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Site-Specific Management of *Meloidogyne chitwoodi* in Idaho Potatoes Using 1,3-Dichloropropene; Approach, Experiences, and Economics

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Abstract: Fumigation for nematode management in irrigated potato production systems of Idaho is widely practiced. Soil injection is the only labeled application method for 1,3-dichloropropene that is conventionally applied on a whole-field basis. Plant-parasitic nematode species exhibit spatially variable population densities that provide an opportunity to practice site-specific fumigation to reduce chemical usage and production costs. During 2002 to 2008, 62 fields intended for commercial potato production in eastern Idaho were sampled using a geo-referenced grid sampling system for plant-parasitic nematode population densities. In total, 4,030 grid samples were collected representing nearly 3,200 ha of commercial potato production. Collectively, 73% of the grid samples had Columbia root knot (CRN) (*Meloidogyne chitwoodi*) population densities below detectable levels. Site-specific fumigation is the practice of varying application rate of a fumigant based on nematode population density. In 2007, 640 ha of potato production were site-specific fumigated for CRN nematode control in eastern Idaho. On average, this practice resulted in a 30% reduction in chemical usage and production cost savings of $209/ha when 1,3-dichloropropene was used as the sole source of nematode suppression. Reductions in usage of 1,3-dichloropropene can exceed 50% if used in combination with a nonfumigant nematicide such as oxamyl. This combination approach can have production cost savings exceeding $200/ha. Based on farm-gate receipts and USDA inspections provided by potato producers from 2001 to 2011, potato tuber yield and quality have not been adversely affected using site-specific fumigation.

Key words: Columbia root-knot nematode, 1,3-dichloropropene, management, *Meloidogyne chitwoodi*, oxamyl, potato, site-specific precision agriculture, spatial distribution, technique.

Based on U.S. Department of Agriculture (USDA) crop production statistics for 2010 (USDA, 2011), Idaho produces 31% by weight and 28% by value ($854 million) of all fall potatoes grown in the United States. Columbia root-knot nematode (CRN) (*Meloidogyne chitwoodi*) is a significant threat to potato quality in Idaho and the Pacific Northwest. Columbia root-knot nematode infects and develops in potato tubers but does not cause yield loss. Columbia root-knot nematode causes quality defects such as galling on the surface and small brown spots surrounding adult females when peeled (Ingham et al., 2007). The external and internal defects render tubers unacceptable for fresh market sales and internal defects are unacceptable for processing. For the fresh market, if 5% of the tubers in the field have visual defects the whole-field crop can be rejected. For processed potatoes, if between 5% and 15% of the tubers in a field have visual defects the whole-field crop can be substantially devalued or rejected. Based on USDA 2010 yields and prices, the average gross value of potatoes in Idaho was $6,921/ha. The rejection of a potato crop grown on an average 52.6-ha center-pivot-sprinkler-irrigated field represents a loss of $364,000. Export markets have a zero tolerance for CRN, and their presence will result in rejection and return of the entire shipment. There is zero tolerance for CRN in seed potato production as well. The potential for dire financial consequences from the presence of CRN in potato tubers is taken very seriously by producers.

Columbia root-knot nematode can reproduce rapidly in warm seasons (Pinkerton et al., 1991). Because of this, it is difficult to provide accurate population thresholds for a decision on when to use fumigants on a field, or when to use a less expensive, nonfumigant nematicide. Because potential for crop rejection exists with low population levels at planting, fields with any CRN must be treated with a preplant fumigant, nonfumigant nematicides, or both. Several products are available to reduce potato tuber infection to acceptable levels (Ingham et al., 2000). Fumigant nematicides include 1,3-dichloropropene (1,3-D) (Telone II), sodium N-methyldithiocarbamate (MS) (VAPAM HL), and potassium N-methyldithiocarbamate (KS) (K-PAM HL). Nonfumigant nematicides include ethoprop (Mocap EC) and oxamyl (Vydate C-LV). Use of a single nematicide is often insufficient to limit potato tuber damage to acceptable levels (Ingham et al., 2007). For improved CRN suppression, use of a combination of nematicides is often practiced; for example, 1,3-D with MS has become a potato industry standard in the Columbia Basin of Oregon and Washington (Ingham et al., 2007).

For Idaho, the label application rates for the fumigant nematicides are 188 liter Telone II/ha for 1,3-D, 352 to 704 liter VAPAM HL/ha for MS, and 280 to 582 liter K-PAM HL/ha for KS. Label application rates for the nonfumigant nematicides are 19 liter Mocap EC/ha for ethoprop and 2.5 liter Vydate C-LV/ha for oxamyl. Oxamyl is labeled for suppression of CRN in potatoes for preplant population counts below 150 J2/250 cm^3 of soil with repeated application every 14 d after 880 degree-days Celsius, and limited to a total seasonal

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application of 22.5 liter Vydate C-LV/ha or eight applications.

Spatial dependence of an attribute can be evaluated using geostatistical techniques to quantify the average distance of spatial correlation by direction, and the variability of measurements separated by short distances (Rossi et al., 1992). Geostatistical analyses have been used to evaluate the spatial dependence of plant-parasitic nematode population densities within agricultural fields with the goal of estimating population densities at unsampled locations within field boundaries (Webster and Boag, 1992; Wallace and Hawkins, 1994; Robertson and Freckman, 1995; Boag et al., 1996; Marshall et al., 1998; Evans et al., 2002; Wrather et al., 2002; Wyse-Pester et al., 2002; Avendaño et al., 2004; Ortiz et al., 2010). When spatial dependence in nematode population was found in these studies, spatial correlations ranged from nonexistent to distances of 800 m depending on nematode species.

Identification of specific areas within individual fields for nematicide application may allow producers to reduce the amount of nematicide applied and lower production costs (Evans et al., 2002), depending on perceived risk. Combination of the spatially aggregated nature of nematodes, the relatively high cost of fumigant nematicides, the fact that some growers use multiple types of nematicides on the same crop, and the relatively high crop value of potatoes makes site-specific fumigation appealing from an economic stand point. Evans et al. (2002) evaluated the potential of site-specific nematode management in potato production systems in the UK. The nematodes of concern were the potato cyst nematodes (PCN) (*Globodera pallida and G. rostochiensis*), which causes yield reduction but not whole-field crop rejection. They found that the inverse relationship between population density before planting and rate that PCN multiply makes it difficult to devise reliable spatial nematicide application procedures, especially when preplanting population density is just less than the detection threshold. The spatial dependence found for PCN indicated that 100-m-spaced sampling grids used commercially would likely produce misleading distribution maps. They concluded that the best recommendation for site-specific PCN nematode management was to apply more expensive fumigant nematicides to "hotspots" of infestation and treat the whole-field with less expensive nonfumigant nematicides to prevent excessive multiplication of nematodes in nonfumigated areas of the field. This multiple nematicide type of approach can be applied to CRN in Idaho production to reduce the risk of crop rejection resulting from imperfect CRN mapping and sampling error.

