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Relationship of Aerial Broad Band Reflectance to *Meloidogyne incognita* Density in Cotton

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Abstract: Aerial images were obtained on 22 July 1999 and 4 August 2000 from five cotton sites infested with *Meloidogyne incognita*. Images contained three broad bands representing the green (500–600 nm), red (600–700 nm), and near-infrared (700–900 nm) spectrum. Soil samples were collected and assayed for nematodes in the fall at these sites. Sampling locations were identified from images, by locating the coordinates of a wide range of light intensity (measured as a digital number) for each single band, and combinations of bands. There was no single band or band combination in which reflectance consistently predicted *M. incognita* density. In all 10 site-year combinations, the minimum number of samples necessary to estimate *M. incognita* density within 25% of the population mean was greater when sampling by reflectance-based classes (3 to 4 per site) than sampling based on the entire site as one unit. Two sites were sampled at multiple times during the growing season. At these sites, there was no single time during the growing season optimal to take images for nematode sampling. Aerial infrared photography conducted during the growing season could not be used to accurately determine fall population densities of *M. incognita*.

Key words: aerial infrared photography, broad band reflectance, cotton, *Meloidogyne incognita*, multi-spectral reflectance, remote sensing, root-knot nematode.

The southern root-knot nematode, *Meloidogyne incognita* (Kofoid & White) Chitwood, is an important pathogen of cotton (Orr and Robinson, 1984). Yearly fall sampling to determine the population density of *M. incognita* can be used to better manage the crop (Wheeler et al., 2000). *Meloidogyne incognita* is a highly aggregated organism (Bélair and Boivin, 1988; Noe and Campbell, 1985; Wheeler et al., 1994), which means that many soil samples are necessary to estimate population mean and variance accurately. Typically, management recommendations are based on one or a few composite soil samples per field to estimate nematode density. As population variance decreases, so does the number of samples necessary to represent a population mean adequately. If soil cores for a sample are taken within an area that encompasses both high and low nematode densities, then the average nematode density for that sample is difficult to interpret for management recommendations. When sampling large regional areas, it is desirable to compartmentalize sources of variance such that there is a greater proportion of variance among fields than within fields (Neher and Campbell, 1996). Similarly, within a field, it is desirable to compartmentalize the field into areas with similar nematode population densities, and take one or more composite samples in each area. The population variance within each "similar area" would be substantially smaller than for the entire field. Sampling zones can be delineated by various tools, such as soil survey maps and yield maps, and by remote sensing instrumentation, including satellite or aerial images.

Aerial infrared photography has been available for many decades (Toler et al., 1981). Light (electromagnetic radiation) is reflected, absorbed, or transmitted through plants and soil (Hatfield and Pinter, 1993). The spectrum of light that is visible includes the blue (400–500 nm), green (500–600 nm), and red (600–700 nm) wavelengths (Aldrich and Bartok, 1994). Soil reflects light in the red spectrum generally more strongly than plants (Hatfield and Pinter, 1993). Plants reflect light in the near-infrared (NIR) spectrum (700–900 nm) greater than in the visible spectra (Gausman and Allen, 1973). Therefore, many imaging tools rely on capturing light reflected in the NIR wavelengths. Color, infrared film can be used to quantify and record reflectance in the green, red, and NIR wavelengths. This type of sensor is multispectral (few bands), and each band covers a broad spectrum of light. Filters can be used with color, infrared film to narrow the spectrum of any band, if a target wavelength is desired.

Remote sensing based on reflectance has been related to yield (Plant et al., 2000), water stress (Moran, 1994), soil organic matter, water content, and soil color value (Zheng and Schreier, 1988), weeds (Brown et al., 1994), diseases (Everitt et al., 1999; Toler et al., 1981) and nematodes (Nutter et al., 2002; Orion et al., 1982). Aerial photographs are used routinely by the USDA National Agricultural Statistics Services to conduct agricultural surveys (Neher and Campbell, 1996). In light-colored soils, reflectance from aerial images obtained early in the growing season are dominated by soil properties, while those obtained after the canopy has covered the row are dominated by plant properties (Huete, 1989). Remote sensing has the potential to detect disease injury that results in specific physiological and morphological damage that impacts reflectance properties directly (Moran et al., 1997). For example, *M. incognita* can stunt cotton (Smith et al., 1991; Thomas and Smith, 1993) or cause water stress (Kirkpatrick et al., 1995; O'Bannon and Reynolds, 1965) compared to cotton that is free of nematode pressure.

Nematode damage is a function of initial population

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density (Seinhorst, 1965). If remote sensing can be used to improve the process of sampling for nematodes, it must be able to differentiate between the effect on plants of different nematode densities, which is a quantitative, not qualitative response. The utility of image products from aerial infrared photography is considered qualitative or semi-qualitative at best (Asrar, 1989). The objective of this study was to determine if broad-band, multispectral aerial imagery collected during the growing season was sufficiently accurate to predict fall *M. incognita* population density in cotton fields.

Materials and Methods

Relationship of reflectance with nematode population densities: The objective of this experiment was to determine if imagery taken at one time in the growing season could be related through regression analysis to fall population density of *M. incognita.* Is the technique successful over a broad range of conditions (all fields), or a narrow range of conditions, which might correspond to a level of nematode pressure, or certain soil conditions? In short, how robust is this technique for the variety of situations that exist?

