Effects of Soil Temperature and Planting Date of Wheat on *Meloidogyne incognita* Reproduction, Soil Populations, and Grain Yield

P. A. Roberts, S. D. Van Gundy, and H. E. McKinney[1]

Abstract: Wheat cultivars Anza and Produra grown in winter in California were planted in *Meloidogyne incognita* infested and noninfested sandy loam plots in October (soil temperature 21 C) and November (soil temperature 16 C) of 1979. *Meloidogyne incognita* penetrated roots of mid-October planted Anza (427 juveniles/g root), developed into adult females by January, and produced 75 eggs/g root by harvest in April. Penetration and development did not occur in late plantings. Anza seedlings grown in infested soil in pots buried in field soil in early spring were not invaded until soil temperature exceeded 18 C. *Meloidogyne incognita* juveniles can migrate through soil and penetrate roots at temperatures above 18 C (activity threshold), however development can occur at lower temperatures. Grain yields were not significantly different between nematode infested (3,390 kg/ha) and noninfested (2,988 kg/ha) plots. Winter decline of eggs and juveniles in two late plantings and in fallow soil were 69, 72, and 77%, respectively, but egg and juvenile decline was only 40% in the early Anza plots that supported nematode reproduction in the spring. Delay of planting date until soil temperature is below 18 C is suggested to maximize the use of wheat in rotation as a nematode pest management cultural tactic for suppressing root-knot nematodes. *Key words:* root-knot nematodes, population dynamics, nematode pest management, *Triticum aestivum*.

All commercial cultivars of bread wheat (*Triticum aestivum* L. em Thell) and durum wheat (*T. turgidum* L. var. *durum* Desf.) that have been screened in glasshouse tests are hosts for *Meloidogyne incognita* (Kofoid and White) Chitwood and *M. javanica* (Treub) Chitwood (3,8,12,15, and Roberts unpublished data). However, previous field tests failed to detect the reproduction of these nematodes (13,15). In areas that are warm enough for the reproduction of *M. incognita* and *M. javanica*, wheat is generally planted in autumn and harvested for grain in late spring and early summer. Thus, soil temperatures from planting until harvest are a critical factor in the establishment and reproduction of these nematodes. Soil temperature in southern California rarely declines below the temperature development threshold of about 10 C for *M. incognita* (15,16,17,19). Minimum winter soil temperatures are consistently above this level at lower latitudes such as Sonora, Mexico (18). Estimations on the number of heat units (degree-hours above a basal temperature of 10 C) required for development and reproduction of these *Meloidogyne* spp. indicate that temperature should not limit the completion of a generation during the winter in the warm wheat-growing regions (9,15,17,19).

The cultivation of irrigated winter-grown spring wheat is increasing in mild winter regions. The area planted to winter-grown wheat in California has increased by 35% in 3 yr to an estimated 405,000 ha in 1979–80 (2). In 1978–79 cultivar Anza represented 50% of the bread

Received for publication 8 October 1980.

[1]Department of Nematology, University of California, Riverside, CA 92521. Present address of senior author: Cooperative Extension, University of California, Parlier, CA 93648.

wheat acreage (146,000 ha) and cultivar Produra represented 51% of the durum wheat acreage (9,300 ha). Damage to wheat by *M. incognita* and *M. javanica* has not been reported, although damage to susceptible summer crops following winter cereals on soil infested with these species has been recorded (15).

The increased wheat acreage on *Meloidogyne* infested land, and a trend towards earlier autumn planting dates warrant studies to determine the effect of *M. incognita* on yield of winter-grown wheat and the influence that soil temperature and planting date have on the development, reproduction, and winter survival of the nematode.

MATERIALS AND METHODS

Plot design and management: Plots were established in autumn 1979 on a sandy loam field near Tustin, California. Plots on *M. incognita* infested soil were summer cropped with susceptible vegetables; plots on noninfested soil were summer fallowed. All plots received a preplant application of 16–20–0 fertilizer at 420 kg/ha. Wheat cultivars Produra and Anza were planted on 18 October and/or 15 November 1979 at 151 kg seed/ha with a tractor-drawn seed drill, rows on 10-cm centers. Plots were sprinkler irrigated when necessary until rainfall supplied sufficient moisture. All plots were treated with a broad-leaf herbicide (2,4-Dichlorophenoxyacetic acid) at 0.54 kg/ha 4 wk after seedling emergence. October plantings of Anza on the infested and noninfested sites consisted of five adjacent replicate plots (46.6 m^2) per site. November plantings of Anza and Produra and the fallow plots were established on the infested site near the October plantings and consisted of five replicate plots (46.6 m^2) per cultivar and fallow in a complete random design. A 20.8 m^2 area was machine harvested from the center of each plot on 28 April 1980.

