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Impacts of European Earthworms on Maple-Basswood Forests

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Abstract

The purpose of this study was to examine the density and diversity of European earthworms and their possible effects on the soil and vegetation of native maple-basswood forests from three forest sites in Rice County, Minnesota. Earthworms were sampled from 36 plots (0.11 m2) using a liquid mustard extraction method. Herbaceous and woody vegetation were sampled adjacent to each earthworm plot. Soil samples from each site were analyzed to determine soil type, soil moisture, organic matter, pH levels, nitrite nitrogen, phosphate, and potassium content, and the litter layer was measured and weighed. Results of sampling showed that the plots with the highest numbers and highest species diversity of earthworms tended to occur in loam soil, while fewer earthworms were found in sandy soil. Vegetation density per plot was lower in areas with higher numbers of earthworms. Nitrogen levels were higher in sites with more anecic earthworm species (large species that tend to move a large amount of organic matter), and higher earthworm population densities occurred in sites with optimal pH levels. Dry conditions may have been a factor contributing to relatively low numbers of earthworms and a large proportion of juveniles. These results provide a basis for future study and suggest that earthworm density and diversity have a significant impact on the vegetation and the soil composition in southeastern Minnesota.

Introduction

Ecologists have long realized that introduced species can have a negative impact on the native species living in the ecosystem that is being invaded. Not only do these exotic species present an additional competitor for resources, but introduced species also alter community and ecosystem characteristics and interactions. According to Vitousek (1990), exotic species affect resource acquisition, alter the tropic structure, and change the disturbance frequency of native communities, especially when use of resources differs considerably from the native species (Williamson 1996). As Williamson (1996) states, any successful invasion must have consequences for the other species present. Species introduced into forest ecosystems can reduce native plants and reduce native invertebrates, fungi, and bacteria in the soil (Stiling 1999).

The introduction of the European earthworm into previously earthworm-free North American hardwood forests is just one example of species introduction that has the potential to cause detrimental consequences. Native American earthworms were eradicated from northern areas of North America that experienced quaternary glaciation (Figure 1, James 1990) and little recolonization of the previously glaciated areas has occurred (Linden 1997). All of the earthworm species presently found in Minnesota are of European origin, and there is still uncertainty as to whether native earthworms ever existed in Minnesota (Mortensen 1998). All nine species of earthworms in Minnesota have been introduced by European settlement mainly in soil or the roots of introduced plants (Gates 1982). Dispersal of these exotic worms by logging activities and forest vehicles, as well as an increase in growth of the recreational fishing industry in which European earthworms are used as the main type of bait, have been identified as the sources of distribution. Therefore, the hardwood forests of Minnesota, Northern Wisconsin, Michigan, and Canada developed without earthworm activity, and earthworm presence has the potential to cause irreversible changes in the forest ecosystem.

Although there have been no published studies on the total distribution and density of earthworm populations in Minnesota, preliminary figures from research now in progress in the Chippewa National Forest (Hale personal comm.) and in Canada (Dymond et al. 1997) indicate a rate of invasion of earthworms at a speed of three to five meters per year. A rapid increase in the rate and extent of the European earthworm invasion has been noted (Lee 1995) and in the past two decades, the rate of invasion has increased rapidly (Alban and Berry 1994). The only published study of earthworm population size in Minnesota forests (Alban and Berry 1994), showed a population increase from zero to 592 individuals per square meter over a fourteen-year period. This introduction resulted in an observed forest litter thickness and weight decrease of eight-five percent. Also observed was an increased development of the A horizon in the soil which contributed to an increase in carbon and nitrogen content in surface soil.

Earthworms have a significant impact on their surroundings due mainly to their activities, and different species affect the ecosystem in distinct ways and to various extents. Size and species composition of earthworm populations has been shown to be associated with the amount and rate of loss in the forest floor mass (Cothrel et al 1997). All earthworm species in Minnesota are of the family *Lumbricidae* (Bouche 1977). Linden (1997) has documented six common species of European earthworms in Minnesota. These species include *Lumbricus rubellus* (dew worm), *Lumbricus terrestris* (common nightcrawler), *Eisenia fetida* (red wiggler), *Aporrectodea tuberculata* (Canadian gray, or field worm), *Aporrectodea trapezoides* (southern worm), and *Octolasion tyrtaeum* (woodland white worm). Other species recorded in Minnesota include *Aporrectodea calinosa*, *Allolobophora cholorotica*, and *Dendrobeana octaedra* (Hale 2000, personal comm.).

Taxonomists have grouped all species of earthworms into three categories (epigeic, endogeic, anecic) based on their physical, behavioral, and habitat characteristics (Lee 1995). Epigeic species are small in body size and form horizontal, shallow burrows in the litter layer. There are three species of epigeic earthworms present in Minnesota. These include *D. octaedra, L. rubellus*, and *E. fetida*. Endogeic species are medium size worms that form burrows in the upper layers of the soil, and consume organic material in that area. Endogeic species are the largest of the three types of earthworms, having five species found in Minnesota soil (*A. tuberculata, A. trapezoides*, *A. calinosa*, *A. cholorotica, and O. tyrtaeum*). Anecic species, the largest of the European earthworm species, form vertical burrows, and combine large amounts of organic material with soil. The common nightcrawler (*L. terrestris*) is the only anecic species found in Minnesota.

Two of the species most commonly found in highly disturbed and agricultural lands are *A. tuberculata* and *L. terrestris*. Once established in a community, these are the species that dominate (Linden 1997). Invasions of these two species seem to supersede the invasion of other, less harmful species (Hale 2000, personal comm.). It is thought that *A. tuberculata* and *L. terrestris* replace previously established litter dependent species by reducing or destroying the litter layer (Edwards 1998). Large areas in some forests have reported an absence of litter due to breakdown by earthworms, especially *L. terrestris* (Hale 2000, personal comm.). *L. terrestris* collects leaves from the surface, pulls them in to its burrow (Dindal 1990), and is suspected to be responsible for the major disturbances in the forest (Hale 2000, personal comm.)

Earthworms are detritivores (decomposers) that survive by eating leaf litter, soil organic matter, and associated microorganisms (Doube and Brown 1998). The distribution of earthworms is affected by several factors including soil moisture, organic matter, pH levels, temperature, and habitat preference (Scheu and Parkingson 1994). Increasing biomass of earthworms is highly correlated with the quality and amount of deciduous tree litter present on the forest floor (Shakir and Dindal 1997). Optimal conditions include soil moisture 20-35%, a pH of 5.8-6.4, climate with a warm season, and sufficient organic matter (Lee 1995). Earthworm densities have been reported to range from as low as zero individuals per square meter to well over three thousand individuals per square meter in deciduous forests of North America (Alban and Berry 1994, Dymond et al 1997, Hale 2000 personal comm.). Continuing research on the leading edge of the European earthworm invasion in Chippewa National Forest in northern Minnesota has shown population densities to be over three hundred individuals per square meter (Hale 2000, personal comm.). Densities of European earthworms in their native European beech forest habitats average two hundred species per square meter (Staaf 1987).