The success of commercial adoption of site-specific nematode management will require the development of affordable nematode distribution maps (Wyse-Peste et al., 2002). The risk of yield loss will have to be balanced by substantial cost savings from reduced chemical application. In the case of CRN, the risk of unacceptable levels of control will have to be virtually eliminated because of the potential economic consequences of potato tuber quality defects. Site-specific CRN management in irrigated potato production systems of eastern Idaho is being offered commercially. The goal of this project was to promote new technology to reduce chemicals applied in commercial irrigated potato production systems. The objective of this paper is to describe the approach being implemented and associated experiences and economics.

Methods and Materials

Field sites: Plant-parasitic nematode population densities, namely CRN, root-lesion (RLN, *Pratylenchus* spp.), and stubby-root (SRN, *Trichodorus* and *Paratrichodorus* spp.) nematodes were sampled using geo-referenced grid soil sampling in 62 commercial fields prepared for potato production in eastern Idaho from 2002 through 2008. Fields were located in Power, Bingham, Bonneville, Jefferson, and Fremont counties and ranged in size from 16 to 125 ha. Soil textures ranged from loamy sand to silt loam. Elevation ranged from 1,300 to 1,530 m.

Field sampling: Fields scheduled to be planted to potatoes were sampled for nematodes using a grid sampling approach in August or September of the preceding year following harvest of small grain crop. A square grid of sampling locations was established within a field using a Trimble AgGPS 132 DGPS receiver for GPS data collection and Trimble's EZ-Map software (Trimble Navigation Limited, Sunnyvale, CA) connected to a portable laptop computer, mounted to a vehicle. The vehicle with GPS equipment was driven around the field boundary and the software generated an image of the field border on the computer display. The software was used to overlay a square grid of sampling points on the field map. The spacing between grid points ranged from 90 to 95 m with each grid point representing 0.8 to 0.9 ha. Each sample grid point was located by driving the vehicle via GPS guidance to a specific grid location selected on the computer display.

Sampling at each grid point consisted of taking eight to 10 subsamples of soil from a 10- to 25-cm soil profile using a shovel. The first two subsamples were collected within 2 m of the grid point and an additional six to eight subsamples were collected on approximately a 15-m radius at random around the grid point. Each subsample was collected by taking approximately 250 cm^3 of soil from each shovel sample and depositing into a bucket. The subsamples were uniformly mixed and separated as one single 750 cm^3 soil sample for each grid location for nematode analysis. Soil samples were collected in this manner to reduce potential sampling error resulting from a single grid point sample in the presence of an aggregated nematode distribution.

Sample analysis: Immediately following collection, soil samples were sent to Western Laboratories (Parma, ID) for nematode extraction, identification, and enumeration using traditional methods. The lab moistened the soil samples uniformly and incubated them at ambient temperature for up to 1 wk to minimize differences in nematode extraction efficiency because of differences in soil moisture content. A modified elutriation method (Ingham, 1994) was used to extract all soil-dwelling nematodes from 250-cm^3 subsamples of soil plus root fragments. Using an Oostenbrink elutriator with a flow rate of 2.6 liter/hr, coarse material was collected on a 500-µm sieve and nematodes on a stack of two 38-µm and two 32-µm sieves. Nematodes were washed into 100-ml cups, suspensions were stored overnight, and settled nematodes were transferred to 50-ml centrifuge tubes and concentrated by 3,200 rpm for 5 min. Water was discarded, replaced by magnesium sulfate solution at specific gravity 1.180, mixed by spatula, and centrifuged again for 4 min. The supernatant solution containing nematodes was passed over a 20-µm sieve, transferred to another 50-ml tube, and allowed to settle for at least 2 h before counting. Nematode collection efficiency was approximately 65% (H. Kreeft, personal communication), which is consistent with a recovery efficiency of 75% reported by Banerjee and Basu (1976) using a similar collection approach on an introduced population of CRN.

Enumeration of nematodes was performed by reducing the volume of suspension in the 50-ml tubes to 10 ml, mixing the remaining suspension in a mini-vortex mixer for 5 s, removing 4 ml of suspension, placing 1 ml on a Peter's counting slide, counting and identifying all plant-parasitic nematode genera on the slide, and reporting nematodes in number of CRN J2/500 cm^3 soil.

Data analysis: Sample nematode data from all 62 commercial fields were analyzed by field and as a collective group for fraction of grid points where CRN were detected. For fields where estimation of the spatial distribution of CRN was desired, geostatistical semivariogram analysis using GS+ version 7 (Gamma Design Software, Plainwell, MI) was conducted. Isotropic models were fitted in all cases and selection of semivariogram models was based on residual sums of squares and coefficients of determination (r^2) (Robertson, 2008). The spatial index proposed by Cambardella et al. (1994) was used to evaluate the degree of spatial dependence for CRN. The spatial index is the ratio between nugget semivariance and total semivariance or sill and used to define different classes of spatial dependence. If the ratio is $\leq$ 0.25, CRN was considered to be strongly spatially dependent, or strongly distributed in clusters; if the ratio was 0.26 > 0.75, CRN was considered to be moderately spatially dependent; and if the ratio was > 0.75, CRN was considered to be weakly spatially dependent. Best fit model semi-variograms were used with SSToolbox software (SST Software, Stillwater, OK) to interpolate CRN population density at unsampled 0.09 ha (30-m $\times$ 30-m) field locations using ordinary block. The resulting CRN distribution map was used to construct a site-specific 1,3-D prescription map using a management strategy described below. Initially, CRN distribution in every sampled field was mapped to construct an application map. After about 20 fields were grid sampled and mapped, it became apparent that fields where approximately 50% or more of the sample grids had CRN detected, the CRN management recommendation was uniform application of nematicide. Subsequently, whenever 50% or more of the grid samples from a field had CRN, uniform application of a nematicide was recommended and a map was not constructed. Consequently, most but not all fields were mapped for CRN spatial distribution in preparation for making a site-specific fumigation map. The resulting map was downloaded to either a Raven Viper Pro (Raven Industries, Souix Falls, SD) or John Deere Greenstar (Deere & Company, Moline, IL) variable rate control system on custom applicator equipment.