Sites were examined over a 2-year period (with one image per year). Aerial infrared photographs were taken using a 35-mm camera equipped with a yellow (#12) Tiffen 62M filter and using the film Kodak Ektachrome Infrared EIR 135–36. The use of the filter eliminated the blue band, so that images consisted of the green, red, and NIR bands. Images of 24 and 48-ha circles were obtained at altitudes of approximately 615 and 1,231 m. The plane had a 15-cm-diam. hole in the floor, and the camera was placed in the hole in a level position for taking images. Images were obtained on 22 July 1999 and 4 August 2000 for all five sites. The fields selected for this study represented a variety of soil types and differing densities of *M. incognita* (Table 1). Sites were all deficit-irrigated with center pivot systems. This means that irrigation was insufficient to replace all the water that the crop used through evapotranspiration.

Site 1 (Dawson County) had a single soil series (Amarillo) with two surface soil types: sandy and sandy clay loam. There were landscape differences that affected cotton growth and yield (Li et al., 2001). The northern area of the site, which was on a slope, produced lower yields than the rest of the site. The low areas of the site always had higher yields than either the northern or southern sloped areas. Because there were different research projects ongoing at that site, only 21 ha of the circle was used in this study. This corresponded with an area that had been in minimum tillage cotton for at least 10 years. In 1999, irrigation in the seventh span of the test area (the circle contained eight spans, each span had 48 rows, with 1-m centers between rows) consisted of low-elevation spray application (LESA) on 2-m spacing. The rest of the test area was irrigated using Low-Energy Precision application (LEPA) to alternate furrows with drop hoses. In 2000, the entire test area was under the LEPA application system. Both LEPA and LESA treatments applied 75% replacement of evapotranspiration (ET), but with LEPA, less water is lost through evaporation from soil than with the LESA system (Bordovsky et al., 1992; Lyle and Bordovsky, 1983). Plants in the LESA irrigated areas are usually under more water stress than in LEPA areas.

Site 2, located in Terry County, Texas, had a Midessa fine sandy loam soil. There were nodules of calcium carbonate ($CaCO_3$) visible on the soil surface of this site, which are associated with calcareous soils. This site was farmed using conventional tillage. Site 3, located in Crosby County, Texas, had one soil series (an Amarillo fine sandy loam) and was farmed using conventional tillage. Site 4, also in Crosby County, had a Brownfield fine sand and was farmed using conventional tillage. This site had very coarse, white sand that had drifted into the eastern part of the field. Site 5, located in Hockley County, Texas, had two distinct soil series: an Amarillo sandy and sandy clay loam and Portales sandy clay and sandy clay loam. The calcareous Portales soil had areas white with $CaCO_3$. This site was managed using minimum tillage. There was a slope (landscape

Table 1. Attributes of fields selected for remote sensing.

	Meloidogyne incognita/500 cm^3 soil						
Site	Year	Mean	SD[a]	N[b]	County	Cotton cultivar	Sampling date
1	1999	8,545	11,483	41	Dawson	PM 2326RR	29 Sept. 1999
1	2000	5,107	4,848	29	Dawson	PM 2326RR	14 Nov. 2000
2	1999	1,471	2,752	34	Terry	PM HS-26	22 Sept. 1999
2	2000	289	555	49	Terry	PM 2326RR	8 Dec. 2000
3	1999	2,858	3,419	70	Crosby	PM 2326RR	24 Sept. 1999
3	2000	1,049	1,777	38	Crosby	PM 2326RR	20 Dec. 2000
4	1999	5,365	6,796	53	Crosby	BXN 16	14 Sept. 1999
4	2000	995	1,866	52	Crosby	BXN 16	15 Dec. 2000
5	1999	542	951	49	Hockley	PM 2326RR	10 Oct. 1999
5	2000	524	892	57	Hockley	PM 2326RR	21 Oct. 2000

[a] SD = standard deviation.
[b] Sample size.

differences) present in part of this site with the Portales soil. The area with the Amarillo soil series was fairly flat.

Multiple dates for image collection within a season and relationship with nematode densities: The objective of this experiment was to determine if there was an optimal time during the growing season for collection of imagery to relate with fall population of *M. incognita*. Site 1 was chosen in 1999 to take images three times in the season (25 May, 8 July, and 11 August). In 2000, site 5 was flown five times (22 June, 10 July, 4 August, 22 August, and 13 September) and site 1 was flown four times (10 July, 4 August, 22 August, and 13 September).