Earthworms have long been regarded as beneficial to soil systems. It is widely accepted that earthworms are helpful in agriculture and gardening by breaking down plant material, recycling nutrients, and mixing soil. Researchers are now beginning to realize that earthworms may not be beneficial in all ecosystems, especially when they are an introduced species in that area (Edwards 1998). Earthworms have a large impact on the trophic structure, change the disturbance frequency, alter the soil chemistry, and consume the litter layer on the forest floor. This, therefore, changes the vegetation of the forest, due mainly to the exposure of mineral soil and lack of rooting medium (Figure 2, Doube and Brown 1998). The most apparent impact in a forested ecosystem after an invasion by exotic earthworms is the loss of a well-developed litter layer (Alban and Berry 1994). This can result in changes in soil structure, chemical composition, and nutrient status (Cothrel et al 1997).

Earthworm activities such as burrowing, feeding and casting (the act of depositing waste in the form of a cluster of soil on the forest floor) impact the physical and chemical properties of the soil in that particular ecosystem (Dindal 1990). The precise effect of earthworms on these properties is not fully known, although generalizations can be drawn. Earthworm activity increases soil penetrability and infiltration (Lee 1995, Bouche and Al-Addan 1997). The introduction of earthworms has been documented to lead to an increase in pH levels and nitrogen content (Haimi and Huhta 1990).

Healthy hardwood forests have a thick, intact duff layer that serves as a rooting medium for many herbaceous plants and seedlings. This intact duff layer is produced from the accumulation of decomposing organic material, mainly fallen leaves, over time (Hale personal comm.). Introduced earthworms reduce or eliminate the litter layer, making it more difficult for seedlings to become established in some areas (James 1995). Reduced litter layer may also change the entire tropic structure of the forest through changes in seedling establishment and nutrient availability (Doube et al. 1997). The effects of the introduction of European earthworms are not uniform in all forests. According to Coderre et al (1995), some forest stands may be able to maintain their current composition despite the introduction of earthworms while others change greatly. Some stands have been observed to have nearly completely lost their understory vegetation. Other factors that may influence the vegetation abundance and quality are deer grazing, human activities, and soil composition.

Although there have been no published studies in North America designed explicitly to investigate the relationship between understory vegetation and increasing invasion of exotic earthworm species, research is currently in progress in Chippewa National Forest in northern Minnesota. Preliminary results show distinct changes in understory vegetation following earthworm invasion of maple-basswood and northern hardwood forests (Mortensen 1998, Hale 2000 personal comm.). Results from these studies will lead to more extensive research in possible solutions to the problem including eradication or biological control, if possible, or restoration of forest communities impacted negatively by earthworm presence.

The purpose of this study is to examine the interactions between introduced European earthworms and the native maple-basswood forests of southeastern Minnesota. The specific objectives are as follows: 1) To determine earthworm density and diversity in three maple-basswood hardwood forests of Rice County. 2) To examine plant density, size, and diversity in these forests. 3) To compare soil composition in each forest site. 4) To investigate the relationship between earthworm populations and the growth, productivity, and diversity of forest vegetation. 5) To provide a baseline information for continuing research.

Methods

I chose three separate hardwood forests in Rice County as locations for sampling. At each of these locations, I selected two different sites. At each of these sites, I laid out two fifty meter transects. Along each transect, I marked three plots, chosen randomly, with wooden stakes. I choose a total of thirty-six plots, six at each site. I then recorded the location of each of the plots using a Trimble Global Positioning System with a one-meter resolution and mapped these coordinates using ArcView 3.1(1996) (Figure 3 and Appendix A). In Nerstrand Big Woods State Park, one of the last remaining remnants of Big Woods forest, previously plotted sites near deer exclosures were used. One site was located north of the road and the other site was south of the road separating the park. In Cannon River Wilderness Area, six plots were marked at one site east of the Cannon River and six were marked at one site west of the river. At St. Olaf College, plots were marked on college owned lands in Norway Valley and a wooded area adjacent to Heath Creek.

Vegetation sampling. At each site, vegetation was sampled in three different quadrats in early July, according to type and size. I identified and measured mature tree individuals, greater than 10-cm dbh, in a 4.5-m radius circular plot. I counted sapling individuals (as defined as tree saplings <10-cm dbh, tree seedlings, and shrubs) in a 1.75-m radius circular plot and estimated percent cover for each species. The number of herbaceous individuals and percent cover of each species were recorded in a 1.0-m radius circular plot. I identified vegetation using Booth and Zimmerman (1972), Gleason and Cronquist (1963), Peterson and McKenny (1968), and Rathke (1995) as authorities.

Soil sampling. Using a soil corer, I collected soil samples from the one meter mark of each transect in early July, August, and September. Soil moisture, organic matter, and pH levels were determined according to a guideline outlining methods used in the ecology lab at St. Olaf College (Appendix B). In the laboratory, I performed soil analysis tests for nitrate nitrogen, phosphate, and potassium content using techniques outlined in the Hach soil manual (Hach Company 1988). In addition, soil samples from July sampling were sent to the University of Minnesota for total nitrogen, nitrate nitrogen, and phosphate analysis. These results were used as a comparison to confirm the accuracy of the methods I used in soil analysis. I determined soil type using a flow diagram (Thien 1997 as cited by Brower, Zar, and von Ende 1997), and by referring to the Rice County Soil maps for 1975 (Soil Conservation Service).

Forest floor sampling. At each of the plots just prior to earthworm sampling, I measured the litter depth, collected the litter, and weighed the litter after drying for forty-eight hours. I also noted observations on earthworm activity, such as visible burrows or casts on the surface of the forest floor.

Earthworm sampling. I sampled earthworm populations in late October using a liquid extraction method developed by Cindy Hale at the University of Minnesota. Due to the dry conditions in all sites, I poured one gallon of water over each plot prior to liquid extraction to ensure that the solution would permeate a sufficient depth in order to reach the earthworms. Then, I poured a mixture of forty grams of mustard seed flour and one gallon of water slowly over a $0.11m^2$ area (a square thirty-three centimeters on each side) at the northwest corner of each plot. Earthworms were collected for fifteen to twenty minutes after all of the solution had been poured over the plot, and were stored in water. In the lab, I cleaned earthworms and stored the samples in a ten-percent formalin solution for future identification. I identified earthworms by ecological type and species using the Minnesota Worms Watch website (Hale 2000), the Soil Biology Guide (Schwert 1990), and with the help of direct communication and notes prepared by Cindy Hale.