Kriging is not an exact interpolator, unlike inverse distance weighting that honors data values at sample locations. A kriged estimate of CRN population density at an unsampled location is a weighted mean of data values within a surrounding neighborhood where the weights are determined based on modeled spatial dependence of the data set (Isaaks and Srivastava, 1989; Burrough and McDonnell, 1998). Consequentially, a low CRN grid sample value surrounded by high CRN grid samples will result in an estimated value greater than sample value and vice versa. Underestimation of high CRN population densities is generally not an issue as the threshold value of CRN for fumigation with 1,3-D is low compared with population densities commonly found in the fields of eastern Idaho where substantial populations levels of CRN are present. Overestimation of CRN population densities in the neighborhood of high CRN values is also not a critical issue as it provides a means of incorporating a buffer of fumigation around locations with high CRN population densities, which is desired to reduce risk. However, underestimation of CRN population densities surrounding one or two sample locations where the sample CRN population density is near but greater than the threshold value could potentially result in inadequate CRN treatment. Three empirical approaches are possible to develop localized fumigation prescriptions when this occurs. One possibility is to modify the sample data set by artificially increasing the CRN population value at the grid point and using kriging to generate a new spatial distribution based on the original variogram model. The problem with this approach is that a priori knowledge of how much to arbitrarily increase the CRN population value to generate a suitable fumigation zone is unknown. A second approach is to use kriging and inverse distance weighting to generate two sets of spatial estimates for CRN population distribution. The two spatial estimates are then combined by selecting the maximum value at a given location. This approach results in CRN values at sample data locations that equal or exceed the sample values, while incorporating some spatial dependency of the data. A third approach is to simply estimate a fumigation zone near the grid sample location based on surrounding CRN sample values and the producer's aversion to risk. This latter approach was used for simplicity. For instances where a CRN sample value was above the fumigation threshold and surrounded by low CRN sample population densities, the highest fumigation rate was assigned to one or more 0.09 ha (30-m × 30-m) management zones at and near the grid sample location. The number of management zones assigned the highest fumigation rate was dependent on the CRN population density measured at the sample location relative to the fumigation threshold and producer aversion to risk. A lower fumigation rate was assigned to 0.09 ha (30-m × 30-m) management zones bordering management zones with the high fumigation rate. In some instances, an additional 0.09-ha border area was added and assigned the lower fumigation rate, depending on producer preference. Similarly, border management zones with lower fumigation rate(s) were added to all areas where estimated CRN was greater than the fumigation threshold.

Site-specific CRN management strategies: Site-specific nematode management strategies were based on the proposed approach of Evans et al. (2002) to apply the more expensive fumigant nematicides to "hot-spots" of infestation and treat the whole-field with less expensive nonfumigant nematicides to prevent excessive replication of damaging nematodes. Nematicides used in this study were 1,3-D, KS and oxamyl. Both KS and oxamyl can be applied with water through the sprinkler irrigation system for whole-field uniform application or on a site-specific basis with ground based application systems. Recent USEPA reregistration labeling for MS and KS has placed restrictions on use through irrigation that will likely reduce suitability for this method of application. 1,3-D can only be applied to potato through shank injection using ground-based equipment. Site-specific application of nematicide fumigants 1,3-D and KS was applied in September or early October following nematode grid sampling in the year prior to the potato crop. The particular combination of chemicals used was determined by each producer. The producer's experience with CRN and other crop pests in previous potato crops on the field sites influenced chemical selection and application strategy. Fields where 30% or more of the sampling grids had CRN detected were treated with KS or oxamyl in addition to 1,3-D when available, to reduce risk. Site-specific nematicide application strategies were as follows.

Site-specific 1,3-D application only: Only spatially interpolated map locations with estimated CRN population density > 0 (detected) received 1,3-D application. 1,3-D application rate was 140 liter Telone II/ha for CRN between 0 and 50 J2/500-cm^3 soil and 188 liter Telone II/ha for estimated with > 50 J2/500-cm^3 soil. The lower application rate was applied to variable rate management zones bordering management zones with estimated CRN population density > 0 (detected). This CRN management strategy was only used where CRN were detected at relatively low population levels, limited to a relatively small single location in the field, and where the field did not have a history of crop damage by CRN.

Site-specific 1,3-D with uniform application of KS or oxamyl: Spatially interpolated map locations with estimated CRN population density > 50 J2/500-cm^3 soil received 1,3-D application at 188 liter Telone II/ha. 1,3-D was applied to variable rate management zones bordering spatially interpolated map locations with estimated CRN > 50 J2/500-cm^3 at 1 or 2 lesser rates (140 liter Telone II/ha and 70 liter Telone II/ha) to reduce perceived risk of crop damage from inadequate CRN population control surrounding "hot spots." KS or oxamyl was also applied uniformly to the whole-field. KS was applied through the irrigation system with an application rate of 280 to 375 liter K-PAM HL/ha in September or early October following site-specific 1,3-D application. Oxamyl was applied through the irrigation system at an application rate of 2.5 liter Vydate C-LV/ha two to four times during the growing season on a 14-d interval depending on crop history, with initial application based on growing degree-days.

Combined site-specific 1,3-D and KS application: Spatially interpolated map locations with estimated CRN population density > 50 J2/500-cm^3 received 1,3-D application at 188 liter Telone II/ha. 1,3-D was also applied to variable rate management zones bordering interpolated map locations with detected CRN > 50 J2/500-cm^3 at the same rate. KS was applied by shank application at a rate of 280 to 375 liter K-PAM HL/ha proportional to estimated CRN population density to areas not receiving 1,3-D application. One custom applicator had the capability to select between two chemicals as well as variable rate application of both fumigants.

