Overview of Plant-Pathogenic Nematodes
Why they are important, and difficult to manage.

Donald W. Dickson, Nematologist–Plant Pathologist
University of Florida, Gainesville, FL

We are the Gators!
<table>
<thead>
<tr>
<th><strong>OUTLINE</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>What is a nematode</td>
</tr>
<tr>
<td>Type of nematodes</td>
</tr>
<tr>
<td>Plant-parasitic nematodes – Types</td>
</tr>
<tr>
<td>General morphology</td>
</tr>
<tr>
<td>Disease cycles</td>
</tr>
<tr>
<td>Most important kinds of PPN</td>
</tr>
<tr>
<td>Damage and symptoms</td>
</tr>
</tbody>
</table>
Nematodes have colonized nearly every conceivable habitat on earth, including such unlikely places as in felt pads used as beer coasters in Germany (Panagrellus silusiae). Some nematodes are also extreme habitat specialists, living, for example, only in the placentas of sperm whales (Placentonema gigantissima), or the right kidneys of minks (Dioctophyme renale).

Nematodes are the most numerous multicellular animals on earth. A handful of soil will contain thousands of the microscopic worms, many of them parasites of insects, plants or animals. Free-living species are abundant, including nematodes that feed on bacteria, fungi, and other nematodes, yet the vast majority of species encountered are poorly understood biologically. There are nearly 30,000 described species classified in the phylum Nematoda.
Animal Parasites

through their eggs which then develop into larvae. There are many kinds of animal parasites that affect humans: hookworms; trichina, the cause of trichinosis, another extremely common parasite, even anthrax; and schistosomiasis, transmitted from human to human by eggs floating in the water. These are tropical parasites that cause diseases such as bilharziasis (schistosomiasis) and onchocerciasis (river blindness).
Parasitic nematode species affect humans directly or indirectly through their domestic animals. These probably infest more than half the world’s humans: hookworms; trichina, the worms that cause trichinosis; pinworms, another extremely common parasite, even in the United States, which can be transmitted from human to human by eggs floating in household dust; and filarial worms, primarily tropical parasites that cause diseases such as filariasis (elephantiasis) and onchocerciasis (river blindness).
And do not forget, **dog heart worms** are animal parasitic nematodes.  

*Dirofilaria immitis*

A horrible disease for man’s best friend, one completely preventable. Dog heart worms are vectored by mosquitoes.
Free-Living Species

Free living nematodes play critical ecological roles as regulators of decomposition and nutrient cycling by feeding on microorganisms.
Free-Living Species

Free living nematodes play critical ecological roles.
Marine Inhabitants
(Including parasites of marine fauna)
Plant Parasites

NOT just another can of worms!
Plant Parasites

- Stylet-bearing
- Soil-inhabiting
- Obligate parasites
- Direct life cycle
- Ca. 4,000 species
- 100-125 genera

NOT just another can of worms!
Root-knot Nematode -- Direct Life Cycle

_Meloidogyne_ spp.

- **Egg**
- **J1 in egg**
- **1\textsuperscript{st} molt in egg**
- **J2 Hatches**
- **J2 Infects root**
- **Infected J2**
- **Parasitic J2**
- **Egg Mass**
- **Adult Female**
- **Adult Male**
- **Adult male leaves root to seek female**
- **J3**
- **J4**
- **4\textsuperscript{th} Molt**
- **3\textsuperscript{rd} Molt**
- **2\textsuperscript{nd} Molt**

Drawings by C.S. Papp
Single mature *Meloidogyne* female with egg mass

- Eggs within mass
- Galled tissue
- Vascular tissue
- Female nematode
Pratylenchus penetrans - lesion nematode
Disease Causing Plant-Parasitic Nematodes
(Agrios, 1997)