Data analysis. I used Shannon and Simpson diversity indices to compare species diversity of earthworms and vegetation between sites (Brower, Zar, and von Ende 1997). The Jaccard coefficient was used to quantify community similarity of vegetation between sites (Brower, Zar, and von Ende 1997). I performed statistical analysis of soil, vegetation, and earthworm data using Statview (1998). I used ANOVA tests to compare density and diversity of vegetation and earthworms, and soil properties and litter data. Graphs and mean tables of data were used to detect any significant differences between populations and examine relationships between earthworm density and diversity and forest vegetation species density and diversity as well as soil properties.

Results

Plots in Norway Valley and Heath Creek produced higher numbers of earthworms collected and higher species diversity than other sites, as shown by Shannon and Simpson tests. (Figure 4 & Table 1). These differences among sites are shown to be significant for both density and diversity. Density (per $0.11m^2$ plot) of earthworms per site by their respective ecological type showed that Norway Valley had the highest number of anecic species while Cannon River – West and Nerstrand South had no anecic species (Figure 5). Endogeic species were the most abundant type of earthworm although differences among sites are significant in only epigeic earthworms (Figure 5). The mean density of individuals per species displays a significant difference in numbers of *L. rubellus* and *D. octaedra* collected between sites (Table 2). The significant differences exist in depth and weight litter collected at each site. Plots in Nerstrand North and Heath Creek had a deeper litter layer on average than other sites (Table 3).

Results from soil analysis are shown in Table 4. Differences in all nutrients can be observed, although statistical analysis showed only the difference in nitrate levels was significant. Differences in soil moisture and pH levels were significant, and showed that Cannon River – West had the lowest values for both nutrients and soil properties. Loam soil was the most common soil type and was found at Norway Valley, Heath Creek, and Cannon River – East.

Vegetation sampling showed a significant difference in vegetation sampling for all types of vegetation except mature species (Figures 6 & 7). Nerstrand North had the highest number of individuals, while Cannon River – West had the highest diversity of species. Norway Valley and Heath Creek had a lower mean density in total vegetation as well as lower species richness (Figure 6). Mean density of herbaceous individuals was lower in Norway Valley and Heath Creek (Figure 7). Results of Shannon and Simpson diversity tests are shown in Table 5 for total vegetation as well as each type of vegetation at each site. Diversity was found to be generally higher in Cannon River – West and Nerstrand North and lowest in Norway Valley. The most common species at each site for each type of species is shown in Table 6. Sugar maple *(Acer saccharum*) is by far the most common mature species. *A. saccharum* and gooseberry *(Ribes grossularia)* are the most common sapling species. Wild ginger (*Asarum canadensis*) appears to be the most common of the herbaceous vegetation. Appendix C shows a list of all species sampled throughout all six sites. Community similarity tests show a low similarity between sites at the same general location (Table 7).

Discussion

Overall densities of earthworms collected ranged from twenty-three to one hundred and fifty earthworms per square meter. The greatest number of earthworms and highest earthworm diversity was found at the sites on St. Olaf College owned lands (Norway Valley and Heath Creek). These sites also had the lowest vegetation density of overall vegetation and herbaceous vegetation (Figures 4, 6, and 7). Statistical analysis showed differences between sites for earthworm densities to be significant. This suggests that earthworm density and diversity have a notable effect on the density of individual vegetation and specifically on the density of herbaceous vegetation.

The impact of earthworm activity was found to vary depending on the ecological type of the earthworm. Sites with a low density of herbaceous vegetation had more anecic species (Norway Valley and Heath Creek), and the site with the highest density of herbaceous vegetation had the most epigeic species (Nerstrand North). Endogeic species were the most abundant ecological type found, with the greatest density collected in Nerstrand Big Woods State Park. This suggests that Nerstrand may be experiencing medium effects of earthworm invasion as the endogeic species are replacing the epigeic species, and the anecic species is beginning to move into the Big Woods habitat.

Differences in species found between sites have an impact on the characteristics of the ecosystems. *Aporrectodea tuberculata* was found at sites directly adjacent to agricultural activity. This species is one of the most common earthworm species in Minnesota, primarily due to its resistance to harsh conditions. For this reason it was the dominant species found in Cannon River – West where sandy soil type and low soil moisture provide less than optimal conditions for earthworm inhabitance. The only sites with a noticeable duff layer and also the highest litter depth (Heath Creek and Nerstrand North) were also the only sites where *Dendrobaena octaedra*, a litter dependent species, was found. Plots in Nerstrand North and Heath Creek had the deepest litter layer on average as well as having the highest number of litter dwelling species. As observed by Alban and Berry (1994), loss of a litter layer can be attributed to higher earthworm densities in forest ecosystems. This litter layer, in turn, is necessary for vegetation, especially herbaceous vegetation, to become established and grow in the forest understory.

Soil pH levels are an important factor in the abundance of earthworms. Optimal pH range for earthworms is 5.8 – 6.4 (Edwards 1998). Soil pH levels in Norway Valley and Heath Creek fell within this range. A comparison of the results of soil analysis performed at St. Olaf College were very similar to results found by more intense testing performed at the University of Minnesota (Appendix D). This suggests that the methods used to test for nutrients in soil used in this study were quite accurate. Nitrogen levels also affect earthworm activity. Sites with high nitrogen content in the soil were those where the nightcrawler (an anecic species) was found. Soil type had a great impact on the abundance of earthworms present. Loam soil had the highest density of earthworms while sandy loam had the lowest density of earthworms (Figure 8). Low soil moisture is characteristic of the sandy loam soil in Cannon River – West, the site with the lowest earthworm density and diversity.

Sugar maple (*Acer saccharum*) was found in all sites and was determined to be the most dominant species among sites. Gooseberry *(Ribes grossularia)* was the most common sapling species, and herbaceous vegetation did not have one species that was clearly dominant in every site. The presence of Jack-in-the-pulpit (*Arisaema triphyllum*) as the dominant herbaceous species in Norway Valley is characteristic of forest ecosystems that are heavily impacted by earthworm activity (Hale personal comm). Low community similarity values for vegetation between sites in the same forest suggest that earthworm invasion is not dependent on specific forest communities as earthworms were found to be invading hardwood forests with a large range of understory vegetation.

Dry conditions were a factor in collection of earthworms and analysis of soil properties demonstrated drought conditions. Soil moisture values were low in comparison to expected moisture levels in forest ecosystems. Relatively low numbers of earthworms were found, and many of those earthworms were unidentifiable juveniles. Prior studies of earthworm density and diversity in Rice County by St. Olaf students found earthworm densities in Nerstrand Woods to be approximately two hundred individuals per square meter (Hokanson 1999) and well over two hundred per square meter on St. Olaf campus (Christensen 1998). Densities found in this study at Nerstrand Woods were one hundred earthworms per square meter and one hundred and fifty on St. Olaf campus. Densities of three hundred to four hundred individuals per square meter have been reported in Chippewa National Forest (Hale 2000 personal comm.).

