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Geostatistics for Mapping Weeds, with a Canada Thistle (*Cirsium arvense*) Patch as a Case Study[1]

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Abstract. **Geostatistical methods were used to describe and map nonrandom distribution and variation (standard deviation) of shoot density and root growth across a well-established patch of Canada thistle, a perennial weed. Semivariogram functions and kriging, an interpolation method, were used to prepare isoarithmic contour maps and associated error maps. Maps consisted of interpolated contours of uniform weed density and other measured or calculated regionalized variables between measured X-Y control points, as well as maps of error (standard deviation) associated with contour estimation. Mapped regions of greatest shoot density across a patch not only had the greatest underlying root biomass and, often, greatest density of adventitious root buds, but also had more deeply growing root biomass. Nomenclature: Canada thistle, *Cirsium arvense* (L.) Scop. # CIRAR[3].**

Additional index words: **Adventitious root buds, density, growth, mapping, patch, root, semivariance, shoots, spatial statistics, spatial dependence.**

INTRODUCTION

Weeds are not uniformly or randomly distributed (6, 14, 16, 17, 18). Rather, distribution of weeds across the landscape has spatial dependence, especially, for many perennial weeds that grow in patches, such as Canada thistle (6). Spatial dependence can imply that sites with high weed densities are often surrounded by high weed densities, and sites with low weed densities are bordered by low weed densities. Canada thistle shoots arise from adventitious root buds that form on an extensive, interconnected perennial root system (5). Emerged shoots likely influence shoot density or growth of neighboring shoots of perennial weeds more than distant shoots.

Geostatistical analysis can be used to map weed distribution across landscapes and characterize variability or error of measured variables (termed "regionalized variables" in geostatistics) that are not uniformly or randomly spread across a landscape. Regionalized variables are measured variables, such as weed density, which are assumed to have spatial dependence. Geostatistics and regionalized variable theory were originally developed for spatial analysis of ore deposits in mining (5, 15) and are well-established statistical methods in a variety of earth science disciplines, including soil science (22, 24, 29, 30, 31).

Geostatistics allows spatial relationships of sampled values for a regionalized variable to be used for interpolation (i.e., prediction or estimation) of values at nearby unsampled locations in preparing isoarithmic (contour) maps (29). Geostatistics allows calculation of the error of interpolation (i.e., standard deviation), subject to certain statistical assumptions (5, 12, 29). In geostatistics, isoarithmic contour maps consisting of interpolated contours of uniform weed density or other measured regionalized variables between measured X-Y control points can be prepared with associated maps of error using kriging, an interpolation technique.

Natural weed infestations have not been mapped often, perhaps because of a perceived lack of statistical methods for analyzing maps and defining data variability. Although geostatistical methods for statistically analyzing mapped variables exist (17, 27), they are not typically part of agricultural statistical training. Geostatistical analysis is one approach that could be used to characterize or model variability of weed density and other biological variables at various scales, such as in localized patches, at the field scale, and across the landscape. For example, geostatistical analysis can be used to generate contour maps of weed density with associated maps of the standard deviation of estimated density. Other mapping techniques do not estimate error associated with generating isoarithmic contour lines for regionalized variables, such as weed density. Other potential uses for geostatistics in weed science are briefly covered at the end of the Results and Discussion section.

Canada thistle shoot density varies across patches and often decreases near patch borders (1, 6, 33), but not as a uniform trend. Canada thistle shoot biomass exhibited a bell-shaped distribution across a 35-m-wide patch in Colorado (28). However, Pavlychenko (23) noted that dense patches of Canada thistle became ring-like after prolonged drought. More shoots emerged on patch borders than in the center. Others observed that areas of greatest shoot density shifted from year to year within Canada thistle patches (25). No publications report the quantitative distribution of Canada thistle roots across entire patches, only shoot growth along transects (28) or anecdotal observations (23, 25).

The first objective of this descriptive research was to use geostatistics to map Canada thistle shoot density across an established patch, as well as root growth at progressively greater depths in the soil profile across a patch. A second objective was to characterize mapped variation (error of interpolation) of Canada thistle shoot density and root growth across a Canada thistle patch. Mapping weed distribution has not been a traditional goal of weed science research, but it is useful before studying why

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[3]Letters following this symbol are a WSSA-approved computer code from Composite List of Weeds, Revised 1989. Available from WSSA, 1508 West University Ave., Champaign, IL 61821-3133.

weeds are distributed as they are or before conducting long-term control research.

MATERIALS AND METHODS

Measurements. The Canada thistle patch that was studied was located on level ground at the North Dakota State University Experimental Farm, Fargo (46° 16.36 N, 96° 14.54 W, 272 m altitude), on a Fargo silty clay (fine, montmorillonitic, frigid Vertic Haplaquolls) with 2.5% sand, 51.6% silt, 45.8% clay, 4.8% organic matter, and a pH of 7.9. The Canada thistle subspecies 'arvense' (Wimm. and Grab.) was the only subspecies present (19).

Values of regionalized variables, such as shoot density, adventitious root bud number or root fresh weight, were gathered in a uniform grid at X-Y control points across a Canada thistle patch. For example, Canada thistle shoot density was determined July 30 to 31, 1986, on a uniformly spaced, square 1.8-m grid in a rectangular area (12 m by 16 m) across a naturally established patch which bordered a road on one side (N = 204 samples). Shoot density was determined in circular quadrats (0.2 m^2) centered at each grid control point as described above. Only Canada thistle shoots arising from adventitious root buds were counted; seedlings from newly germinated seed were not counted because they were rare.