Total of 24 genera

- Longidorus – Needle nematode
- Dolichodorus – Awl nematode
- Belonolaimus – Sting nematode
- Anguina – Seed gall nematode
- Xiphinema – Dagger nematode
- Hoplolaimus – Lance nematode
- Rotylenchus – Spiral nematode
- Hemicycliophora – Sheath nematode
- *Ditylenchus – stem & bulb nematode
- Aphelenchoides – Foliar nematode
- Tylenerchorynchus – Stunt nematode
- Paratrichodorus – Stubby root nematode
- Radopholus – Burrowing nematode
- Pratylenchus – Lesion nematode
- Criconemella – Ring nematode
- Paratylenchus – Pin nematode
- Helicotylenchus – Spiral nematode
- Rotylenchulus – Reniform nematode
- Tylenchulus – Citrus nematode
- Criconema – Ring nematode
- *Globodera – Round cyst nematode
- Meloidogyne – Root-knot nematode
- Heterodera – Cyst nematode

Scale = μ
## 14 RKN species in Florida, USA

<table>
<thead>
<tr>
<th>Species</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>M. incognita</em></td>
<td><em>M. partityla</em></td>
</tr>
<tr>
<td><em>M. arenaria</em></td>
<td><em>M. graminis</em></td>
</tr>
<tr>
<td><em>M. javanica</em></td>
<td><em>M. graminicola</em></td>
</tr>
<tr>
<td><em>M. hapla</em></td>
<td><em>M. marylandi</em></td>
</tr>
<tr>
<td><em>M. enterolobii</em></td>
<td><em>M. christiei #</em></td>
</tr>
<tr>
<td><em>M. floridensis #</em></td>
<td><em>M. cruciani</em></td>
</tr>
<tr>
<td><em>M. haplanaria</em></td>
<td><em>M. thamesi</em></td>
</tr>
</tbody>
</table>

Red = important species in vegetable and agronomic crop production.
# Currently only reported in Florida & California.
Real ugly gardenia

Gardenia badly diseased by root-knot nematodes

Solution – pull up roots, leave fallow for months
Healthy gardenia
“Tifguard” peanut, Levy County 2012, Fence row to fence row root-knot nematode infected peanut.
Root galling on peanut cv. ‘Tifguard’
Caused by *Meloidogyne arenaria*
The guava root-knot nematode, *Meloidogyne enterlobii*

Pernambuco, Petrolina, Brazil 2016
11 RKN species of concern of which 7 do not currently reside in Florida.

<table>
<thead>
<tr>
<th>Species</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>M. enterolobii</td>
<td>FL, NC, Wide</td>
</tr>
<tr>
<td>M. graminicola</td>
<td>FL, Wide</td>
</tr>
<tr>
<td>M. floridensis</td>
<td>FL</td>
</tr>
<tr>
<td>M. hispanica</td>
<td>NA, Wide</td>
</tr>
<tr>
<td>M. minor</td>
<td>WA, Europe</td>
</tr>
<tr>
<td>M. paranaensis</td>
<td>Hawaii, Brazil</td>
</tr>
<tr>
<td>M. fallax</td>
<td>CA, Europe</td>
</tr>
<tr>
<td>M. ethiopica</td>
<td>Europe, Africa</td>
</tr>
<tr>
<td>M. artiellia</td>
<td>Europe</td>
</tr>
<tr>
<td>M. chitwoodii</td>
<td>NA, Europe</td>
</tr>
<tr>
<td>M. haplanaria</td>
<td>TX, FL</td>
</tr>
</tbody>
</table>
Okra galled by *Meloidogyne enterolobii*
Sting nematode damage on ‘Tiftguard’
Sting nematode damage on ‘Tiftguard’
Sting nematode damage on peanut pods and pegs.
Management of nematode pathogens – Based on concept of maintaining nematode damage or losses below economic injury level.

A continuous process is needed because it is a continuous problem.

Publications on nematodes

Nematode management guides via IFAS EDIS publications.

Entomology and Nematology Feature Creatures publications.

Remembering major events that shaped our programs:


Nemagon, a great effective nematicide, was sold in one gallon glass jugs at your local garden center, and methyl bromide, a broad spectrum fumigant, took the vegetable industry by storm.