Soil and root sampling: Three soil samples per plot were collected on each sampling date. Each sample consisted of 10 cores (2 cm $\times$ 45 cm deep). A 600-g aliquant from each sample was processed through a 40-mesh sieve to collect egg masses and through a 325-mesh sieve followed by Baermann funnel extraction to collect second-stage juveniles.

Samples of roots 25 cm deep were removed from each plot, washed in tap water, damp-dried and weighed, stained in acid fuschin in lactophenol, and macerated to release *M. incognita* juvenile and adult stages for counting.

Buried pots: On 21 March 1980, 15-cm-d pots containing 7-d-old Anza seedlings in steam-sterilized field plot soil maintained at 12 C were inoculated with 7,500 newly hatched *M. incognita* second-stage juveniles and buried to their rims at the field plot site. Pots were removed periodically and the Anza roots examined for invasion and development of *M. incognita* as described above.

The soil temperature at 23 cm deep was recorded continuously at the field trial site (soil temperature recorder, Foxboro Company, Foxboro, Mass.).

RESULTS

Plants of both cultivars in field plots emerged about 7 d after each planting date. The seminal roots of Anza seedlings contained 427 second-stage juveniles/g root within 14 d after the October planting date and subsequent root samplings indicated that no further penetration of roots occurred from November onward (Table 1). Third- and fourth-stage juveniles were present by late November when about 6,400 heat units had accumulated. Adult female nematodes were present in roots in late January, and egg production had started by the time 12,200 heat units had accumulated. At harvest approximately 75 eggs/g fresh weight were recovered from the roots. Most of the roots were dead, although egg masses remained attached to root material. Small median and terminal galls were observed on seminal roots during the winter, and occasionally two females were associated with the same gall. Apart from a few second-stage juveniles found in Produra roots in January, roots of Anza and Produra planted in November did not contain second-stage juveniles; penetration, development, and reproduction were not detected throughout the season (Table 1).

Soil temperature at planting declined from 21 C in October to 16–17 C in Novem-

Table 1. The penetration and development of *M. incognita* in winter grown wheat in infested field plots at two planting dates.

Sampling date	Wheat variety	Days from wheat emergence	Accumulated heat units from emergence	Mean fresh root wt (g)*	Mean numbers of *M. incognita* development stages/g fresh root*: Early second stage	Late second stage	Third-fourth stage	Adult male	Adult female	Eggs
A) Planting date: 10/18/79										
11/1/79	Anza	7	1800	1.5	427	0	0	0	0	0
11/29/79	"	35	6400	6.3	9	25	6	0	0	0
1/24/80	"	91	12200	29.5	0	1	3	1	2	+†
3/21/80	"	147	19700	23.7	1	0	1	1	5	+
4/16/80	"	173	23700	32.9	0	0	0	0	3	+
5/6/80	"	193	27000	24.0	—	—	—	—	—	75±10
B) Planting date: 11/15/79										
11/29/79	Anza	7	900	2.0	0	0	0	0	0	0
	Produra	7		2.9	0	0	0	0	0	0
1/24/80	Anza	63	6600	30.8	0	0	0	0	0	0
	Produra	63		22.2	4	0	0	0	0	0
3/21/80	Anza	119	14200	15.0	0	0	0	0	0	0
	Produra	119		12.0	0	0	0	0	0	0
4/16/80	Anza	145	18200	32.4	0	0	0	0	0	0
	Produra	145		23.7	0	0	0	0	0	0

*Means of ten replicates in A), and five replicates in B).

†+ = Eggs present, but numbers not assessed.

ber (Fig. 1). The soil temperature continued to decrease to a low of 11–12 C in January and then gradually increased during the remainder of the experiment. The *M. incognita* activity threshold (18 C) was not exceeded until the first week of April.

Anza roots in buried pots were penetrated by *M. incognita* juveniles in early April (Table 2) when soil temperature exceeded 18 C. Juveniles developed into adults in the following month. By the time soil temperature exceeded 18 C in early April, the plant roots in field plots were senescing and no indication of infection was apparent.