Soil cores (6.4 cm in diam by 90 cm deep) were gathered with a soil corer[4] at each grid control point between August 1 and 11, 1986, to obtain root samples. Cores were sectioned into depth increments of 0 to 30, 31 to 60, and 61 to 90 cm before extraction of Canada thistle roots, as previously described (4). Numbers of adventitious root buds, thickened root fresh weight (4), and root length were determined as measures of root growth. The percentage of emerged shoots was calculated as the ratio of number of emerged shoots divided by the sum of the number of emerged shoots plus adventitious root buds m^{-2} in the 0- to 30-cm-deep section multiplied by 100. Adventitious root bud g^{-1} fresh weight of root was calculated, as well.

Geostatistical analysis. Semivariogram functions were graphed relating semivariance $\gamma(h)$ of each regionalized variable (such as shoot number m^{-2} and adventitious root bud number m^{-2}) to the sampling "lag" distance h intervals between pairs of values at increasing distances from one another at control points (i.e., multiples of lag h) (26, 30). Graphs of semivariance versus lag distance h are usually used to establish whether a regionalized variable exhibits spatial dependence and at what lag distance h values become independent of one another. The smallest lag h used in this research was 1.8 m, the minimum lag h. Lowercase letters [e.g., $z(x_i)$] are used for observed values of regionalized variables and uppercase letters [$Z(x_i)$] are used for regionalized variables throughout this manuscript.

Estimation of semivariogram functions has been reviewed (22, 24, 29, 30, 31) and steps involved in data processing are summarized (Figure 1). Semivariogram functions for regionalized variables are estimated mathematically by

$$\gamma_i(h) = \left(\frac{1}{2}\right) N(h) \sum_{i=1}^{N(h)} [z_i(x_i + h) - z_i(x_i)] \qquad (1)$$

where $\gamma_i(h)$ = semivariance of the regionalized variable $Z(x_i)$ with a lag h. N(h) is the number of pairs of points within the lag interval [h + Δ(h)]. Several alternative models were tested to describe the semivariogram functions for each regionalized variable using least squares regression for the eight nearest sample pairs at each lag (29) with a tolerance of 22.5°.

The fit of semivariogram functions to linear, linear/sill, spherical, exponential and Gaussian models with and without a

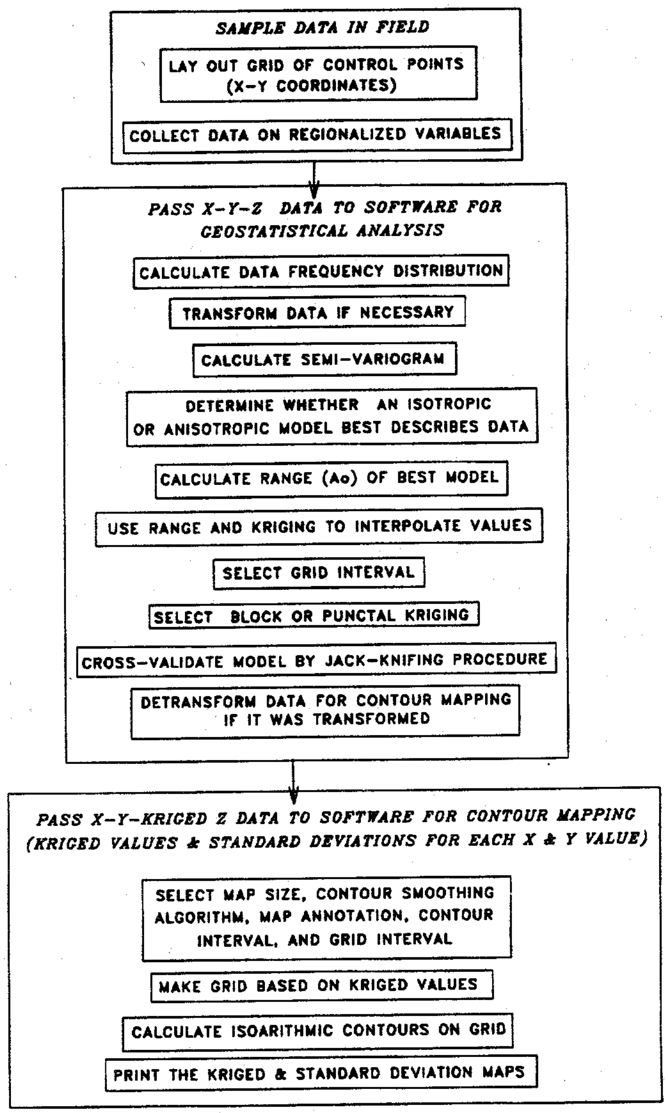

Figure 1. Flowchart of steps taken in geostatistical analysis of spatial data.

[4]Gidding Machine Co., P.O. Drawer 2024, Ft. Collins, CO 80522.

nugget variance (Co) was examined for each regionalized variable. The semivariogram model for preparation of maps by kriging was chosen as the one with a minimum residual sum of squares and largest coefficient of determination (r^2).

Nugget variance (Co) is the variance at zero distance (lag h = 0) in the semivariogram (Figure 2). Nugget variance is usually considered to be unexplained random measurement or sampling error, such as an improperly chosen scale of sampling (i.e., too large a lag distance h between samples) relative to the scale of natural variation of measured regionalized variables (29). When the nugget variance approaches zero, variance can be explained almost totally by "structural" variance (C) due to the spatial dependence of the regionalized variable. The "sill" (C + Co) is the asymptotic plateau value of the semivariogram function and is used to estimate the "range" distance (Ao) in multiples of lag h. The sill is the lag distance between measurements at which one value for a regionalized variable does not influence neighboring values. The range is the distance at which values of a regionalized variable become spatially independent of one another.