Vietnam war raging, civil right issues brought to the front, no computer, no cell phone, and photocopy machines rare.
Nematode management options for important agricultural crops -- 2019.

<table>
<thead>
<tr>
<th>Legislative (quarantine)</th>
<th>Host-plant resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevention</td>
<td>Conventional breeding</td>
</tr>
<tr>
<td>Avoidance</td>
<td>Grafting</td>
</tr>
<tr>
<td>Nematicides</td>
<td>Molecular innovations</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fumigant and nonfumigant</th>
<th>Biological control</th>
</tr>
</thead>
<tbody>
<tr>
<td>New chemistries</td>
<td>Fungi &amp; bacterial</td>
</tr>
<tr>
<td>(Application methods, equipment, &amp; dosages)</td>
<td>Physical</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cultural</th>
<th>Physical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotation and cover crops</td>
<td>Heat</td>
</tr>
<tr>
<td>Sanitation &amp; clean planting stock</td>
<td>Fallowing &amp; flooding</td>
</tr>
<tr>
<td>Destruction of crop residue</td>
<td>Solarization</td>
</tr>
<tr>
<td>Time of planting</td>
<td></td>
</tr>
<tr>
<td>Nutrition &amp; general care of crop</td>
<td></td>
</tr>
<tr>
<td>Trap &amp; antagonistic crops</td>
<td></td>
</tr>
<tr>
<td>Allelopathic plants</td>
<td></td>
</tr>
</tbody>
</table>
Misinformation on web about nematode management

- Fallowing – flooding
- Fumigate with Vapam® (metam sodium – Sodium dithiocarbamate) **Not legal**
- Solarization
- Plant nematode suppressive plants, e.g., French marigolds
- Host-plant resistance always works, the ultimate.
Best Nematode Management Tactic

- Avoidance – Don’t move harmful nematodes.
  - Farm machinery
  - Transplants, especially perennials
  - Wind storms, floods
  - Animals, including birds
Examples of nematode quarantine nematode pathogens

First line of defense against nematodes is prevention

2012 USDA-APIHS Regulated Offshore list of A rated nematodes

- *Anguina funesta* (H)
- *Anguina tritici* (H)
- *Bursaphelenchus cocophilus* (H)
- *Globodera pallida* (H)
- *Globodera rostochiensis* (H)
- *Heterodera latipons* (M)
- *Longidorus attenuatus* (L)
- *Meloidogyne artiellia* (M)
- *Meloidogyne fallax* (M)

Images from: grainews, EPPO, UGA

Courtesy of Dr. Inga Zasada
Global Importance of Potato Cyst Nematodes
Global PCN distribution

Distribution Maps of Quarantine Pests for Europe

Globodera rostochiensis

Globodera pallida

Courteous of Dr. Inga Zasada
**Soybean Cyst Nematode**

SCN
*Heterodera glycines*
First reported NC 1954

Host
Soybean

UF campus, breeding plots, site is now the ladies softball field
Impact of Soybean Cyst Nematode (SCN)

- *Heterodera glycines* causes an estimated annual loss >$1 billion to soybean production in the USA alone.
- SCN is found wherever soybeans are grown.

First reported 1954 on farm along coast of North Carolina. **Quarantined and regulated** but programs failed as SCN quickly inhabited all soybean growing regions in USA and much of Canada.

First reported early 1990’s in Brazil.
Current Model of Cyst Nematode CLE Peptide Signaling

CLE = CLAVATA 3/ESR-like effector protein

Cell to be incorporated

- Phytohormone Signaling?
- Defense?
- Development?