Although preliminary evidence suggests a direct correlation between earthworm density and diversity, and vegetation diversity and density, several more studies are needed to confirm these results. This study established a baseline for future studies of earthworm populations and their impact on hardwood forests in Rice County. Once the full extent of the impact of earthworms on forest ecosystems is known, steps can be taken to reduce or eliminate the problem. At this time, possible attempts at eradication or biological control of earthworms seems impracticable, although possibilities for restoration of forest communities that have been impacted by earthworm activity may be feasible. Future studies may show the effect of deer grazing on the recovery on a forest after the invasion of earthworms. The combination of deer grazing and earthworms may make it more difficult for especially the herbaceous layer to survive.

This study suggested a correlation between earthworm density and diversity and vegetation density and diversity. It also implied that different species type and ecological classification of earthworms have different impacts on the both the vegetation present and the soil characteristics of an ecosystem. Earthworm activity was shown to greatly reduce the litter layer in hardwood forests, making it nearly impossible for new individuals in the understory vegetation to take root and thrive. Further studies are essential to determine the extent of the earthworm invasion in Minnesota and the consequences that this introduction has already had on the declining maple-basswood forests of the state.

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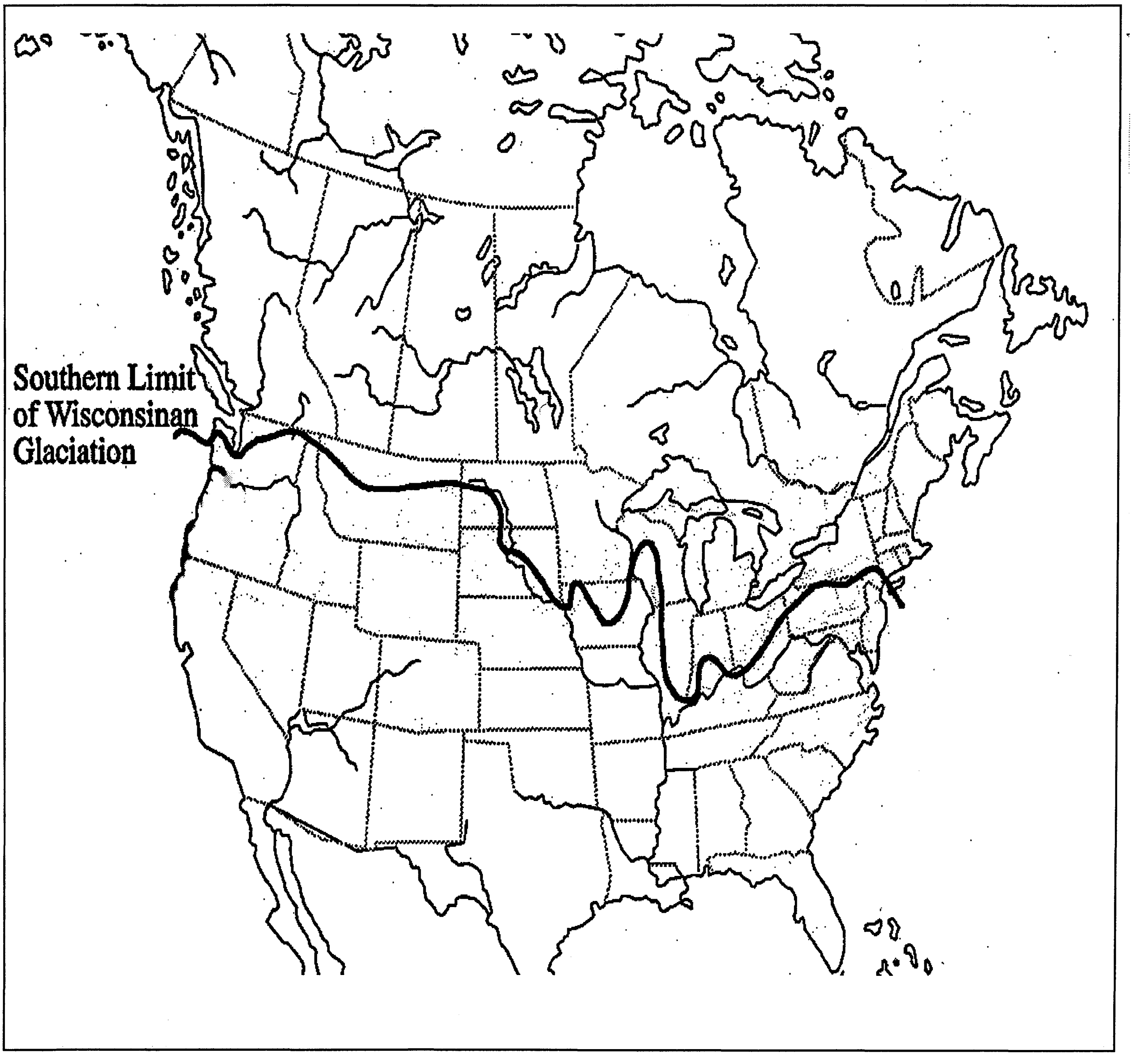

Figure 1: Southern limit of Wisconsinan glaciation thought to have eradicated native earthworms from northern North America