Semivariogram functions for each regionalized variable were calculated at several angles (e.g., α values = 0, 45, 90, and 135° or other angles) with a tolerance of 22.5° to determine whether semivariogram functions depended on sampling orientation and direction (i.e., were anisotropic) or not (i.e., were isotropic). Spherical isotropic models for the semivariogram function are most commonly used to describe data variability and are defined by

$$\gamma(h) = C_o + C\left[\left(\frac{3}{2}\right)\left(\frac{h}{Ao}\right) - \left(\frac{1}{2}\right)\left(\frac{h}{Ao^3}\right)\right] \quad 0 < h < Ao \quad (2)$$

$$\gamma(h) = C_o + C = \text{sill} \quad h \geq Ao \quad (3)$$

where Co, Co + C, and Ao are the nugget variance, the sill (nugget plus structural variance), and the range (lag distance to the sill), respectively. Exponential isotropic models are described by

$$\gamma(h) = C_o + C\left[1 - \text{EXP}\left(-\frac{h}{a}\right)\right] \quad (4)$$

Other models are described in geostatistical texts (5, 15) and the GS^+ software[5] used.

Contour maps were prepared using block kriging (2, 13, 26, 30). Block kriging employs weighted local averaging using the semivariogram range (Ao) from the best semivariogram function and gives unbiased predictions of interpolated values of regionalized values between sampled grid control points which minimize estimation variance (error) (29, 31). Kriging provides unbiased estimates of regionalized variables in unsampled locations which depend only on semivariogram properties based on the data set. Kriging also calculates the standard deviation associated with these interpolated estimates.

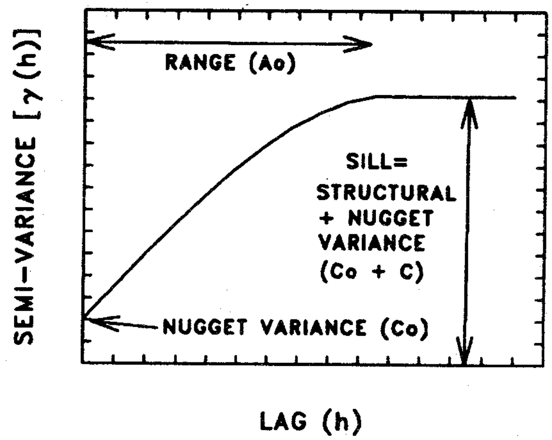

Figure 2. Semivariogram function for a spherical isotropic model with a nugget variance.

Geostatistical analysis and kriging were conducted on measured and calculated regionalized variables using GS^+ software, and contour maps were generated using GRIDZO contour mapping software[6] based on GS^+ kriged values (Figure 1). GRIDZO used the kriged estimates for each regionalized variable to interpolate a grid of uniformly spaced values before calculating isoarithmic contours for the grid. GRIDZO allows researchers to arbitrarily choose mapping parameters, such as map size, contour interval, annotation labeling, types and numbers of smoothing algorithms, and other factors controlling computer-drawn map appearance.

RESULTS AND DISCUSSION

Semivariogram functions. Calculation of the semivariogram function tests the null hypothesis that the regionalized variable does not exhibit spatial dependence at the lag h chosen. If the semivariogram function is a horizontal line parallel to the x axis (x = lag h), then the regionalized variable does not exhibit spatial dependence at multiples of the lag h chosen. Semivariogram functions showed that shoot density, percent shoot emergence, adventitious root bud density, and root fresh weight exhibited different spatial dependence from one another across the Canada thistle patch studied (Table 1 and Figure 3). In contrast, semivariogram functions show that adventitious root bud numbers g^{-1} of root fresh weight did not exhibit spatial dependence at lag h at some depth increments. This suggests that additional sampling of adventitious root bud numbers g^{-1} at smaller lag distances spaced closer together might be needed to detect spatial dependence, if it is present.

The nugget variance (Co), sill variance (Co + C), and range (Ao) of the semivariogram function provide quantitative measures of spatial dependence for different regionalized variables (Table 1 and Figure 3). These components of the semivariogram

[5] GS^+ ver. 2. software. Gamma Design Software, P.O. Box 201, 457 East Bridge St., Plainwell, MI, 49080.

[6] GRIDZO Gridding and Contouring software ver. 6.0. RockWare, Inc., 4251 Kipling St., Suite 595, Wheat Ridge, CO 80033.

Table 1. Semivariogram functions for various regionalized variables describing Canada thistle shoot and root growth across a patch based on a sample spacing of 1.8 m.

Regionalized variable	Depth increment	Best semivariogram function	Nugget variance (Co)[b]	Sill (Structural + nugget variance) (C + Co)	Model range (Ao)	r^2
	cm				m	
Shoot density (no. m^{-2})	NA[a]	Isotropic (spherical)	10 (0.2%)	5107	20.26	0.99
Root biomass (g m^{-2})	0 to 30	Isotropic (spherical)	33 700 (42%)	80 420	11.82	0.85
	31 to 60	Isotropic (linear with sill)	19 800 (55%)	36 230	9.82	0.81
	61 to 90	Isotropic (linear with sill)	9510 (60%)	15 870	9.78	0.80
Adventitious root bud number (no. m^{-2})	0 to 30	Isotropic (exponential)	139 000 (35%)	398 500	10.28	0.74
	31 to 60	Isotropic (spherical)	64 200 (56%)	115 200	5.08	0.56
	61 to 90	Isotropic (spherical)	19 500 (54%)	36 440	4.24	0.21
Percent emergence (no. emerged/no. emerged shoots + adventitious root buds 0–30 cm deep)	0 to 30	Isotropic (exponential)	390 (12%)	3371	15.66	0.99
Adventitious root buds per gram fresh weight root (no. g^{-1} root)	0 to 30	Isotropic (linear)	36.8 (98%)	37.7	21.3	0.002
	31 to 60	Isotropic (linear)	4.02 (74%)	5.38	21.3	0.70
	61 to 90	Isotropic (linear)	4.52 (100%)	4.52	21.3	0.33

[a]NA = not applicable.