Site-specific KS application only: Because of limited availability of 1,3-D, site-specific KS application was used for CRN management on several occasions. This was not the CRN management strategy of choice, but one of necessity as it was the only feasible solution for fields where grid sample CRN population density exceeded the level labeled for oxamyl. Spatially interpolated map locations with estimated CRN population density > 0 (detected) received KS application at the rate of 424 liter K-PAM HL/ha. Variable rate management zones bordering spatially interpolated map locations with estimated CRN population density > 0 also received KS application at the rate of 424 liter K-PAM HL/ha. Variable rate management zones with estimated CRN population density = 0 (undetected) received KS application at the rate of 280 liter K-PAM HL/ha to control additional crop pests or disease.

The number of fields and area treated by each of the CRN management options from 2002 through 2008 is shown in Table 1. The large proportion of area that received site-specific KS application only was because of limited availability of 1,3-D during some project years.

Input costs: Chemical costs used in economic analyses were \$3.50/liter, \$1.70/liter, and \$23.80/liter for Telone II, K-PAM HL, and Vydate C-LV, respectively. These costs were for 2011 to reflect current economics of site-specific CRN management. Costs for sampling, nematode analysis, and mapping were \$35/ha for 0.8-ha grid sampling size. Custom uniform fumigant application costs were \$84/ha for KS and \$49/ha for 1,3-D. The lower application cost for 1,3-D is because of the manufacturer cost sharing application costs. Custom site-specific fumigant application costs were \$94/ha for KS, \$109/ha for 1,3-D, and \$134/ha for both. Site-specific application costs for 1,3-D were greater because the manufacturer did not cost share with site-specific management. Additional application costs for injection through the irrigation system with water were assumed to be zero since this is a standard producer practice.

Results

Columbia root-knot nematode distribution: In total, 4,030 grid samples were collected representing nearly 3,200 ha of sprinkler-irrigated commercial potato production in eastern Idaho over a 7-yr period. All field sites had a history of whole-field nematicide application whenever applied. Of the grid samples, 73% had undetected CRN; 10% had detected CRN population densities < 50 J2/500 cm^3 of soil; and 17% had greater CRN population densities. Relative to conventional whole-field fumigant nematicide application, site-specific fumigant application had the potential to reduce environmental chemical loading by 73% if fumigant could be applied only to grids where nematodes were detected. The sampled fields are not necessarily statistically representative of CRN distribution in eastern Idaho since the fields were not randomly selected, but likely indicate the potential for wide scale reduction of chemical loading in the region.

Table 1. Number of fields and total area treated using different site-specific nematode control strategies from 2002 to 2008.

Treatment method	Number of fields	Total area (ha)
Site-specific 1,3-D and uniform oxamyl	18	683
Site-specific 1,3-D only	1	52
Uniform 1,3-D only	7	442
Site-specific 1,3-D and site-specific KS	3	151
Site-specific KS and uniform oxamyl	2	102
Site-specific KS only	24	1,466
Uniform KS only	4	213
Uniform oxamyl	3	141
No control	0	0

More than 35% of the fields grid sampled had more than 90% of the grid sample sites in which CRN was not detected (Fig. 1). In approximately 50% of the grid sampled fields, CRN was not recovered from 70% or more of the grid sample sites. Thus, approximately half of the fields sampled could potentially reduce nematicide use by 70% or more if risk was not a factor in implementing site-specific CRN management. In approximately 50% of the fields sampled, 10% of the grid sample sites had CRN population densities > 50 J2/500 cm^3 of soil. Thus, half of the fields sampled had some "hot spots" in CRN population density. Fifty-three percent of the fields grid sampled had CRN detected but < 50 J2/500 cm^3 of soil. Nearly all of the fields sampled had < 40% of the grid sample sites where CRN were detected but at levels < 50 J2/500 cm^3 of soil. Collectively, all the

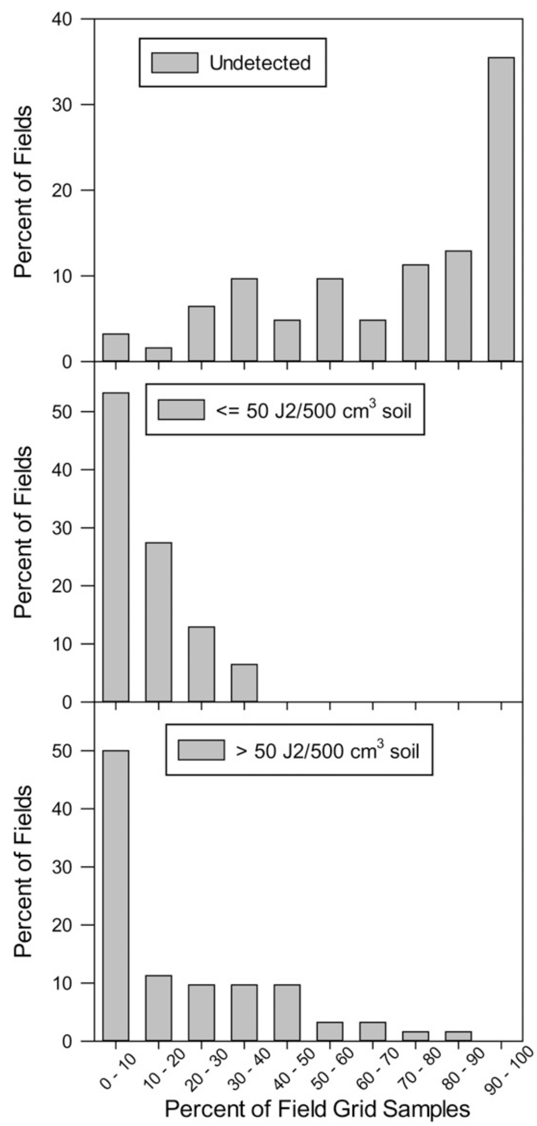

Fig. 1. Histograms of the percentage of sampled fields versus percentage of field grid samples having Columbia root-knot nematode (CRN) population densities of undetected, ≤ 50 J2/500 cm^3 soil and > 50 J2/500 cm^3 soil (i.e., 35% of fields sampled had undetected CRN population densities in more than 90% of the grid samples).

fields sampled exhibited spatial distributions in detected CRN that would result in reduced fumigant nematicide use if site-specific fumigation technology was used.

Site-specific management examples: To demonstrate the approach used for site-specific CRN management, two sampled fields were selected as examples (Fig. 2), where CRN were clustered in a portion of the field (Fig. 2A), and where they were dispersed across the field area with high population "hot spots" (Fig. 2B). Sample and model variograms for the two fields are depicted in Fig. 3.

