining the level of damage that occurs (Overstreet et al. 2014).

15.8.5 Management Strategies

A phenomenon that has been reported in Louisiana and Texas is the occurrence of soils that suppress reniform nematode (Robinson 2008). Suppressive soils simply mean that nematode populations don't build up as expected on a susceptible host. These soils are believed to have some type of transferable agent, likely some types of biological control organisms. A nematophagous fungus, originally designated as ARF (Arkansas fungus) 18 and recently identified as *Brachyphoris riggsii* (B. Bluhm, pers. comm.), has been found in the Mid-South and was reported to suppress reniform nematode populations in greenhouse experiments (Wang et al. 2004). Alternately, some fungi such as *Rhizoctonia solani,* that causes a seedling disease of cotton called sore shin, have been found to increase infection and subsequent population densities of the nematode (Sankaralingam and McGawley 1994a, b).

The reniform nematode is often found in association with other nematode species (Fig. 15.5b). The interactions between reniform nematodes with the southern root knot nematode (*M. incognita*) have been studied in the Mid-South (Stetina et al. 1997a, b). Based on these studies, root knot nematodes suppressed reniform nematode populations. However, field observations in the Mid-South imply that reniform nematodes appear to become the dominant nematode over time and it actually becomes difficult to find any root knot nematode. This is particularly true when cotton is grown as a monoculture crop. Since some cultivars of soybean or cotton may have some resistance to root knot nematodes and reniform nematode has a shorter life cycle, populations of reniform nematode may simply reach higher levels (Stetina et al. 1997a). However, crop rotations with corn (favors root knot but not reniform nematode) have begun to reverse this trend and more fields now have detectable populations of both nematodes (Overstreet et al. 2011a).

Currently, there are no cultivars of cotton that are resistant to the reniform nematode (Robinson et al. 2004). Breeding efforts have been underway for over three decades to find and incorporate resistance in cotton. Early reports indicated that all of the cotton cultivars and breeding lines in the upland cotton species (*Gossypium hirsutum*) planted in the Mid-South, were susceptible (Birchfield and Brister 1963). Some of the early screening of other *Gossypium* species indicated that resistance to the reniform nematode was present in some species of cotton (Yik and Birchfield 1984); however, incorporating this resistance into *G. hirsutum* proved to be a difficult process. One of the first breeding lines with strong resistance was derived from the cotton species, *G. longicalyx* and released as LONREN (Bell et al. 2014). Unfortunately, LONREN breeding lines showed severe stunting when planted in areas with high population densities of the reniform nematode (Bell et al. 2009). It is likely that a hypersensitive reaction to infection by the nematode in the cotton roots was involved, particularly since LONREN was very effective in killing the nematode as it began to develop with the roots. Germplasm lines with moderate level of resistance were reported from crosses with a germplasm line from Brazil (McCarty et al. 2012). Recently breeding lines derived from *G. barbadense* and referred to as BARREN have been reported (McCarty et al. 2013). The absence of high levels of nematode resistance and poor agronomic performance of BARBREN lines across geographic areas has limited their use for US cotton production.

Although all U.S. cotton is considered susceptible, some cultivars appear to have some level of tolerance. Tolerance implies that the plant may be attacked by the nematode but can still yield well even if it doesn't inhibit nematode reproduction. In a recent study, three cultivars were identified to have some degree of tolerance to the reniform nematode (Stetina et al. 2009). Further research from Mississippi indicated that six of thirteen cultivars tested were considered tolerant of the reniform nematode (Blessitt et al. 2012). These cultivars did not reduce nematode populations at the end of the year, but they did limit economic loss from the nematode. Although tolerant cultivars don't reduce reniform nematode populations they could play a vital role in the overall management of cotton, particularly when combined with other management options.

Aldicarb (Temik® 15G) is a non-fumigant nematicide that was the primary nematicide used in cotton from the early 1980s until recently (Lawrence and McLean 2000; Greer et al. 2009). Aldicarb was effectively used in the Mid-South to reduce nematode losses until 2011 when the product was no longer manufactured. Temik® 15G was applied at low rates (3.4–5.6 kg/ha of formulated material) at the time of planting. The product worked across most soil types and provided early season insect management as well as nematode suppression. The typical response reported in most fields infested with reniform nematode was about 112 kg/ha of lint (Overstreet and McGawley 1994; Overstreet et al. 2002). Aldicarb is available from another company as AgLogic™ 15GG but is not widely available yet. Unfortunately, the long term use of aldicarb in some areas in the Mid-South resulted in reduced benefits of using this product, likely due to accelerated microbial degradation (McLean and Lawrence 2003). Oxamyl (Vydate® C-LV), another carbamate with both insecticidal and nematicidal activity, was also used in cotton throughout the Mid-South until very recently. Oxamyl has been shown to be translocated from leaves to the roots and was available in a liquid formulation that was applied as a foliar spray to cotton to suppress nematode infection. Usually oxamyl was applied at pin-head square and was used in combination with an at-planting nematicide (McLean and Lawrence 2000). Combinations of nematicides such as a fumigant and aldicarb or oxamyl have been reported to provide the greatest yield for cotton (Lawrence et al. 1990).