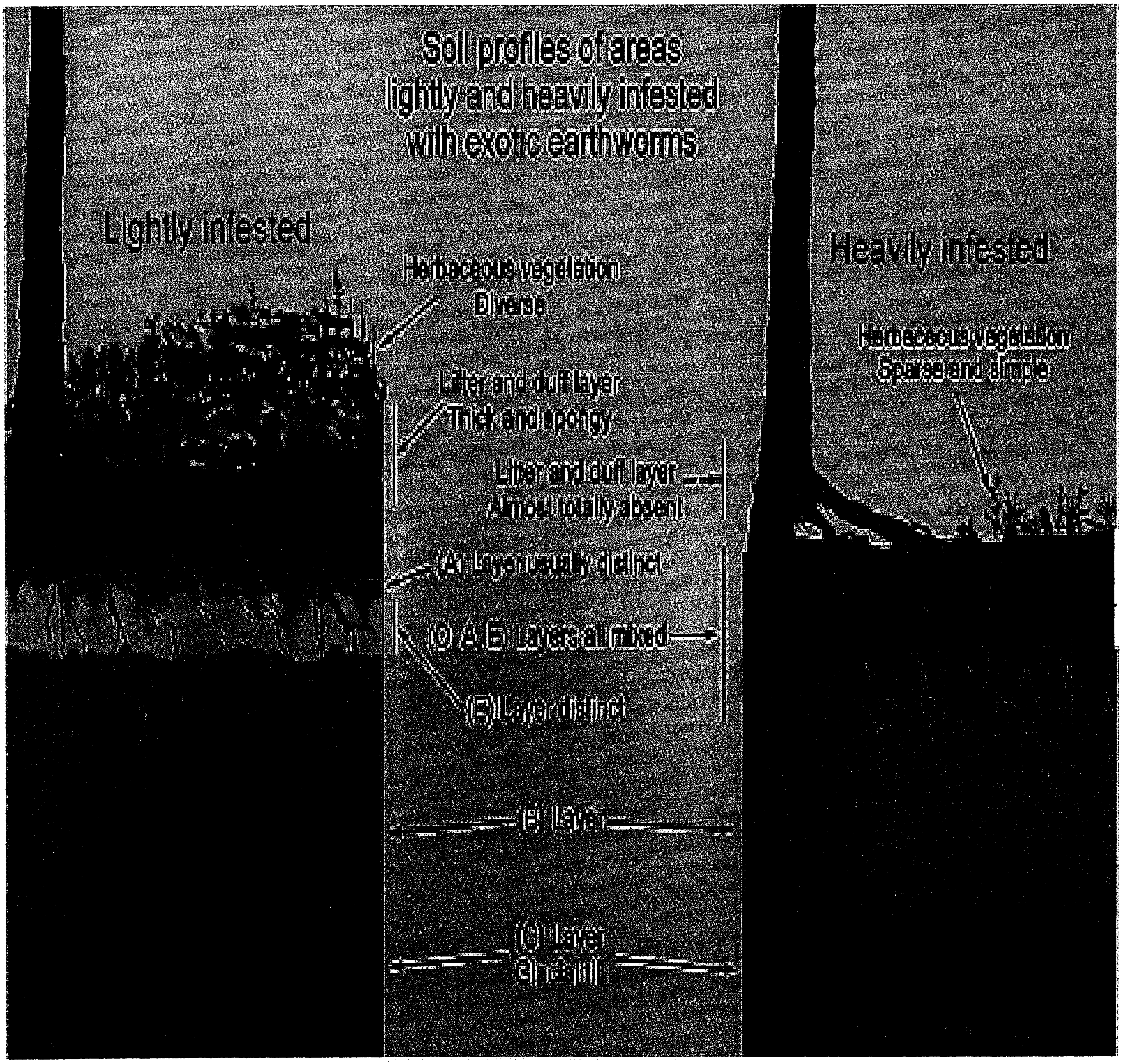

Figure 2: Hardwood forest prior to earthworm invasion (left) and following invasion (right). (Hale 2000)

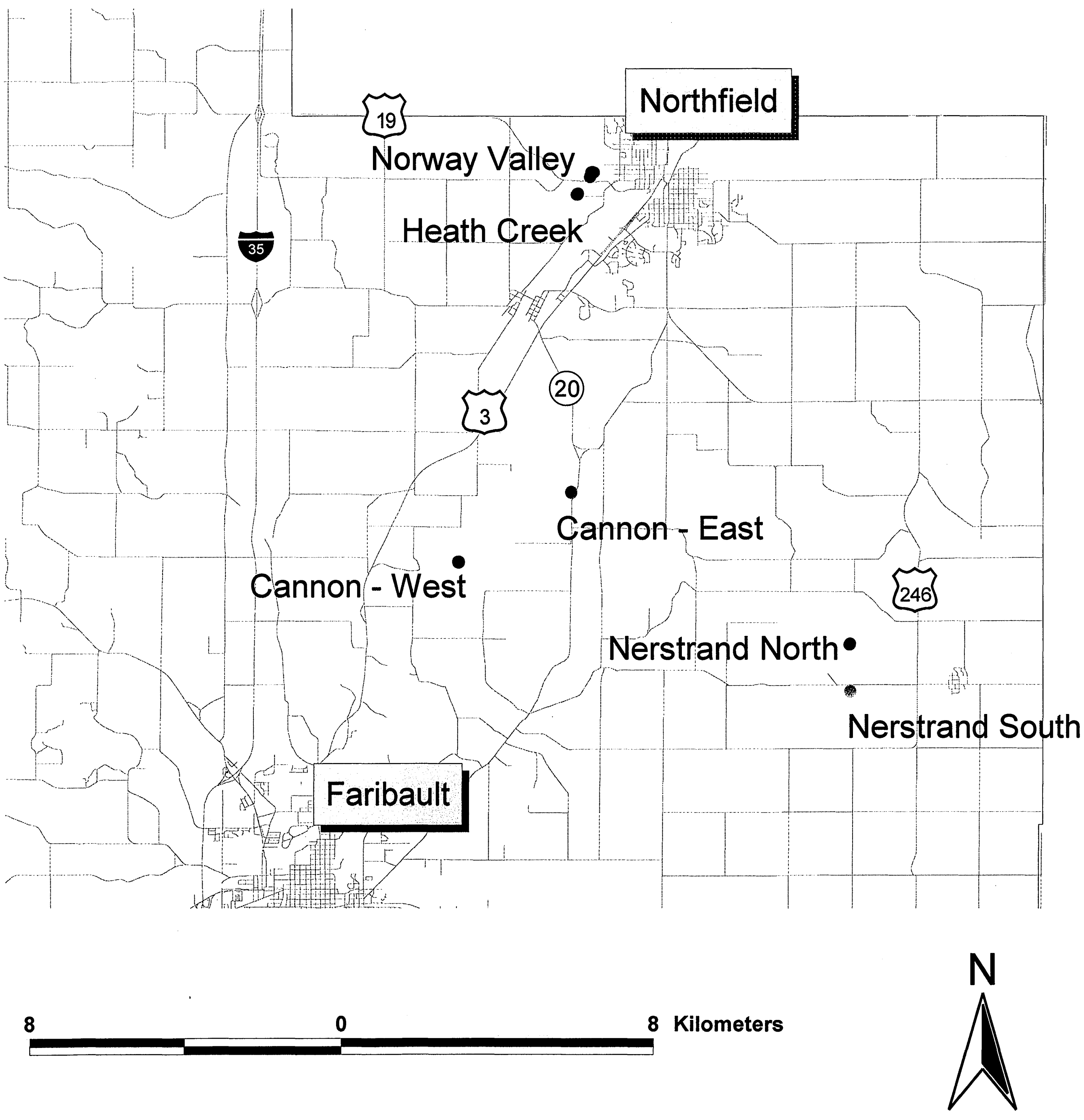

Figure 3: Site Locations in Rice County

Site	Total Earthworms	Mean Density
Nerstrand North	66	11.00
Nerstrand South	49	8.17
Norway Valley	92	15.33
Heath Creek	98	16.33
Cannon River - West	15	2.50
Cannon River - East	49	8.17
p-value	-	0.0096