[b]Values in parentheses are nugget variance expressed as a percent of the sill (structural + nugget variance).

function can be used to measure differences between regionalized variables in spatial distribution across a Canada thistle patch or for one regionalized variable measured at several depth increments in the soil profile.

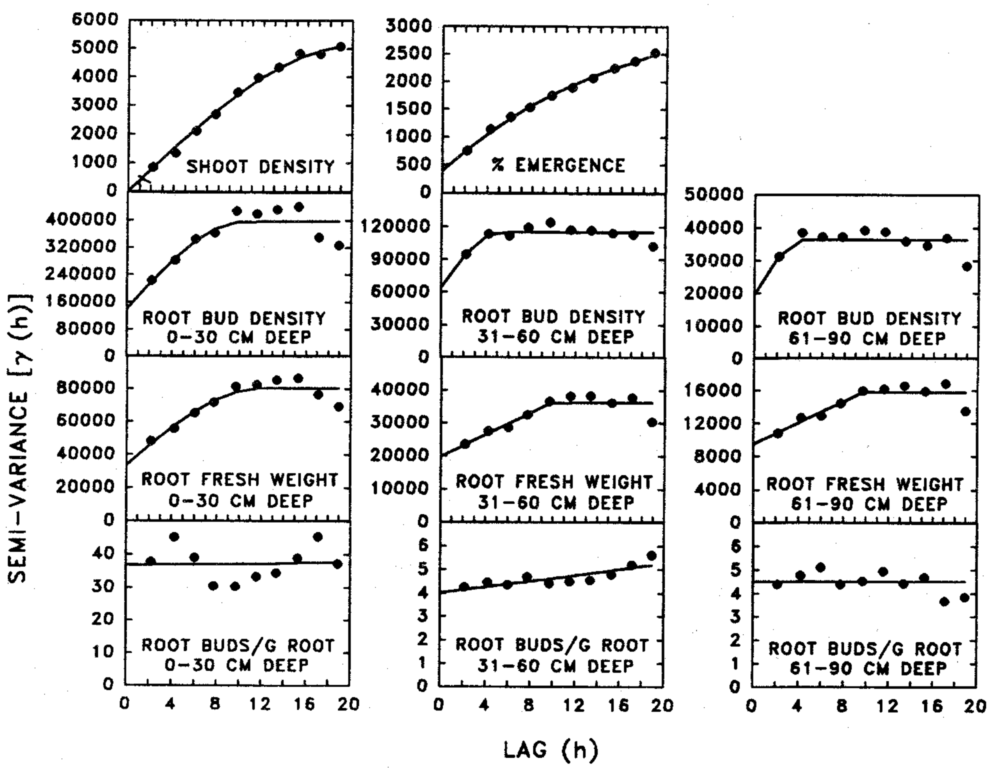

Figure 3. Semivariogram functions [semivariance $\gamma_i i(h)$ versus lag h] for Canada thistle shoot density (no. m^{-2}), percent shoot emergence (% of no. emerged/sum of emerged with adventitious root buds in 0- to 30-cm depth increment), root bud density (no. m^{-2}), root fresh weight (g m^{-2}), and root bud numbers g^{-1} root fresh weight.