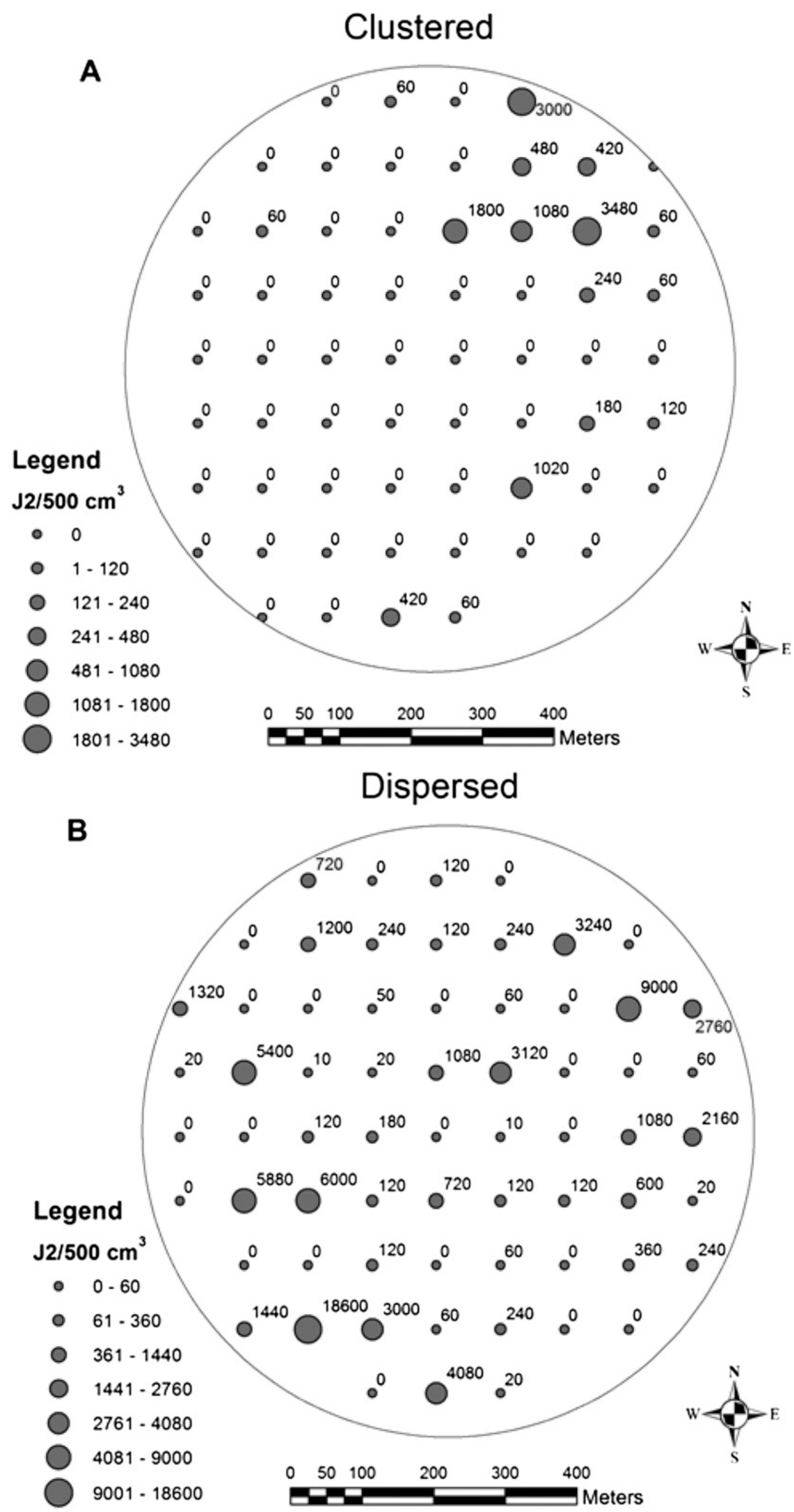

Fig. 2. Distribution of Columbia root-knot nematode (CRN) population density from two sampled fields; one where CRN was clustered in a portion of the field (A) and another where CRN was dispersed across the field (B) with high population density "hot spots" (0 = undetected).

A spherical model was used to represent both experimental variograms and provided a good fit to the data. For the clustered CRN field, the model variogram had a semivariance nugget of 127,195, a sill of 396,426, and a range of 261 m providing an r^2 of 0.91 and a spatial index of 0.32. For the dispersed CRN field, the model variogram had a semivariance nugget of 4,628,129, a sill of 7,290,299, and a range of 291 m providing an r^2 of 0.95 and a spatial index of 0.63. Based on the spatial index, the data for both fields indicated moderate spatial dependence of CRN, but greater for the clustered field. Block kriging estimation of the spatial distribution of CRN for the two fields is illustrated in Fig. 4. Estimated CRN population densities for the entire dispersed field (Fig. 4B) were essentially entirely greater than the fumigation threshold of 50 J2/500 cm^3, indicating that this field was not suitable for site-specific fumigation. The field needed to be whole-field fumigated at the maximum application rate to minimize risk of crop damage. For the field with clustered CRN distribution (Fig. 4A), estimated CRN population densities for a large contiguous area of the field was less than the fumigation threshold of 50 J2/500 cm^3, allowing application of oxamyl for managing CRN populations on a substantial portion of the field. Estimated CRN population densities were below the fumigation threshold of 50 J2/500 cm^3 at and near the single grid sample CRN measurement of 60 J2/500 cm^3 in the northwest quadrant of the field (Fig. 4A) and population densities greater than the fumigation threshold of 50 J2/500 cm^3 were estimated at grid sample locations with no detected CRN surrounding the contiguous area of high CRN population densities. These instances of differences between estimated CRN and measured CRN at grid sample locations were due to the spatial structure (Fig. 3A) used in kriging.