Image processing: Aerial images were scanned and saved as JPEG files and read into ArcView GIS 3.2 (ESRI, Redlands, CA) image analysis program. The images were georectified based on known locations in the field (corners, pivot center, pumps, etc.), and images were saved as .IMG files. The .IMG files were imported into the Environment for Visualizing Images (ENVI 3.5, Research Systems Inc., a division of Kodak, Boulder, CO) and overlaid with the location of the nematode sampling sites. ENVI header files were modified by pixel size and with known coordinates to georectify the image in ENVI. Polygons were drawn around each sampling area (usually representing at least 200 pixels), and digital numbers (ranging from 0 to 255) for the NIR, red, and green bands were averaged over each polygon. The averaged digital number represents a relative reflectance value for the sampling site. This value was used in analyses both as the uncorrected average, and also corrected with a dark-object subtraction (Chavez, 1988). Dark-object subtraction is one method to calibrate the digital numbers so that comparisons could be made between fields, or with images taken at different times in the same field. With this procedure, the darkest object in the field is considered to have a value of 0 (black), though the digital number may be greater than 0, due to inconsistencies in film, for each of the three bands at that point. The digital numbers across the field can then be adjusted by the differences for each band where the value should be 0. In the case of these five sites, there were no suitable objects at these sites (naturally black in color) to use for dark-object subtraction to obtain absolute reflectance values. Therefore, a decision was made to present only the analyses from actual uncorrected digital numbers. This means that equations developed from one site at one time period will be difficult to use for prediction with other sites or even the same site at a different time. It does, however, allow for the basic hypothesis to be tested for each individual site and image, i.e., can nematode density be predicted with acceptable accuracy based on imagery of a site.

There are procedures that can divide an image into different groupings (clusters or classes) based on pattern classification distance functions (Tou and Gonzalez, 1974). Methods for classification are based on minimum-distance patterns, i.e., the smaller the distance, the greater the similarity. An unsupervised classification using the isodata classification method (Tou and Gonzalez, 1974) was performed on a rectangle drawn around the field in each image. This rectangle also included some of the dryland corners for all the sites (areas not included under the center pivot irrigation system). Each test area was then divided into at least three and not more than six classes. The three parameters used in determining clusters was the intensity (digital number) of the green, red, and NIR bands. Isodata represent a set of heuristic procedures that include 14 steps, based around the distance between reflectance intensity for each band from the cluster center. New clusters are formed, or clusters are lumped in the iterative procedure as additional sample sites are considered. The average reflection intensity values for the three bands that formed each cluster is provided in the results. This or similar procedures are available in commercial image analysis software packages by PCI Geomatics (Arlington, VA); ERDAS (Leica Geosystems GIS and Mapping Division, Atlanta, GA); ENVI, Earth Resource Mapper (San Diego, CA); Intergraph Corp. (Huntsville, AL); and the Idrisi Project (Brown, 2000). They provide a simple method to compartmentalize a field for nematode samples (based on reflectance patterns).

Soil samples: Soil samples were taken in the fall at selected locations in each site (Table 1). Time of sampling was dependent on when there was sufficient soil moisture in the fall for sampling to a depth of 30 cm and, at some sites, producers requested that samples be taken after the cotton had been harvested. Harvest operations typically stretch from late September through December in west Texas. These sampling locations were selected by examination of the images as single bands, two-band combinations, three-band combinations, band ratios, and with isodata class combinations. A wide range of digital numbers were selected as sampling points. For example, at site 1 in 2000, digital numbers for the NIR, red, and green bands over the entire image ranged from 129–255, 82–246, and 96–250, respectively. The ranges of digital numbers for the NIR, red, and green bands selected for sampling locations were 228–252, 157–232, and 196–235, respectively. Areas in the images that had lower or higher digital numbers than the selected sampling locations were too small (1 to 10 pixels in size) to locate with sufficient accuracy. In a small area of a site, many samples could be taken if sufficient variation in band digital numbers was observed. Similarly, only a single sample was taken in large areas if little variation in digital number was observed across all single-band or band combinations.

Samples taken in dryland corners were not included in any analyses. The samples were collected around a location by taking five soil cores, using a narrow bladed shovel (10–14-cm width) to a depth of approximately 30 cm. Each core was taken within a 7-m radius of the sample location. The cores were mixed in a bucket, and 1-liter soil was placed in a plastic bag. The samples were stored at 4 °C until processing. All samples were processed within 2 weeks of collection. Second-stage juveniles (J2) of *M. incognita* were assayed by a modified Baerman funnel (Thistlethwayte, 1970) using 200 cm^3 soil including root fragments. For the egg extraction, 500 cm^3 soil was mixed with 2-liters water for 15 seconds and allowed to settle for 15 seconds. The water and organic matter mixture was poured through a 230-µm-pore sieve. Then, eggs were extracted from the organic matter caught on the sieve by the sodium hypochlorite (NaOCl) extraction method (Hussey and Barker, 1973). *Meloidogyne incognita* population density for each sample was either the number of eggs or J2 per 500 cm^3 soil, with the higher count representing the sample density. These numbers are not summed to estimate density because the modified Baerman funnel technique results in hatch of some unknown percentage of the eggs to J2. Eggs, which make up the bulk of the population in September, can be reduced in number later in the fall due to hatching or degradation of the roots, which results in egg masses being lost through the initial sieving procedure. In general, *M. incognita* populations in a field were represented primarily by egg counts if sampled in the early fall, primarily by J2 if sampled late in the year, and by some proportion of both in between those times.

Global positioning system: Nematode samples were georeferenced using a differential global positioning system (DGPS). Two different systems were used depending on the availability of units. One system was an Omnistar 7000 differential receiver equipped with a Corvallis Microtechnology global positioning receiver (March II) and software (PCGPS, Corvallis Microtechnology, Corvallis, OR). The second unit consisted of a Satloc differential and GPS receivers (GIS Services, Tucson, AZ) and Fieldworker Pro software (Fieldworker Products Limited, Toronto, ON M4G 3A9). Both units are accurate to 1 to 2 m.