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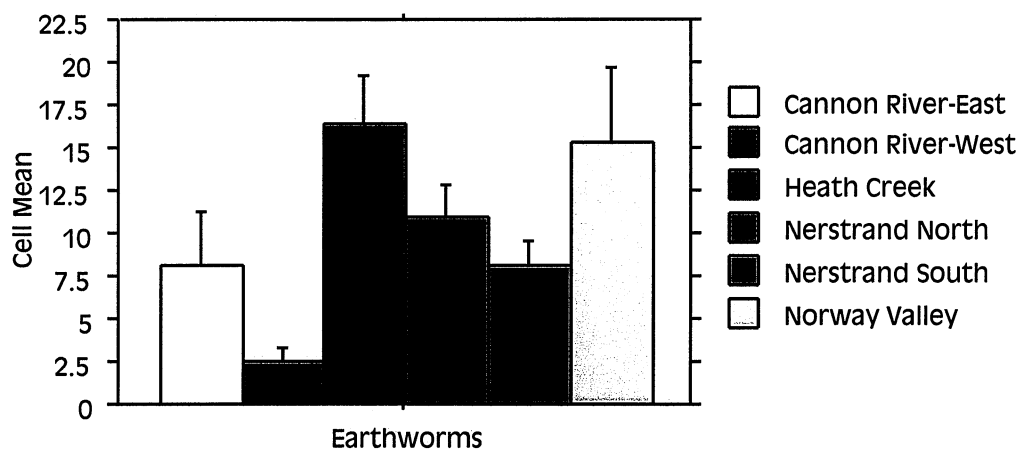

Figure 4: Comparison among sites of the results of earthworm sampling using mustard seed liquid extraction in $0.11m^2$ plots. Mean earthworm density is shown in the histogram with standard error bars. The total number of individuals collected and a significant analysis of variance result (0.0096) are shown above.

Site	epigeic	endogeic	anecic
Nerstrand North	32	29	2
Nerstrand South	2	47	0
Norway Valley	28	51	9
Heath Creek	29	47	4
Cannon River - West	0	15	0
Cannon River - East	10	13	5
p-value	0.0004	0.0621	0.1573

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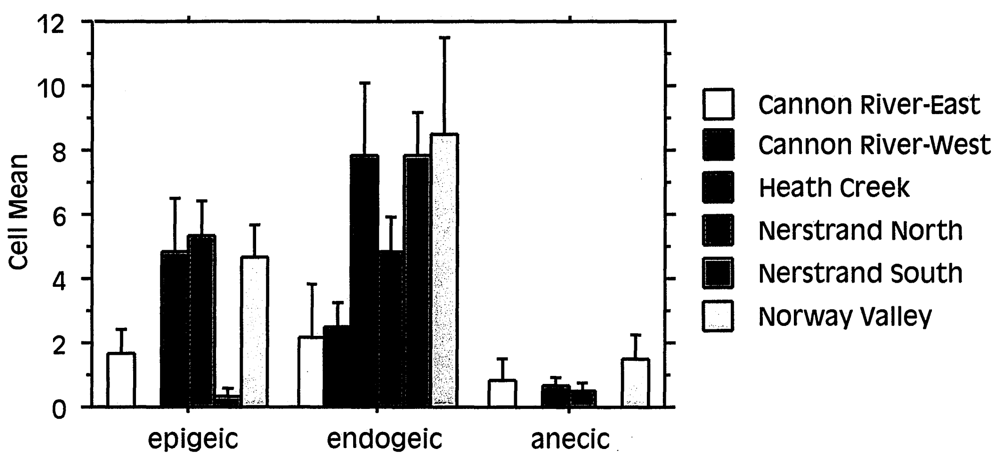


Figure 5: Comparison among sites of earthworm density per ecological type in $0.11 m^2$ plots. Mean worm density for each type is shown in the histogram with standard error bars. Actual number collected and a significant analysis of variance result (0.0004) are shown above.

Site	Mean Total Vegetation	Species Richness
Nerstrand North	82.17	11.17
Nerstrand South	54.17	8.50
Norway Valley	41.67	4.33
Heath Creek	47.83	7.50
Cannon River - West	65.67	14.00
Cannon River - East	58.83	7.50
p-value	0.016	<.0001
	S	S

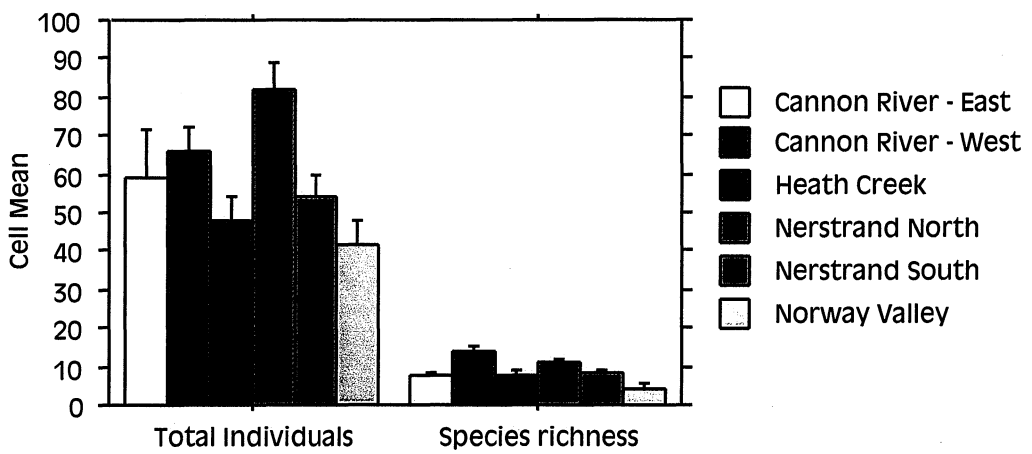


Figure 6: Comparison of the results of vegetation sampling among sites. Mean of total number of individuals and species richness is shown in the histograms (with standard error bars). Significant analysis of variance results (0.016 and <.0001, respectively) are shown above.