There was no significant difference ($P = 0.05$) in Anza grain yield from either the October or November plantings in *M. incognita* infested or noninfested soils (Table 3). No differences were visible in top growth, plant height, leaf color, and amount of tillering in November and December be-

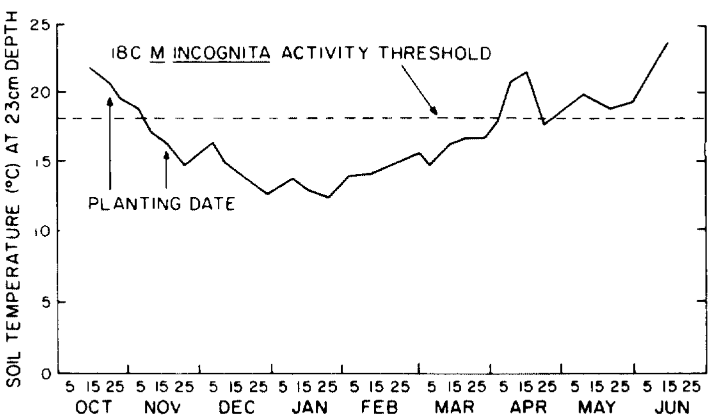

Fig. 1. Mean weekly soil temperature at 23-cm depth during the 1979 winter wheat growing season in Tustin, southern California.

Table 2. Penetration and development of *M. incognita* in Anza wheat in buried pots and soil temperature at 23-cm depth from March to June.

Sampling date	Mean temp (C) for week preceding sampling date		*M. incognita* numbers/root system		
	Min.	Max.	2nd stage	3rd-4th stage	Adult female
4/1/80	15.9	17.8	0	0	0
4/10/80	18.2	20.3	30	0	0
4/24/80	19.1	21.0	0	30	0
5/6/80	18.9	20.5	0	20	0
5/15/80	18.7	19.6	0	20	10

Table 3. Grain yield of Anza wheat on *M. incognita* infested and noninfested field sites and on two planting dates.

Planting date	No. *M. incognita* eggs and second stage juveniles/600 g soil*		*M. incognita* reproduction	Grain yield (kg/ha ± sd)†
	October-November (preplant)	May (postharvest)		
10/18/79	2,356	1,432	Observed (cf. Table 1)	3,390‡ ± 348
10/18/79	1	< 1	None observed	2,988 ± 473
11/15/79	801	252	None observed (cf. Table 1)	3,175 ± 217

*Mean of 15 samples from five replicate plots.
†Mean yield from five 20.8m² harvested areas from five replicate plots.
‡Differences in yield between treatments not significant at $P = 0.05$, according to t test.

Table 4. Soil population levels of *M. incognita* eggs and second-stage juveniles during the winter under fallow and different plantings and cultivars of wheat.

Sampling date	*M. incognita* numbers/600g soil*											
	Eggs				Second-stage juveniles				Total eggs and second-stage juveniles			
	Early Anza	Fallow	Late Anza	Late Produra	Early Anza	Fallow	Late Anza	Late Produra	Early Anza	Fallow	Late Anza	Late Produra
10/17/79–11/13/79	555 (100)†	492 (100)	193 (100)	295 (100)	1,800 (100)	900 (100)	608 (100)	1,229 (100)	2,356 (100)	1,398 (100)	801 (100)	1,525 (100)
2/6/80	161 (29)	57 (11)	149 (77)	51 (17)	1,311 (72)	370 (41)	365 (60)	473 (38)	1,472 (62)	427 (30)	514 (64)	524 (34)
5/5/80	79 (14)	31 (6)	1 (1)	2 (1)	1,353 (75)	302 (33)	251 (41)	438 (35)	1,432 (60)	332 (23)	252 (31)	440 (28)

* Means of 15 samples from five replicate plots.

†Numbers in parentheses are percent values of the October-November preplanting population for each nematode stage and field treatment.

tween young infected and noninfected plants.

The number of *M. incognita* eggs and juveniles in all treatments declined during the winter (Table 4, Fig. 2). Population levels had declined 36–70% by February and continued to decline until harvest in early May. Highly significant differences ($P = 0.01$) occurred between treatments in the percentage decline of eggs and juveniles from autumn to spring harvest. On October planted Anza, the *M. incognita* population declined 40%, compared to 77, 69, and 72% decline, respectively, under fallow and November planted Anza and Produra (Fig. 2). Significant differences in decline were also found between the fallow and the November planted Anza and Produra treatments ($P = 0.01$), and also between the November planted Anza and Produra treatments ($P = 0.05$). Since fewer eggs than juveniles were detected it appears that a large percentage of the *M. incognita* population overwintered as second-stage juveniles (Fig. 2, Table 4). However, extraction of eggs was less efficient than extraction of juveniles because many free eggs and possibly some smaller egg masses were probably not recovered. Some eggs that normally would not hatch until late spring may have hatched during the mild autumn and winter temperatures.