Statistical Analysis: Various indices have been developed to relate crop health to plant growth (primarily biomass). These include band ratios such as NIR/red, NIR/green, green/red, and the normalized difference vegetation index (NDVI), which is (NIR – red)/(NIR + red)) (Rouse et al., 1974). Regression analysis (PROC REG, SAS version 8.0, Cary, NC) were used to relate nematode density and nematode density transformed ($\log_{10}$(*M. incognita* + 1)/500 cm^3 soil) with reflectance of individual bands (expressed as a digital number) and band combinations described earlier. No adjustments were made for extraction efficiency. In each equation, the *t*-test was significant at $P = 0.05$ for a band or band combination to be acceptable.

Linear regression analysis provided an indication of whether images could be used to predict *M. incognita* population density. However, it does not address whether sampling nematodes by using imagery to divide the site into different groupings is more cost-effective than sampling the entire site as one unit. *Meloidogyne incognita* population density mean and standard deviation were calculated for each site as a whole (all samples) and for each of the classes (clusters) that were described within each site. The sample number (n), which should be adequate for a percent-coefficient of variation (CV) of 25%, was estimated for the site as a whole unit, and for each class, based on the equation $n = S/(mCV)^2$ (Elliott, 1983), where S is the standard deviation and m is the mean of the $\log_{10}$(*M. incognita*/500 cm^3 soil + 1). Each sample was estimated to cost $25. Management of *M. incognita* for cotton generally is by application of nematicides. Costs of nematicide applications were estimated at $20.25/kg a.i. of aldicarb/ha, and at $1.23/kg a.i. of 1,3-dichloropropene/ha (Baird et al., 2001). Decision rules for pesticide rates based on sample averages of *M. incognita* were obtained for aldicarb (Wheeler et al., 1999) and 1,3-dichloropropene (Baird et al., 2001). Estimations are provided on the cost of sampling for whole site vs. the image classification-based method.

Results

Relationship of reflectance with nematode population densities: Average *M. incognita* density at the five sites over the 2 years ranged from 289 to 8,545 *M. incognita*/500 cm^3 soil (Table 1). The variance was greater than the mean density for all sites. Site 1 represented the highest level of risk, with most samples (79% in 1999 and 97% in 2000) having densities of *M. incognita* $\geq$1,000/500 cm^3 soil (Fig. 1A). At sites 2 and 5, >60% of the *M. incognita* densities were <1,000/500 cm^3 soil (Fig. 1B,E). Sites 3 and 4 had a wide range of *M. incognita* densities (Fig. 1C,D).

There was no relationship between *M. incognita* density and reflectance at site 4 in both years, nor at site 2 in 2000 (Table 2). There was only one band that was related to nematode density for sites 1 and 3 in 1999 ($R^2 = 0.09$ and 0.32, respectively) and site 5 in 2000 ($R^2 = 0.09$). At sites 1 and 3 in 2000 and sites 2 and 5 in 1999, there were many band or band combinations that could be used to predict *M. incognita* population density (Table 2). Only at sites 3 and 5 was there a significant relationship between reflectance of the same band (NIR for both sites) and *M. incognita* density in both years. At site 3, the relationship between relative reflectance for the NIR band and *M. incognita* density was negative in 1999 and positive in 2000 (Table 2). At site 5, reflectance at the NIR band was negatively related with nematode density in both years, though only a marginal correlation was found in 2000 ($R^2 = 0.09$) compared with greater correlations observed in 1999