Initial syncytial cell

- CLV2
- CRN
- CLEs

Post-translational modification

DGA

Courteous of Dr. Jianying Wang

Nematode Management with Nematicicides
<table>
<thead>
<tr>
<th>Fumigant nematicides</th>
<th>Nonfumigant nematicide insecticides</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-D</td>
<td>Fensulfothion</td>
</tr>
<tr>
<td>DBCP</td>
<td>Fenamiphos</td>
</tr>
<tr>
<td>EDB</td>
<td>Demeton</td>
</tr>
<tr>
<td>Broad-Spectrum fumigant</td>
<td>Diazinon</td>
</tr>
<tr>
<td>nematicides</td>
<td></td>
</tr>
<tr>
<td>D-D Mencs</td>
<td>Carbofuran</td>
</tr>
<tr>
<td>Methyl bromide</td>
<td>Aldicarb</td>
</tr>
<tr>
<td>Methyl iodide</td>
<td>(AgLogic 15G)</td>
</tr>
</tbody>
</table>

- OP’s
- Carbamates
Nematicide characteristics desired -- challenging

1. Efficacy
2. Economical
3. Effective at low dosage
4. Low mammalian toxicity
5. Environmentally friendly
6. Nonpersistant
7. No microbial degradation
8. No phytotoxicity
9. Easy to apply – preplant, at plant, post plant
10. Active against polyspecific nematode community
11. Little or no leaching, run off into streams, no groundwater issues
12. Little or no odor issues
13. No off-site issues
14. No onerous regulations, e.g., Fumigant Management Plan
Montreal protocol began process to cancel most agricultural uses of mbr 1993.

Staked tomato in south Florida

2014 D. W. Dickson, Univ. of Florida
Pepper production in Florida -- MBR

Pepper production in south Florida

2014 D. W. Dickson, Univ. of Florida
Purple and yellow nutsedges
Crabgrass overwhelming
Germinates and grows via the plant hole.
Registered Fumigants, Non-fumigants

Methyl bromide 80-20 – available for nurseries only

**Broad-spectrum fumigants**
- Telone C35 (1,3-D + chloropicrin)
- Paladin (dimethyl disulfide)
- Chloropicrin formulations
- Metam sodium and metam potassium
- Pic-Clor 60
- Dazomet (basamid)

**Nematicides for vegetables**
- Telone II (1,3-D)
- Nimitz (fluensulfone)
- Vydate (oxamyl)
- Velum Total, Indemnify (fluopyram)

**Biological Nematicides**
- Melocon & other (*Purpureocillium lilacinum*)
- DiTera (*Myrothecium verruearia*)
- Nortica (*Bacillus firmus*): turfgrasses
- Clariva (*Pasteuria nishizawai*) soybean
- Avicta (abamectin)
- Neem oil
- Majestene (*Burkholderia* spp.)

**Nematicides - other**
- Pylon (chlorfenapyr) foliar nemas
- Multiguard protect (Furfural): turfgrasses
- Mocap (ethoprop)
- Aeris (thiodicarb + Imidacloprid) cotton
- Counter (terbufos)
- Dominus (ally isothiocyanate)
Fumigation – Laying PE

2014 D. W. Dickson, Univ. of Florida
Telone C17
Pig cylinder, ca. 1,500 lbs.
81% 1,3-D + 17% Chloropicrin
NEW CHEMISTRY TRIALS

- Soybean
- Peanut
- Carrot
- White potato
- Sweet potato
- Cantaloupe
- Cucumber
- Tomato
- Watermelon
- Tobacco
- Strawberry
- Field corn