DISCUSSION

The field data show conclusively that *M. incognita* can infect autumn-sown wheat plants and complete one generation during the winter growing season. Previous estimates of accumulated heat units from the winter growing season in southern California (15) and those reported in Table 1 appear to be well above the number required for *M. incognita* (19) and *M. javanica* (9) to complete one generation. However, nematode development is dependent on soil temperature at planting and emergence because this affects nematode movement and subsequent penetration of root tissue. A comparison of soil temperature with *M. incognita* penetration during October and November (Fig. 1, Table 1) indicates a soil temperature threshold of 18 C for activity of *M. incognita* second-stage juveniles. When soil temperature was above 18 C (from the October planting date until early November), *M. incognita* was active in the soil and penetration of roots occurred. But when soil temperature had fallen below the activity threshold (from mid-November onward) the roots were not penetrated. An activity threshold of 18 C was also indicated by penetration of roots in buried pots during the spring (Table 2). Roots were not penetrated before 1 April, when soil temperature was below 18 C, but penetration had occurred by 10 April when the soil temperature rose to 20 C. Migration studies on *M. incognita* second-stage juveniles (10) have shown that they are mostly inactive in soil at or below 18 C but they readily migrate through soil at 20 C.

Nematode development in roots of October planted Anza indicate that feeding, development, and egg production can proceed at soil temperature well below the activity threshold for migration and penetration. The threshold temperature for development of *M. incognita* is reported to be about 10 C (19); soil temperature was above this (Fig. 1) throughout the winter

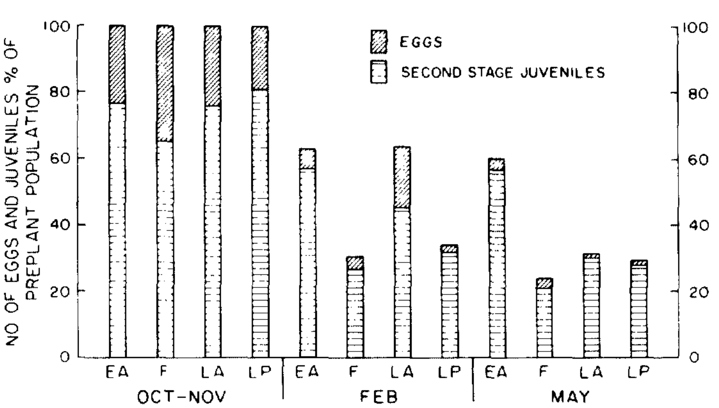

Fig. 2. Relative soil population levels of *M. incognita* eggs and juveniles during the winter growing season under early planted Anza (EA), fallow (F), late planted Anza (LA), and late planted Produra (LP).

in southern California. Thomason (15) reported that reproduction of *M. javanica* did not occur on susceptible winter-grown barley even though enough heat units for reproduction had accumulated. Apparently the November planting date occurred after the soil temperature had fallen below the nematode activity threshold. However, it is probable that *M. javanica*, like *M. incognita*, will reproduce on susceptible winter-grown cereals (barley, oats, wheat) planted early in the fall if conditions are favorable for penetration. The use of heat units to predict development and reproduction is apparently meaningful only after juveniles have penetrated the plant roots and should be considered in conjunction with the temperature threshold for migration in soil and for root penetration. Penetration of clover roots by *M. incognita* in North Carolina at a temperature as low as 12 C (19) could be due to juveniles entering the roots before they adjusted to the test temperature, or it may indicate adaptation of populations to temperature regimes at different localities. The type of host plant could also influence nematode response to temperature.

Yield data (Table 3) indicate that, unlike *Pratylenchus thornei* infection of wheat (18), *M. incognita* infection did not affect grain production of Anza wheat, even though plants were invaded as young seedlings shortly after germination. The yields compared well with those from winter plantings of other cultivars grown in Sonora, Mexico, (18) and with the 1978 mean yield (3,432 kg/ha) of bread wheat in California (1). Controlled greenhouse tests showed that Anza wheat is tolerant to *M. incognita* even with heavy infestations at optimal temperature (11). Thus, it is unlikely that warm climate *Meloidogyne* spp. contribute significantly to the overall 5% estimated annual U.S. crop loss for wheat due to nematodes (4).

The potential economic importance of *Meloidogyne* reproduction on winter cereals is in increasing the primary inoculum level in the soil and the damage to the following susceptible crop (14). In the absence of reproduction on weeds or winter crops, *Meloidogyne* populations decreased during the winter by up to 80% of the autumn population (15). The 69–72% decline under late planted Anza and Produra was similar to that under fallow (Fig. 2). However, the 40% decrease in eggs and juveniles under early planted Anza was significantly less (Fig. 2, Table 4). Egg production during the winter did not fully compensate for the normal winter decline, but it significantly increased the primary inoculum for the following crop.