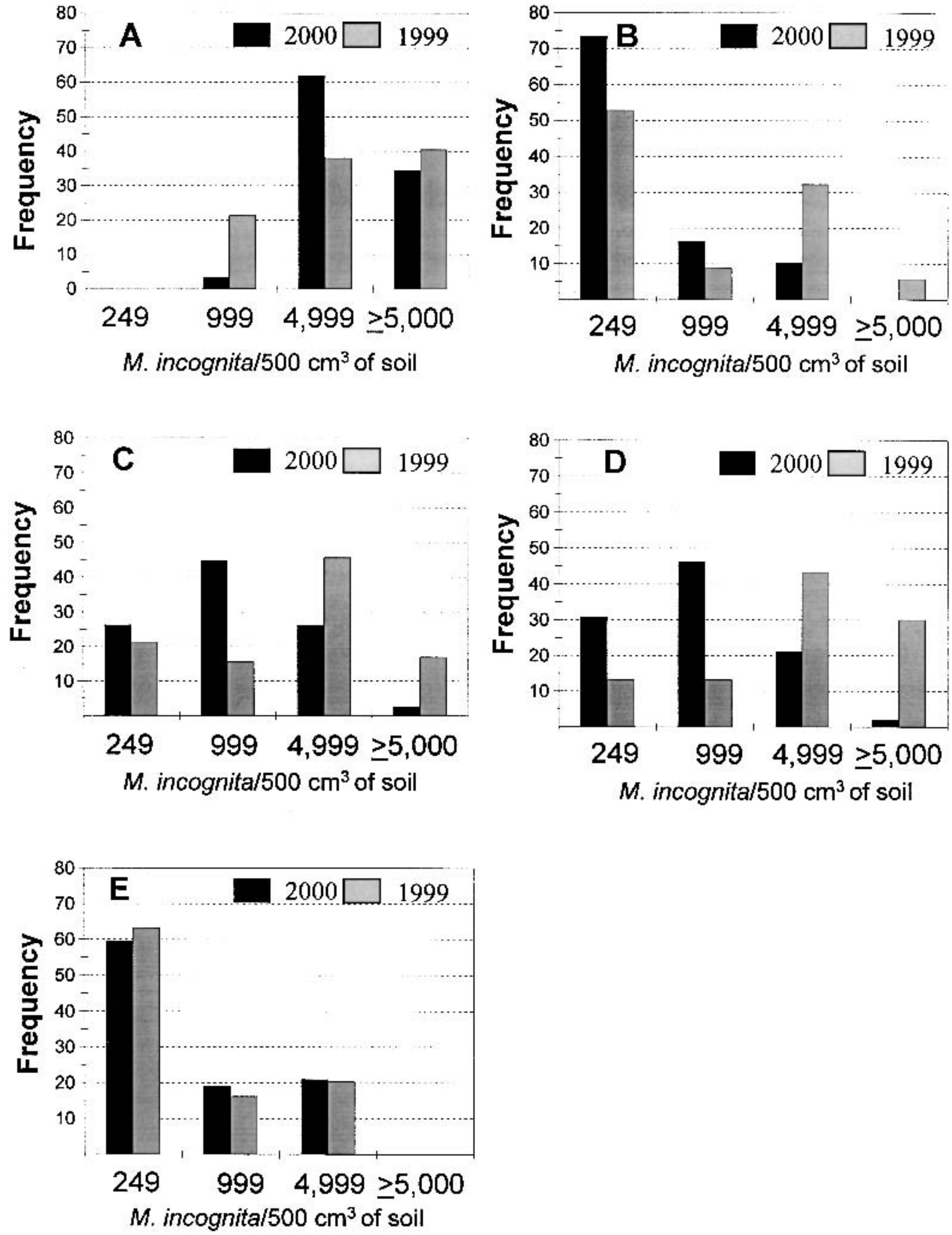

FIG. 1. Frequency of the population density of *Meloidogyne incognita*/500 cm^3 soil sampled during fall 1999 ▨ and 2000 ■ at five fields. A) Site 1. B) Site 2. C) Site 3. D) Site 4. E) Site 5.

(maximum R^2 = 0.31) (Table 2). Of the 10 site-year combinations, NIR, red, and green bands were fitted to 4, 4, and 2 equations, respectively. The ratios of NIR/red, NIR/green, green/red, and NDVI were fitted to 3, 3, 4, and 3 equations. Therefore, there was no single band or band combination that would be favored in using imagery to predict *M. incognita* population density.

Sampling nematode populations based on separation of fields into reflectance classes: The classification procedure resulted in three classes for site 1 in 2000 and site 4 in 1999, and four classes for the other eight site-year combinations. At site 1, the "red" class in 2000 had a greater mean *M. incognita* density than the area of the field represented by the "green" and "blue" classes (Table 3). For each of these classes, one sample was adequate to represent the mean *M. incognita* density (Table 3), similar to the entire test area, when one sample was also adequate [$\log_{10}$ transformed mean density (LMi) = 3.56 and standard deviation (SD) = 0.35]. Sampling by reflectance class would result in more samples than representing the entire test area by a single unit, though the benefit would be to separate the area representing

TABLE 2. Linear regression analysis of reflectance[a] at different bands from aerial infrared images to the population density of *Meloidogyne incognita* [MI = B_0 + B_1(Band)].

Site	Year	Trans[b]	Band	B_1	SE[c]	Prob. > t	B_0	R^2
1	1999	MI	Red	65.5	32.8	0.05	2,608	0.09
1	2000	MI	Red	−80.5	38.3	0.04	21,450	0.14
1	2000	MI	NIR/Red	16,776	7,151	0.03	−15,116	0.17
1	2000	MI	NIR/Green	52,587	20,553	0.02	−53,229	0.20
1	2000	MI	Green/Red	27,236	12,708	0.04	−24,429	0.15
1	2000	MI	NDVI	42,470	17,997	0.03	1,255	0.17
2	1999	LMI	NIR/Red	−10.9	4.0	0.01	14.7	0.19
2	1999	LMI	NIR/Green	−22.8	8.0	0.001	29.4	0.20
2	1999	LMI	Green/Red	−16.7	8.2	0.05	18.2	0.11
2	1999	LMI	NDVI	−27.8	10.1	0.01	4.1	0.19
3	1999	MI	NIR	−520	92	0.001	134,506	0.32
3	2000	LMI	NIR	0.046	0.012	0.001	−8.2	0.29
3	2000	LMI	Red	0.030	0.0077	0.001	−4.3	0.30
3	2000	LMI	Green	0.042	0.011	0.001	−7.1	0.27
3	2000	LMI	Green/Red	−7.3	3.0	0.02	10.1	0.14
5	1999	LMI	NIR	−0.036	0.0080	0.001	9.9	0.30
5	1999	LMI	Red	−0.013	0.0035	0.001	3.1	0.22
5	1999	LMI	Green	−0.019	0.0042	0.001	4.9	0.31
5	1999	LMI	NIR/Red	0.92	0.25	0.001	−0.56	0.22
5	1999	LMI	NIR/Green	2.9	0.70	0.001	−2.62	0.27
5	1999	LMI	Green/Red	1.6	0.67	0.02	−1.1	0.11
5	1999	LMI	NDVI	4.2	1.2	0.001	0.028	0.21
5	2000	LMI	NIR	−0.048	0.020	0.02	12.9	0.09