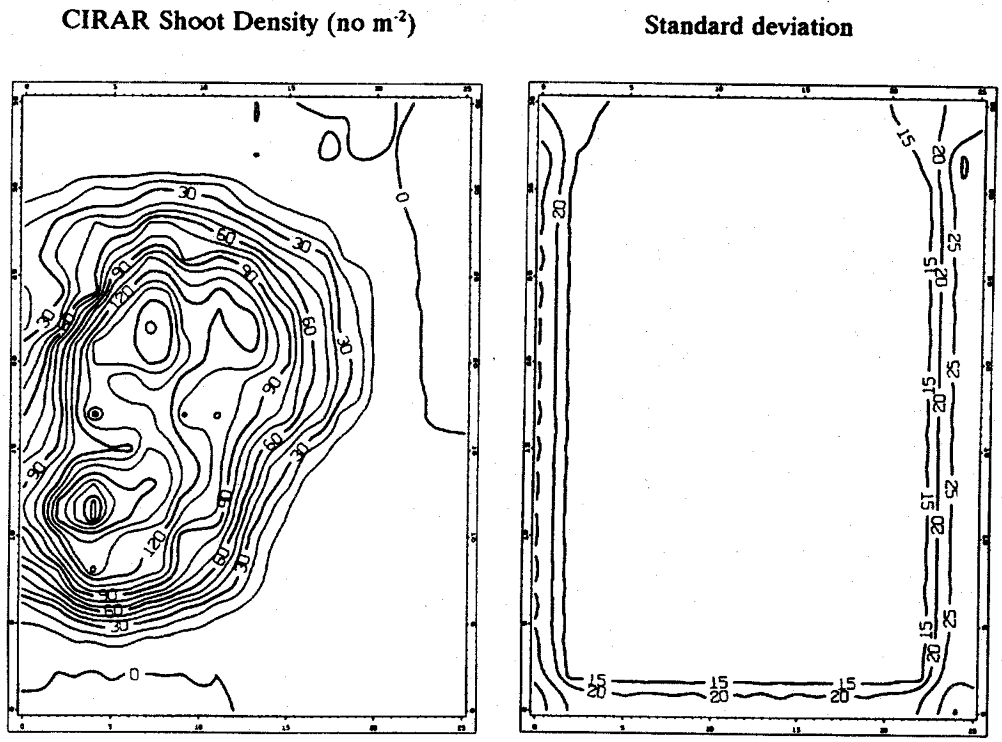

Figure 4. Isoarithmic map of Canada thistle shoot density (no. m^{-2}) and standard deviation across a Canada thistle patch based on the kriging of the semivariogram function pictured in Figure 3 and Table 1. The X and Y axes were 25 and 35 m long, and a road stopped Canada thistle growth on the left of this figure.

The range (Ao) for the semivariogram functions of shoot density (Ao = 20.26) and percent emergence (Ao = 15.66) were much greater than the range for either adventitious root bud density (Ao = 4.24 to 10.28) or root fresh weight (Ao = 9.78 to 11.82) (Table 1 and Figure 3). A larger range indicates that observed values for shoot density and percent emergence at each control point across the patch are influenced by other values of these regionalized variables over greater distances than are values for either adventitious root bud density or root fresh weight which have smaller ranges. The range for root fresh weight was greater than for adventitious root bud density at all depth increments, even though values for these regionalized variables were measured from the same soil core samples (Table 1 and Figure 3). Thus, values of root fresh weight influenced neighboring values of root fresh weight over greater distances than for adventitious root bud density at all depth increments measured. Because the range for adventitious root bud density and root fresh weight decreased with progressively greater depth increments in the soil profile, values for these regionalized variables influenced neighboring values over progressively shorter distances for progressively greater depth increments. Additional physiological research is needed to explain why adventitious root buds may influence the spatial dependence of nearby adventitious root buds.

Because the nugget variance (Co) of the semivariogram function for shoot density was very small and approached zero, the scale of sampling (1.8 m) closely matched the spatial variation of shoot density (Table 1 and Figure 3). In contrast, the nugget variance contribution to total semivariance $\gamma_i(h)$ for percent emergence, adventitious root bud density, and root fresh weight ranged from 12 to 60%. At progressively deeper increments in the soil profile, the nugget variance decreased in absolute magnitude for adventitious root bud density and root fresh weight m^{-2} although it still represented a large percent of total semivariance $\gamma_i(h)$.

The nugget variance for percent emergence, adventitious root bud density, and root fresh weight (Table 1 and Figure 3) probably is due to the lag h chosen for sampling. The lag h was apparently not matched to the spatial variation of these latter regionalized variables. Additional, more closely spaced grid samples could probably help generate more complete semivariograms with smaller nugget variance, making the kriged estimates more precise for mapping purposes. Large nugget variance might be caused by discontinuities in Canada thistle root distribution in the soil profile (e.g., roots growing preferentially along root channels, soil fractures, or ped faces).

Semivariogram functions suggest that no change in sampling lag h or numbers of samples is needed for shoot density (Table 1 and Figure 3). The large nugget variance for percent emergence, root fresh weight, or adventitious root bud density suggests that the lag h for sampling should be decreased and the number of samples increased in the future to better characterize spatial dependence for these regionalized variables. In particular, the flat horizontal semivariogram function for adven-