Nimitz
Velum Total
Solipro
<table>
<thead>
<tr>
<th>Host plant</th>
<th>Gene or source</th>
<th>Meloidogyne spp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrot</td>
<td>Mj - 1</td>
<td>Mi, Mj</td>
</tr>
<tr>
<td>Clover</td>
<td>TRKR</td>
<td>M. trifoliophila</td>
</tr>
<tr>
<td>Coffee</td>
<td>Mex - 1</td>
<td>M. exigua</td>
</tr>
<tr>
<td>Common bean</td>
<td>Me 1, Me2, Me 3</td>
<td>Mi, Mi, Mj</td>
</tr>
<tr>
<td>Cotton</td>
<td>Rkn 1, RKN2</td>
<td>Mi</td>
</tr>
<tr>
<td>Cowpea</td>
<td>RK, Rk2, rk3</td>
<td>Ma, Mh, Mi, Mj</td>
</tr>
<tr>
<td>Grape</td>
<td>N, Mur1</td>
<td>Ma, Mi</td>
</tr>
<tr>
<td>Lucerne</td>
<td>Mj - 1</td>
<td>Mh, Mi</td>
</tr>
<tr>
<td>Lima bean</td>
<td>Mir - 1, Mig- 1, Mjg- 1</td>
<td>Mi, Mj</td>
</tr>
<tr>
<td>Groundnut</td>
<td>Arachis spp. hybrids</td>
<td>Ma, Mj</td>
</tr>
<tr>
<td>Pepper</td>
<td>Me1, 3,4,7; Mech1,2</td>
<td>Ma, Mi, Mj, M. chitwoodi</td>
</tr>
<tr>
<td>Potato</td>
<td>Rmc1, MfaXIIspl</td>
<td>M. chitwoodi, Mh, M. fallax, Mi</td>
</tr>
<tr>
<td>Prunus</td>
<td>Ma</td>
<td>Mj, Mi, Ma, Mf</td>
</tr>
<tr>
<td>Soybean</td>
<td>2 QTLs</td>
<td>Mj</td>
</tr>
<tr>
<td>Sugarbeet</td>
<td>Beta vulgaris spp.</td>
<td>Ma, M. chitwoodi, Mh, M. fallax</td>
</tr>
<tr>
<td>Sweet potato</td>
<td>complex</td>
<td>Mi, Mj, Ma</td>
</tr>
<tr>
<td>Tobacco</td>
<td>Rk</td>
<td>Mi</td>
</tr>
<tr>
<td>Tobacco</td>
<td>Mi1 – Mi9</td>
<td>Ma, Mi, Mj</td>
</tr>
<tr>
<td>Wheat</td>
<td>Triticum tauschii</td>
<td>Mi, Mj, M. chitwoodi</td>
</tr>
</tbody>
</table>
Nematode host plant resistance

• **Endoparasitic nematodes** – Resistance is available for sedentary endoparasitic nematode (e.g., root-knot, cyst, and reniform nematodes.

• Resistance available for migratory endoparasitic nematodes, e.g., BN & citrus nematode on citrus rootstock.

• **Ectoparasitic nematodes** – Resistance is not available, but some cultivars provide tolerance.

• **Note** – Nematode races and species exist whereby the resistant gene is nonfunctional.
Tomato gene Mi-1

- Currently best characterized nematode resistance gene
- Confers resistance against Mi, Mj, and Ma
- Originally discovered in wild species *Solanum peruvianum*
- Ingression began with embryo rescue of single plant from a cross of *S. peruvianum* x *S. lycopersicum* – 1940’s
RKN resistance in tomato

• *Mi-1* gene is ineffective at high soil temperature (>28 C)
• And not effective against --
  – *Meloidogyne hapla* – northern rkn
  – *Meloidogyne enterolobii* – guava rkn
  – *Meloidogyne floridensis* – peach rkn
  – *Meloidogyne haplanaria* – Texas rkn
  – *Meloidogyne hispanica* – Seville rkn
  – *Meloidogyne brasiliensis* – Brazilian rkn
  – And some populations of *Mi*, *Mj*, and *Ma*, races have
    build up over time that break the plants resistance
## Occurrence of virulent *Meloidogyne* spp. on tomato