[a] Reflectance, which is represented by a digital number from 0 to 255, is measured at three broad wavelengths: near-infrared (NIR) band ranges from 700–900 nm, red band ranges from 600–700 nm, and green band ranges from 500–600 nm. Their ratios (NIR/red, NIR/green, red/green) were computed by the quotient of reflectance values. NDVI is estimated by the formula (NIR − red)/(NIR + red).
[b] *Meloidogyne incognita*/500 cm^3 soil is represented as MI (nontransformed) or LMI [$\log_{10}$(MI + 1)].
[c] SE = standard error of B_1.

a very high damage category (8,918 *M. incognita*/500 cm^3 soil) from a more moderate damage category (2,745 and 3,554 *M. incognita*/500 cm^3 soil). However, in terms of nematicide rates, all three classes would receive the same treatment (Baird et al., 2001; Wheeler et al., 1999). A similar situation was found at site 1 in 1999, with each of the four classes requiring one sample to adequately represent mean nematode density (ranging from 5,866 to 10,309 *M. incognita*/500 cm^3 soil) (Table 3), while sampling the test area as a single unit would have required only one sample (mean LMi = 3.55, SD = 0.58).

At site 2 in 2000, average density ranged from 125 to 424 *M. incognita*/500 cm^3 soil (Table 3). A whole site sampling effort would require 19 soil samples to represent the mean density adequately (mean LMi = 1.21, SD = 1.33), while sampling by class would require 93 soil samples (Table 3). Given the relatively low *M. incognita* densities in this site, it would be less expensive to treat the entire site with one rate of nematicide (adequate for the highest nematode density) than to sample extensively. In 1999, the average density of *M. incognita*/500 cm^3 soil ranged from 276 to 2,186. To sample the entire site adequately would require 11 samples (LMi = 1.87, SD = 1.57), while 66 samples were necessary to sample by class (Table 3). Sampling by class would cost $28.65/ha more than sampling by whole unit. Variable-rate application of nematicides would reduce the cost of aldicarb by $4.82/ha or 1,3-dichloropropene by $12.20/ha.

At site 3 in 2000, the average density of *M. incognita*/500 cm^3 soil ranged from 203 to 1,964 across the four classes (Table 3). Sampling the whole site adequately would require two samples (LMi = 2.59, SD = 0.88), while sampling each class would require 14 samples (Table 3). Sampling by classes would cost $12.50/ha more than whole-site sampling. Variable-rate application would reduce aldicarb costs by $2.50/ha and 1,3-dichloropropene by $10.63/ha. In 1999 at this site, average nematode density was in a high-damage category for all four classes (Table 3). Sampling for nematodes in the whole unit would require three samples (LMi = 2.84, SD = 1.21), while sampling by class would require 11 samples (Table 3). One rate of nematicide would be appropriate across all classes.

At site 4 in 2000, the average density of *M. incognita*/500 cm^3 soil by class ranged from 643 to 1,991 (Table 3). Sampling the entire site as one unit would require only one sample (LMi = 2.71, SD = 0.47), while sampling by class would require four samples (Table 3). Increased sample costs were estimated to be $1.56/ha. The average nematode density overall (995 *M. incognita*/500 cm^3 soil) is very close to a threshold described by both Wheeler et al. (1999) and Baird et al. (2001), which would make for difficult single-rate decisions. Variable-rate applications would increase the cost for both aldicarb ($0.91/ha) and 1,3-dichloropropene ($3.54/ha) over the single-rate application. In this situation, a yield increase would be expected in 18% of the field where nematicide rates were increased for vari-

TABLE 3. The relationship between classification of images based on relative reflectance and density of *Meloidogyne incognita*.