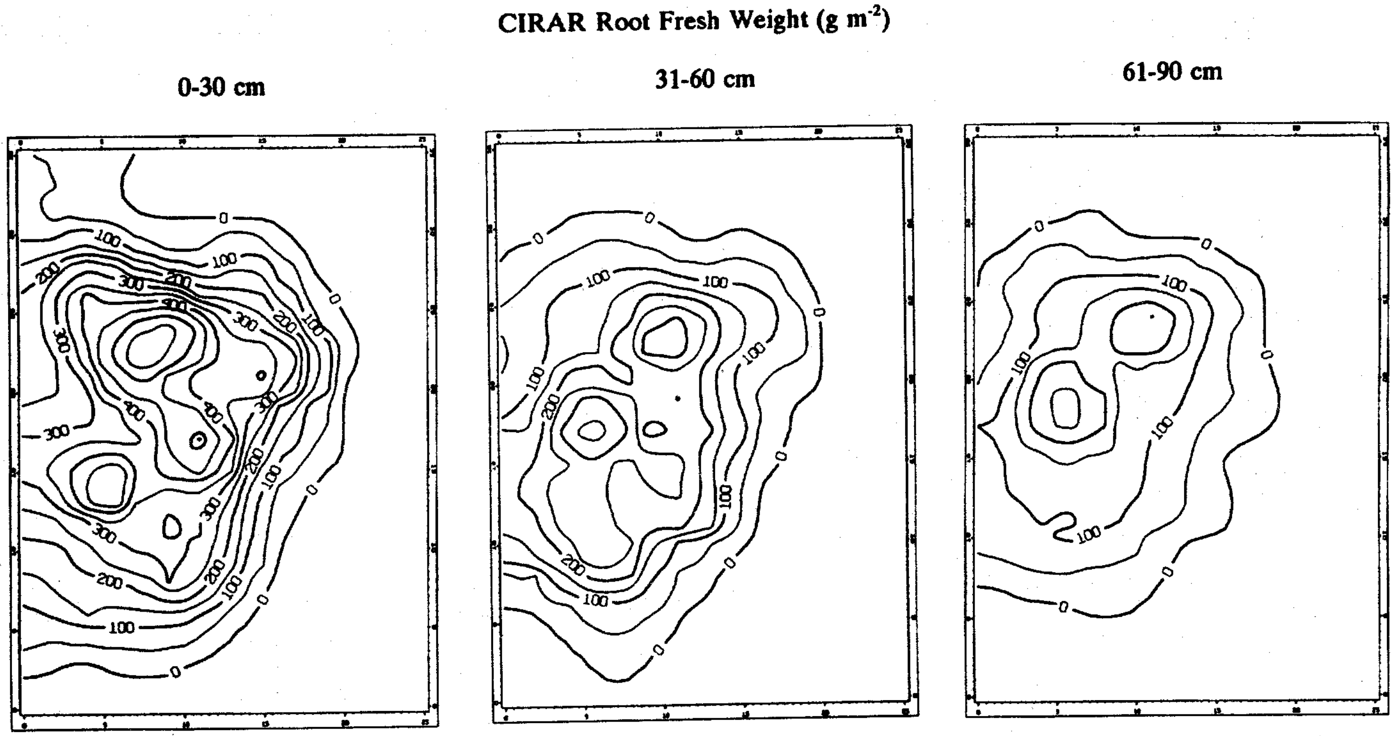

Figure 5. Isoarithmic map of Canada thistle root fresh weight (g m^{-2}) at three depth increments across a Canada thistle patch based on kriging of the semivariogram function pictured in Figure 3 and Table 1. The X and Y axes were 25 and 35 m long, and a road stopped Canada thistle growth on the left of this figure.

titious root bud numbers g^{-1} root indicates a lack of spatial dependence for this regionalized variable at the minimum sampling lag distance h chosen. This suggests that a lag less than 1.8 m may be required if spatial dependence is to be detected, if it is indeed present.

Maps of regionalized variables across a Canada thistle patch. Maps of shoot density and root growth indicated that these variables were not uniformly distributed across a patch, as expected from examination of the semivariogram functions (Figures 4 to 7). Such maps provide detailed positional information lacking in either simple descriptive statistics (32) or previously published observations along transects across Canada thistle patches (1, 23, 25, 28, 33). They also provide more information than in a simple negative exponential model of the statistical frequency distribution of weeds in fields (32) based on random sampling. Such studies lack positional information about weed spatial distribution in mapped fields.

Although Canada thistle shoot density across the patch appeared uniform to the eye, shoot density was as great as 230 shoots m^{-2} in individual quadrats across the patch. Contour maps of uniform shoot density up to contours of 195 shoots m^{-2} are shown (Figure 4). Higher densities were not shown by the contouring program used because the contours represent interpolations between measured control points and there were very few quadrats with densities above 200 shoots m^{-2}. Shoot density increased greatly across a 2-m distance near patch borders. In turn, kriged standard deviations increased toward patch borders, as expected. Near patch borders, both kriged sample numbers and shoot density were lowest (31). To be brief, kriged standard deviation maps are shown only for Canada thistle shoot density (Figure 4); standard deviation maps for most other measured regionalized variables were similar in pattern.

Maps of Canada thistle root fresh weight as a function of depth within the soil profile are presented (Figure 5). The mapped patterns were similar for root length and fresh weight m^{-2} at various depth increments across the patch, so only root fresh weight m^{-2} maps are presented. The areal extent of root fresh weight 0 to 30 cm deep across the patch (Figure 5) was similar (± 0.5 m) to that of shoot density along most of the patch border (Figure 4). The area sampled (0.2-m^2 quadrats) for shoot density was 63-fold greater than that sampled for roots (0.003 m^2 core diameter). Regions of greatest shoot density occurred over regions of greatest root density (Figures 4 and 5). Pearson correlation coefficients (r) are summarized for all combinations of variables (Table 2).

The root fresh weight decreased for progressively greater depths in the soil profile (Figure 5), verifying published observations based on random sampling (20, 21). The areal extent of root fresh weight m^{-2} for the 0- to 30- and 31- to 60-cm depth increments was similar, but decreased for the 61- to 90-cm depth increment. Regions of greatest root growth across the patch at each successive depth increment corresponded to overlying regions of greatest root fresh weight. One could prepare maps of the root fresh weight in each increment as a percent of that in the