Site	Mature Individuals	Sapling Individuals	Herbaceous Individuals
Nerstrand North	5.00	26.17	51.00
Nerstrand South	2.83	33.67	17.67
Norway Valley	1.50	32.00	8.17
Heath Creek	2.83	29.67	15.33
Cannon River - West	2.33	26.50	36.83
Cannon River - East	2.50	11.17	45.17
p-value	0.105	0.038	0.005
		S	S

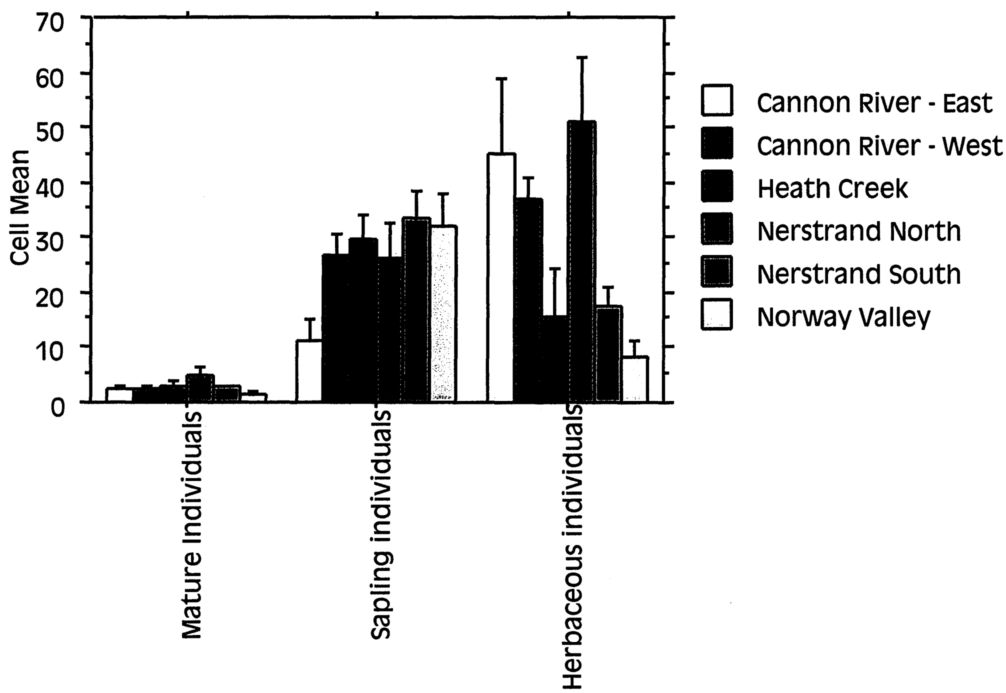


Figure 7: Comparison of the results of vegetation sampling among sites. Mean density of mature, sapling, and herbaceous vegetation is shown in the histograms (with standard error bars). Significant analysis of variance results (0.038 and <.005, respectively) are shown above.

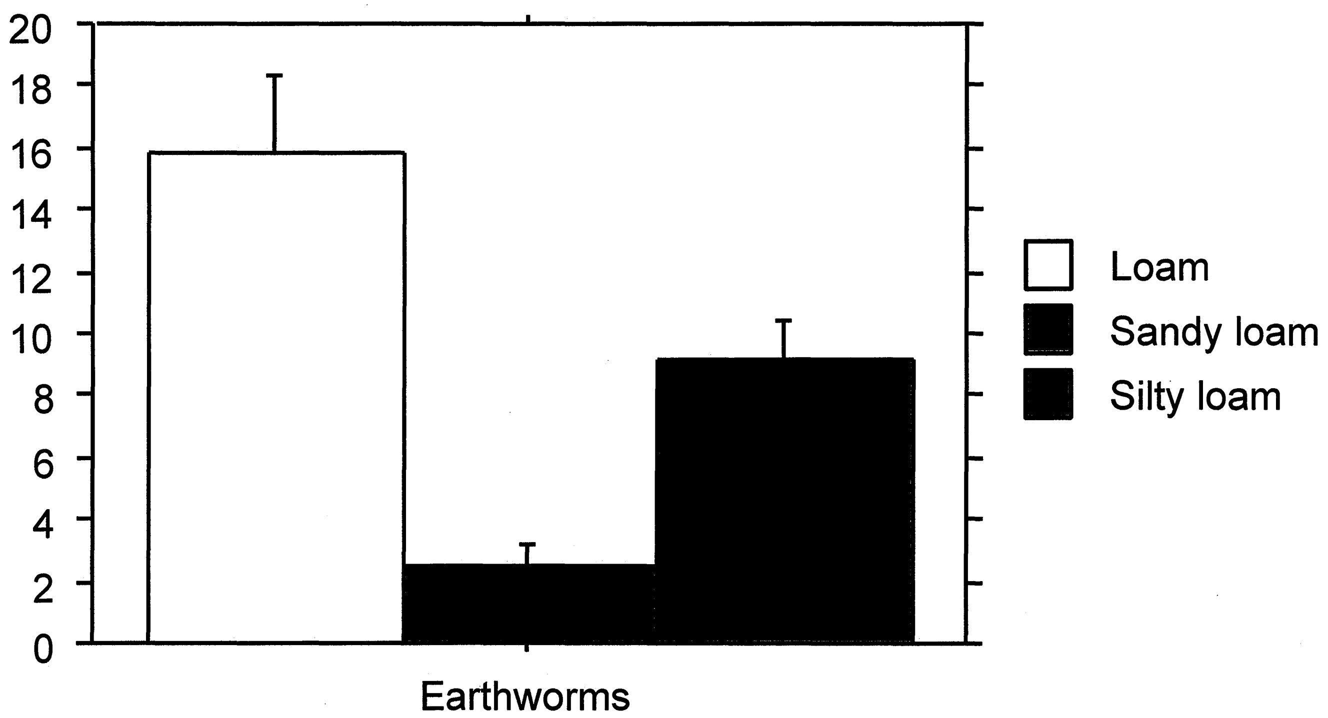


Figure 8: Comparison of the mean density of earthworms among the three soil types found by soil analysis. (Standard error bars are shown)

Table 3: Comparison among sites of mean depth and mean weight of litter collected in 0.11m^2 plots. Significant analysis of variance results (<.0001 and 0.0097, respectively) are shown.

Site	Litter depth	Litter weight
Nerstrand North	6.22	79.96
Nerstrand South	3.77	137.04
Norway Valley	5.06	10.22
Heath Creek	5.20	126.92
Cannon River - West	2.75	107.23
Cannon River - East	4.48	84.28
p-value	<.0001	0.0097
	S	S

Table 1: Comparison between sites of species richness and diversity of earthworms collected in $0.11m^2$ plots. Shannon and Simpson diversity test values and a significant analysis of variance result (0.0075) are shown.

Site	Species richness	Shannon	Simpson
Nerstrand North	5	1.07	0.59
Nerstrand South	4	0.99	0.54
Norway Valley	5	1.19	0.66
Heath Creek	6	1.26	0.65
Cannon River - West	3	0.48	0.25
Cannon River - East	4	1.29	0.73
p-value	0.0075	-	-

S

Table 2: Comparison among sites of the mean density by species of earthworms collected in 0.11m^2 plots. Significant analysis of variance results (0.0003 and 0.0232, respectively) are shown.