Wheat root systems stop growing and senesce after heading is complete (7), particularly under low moisture regimes (6). Thus physiologically active roots are unavailable for penetration and feeding sites, which accounts for the absence of second-stage juveniles in roots in April when soil temperature was above 18 C. However in late planted fields or in slightly cooler climatic areas, healthy roots may remain for invading juveniles that become active in spring. Whether these juveniles would then be 'trapped' by root senescence or would complete a generation in late spring needs investigation.

Our findings support observations in Georgia (5) and North Carolina (19) that *M. incognita* can reproduce in autumn and winter on susceptible weeds and winter crops in the southern United States. In these areas, and in warmer areas where wheat and often other cereals are grown in winter, reproduction of *M. incognita* and *M. javanica* should be avoided by delaying planting dates on infested fields until soil temperature declines below the nematode activity threshold. Thus, temperature threshold considerations may be a very important tactic in nematode pest management systems.

LITERATURE CITED

1. Anon. 1979. Field crop production report, August 1979. Calif. Crop and Livestock Reporting Service. USDA and Calif. Dept. Food and Agriculture, Sacramento, Calif.

2. Anon. 1979. Small grain summary, December 1979. Calif. Crop and Livestock Reporting Service. USDA and Calif. Dept. Food and Agriculture, Sacramento, Calif.

3. Crittenden, H. W. 1961. Studies on the host range of Meloidogyne incognita acrita. Plant Dis. Rep. 45:190-191.

4. Feldmesser, J. (Chairman). 1971. Estimated crop losses from plant-parasitic nematodes in the United States. Soc. Nematol. Spec. Publ. 1.

5. Hogger, C. H., and G. W. Bird. 1974. Weeds and cover crops as overwintering hosts of plant

parasitic nematodes of soybean and cotton in Georgia. J. Nematol. 6:142-143.

6. Hurd, E. A. 1968. Growth of roots of seven varieties of spring wheat at high and low moisture levels. Agronomy J. 60:201-205.

7. Mackey, J. 1973. The wheat root. Pp. 827-842 *in* E. R. Sears and L. M. S. Sears, eds. Proc. Fourth International Wheat Genetics Symposium, Univ. of Missouri, Columbia, Missouri, 6-11 Aug. 1973.

8. Martin, G. C. 1958. Root-knot nematodes (Meloidogyne spp.) in the Federation of Rhodesia and Nyasaland. Nematologica 3:332-349.

9. Milne, D. L., and D. P. Duplessis. 1964. Development of Meloidogyne javanica (Treub) Chitwood on tobacco under fluctuating soil temperatures. S. Afr. J. Agric. Sci. 7:673-680.

10. Prot, J. C., and S. D. Van Gundy. 1981. Influence of photoperiod and temperature on migrations of Meloidogyne juveniles J. Nematol. 13: 217-220.

11. Roberts, P. A., and S. D. Van Gundy. 1981. The development and influence of Meloidogyne incognita and M. javanica on wheat. J. Nematol. 13: 000-000.

12. Sasser, J. N. 1954. Identification and host-parasite relationships of certain root-knot nematodes (Meloidogyne spp.). Univ. Maryland Agr. Exp. Stn. Tech. Bull. A-77.

13. Sauer, M. R., and J. E. Giles. 1957. Effects of some field management systems on root-knot of tomato. Nematologica 2:97-107.

14. Seinhorst, J. W. 1965. The relation between nematode density and damage to plants. Nematologica 11:137-154.

15. Thomason, I. J. 1962. Reaction of cereals and sudan grass to Meloidogyne spp. and the relation of soil temperature to M. javanica populations. Phytopathology 52:787-791.

16. Thomason, I. J., and D. Fife. 1962. The effect of temperature on development and survival of Heterodera schachtii Schmidt. Nematologica 7:139-145.

17. Tyler, J. 1933. Development of the root-knot nematode as affected by temperature. Hilgardia 7: 391-415.

18. Van Gundy, S. D., J. G. Perez B., L. H. Stolzy, and I. J. Thomason. 1974. A pest management approach to the control of Pratylenchus thornei on wheat in Mexico. J. Nematol. 6:107-116.

19. Vrain, T. C., K. R. Barker, and G. I. Holtzman. 1978. Influence of low temperature on rate of development of Meloidogyne incognita and M. hapla larvae. J. Nematol. 10:166-171.