Based on estimated CRN population densities shown in Fig. 4A, the resulting 1,3-D prescription map for the clustered field is shown in Fig 5. An area of 1,3-D application at and near the single grid sample CRN measurement of 60 J2/500 cm^3 in the northwest quadrant of

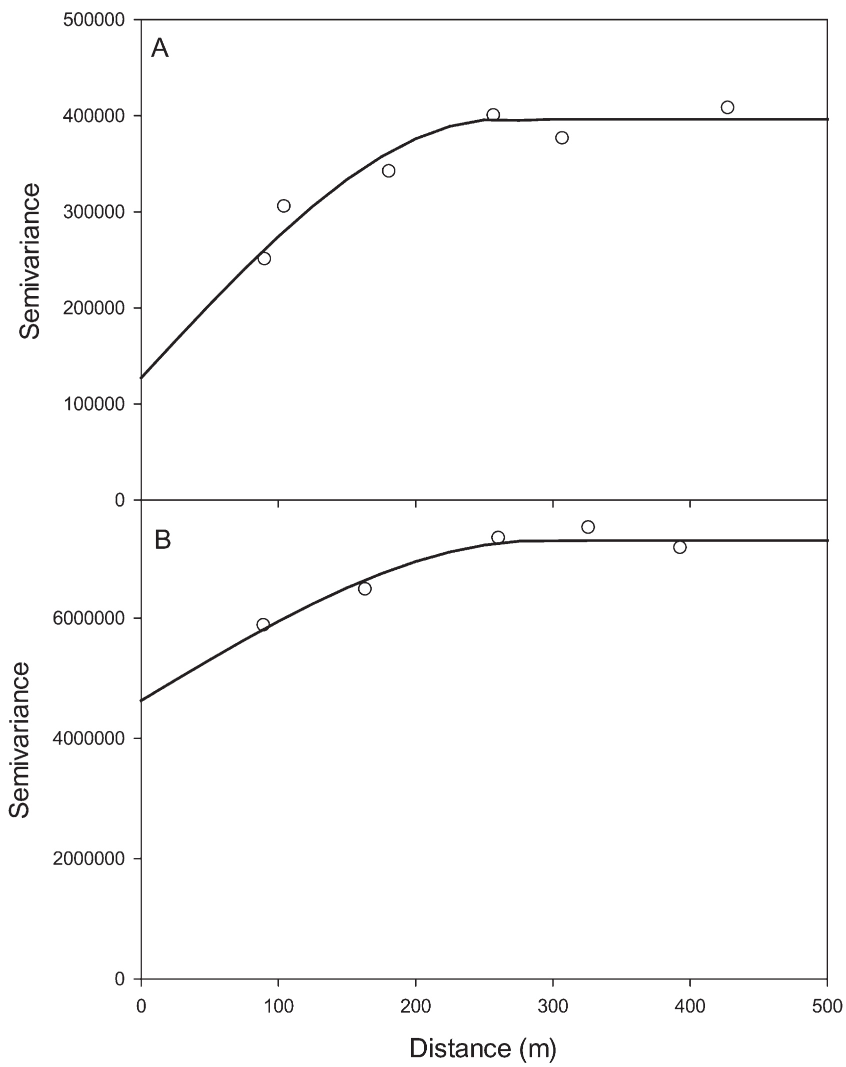

FIG. 3. Experimental (data points) and model (line) variograms for example fields with clustered (A) and disperse (B) Columbia root-knot nematode (CRN) population densities.

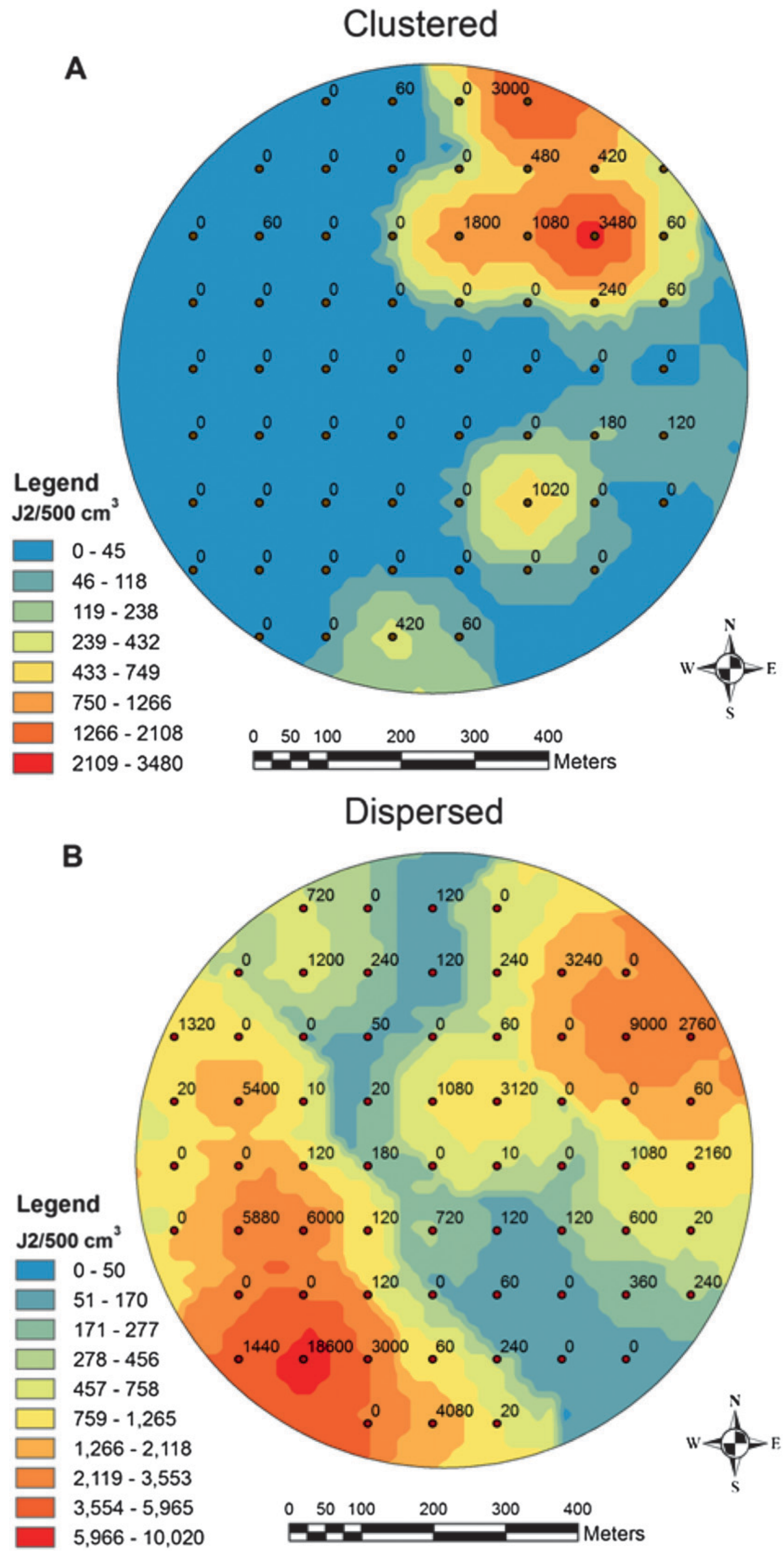

Fig. 4. Estimated spatial population density distribution of Columbia root-knot nematode (CRN) using block ordinary kriging for two sampled fields; one where CRN was clustered (A) in a portion of the field and another were CRN was dispersed (B) across the field with high population density "hot spots" (0 = undetected).