Reflectance class[a]	Average class values			% class[c]	Mi[d]		Log_{10}(Mi + 1)		Sample size	
	NIR[b]	Red	Green		Mean	SD[e]	Mean	SD	Actual	Estimated[f]
Site 1—2000										
Blue	246	218	227	57	3,554	2,370	3.47	0.28	16	1
Green	237	190	212	22	2,745	1,109	3.41	0.19	4	1
Red	238	183	208	21	8,918	6,877	3.81	0.41	9	1
Site 1—1999										
Blue	202	104	112	27	8,725	10,134	3.55	0.70	8	1
Green	173	72	85	24	10,309	14,889	3.56	0.70	11	1
Red	141	48	60	24	5,866	6,919	3.55	0.47	15	1
Yellow	244	139	153	25	8,078	12,795	3.53	0.62	8	1
Site 2—2000										
Blue	233	224	232	42	287	424	1.47	1.32	19	13
Green	229	216	227	21	237	707	0.83	1.25	15	36
Red	224	187	214	16	424	641	1.29	1.51	11	22
Yellow	236	231	237	21	125	189	1.15	1.35	4	22
Site 2—1999										
Blue	251	217	209	40	2,186	3,688	2.34	1.49	16	6
Green	251	210	206	23	276	666	1.09	1.34	9	24
Red	242	189	195	16	915	1,636	1.50	1.79	4	23
Yellow	252	225	216	21	1,780	1,700	2.08	1.90	5	13
Site 3—2000										
Blue	242	237	240	42	1,964	3,062	2.98	0.50	11	1
Green	235	230	235	24	624	506	2.51	0.81	14	2
Red	217	199	212	15	203	206	1.62	1.27	6	10
Yellow	244	240	242	19	1,189	747	2.96	0.38	7	1
Site 3—1999										
Blue	252	222	214	33	4,270	5,357	3.12	1.18	10	2
Green	254	217	209	23	2,561	2,995	2.86	1.14	27	3
Red	253	197	196	20	2,388	3,236	2.53	1.38	26	5
Yellow	255	229	220	24	3,729	1,818	3.52	0.22	7	1
Site 4—2000										
Blue	249	225	235	39	882	1,066	2.64	0.57	13	1
Green	242	199	223	18	672	585	2.71	0.33	13	1
Red	232	151	199	18	1,991	3,710	2.95	0.51	11	1
Yellow	251	240	245	25	643	747	2.60	0.43	15	1
Site 4—1999										
Blue	248	189	192	65	5,549	6,928	3.43	0.57	43	1
Green	219	115	148	8	5,783	8,088	3.20	0.87	6	1
Yellow	253	225	211	10	2,760	3,106	2.43	1.76	4	8
Site 5—2000										
Blue	245	221	231	37	552	746	1.57	1.48	18	14
Green	241	197	219	15	771	1,305	1.48	1.58	14	18
Red	229	158	199	19	483	780	1.72	1.33	18	10
Yellow	249	230	237	29	57	151	0.37	0.98	7	112
Site 5—1999										
Blue	254	149	204	26	365	572	1.18	1.48	12	25
Green	247	114	188	16	25	71	0.29	0.81	8	125
Red	210	70	125	28	1,252	1,346	2.59	1.12	15	3
Yellow	253	197	220	31	223	492	0.79	1.28	13	42

[a] Class values are calculated using the isodata classification method (Tou and Gonzalez, 1974).
[b] NIR = near infrared reflectance band (700–900 nm), red = red reflectance (600—700 nm), and green = green reflectance band (500–600 nm).
[c] % class is the percentage of the sample area plus dryland corners, represented by each class.
[d] Mi = *Meloidogyne incognita*/500 cm^3 soil.
[e] SD = standard deviation.
[f] Sample number (n) was estimated for each class by the equation $n = (S/(mCV)^2)$ (Elliott, 1983), where S is the standard deviation; m is the mean nematode density (for that class); and CV is the coefficient of variation, set at 25% for this equation.

able-rate treatments over the whole-field treatments. At site 4 in 1999, the average density of *M. incognita*/500 cm^3 soil for each class ranged from 2,760 to 5,783 (Table 3). Sampling the entire unit would require a single sample (LMi = 3.33, SD = 0.77), while sampling each class would require 10 samples (Table 3). Because mean *M. incognita* abundance is fairly high in each class, there would not be an advantage to sampling or managing the field by class.

At site 5 in 2000, the average density of *M. incognita*/500 cm^3 soil ranged among classes from 57 to 771 (Table 3). Sampling the entire site adequately would require 16 samples (LMi = 1.45, SD = 1.44), while sampling each class adequately (and the yellow class was not sampled adequately) would require 154 samples (Table 3). The extra cost for sampling by class is $143.75/ha, which would be difficult to recoup by any reduction in nematicide usage, or by yield increase. At this site in 1999, the average density of *M. incognita*/500 cm^3 soil ranged among classes from 25 to 1,252 (Table 3). The entire test area would require 18 samples (LMi = 1.39, SD = 1.47), while sampling by class would require 195 samples (Table 3). The extra cost for sampling by class is $184.38/ha.

Date of image collection and associations with nematode densities: At site 1 during 1999, *M. incognita* density was not related to intensity of any bands from the image taken in May or August, and only weakly predicted (R^2 = 0.09) by the red band in July (Table 4). However, the following year at this same site, *M. incognita* density was predicted with a wide variety of bands or band combinations at each of the four times of the year that images were taken (July, early August, late August, mid-September) (Table 4). The best predictor of *M. incognita* population density (transformed) for all bands or band combinations and image times was the NIR/green band on 13 September (Table 4). At site 5 in 2000, transformed *M. incognita* density was weakly predicted (R^2 = 0.09) with the NIR band in early August (Table 4). In September, *M. incognita* density was predicted by all three bands and the ratio of green to red band, though all R^2 values were ≤0.09 (Table 4).