Seed-applied nematicides came on the market in 2006 with the release of Avicta® Complete Pak for use in cotton which contained a nematicidal component, abamectin, the insecticide thiamethoxam and fungicides azoxystrobin, fludiomonil and mefenoxam. Abamectin provided some protection of the developing seedlings from nematodes when applied on cottonseed (Monfort et al. 2006). The reniform nematode was found to be particularly sensitive to abamectin (Faske and Starr 2006). Although this nematicide was only recommended for use with low to moderate populations of reniform nematode, it quickly became one of the most widely used nematicides. Since this material was already on the seed, it was much more convenient than application of granular or fumigant nematicides. Thiodicarb + imidacloprid (Aeris® seed-applied insecticide/nematicide) was launched in 2008 and serves as another seed treatment nematicide + insecticide in cotton. A formulation of fluopyram + imidacloprid (Velum® Total) applied as an in-furrow spray was registered in 2015 for use in cotton to manage cotton insects and nematodes including the reniform nematode. Although this chemical is an SDHI fungicide, it has been found to be effective against the reniform nematode (Faske and Hurd 2015; Faske et al. 2017). There has been some development of biologicals to manage nematodes in cotton. Poncho®/VOTiVO® is a combination of an insecticide (clothianidin) and a bacterial agent, *Bacillus firmus* that can provide some seedlings protection from early season attack by the reniform nematode. Tioxazafen (NemaStrike™) is being evaluated as a seed-applied nematicide and field efficacy trials are ongoing to determine the impact of this nematicide in cotton production.

Fumigants have been available and used by some cotton producers for many years Fumigant nematicides available today include 1,3 dichloropropene (Telone® II), metam potassium (K-PAM® HL™) and metam sodium (VAPAM® HL) (Greer et al. 2009). Though fumigants are effective, they are also expensive. Fumigants also require special application equipment special permits in some cases and need to be applied prior to planting. Telone® II needs to be applied at least 7 days prior to planting, while VAPAM® HL and K-PAM® HL™ should be applied at least 21 days before planting. Fumigants are applied beneath the row, where they volatilize and move through the soil profile. Although fumigants are very effective against reniform nematode (Fig. 15.5c), whole fields may not require treatment because damaging threshold of the reniform nematode varies among soil texture zones and soil texture zones vary within individual fields. Site-specific application of nematicides has recently been investigated for use in cotton (Overstreet et al. 2014). Fields are divided into management zones (Overstreet et al. 2010) based on apparent electrical conductivity (EC_a), which correlates well with soil texture. This is done with a Veris EC Soil Mapping System which can be used to map the EC_a of a field. The use of verification strips (treated with a nematicide and untreated rows) through the different soil zones can be used to define which zones need to be treated (Overstreet et al. 2010) so, future treatments target only those textural zones where yield loss may occur.

Crop rotation remains one of the most important practices to manage reniform nematode in cotton (Greer et al. 2009). Corn and grain sorghum are excellent rotation crops because they are non-hosts for reniform nematodes and suppress the nematode population density below the damage threshold for the subsequent crop (Stetina et al. 2007; Greer et al. 2009). Two years of corn production is often needed to reduce nematode populations below the damage threshold, particularly if the rotation has followed several years of monoculture cotton production (Stetina et al.

2007). Once the nematode population has dropped, a 1-year corn rotation can reduce damage from reniform in cotton. A few soybean cultivars are resistant to the reniform nematode and can be useful as a rotational crop to reduce the nematode populations in a field. Unfortunately, high populations of reniform nematode can remain deep in the soil profile, allowing population densities to rebound after 1 year of cotton production.

15.8.6 Soybean

The reniform nematode has primarily been an important pathogen of cotton, but in many parts of the Mid-South, soybean is being produced in areas that were previously planted in continuous cotton (Stetina et al. 2014). The reniform nematode has been reported to cause yield losses of 30–60% on soybean (McGawley and Overstreet 2015) and a total yield loss estimate of 3.2 million bushels was reported in 2016 in the Mid-South (Allen et al. 2017a).