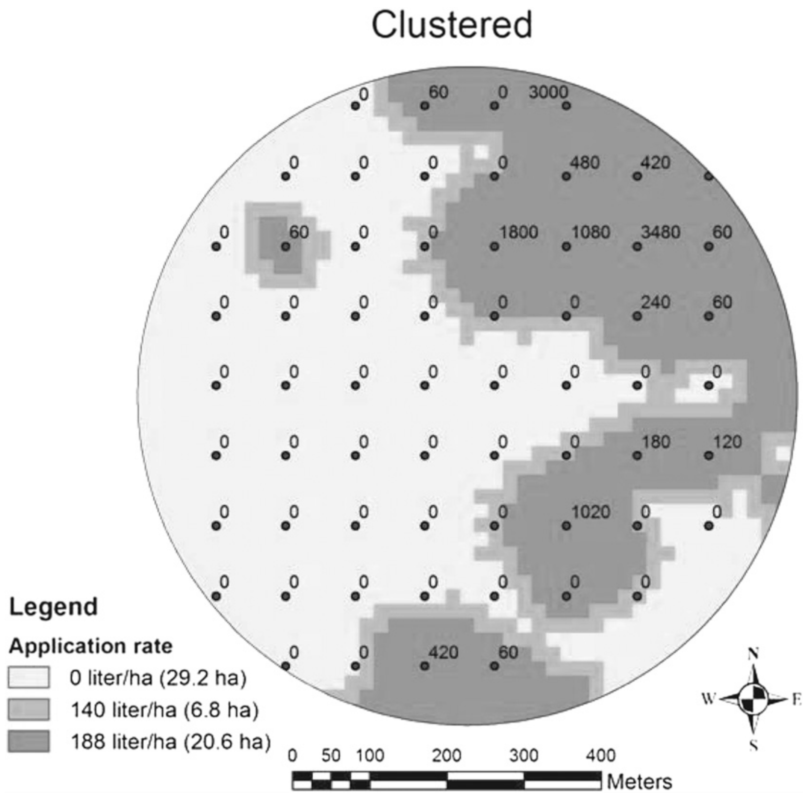

FIG. 5. Example application map for Telone II (1,3-D) for the sampled field where Columbia root-knot nematode (CRN) was clustered. Oxamyl was applied uniformly to the whole-field multiple times to control CRN where estimated population density < 50 J2/500 cm^3.

the field (Fig. 4A) was manually added (as previously described) to the prescription map to minimize risk in this area of the field. The 1,3-D prescription map and CRN control strategy was reviewed with the producer to ensure they were comfortable with the level of risk assumed with implementation of site-specific fumigation for CRN. This approach to site-specific fumigation of CRN has been used since 2002 without unacceptable crop damage. The objective of the methods developed is to reduce 1,3-D application costs with minimum risk of crop damage rather than to optimize estimation of CRN spatial population distribution.

Fumigant usage: Comparison of 1,3-D site-specific application usage relative to conventional whole-field uniform application on fields in the fall of 2007 is given in Table 2. On field sites 6 and 8 there was no reduction in fumigant applied by site-specific application because grid sampled CRN population levels were relatively high and distributed throughout the field area (similar to the dispersed sample field, Fig. 4B, previously discussed).

TABLE 2. Total volume of Telone II (1,3-dichloropropene) fumigant reduced on 11 fields in eastern Idaho where site-specific fumigation technology was applied in fall 2007.

Field site identification	Field area ha	Average application rate liters/ha	Conventional uniform rate liters/ha	Difference between application rates liters/ha	Volume reduction liters
1	47	58.2	188.0	129.8	6,100
2	48	18.8	188.0	169.2	8,122
3	61	144.6	188.0	43.4	2,647
4	52	160.5	188.0	27.5	1,430
5	70	178.3	188.0	9.7	679
6	125	188.0	188.0	0	0
7	55	60.1	188.0	127.9	7,034
8	52	188.0	188.0	0	0
9	55	117.3	188.0	70.7	3,888
10	51	112.6	188.0	75.4	3,845
11	24	0.0	188.0	188	4,512
	Total = 640	Average = 111.6		Average = 76.5	Total = 38,257

On field site 11, grid sampling demonstrated that CRN population densities were relatively low throughout the field area without any “hot spots” > 50 J2/500 cm^3 of soil. The producer decided to use uniform applications of oxamyl during the 2008 growing season. Based on farm-gate receipts and USDA inspections provided by potato producers, potato tuber yield and quality of the 2008 crop were not adversely affected by use of site-specific fumigation technology. Total fumigant volume reduction for the 11 field sites was 38,257 liters Telone II, representing a 1,3-D chemical cost savings of $133,900 or $209/ha. However, this is not a true total chemical cost savings as other nonfumigant nematicides were used to replace fumigant nematicide not applied.