Discussion

In this study, it was demonstrated that *M. incognita* density was predicted poorly with reflectance because, at most, 32% of the variation in nematode density was explained by reflectance intensity of a band or band ratio. Results were inconsistent between sites and across years. The optimal time during the growing season to take an image was not as important as whether that site had any relationship between reflectance and nematode density. If an equation could be fitted, then most or all images of that site-year and multiple bands could be used in the equation. If the prediction was poor (R^2 ≤ 0.10), then it was consistently poor for all images during that growing season.

Producers make management decisions (rates of nematicides) based on minimal sampling effort and without regard for sample location within a field. Variable-rate application of nematicides offers a method of placing the product in the area of a field where it will be most beneficial. The assumption is that because nematode damage is density dependent (Oostenbrink, 1966; Seinhorst, 1965), then nematicide rate should be adjusted for nematode density. The cost of grid sampling for nematodes at sufficient intensity to produce accurate application maps negates much or all of the profits from variable nematicide rates. Using reflectance classes as a method of compartmentalizing a field into

TABLE 4. Linear regression analysis of reflectance[a] at different bands from aerial infrared images taken from two fields at different times during the growing season, to the population density of *Meloidogyne incognita* [MI = B_0 + B_1(Band)].

Site-year	Date[b]	Trans[c]	Band	B_1	SE[d]	Prob. > t	B_0	R^2
1-99	7-10	MI	Red	65.5	32.8	0.05	2,608	0.09
1-00	7-10	MI	Red	−86.5	35.6	0.02	22,726	0.18
1-00	7-10	MI	Green	−213	86	0.02	54,002	0.18
1-00	7-10	MI	NIR-Red	14,172	5,581	0.02	−12,816	0.19
1-00	7-10	MI	NIR/Green	49,511	19,138	0.02	−49,691	0.20
1-00	7-10	MI	Green/Red	23,388	9,425	0.02	−21,537	0.19
1-00	7-10	MI	NDVI	36,826	14,752	0.02	938	0.19
1-00	8-4	MI	Red	−80.5	38.3	0.04	21,450	0.14
1-00	8-4	MI	NIR/Red	16,776	7,151	0.03	−15,116	0.17
1-00	8-4	MI	NIR/Green	52,587	20,553	0.02	−53,229	0.20
1-00	8-4	MI	Green/Red	27,236	12,708	0.04	−24,429	0.15
1-00	8-4	MI	NDVI	42,470	17,997	0.03	1,255	0.17
1-00	8-22	MI	Red	−100	50	0.05	26,014	0.13
1-00	8-22	MI	NIR/Red	17,382	8,377	0.05	−15,436	0.14
1-00	8-22	MI	NIR/Green	58,657	23,260	0.02	−60,386	0.19
1-00	8-22	MI	NDVI	45,921	20,816	0.04	1,367	0.15
1-00	9-13	MI	NIR/Red	8,811	4,091	0.04	−6,952	0.15
1-00	9-13	LMI	NIR/Green	3.69	1.18	0.004	−0.62	0.27
1-00	9-13	LMI	NDVI	1.78	0.82	0.04	3.30	0.15
5-00	8-4	LMI	NIR	−0.048	0.020	0.02	12.94	0.09
5-00	9-13	LMI	NIR	−0.029	0.014	0.05	8.33	0.07
5-00	9-13	LMI	Red	−0.021	0.0090	0.02	1.95	0.09
5-00	9-13	LMI	Green	−0.037	0.016	0.02	10.15	0.09
5-00	9-13	LMI	Green/Red	7.64	3.56	0.04	−6.71	0.08

[a] Reflectance, which is represented by a digital number from 0 to 255, is measured at three broad wavelengths: near-infrared (NIR) bands ranges from 700–900 nm, red band ranges from 600–700 nm, and green band ranges from 500–600 nm. Their ratios (NIR/red, NIR/green, red/green) were computed by the quotient of reflectance values. NDVI is estimated by the formula (NIR − red)/(NIR + red).

[b] Date is represented as month-day.

[c] *Meloidogyne incognita*/500 cm^3 soil is represented as MI (nontransformed) or LMI [$\log_{10}$(MI + 1)].

[d] SE = standard error of B_1.

nematode sampling areas was too expensive when compared to sampling and treating an entire field as a single zone. Reflectance-based zones did not provide a reduction in nematode population variance, compared with that averaged across an entire field.

The images were able to detect other types of stresses more accurately. At site 1, water stress, as denoted by LESA irrigation, was classified separately from LEPA irrigated areas. At site 2, areas where seedling disease caused poor stands (*Rhizoctonia solani*) or poor root growth (*Thielaviopsis basicola*) were at least as important in affecting reflectance patterns as *M. incognita* density. At sites 3 and 4, water drainage patterns dominated the intensity of reflectance on the images. At site 5, calcium carbonate nodules in the Portales soil, which reflected strongly a white color, were distinguished easily from the Amarillo soil series. Aerial infrared photography conducted during the growing season was not sufficiently accurate to predict abundance of fall root-knot nematode populations. Other more precise methods, such as proximal remote sensing that can eliminate the effect of soil reflectance on vegetative reflectance indices (Huete et al., 1985), narrower wavelength spectra such as the 810-nm band (Nutter et al., 2002), and greater number of bands such as found with hyperspectral sensors (Ustin and Trabucco, 2000) may be more successful for predicting root-knot nematode population density than aerial infrared (broad-band, multispectral) photography.

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