<table>
<thead>
<tr>
<th>Country</th>
<th>Place of study</th>
<th>RKN species</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greece</td>
<td>Greenhouse</td>
<td><em>Mj</em></td>
<td>Tzortzakakis <em>et al.</em>, 2005</td>
</tr>
<tr>
<td>Greece - Crete</td>
<td>Growth chamber</td>
<td><em>Mi</em></td>
<td>Tzortzakalus and Gowen, 1995</td>
</tr>
<tr>
<td>USA-California</td>
<td>Field</td>
<td><em>Mi</em></td>
<td>Kaloshian <em>et al.</em>, 1996</td>
</tr>
<tr>
<td>France</td>
<td>Growth chamber</td>
<td><em>Mi</em></td>
<td>Castagnone-sereno <em>et al.</em>, 1993 and 1994</td>
</tr>
<tr>
<td>France</td>
<td>Field and greenhouse</td>
<td><em>Mi</em></td>
<td>Jarquin-Barberena <em>et al.</em>, 1991</td>
</tr>
<tr>
<td>Morocco</td>
<td>Field and greenhouse</td>
<td><em>Mj</em></td>
<td>Eddaoudi <em>et al.</em>, 1997</td>
</tr>
<tr>
<td>Italy</td>
<td>In vitro</td>
<td><em>Mj</em></td>
<td>Molinari and Miacola, 1997</td>
</tr>
<tr>
<td>Spain</td>
<td>Greenhouse and microplots</td>
<td><em>Mj</em></td>
<td>Ornat <em>et al.</em>, 2001</td>
</tr>
<tr>
<td>Cyprus</td>
<td>Field</td>
<td><em>Mj</em></td>
<td>Philis and Vakis, 1977</td>
</tr>
</tbody>
</table>

Field had 6 RKN resistant tomato crops 10 year period.
Resistant tomato not significantly galled in Florida. But yields vary from season to season. (Dickson, 2011)
Resistance in cultivated peanut

- Wild-type gene ingressed from peanut species found in SA.
- First cultivated peanut cv. Coan with rkn resistance.
- Germplasm used to develop Tifguard – First cultivated peanut with both RKN and tomato spotted wilt virus protection.
Tifguard damaged by *Meloidogyne arenaria* in 2012
Peanut cv. Tifguard -- resistant to peanut root-knot nematode.
TifNV HiOleic Peanut Resistant to Ma and MJ
Rotation with bahiagrass, 5 to 6 years
Or soil fumigation with 1,3-D
Peach rootstock cv. Flordaguard
The Ugly

Pecan seedling for sale 2018
Pecan seedlings 2018
BIOLOGICAL CONTROL of PLANT NEMATODES
Biocontrol of nematodes

1. Historically we have known about an array of biological and abiotota agents that suppress plant nematodes since the 18th century.

2. One of first records – Zopt 1888 considered using *Arthrobotrys* (a nematode trapping fungus) for control of the wheat gall nematode, *Anguina tritici*. 
Faculative fungal parasites that infect sedentary females, eggs, egg masses, cysts

- Catenaria
- Cylindrocarpon
- Exophiala
- Fusarium
- *Purpureocillium lilacinum*
- Penicillium
- Phoma
- Neocosmospora
- Stagonospora
- Arkansas Fungus 18
- Pochonia chlamydosporia

*Use of high concentrations of *Purpureocillium lilacinum* spores for biocontrol poses a health risk in immunocompromised humans and more research is needed to determine the human element with the pathogenicity factors of *P. lilacinum*. 
Bacterial endospore forming parasites

- *Pasteuria penetrans* – *Meloidogyne* spp.
- *Pasteuria thornei* – *Pratylenchus* spp.
- *Pasteuria nishizawae* – *Globodera* and *Heterodera*
- *Pasteuria candidatus usgae* – *Belonolaimus longicaudatus*
- *Pasteuria ramosa* – water fleas, *Daphnia, Moina*
**Pasteuria penetrans** – Bacterial parasite

1. Recognition & attachment

2. Infection

3. Nematode development

4. Release of spores

Slide credit: R. M. Savre
EPCOT Spring Flower Festival -- Spectacular
Spinach grown in
THE LAND PAVILLION
Steaming soil at THE LAND DISNEY WORLD, over and over!
Pasteuria highly effective -- reduced root-knot nematode disease in The Land
Services provided by UF Nematode Assay Lab

• Normal soil extraction: $25 in-state, $35 out-of-state
• Mist chamber extraction from roots or turf plugs: $25 in-state, $35 out-of-state
• Molecular species identification with sequencing: $100 per sample (20 specimens per sample)
• Morphological species identification: $100 per sample (20 specimens per sample)
• Different pictures: Dept. building, Assay Lab, People, Forms, Database, Twitter page,
The End.