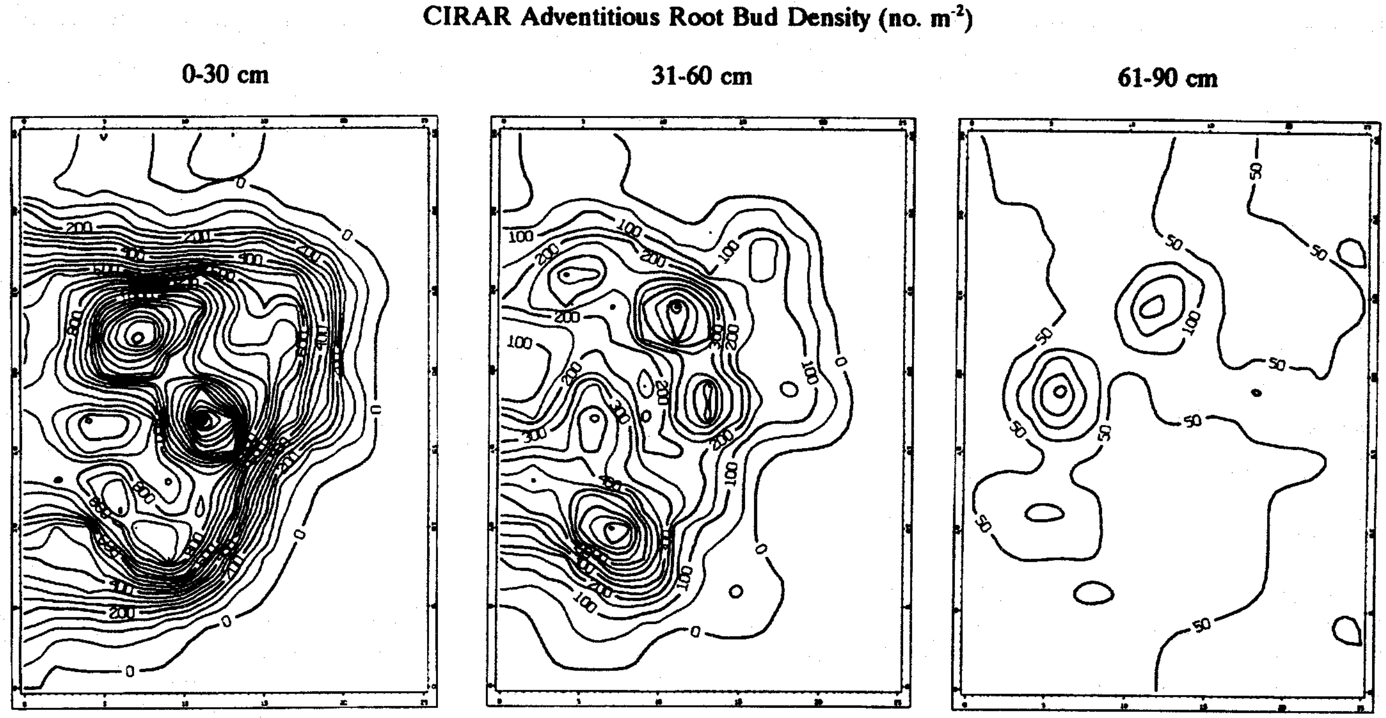

Figure 6. Isoarithmic map of Canada thistle adventitious root bud density (no. m^{-2}) at three depth increments across a Canada thistle patch based on kriging of the semivariogram function pictured in Figure 3 and Table 1. The X and Y axes were 25 and 35 m long, and a road stopped Canada thistle growth on the left of this figure.

total soil profile (0 to 90 cm) to demonstrate this relationship quantitatively across the patch, if desired.

The areal extent of Canada thistle adventitious root bud density (Figure 6) was similar to root fresh weight (Figure 5) at the 0- to 30- and 31- to 60-cm depth increments. Regions of greatest adventitious root bud density corresponded to regions of greatest root fresh weight at these depth increments, as expected. The areal extent of adventitious root bud density decreased as depth increment increased from 31 to 60 and 61 to 90 cm (Figure 6). Distribution of adventitious root bud density at 61 to 90 cm did not correspond to distribution of root fresh weight as closely as it did in the overlying depth increments. However, regions of greatest adventitious root bud density across the patch at each suggestive depth increment corresponded to overlying regions of greatest adventitious root bud density (Figure 6) and root fresh weight (Figure 5).

Across most of the center of the Canada thistle patch, numbers of emerged shoots were roughly 20 to 30% of the sum of the number of emerged shoots plus adventitious root buds at the 0- to 30-cm depth (Figure 7). Percent emergence increased from the patch center to the borders. Consequently, few shoots were present (Figure 4) and the adventitious root bud bank was nearly nonexistent near patch borders (Figure 6). These maps suggest the testable hypothesis that as Canada thistle patches expand,

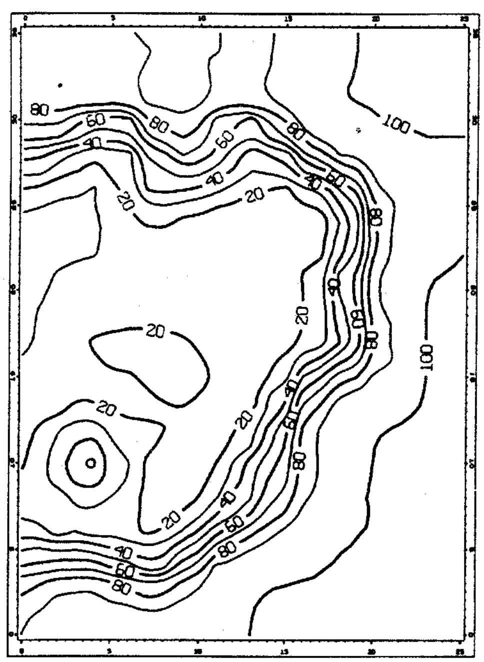

Figure 7. Isoarithmic map of Canada thistle emergence as a percent of the total number of emerged shoots plus adventitious root buds present in the 0- to 30-cm depth increment across a Canada thistle patch based on kriging of the semivariogram function pictured in Figure 3 and Table 1. The X and Y axes were 25 and 35 m long, and a road stopped Canada thistle growth on the left of this figure.

Table 2. Pearson correlation coefficients (r) between regionalized variables measured across a Canada thistle patch. Significance following coefficients values are one-tailed tests where *P = 0.01 and **P = 0.001 (N = 204).