15.8.6.1 Symptoms

Reniform nematode damage may not readily identifiable in soybean as it is generally more uniformly distributed in the field (Kirkpatrick et al. 2014). Symptoms include yellowing, stunting, unthrifty growth of plants (Fig. 15.5d) and empty pods (McGawley and Overstreet 2015), although symptoms can vary among cultivars, soil type, nematode population density and environmental conditions. In some cases, the root systems may be stunted with many of the smaller roots appearing discolored or blackened (Overstreet et al. 1992). One of the signs of reniform nematode is abundant egg masses on the root. Because soil is often attached to the egg masses, the root system has a rough or gritty appearance. Symptoms that may show up late in the growing season may be excessive leaf shedding during dry periods. Reniform nematode causes the greatest amount of damage during periods of moisture stress, usually during drought. However, severe damage may also occur under very wet or saturated moisture conditions. Many of the current cultivars of soybean grown in the Mid-South show little or no visible symptoms under adequate moisture conditions and may not show significant yield loss. The lack of visible symptoms and sometimes lack of yield response has made it difficult to determine just how damaging this nematode is to soybeans. Current damage thresholds range from 20 to 4,000/100 cm^3 soil for reniform nematode on soybean across the Mid-South.

15.8.6.2 Management Strategies

Resistance to the reniform nematode has been identified in some soybean cultivars, but very few have a high level of resistance (Robbins et al. 2016, 2017). Historically, the soybean cyst nematode was considered the most important nematode in the Mid-South and Southern U. S. and most of the breeding programs concentrated on this nematode. A widely used source of soybean cyst nematode resistance was the PI 88788 line. Because resistance was originally thought to be linked between soybean cyst and reniform nematodes, it was assumed that all the cultivars that were resistant to soybean cyst were also resistant to reniform nematodes (Rebois et al. 1968, 1970). It is now known that not all the soybean cyst nematode resistant cultivars are effective against reniform. Cultivars that were developed from PI 88788 have only slight resistance to reniform, whereas, those developed from Peking or PI 90763 are highly resistant (Robbins and Rakes 1996). Some of the highly resistant early cultivars included Forrest, Centennial, Sharkey and Stoneville (Robbins et al. 1994). Though today few commercial cultivars have a high level of resistance to reniform nematodes, soybeans in general are not as susceptible to reniform damage as cotton. Resistant cultivars can be used in rotation to suppress reniform population densities in a crop rotation system.

Other rotational crops include peanut and rice, which are considered to be nonhosts for the reniform nematode (Kirkpatrick et al. 2014). These crops can cause a significant drop in nematode population densities in a single season, but often 2 years are needed in fields with a high population density of reniform nematodes. Alternately, crops like cotton and sweet potato are excellent hosts and can sustain or increase reniform population densities for the subsequent crop.

Few nematicides are available to use on soybeans to manage reniform nematode. Fumigants such as 1,3 dichloropropene (Telone® II), metam potassium (K-PAM® HL™) and metam sodium (VAPAM® HL) are registered for use on soybean, but are not commonly used in the Mid-South due to cost of nematicide, product availability and economic benefit to yield. Aldicarb (Temik® 15G) was registered in some states, but not in the Mid-South to manage reniform nematode on soybean. Research is being conducted on the use of site-specific application of nematicides in soybean. Similar to studies in cotton, reniform nematode causes the greatest amount of damage in coarse-textured soils; these are the soil types that are most likely to respond to the application of a nematicide. Seed-applied nematicides like abamectin (Avicta® 500 FS) and fluopyram (ILeVO® 600 FS) are registered for use in soybean. Similarly, the seed-applied bionematicide *Bacillus firmus* (VOTiVO®) is also marketed for reniform suppression. Producers in the Mid-South most commonly use crop rotation to manage reniform nematode on soybean rather than nematicides.

15.8.7 Sweet Potato

The reniform nematode is a common nematode on sweet potato that affects both storage root quality and yield (Overstreet 2013b). Sweet potato is very susceptible to damage by the reniform nematode, but yield loss estimates in the Mid-South are lacking. High yield losses have reported by reniform nematode on sweet potato (Birchfield and Martin 1965), and yield loss estimates of 5–10% have been reported from Louisiana, although these fields contained both reniform and root knot nematodes (Koenning et al. 1999).

15.8.7.1 Symptoms

Symptoms of reniform nematode on sweet potato are often difficult to recognize in the field since there are generally not any distinct foliar symptoms. Some of the earlier cultivars were reported to express some yellowing when grown in reform nematode infested fields (Overstreet 2013b). Infected plants may have discolored fibrous root and mature later than those grown in non-infested fields even when nematode population densities are low. Cracking can occur on the storage roots (Fig. 15.5e) from early infection by reniform nematode. Root knot nematode can also cause cracking of storage roots. Female reniform nematodes are not found in root cracks, whereas *M. incognita* J2 and females can both be found within cracked roots (Overstreet 2009). Cracking is less common with many of the commercially available cultivars as they are less prone to cracking compared to older cultivars. Yield losses in sweet potato are associated with a reduction in the size of storage roots, which reduces the number of marketable sweet potatoes (Abel et al. 2007).