Cost comparison: Comparison of costs between potential site-specific CRN management scenarios relative to whole-field uniform 1,3-D application at a rate of 188 liter Telone II/ha on a 55-ha field are presented in Table 3. Depending on the percent of area treated with 1,3-D and combination of nematicides used on other areas of the field, the cost savings associated with site-specific fumigant nematicide application can range from -$15,520 to $24,800. The negative savings (= increased cost) associated with 30% 1,3-D and 100% uniform KS application may not be worth implementing unless both fumigants were initially going to be applied uniformly. If that were the case, the cost savings would be $29,990. The largest savings occur when less than 30% of the field area requires 1,3-D fumigation, which allows less expensive nonfumigant nematicides to be used as the sole nematicides on nonfumigated areas of the field. Based on practical experience, site-specific 1,3-D fumigation alone (i.e., without additional nematicides treatment) is not recommended on fields that have CRN spatial densities requiring 1,3-D fumigation on more than 30% of the field area. The cost savings are minimal and the risk of not fumigating an undetected “hot spot” is too great. The exception may be when the area requiring fumigation is contiguous and the remainder of the field has very low or undetected CRN population densities. When 50% or more of the field area requires 1,3-D fumigation, the cost of site-specific fumigation quickly exceeds the cost of uniform application. Savings increase when less than 30% of the field requires 1,3-D fumigation, for example in the case of 10% of the field area (Table 3). However, custom applicators are reluctant or refuse to treat fields with small percentages of fumigation because they make less money per site setup. Over the past 10 years, there have been fields that were grid sampled and resulted in CRN population densities below 50 J2/500-cm^3 soil field-wide so the whole field was treated with oxamyl for CRN management. Conversely, there have been fields that were grid sampled where the whole field was treated with 1,3-D for CRN management. In this situation, grid sampling increased the cost of CRN management relative to conventional whole-field application of 1,3-D due to the added cost of grid sampling.

Discussion

During 2002 to 2008, 62 fields intended for commercial potato production in eastern Idaho were sampled for plant-parasitic nematodes, namely CRN, RLN, and SRN, using a geo-referenced grid system to determine sampling sites. In total, 4,030 grid samples were collected representing nearly 3,200 ha of sprinkler-irrigated commercial potato production over the 7-yr period. Collectively, 73% of the grid samples had no CRN or CRN population densities below the detection limit. Thus, much of the production area would not require whole-field fumigation. Use of site-specific

Table 3. Cost savings from site-specific fumigant nematicide application scenarios relative to whole-field uniform 1,3-dichloropropene application for 55-ha field.

1,3-D	Additional nematicide	Total chemical cost[a,b]	Total sampling cost[c]	Application cost[d]	Total cost	Unit cost	Savings relative to conventional uniform application
		$	$	$	$	$/ha	$
100%	none	36,190	35	2,695	39,578	720	–
50%	100% oxamyl 2 times	31,185	1,925	2,998	36,675	667	2,904
30%	70% site-specific KS	35,401	1,925	5,418	43,387	789	-3,809
30%	100% oxamyl 2 times	23,947	1,925	1,799	28,106	511	11,472
30%	100% uniform KS	45,920	1,925	6,419	55,098	1,002	-15,520
30%	none	10,857	1,925	1,799	14,778	269	24,800
15%	85% site-specific KS	35,232	1,925	5,294	43,091	783	-3,513
10%	100% oxamyl 2 times	16,709	1,925	600	19,537	355	20,041
0%	100% oxamyl 2 times	13,090	1,925	0	15,253	277	24,325

[a] Based on application rates of 188 liter Telone II/ha for 1,3-dichloropropene, 375 liter K-PAM HL/ha for potassium N-methyldithiocarbamate, 5 liter Vydate C-LV/ha for oxamyl.
[b] Product costs = $3.50/liter for Telone II, $1.70/liter for K-PAM HL, $23.80/liter for Vydate C-LV.
[c] Sampling costs = $35/ha for grid sampling, nematode assessment, and construction of a site-specific fumigant application map.
[d] Application costs = $109/ha for 1,3-dichloropropene; $94/ha for shank application of potassium N-methyldithiocarbamate; $134/ha for shank application of 1,3-dichloropropene and potassium N-methyldithiocarbamate in combination; and $0/ha for application of potassium N-methyldithiocarbamate or oxamyl with irrigation.

fumigant application has the potential to reduce environmental chemical loading by 73% relative to whole-field application. Guidelines for site-specific fumigation in combination with whole-field nonfumigant nematicide application for CRN suppression have been developed and used since 2002. In 2007, site-specific CRN management resulted in a 30% reduction in chemical usage and chemical cost savings of \$209/ha when 1,3-dichloropropene was used as the sole source of nematode suppression. Further reductions in usage of 1,3-dichloropropene can exceed 50% if it is used in combination with another nematicide such as oxamyl. This combination approach can have production cost savings exceeding \$200/ha. Based on farm-gate receipts and USDA inspections provided by potato producers from 2001 through 2011, potato tuber yield and quality have not been adversely affected in terms of salability by site-specific fumigation as there has not been a single occurrence of tuber infection rates exceeding acceptable levels. Site-specific potato yield and quality was not directly measured in this project because the cost was prohibitive on such a large scale and replication of such data on proven CRN control measures is of little value. No doubt, there were infected tubers present in the harvested crop, just not at a sufficient level to cause rejection of the crop for the intended use. The 1,3-D label clearly states that the crop is not guaranteed to be free of CRN damage, so harvest of a CRN-free crop is not to be expected even with use of the fumigant. At the farm gate, successful sale of a good yielding potato crop is of utmost importance and was achieved with 100% success in this project.

In this project adequate CRN control was obtained and crop rejection risk controlled by using proven CRN control strategies uniquely combined in a conservative manner to reduce overall CRN control costs. For example, oxamyl was used to control CRN populations where field samples had CRN < 50 J2/500 cm^3, which is one-sixth the CRN control threshold of 150 J2/250 cm^3 stated on the label. Thus, a factor of safety of six was present in using oxamyl to control CRN where 1,3-D was applied on a site-specific basis. Conservatively large border areas were used with site-specific application of 1,3-D to minimize the risk of undetected CRN near high CRN populations detected by the field grid sampling. Risk could potentially be less with site-specific fumigation as the number of soil samples collected to develop a prescription map exceeds the number commonly collected for whole-field nematode management. Thus, chances of detecting a previously unknown high CRN population are increased with grid sampling for site-specific fumigation.

One recurrent issue with site-specific fumigation as applied in this project has been the criticism that fumigants are applied at rates below the label rate(s) in border management zones surrounding field areas with high detected CRN populations. However, FIFRA (1992) defines the term "'to use any registered pesticide in a manner inconsistent with its labeling" means to use any registered pesticide in a manner not permitted by the labeling, except that the term shall not include applying a pesticide at any dosage, concentration, or frequency less than that specified on the labeling unless the labeling specifically prohibits deviation from the specified dosage, concentration, or frequency. Thus, pesticides used in this study can legally be applied at rates less than the label rate without changes to existing labels.

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