	Root fresh weight at 0 to 30 cm ($g\ m^{-2}$)	Root fresh weight at 31 to 60 cm ($g\ m^{-2}$)	Root fresh weight at 61 to 90 cm ($g\ m^{-2}$)	Adventitious root bud density at 0 to 30 cm (no. m^{-2})	Adventitious root bud density at 31 to 60 cm (no. m^{-2})	Adventitious root bud density at 61 to 90 cm (no. m^{-2})
Shoot density (no. m–2)	0.57**	0.49**	0.49**	0.63**	0.37**	0.32**
Root fresh weight at 0 to 30 cm ($g\ m^{-2}$)		0.46**	0.43**	0.80**	0.36**	0.18*
Root fresh weight at 31 to 60 cm ($g\ m^{-2}$)			0.70**	0.43**	0.64**	0.47**
Root fresh weight at 61 to 90 cm ($g\ m^{-2}$)				0.41**	0.53**	0.72**
Adventitious root bud density at 0 to 30 cm (no. m^{-2})					0.41**	0.23**
Adventitious root bud density at 31 to 60 cm (no. m^{-2})						0.50**

roots extend out horizontally near the soil surface in the 0- to 30-cm depth increment before adventitious root buds form on roots. Further research is required to prove this logical possibility based on these geostatistically based maps.

Maps of the distribution of adventitious root buds g^{-1} of root fresh weight (Figure 8) are consistent with this hypothesis, but do not prove it. These latter maps show that Canada thistle roots are able to form adventitious root buds in some regions of the patch better than in others and better at shallower depth increments than at deeper depths in the soil profile. In the 0- to 30-cm depth increment, roots formed more than 3 to 4 adventitious root buds g^{-1} root in the center of the patch (Figure 8), the region of the patch with the greatest shoot density (Figure 4), root fresh weight (Figure 5), and adventitious root bud density (Figure 6). Fewer adventitious root buds formed per gram of root fresh weight from the center toward patch borders (less than 1 adven-

CIRAR Adventitious Root Buds Per Gram Root (no. g^{-2})

Figure 8. Isoarithmic map of Canada thistle adventitious root buds per gram of root fresh weight (no. g^{-1}) at three depth increments across a Canada thistle patch based on kriging of the semivariogram function pictured in Figure 3 and Table 1. The X and Y axes were 25 and 35 m long, and a road stopped Canada thistle growth on the left of this figure.

titious root bud g^{-1} root) (Figure 8). Adventitious root bud numbers g^{-1} root also decreased to 1 adventitious root bud g^{-1} root at progressively deeper increments in the soil profile. Thus, roots near patch borders and at deeper depths in the soil profile formed fewer adventitious root buds per gram of root fresh weight.

Potential uses of geostatistics. Geostatistics can be used to map spatial distribution of weeds in fields, such as the Canada thistle patch described here. One major advantage of geostatistical mapping over other mapping techniques is that it provides an estimate of the error (e.g., standard deviation) for interpolated values on the map. The semivariogram function provides a statistical test of the hypothesis that regionalized variables exhibit spatial dependence, as well as quantitative information that can be used to compare differences in spatial dependence of regionalized variables in areal extent or as a function of depth increment in the soil profile. Maps of calculated ratios (e.g., percent shoot emergence or adventitious root bud number g^{-1} root fresh weight) do not always exhibit the same spatial dependence as the regionalized variables from which they are derived, as reflected in their semivariogram functions and kriged maps.

In this descriptive research, the initial choice of quadrat size, soil core size, and depth increments, and sample grid spacing was arbitrary and may not have been optimum for sampling all regionalized variables. Semivariogram functions depend upon individual sample size, shape, and orientation as well as the natural scale of the measured regionalized variable (31). Geostatistical analysis can help design more efficient sampling strategies for regionalized variables in the field (3). Nugget variance provides information needed to change the lag h used and, consequently, the number of samples needed to better estimate the semivariogram function.

A better knowledge of root and shoot growth across patches of annual or perennial weeds might be helpful in better designing long-term field experiments on weed control on commercial fields. This descriptive research also suggests that maps of perennial weed shoot density could help in more rationally blocking field experiments before herbicide treatments are imposed (6, 7, 8, 10, 11) since randomized complete block designs are most commonly used for such research. Regions of greatest Canada thistle shoot density (Figure 4) across a patch had greater underlying root biomass (Figure 5), greater numbers of underlying adventitious root buds (Figure 6), and a deeper distribution of root biomass. The maps show that if the root system extends beyond the patch border defined by the shoot distribution, it does not extend very far. Previous research shows that shoot density in one year can be used to estimate shoot density of Canada thistle in the subsequent year with greater accuracy and precision than is possible using root growth (9). There was no advantage to using root fresh weight or adventitious root bud distribution as bases for blocking because of the cost, time, and labor involved in sampling roots. Thus, destructive sampling of roots was unnecessary and might impact results of control research. Blocking can be based on shoot density in one year in preparation for research in the following year. Blocking in earlier research on long-term control of Canada thistle root growth was based on shoot density at the start (7, 8, 10, 11).

Geostatistics can be used to frame new types of hypotheses dealing with research questions on weed biology or control on a field scale. For example, geostatistical analysis could be used to relate weed distribution to changes in the distribution of soil physical or chemical characteristics across landscapes. Maps also may help formulate testable hypotheses about the spread of Canada thistle's perennial root system and those of other perennial weeds. Demographic modeling of weed populations over time should address weed spatial pattern.

Geostatistics might be used to study how weed control treatments change weed distribution across landscapes over time. For example, weed growth (such as density and biomass) could be measured over time (e.g., before and after treatment) at the same X-Y control points across a landscape. Then, semivariogram functions and isoarithmic maps could be constructed for the difference between successive measurements of regionalized variables to determine whether weed distribution or density changed over time. Such an experimental approach could also be used to study how differences in weed growth (e.g., density) or distribution across the landscape modify the effectiveness of weed control treatments.

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