Damage thresholds are lower for older cultivars because of cracking sensitivity, but in general. population levels of reniform nematode that are considered damaging range from 10 to 1000 vermiform/100 cm^3 soil (Smith et al. 2008; Anonymous 2017). Population densities are not uniform within a field, but the nematodes may be distributed throughout the entire field (Burris et al. 2009). Reniform population densities can build up quickly on susceptible cultivars such as Beauegard (Fig. 15.5f).

15.8.7.2 Management Strategies

Nematicides have been one of the most effective methods of management of the reniform nematode (Smith et al. 2008). Fumigant nematicides such as 1,3 dichloropropene (Telone® II), metam potassium (K-PAM® HL™) and metam sodium (VAPAM® HL) are the most common nematicides used to manage nematodes in sweet potato (Overstreet 2013b). Though effective and commonly used to prevent reniform damage, they do increase production cost for sweet potato farmers. All of the fumigants must be applied preplant and require a period of time before sweet potato slips can be transplanted. Aldicarb, a non-fumigant nematicide, was reported to increase the number of USDA number 1 and jumbo storage roots in reniform nematode infested fields in Mississippi (Henn et al. 2006). Fluensulfone (Nimitz®) was recently registered for use on sweet potato, providing growers another option in managing reniform nematode.

Currently, none of the sweet potato cultivars grown in the Mid-South are resistant to the reniform nematode (Smith et al. 2008; Overstreet 2013b); however tolerance has been reported in a few cultivars such as Centennial (Clark and Wright 1983). Unfortunately, growing tolerant cultivars can contribute to the buildup of a nematode population density that can affect the subsequent crop if it is susceptible to the reniform nematode.

Crop rotation is a good strategy for producers with reniform nematodes in production fields. Corn, grain sorghum and peanut can greatly decrease populations in a field (Smith et al. 2008). Other cultural practices include washing storage roots free of soil before planting in the plant bed to avoid the possibility of introducing the nematode into plant beds (Overstreet 2013b). Producers that use vine cuttings (slips) for transplants eliminate the potential dispersal of reniform nematode into non-infested fields.

As discussed in this chapter, plant parasitic nematodes are among the most important yield limiting factors that affect row crop production in the Mid-South. Sustainable agriculture is an integrated system of crop production practices that have specific applications. A long-term goal is addressing the needs of consumers, maintaining production at a profitable level and enhancing the quality of life for farmers. Consequently, an integrated system of tools is used to manage nematodes in the Mid-South. One of the most important factors in nematode management is to understand the nematode species that are affecting crop production, keeping in mind that the species complex in a field can change over time. For example, the soybean cyst nematode was prevalent historically in several counties in Louisiana, but over the past 10 years it is been difficult to find. Conversely, root knot and reniform nematodes are more common. Similarly, the soybean cyst nematode was the most frequently found species of nematode in the 1980s on soybean in Arkansas; however, today (2018), although soybean cyst nematodes are still common inhabitants of soybean fields, the root knot nematode is the most important nematode on soybean in Arkansas.

Host plant resistance and the use of a non-host crop in rotation sequences are among the oldest management tools that are still economical and effective ways to manage plant parasitic nematodes. As discussed in this chapter, resistance and rotational crops are limited in some cropping systems in the Mid-South. In these systems, farmers are more likely to depend on nematicides. Research has provided evidence that site-specific nematicide application where only those areas of the field where soil type and nematode population densities affect yield loss can be an effective approach to nematode management. Reducing the amount of nematicide needed results in a cost savings to the farmer, while also limiting the potential environmental impact of a nematicide across an entire field. Since 2006 there has been an interest in seed-applied nematicides and currently, there are several seed-applied chemical or biological agents being evaluated to suppress plant parasitic nematodes in row crops. Seed-applied nematicides provide a uniform delivery of the nematicide at lower quantities compared to granular applications. Similarly, nematicides which are less toxic to the handler and potentially less toxic to off-target pest, due to lower acute toxicity, are being marketed for use in agriculture.

Because production systems vary across the Mid-South, each system may have a different set of tools to manage nematodes. Similarly, each field likely poses different challenges according to weed, disease, irrigation and nematode presence, so decisions on nematode management should be made on a field by field basis rather than farm-wide. Farms in the Mid-South range from several hundred to several thousand hectares. As cropping systems change so will the population of plant parasitic nematodes, emphasizing the importance of continued research and extension in nematology. There is currently a real concern across the discipline of nematology for the future development of applied, field-oriented nematological expertise. This could have a major impact in future agriculture research and services and the long term goals of sustainable agriculture.

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