	Mean Density of Earthworms by Species					
Site	*L. rubellus*	*D. octaedra*	*A. tuberculata*	*A. trapezoides*	*O. tyrteum*	*L. terrestric*
Nerstrand North	5.17	0.17	0.00	0.50	2.50	0.50
Nerstrand South	0.33	0.00	0.83	1.17	3.00	0.00
Norway Valley	4.67	0.00	0.17	0.50	2.17	1.50
Heath Creek	4.17	0.67	0.33	0.33	2.50	0.67
Cannon River - West	0.00	0.00	0.17	0.00	1.33	0.00
Cannon River - East	1.67	0.00	0.00	0.50	0.67	0.88
p-value	0.0003	0.0232	0.2261	0.2551	0.3239	0.1573
	S	S				

Table 4: Comparison among sites of the results of soil analysis of soil samples collected at three times during the study. Nutrient values were assessed using methods outlined by Appendix B and the Hach Soil Testing Manual. Significant analysis of variance results (0.0004, 0.0005, and <.0001, respectively) are shown.

Site	Soil Type	Soil Moisture	Organic Matter	pH Level	Nitrate	Phosphate	Potassium
Nerstrand North	Silty loam	15.31	3.10	6.63	6.49	24.16	122.89
Nerstrand South	Silty loam	12.49	2.38	5.69	1.60	18.83	83.01
Norway Valley	Loam	11.71	2.43	6.33	8.64	27.25	120.18
Heath Creek	Loam	11.32	2.59	6.44	3.43	41.59	107.15
Cannon River - West	Sandy loam	5.35	2.26	5.69	1.95	14.33	75.30
Cannon River - East	Loam	13.39	3.39	6.63	8.05	27.77	104.67
p-value	-	0.0004	0.0849	0.0005	<.0001	0.2465	0.2512
		S		S	S		

Table 5: Comparison among sites of diversity of total vegetation, mature species, sapling species, and herbaceous species between sites as shown by Shannon and Simpson diversity tests.

	Total Vegetation		Mature Species		Sapling Species		Herbaceous Species	
Site	Shannon	Simpson	Shannon	Simpson	Shannon	Simpson	Shannon	Simpson
Nerstrand North	2.50	0.89	1.38	0.73	1.35	0.68	2.03	0.82
Nerstrand South	2.11	0.80	0.86	0.58	1.32	0.56	1.59	0.76
Norway Valley	1.42	0.66	0.63	0.50	0.92	0.51	0.69	0.34
Heath Creek	2.48	0.85	1.14	0.67	1.63	0.68	2.21	0.88
Cannon River - West	2.79	0.92	0.87	0.58	1.91	0.79	2.21	0.86
Cannon River - East	1.46	0.58	0.92	0.59	1.02	0.59	0.81	0.32

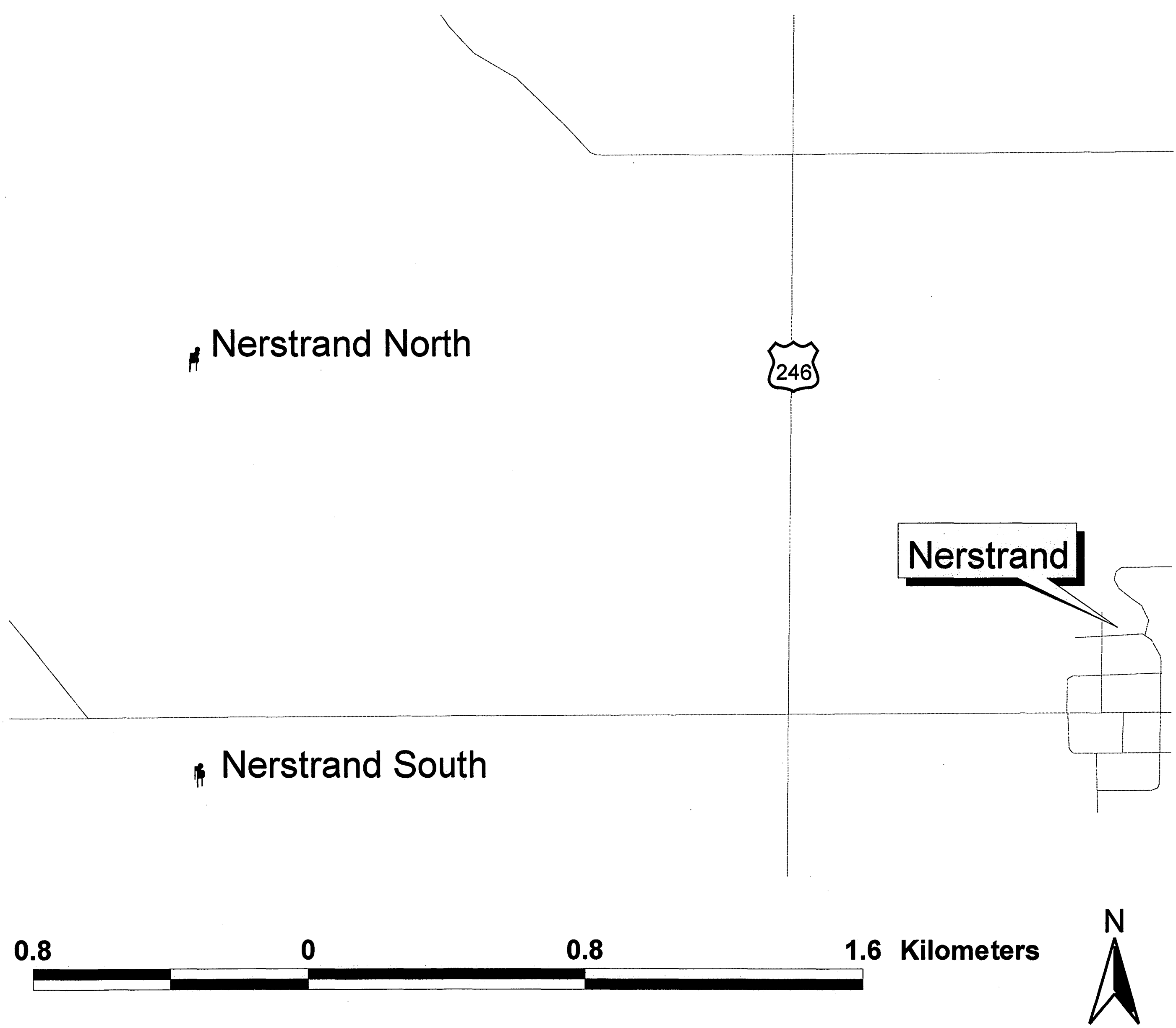
Table 6: Comparison among sites of the most common species by vegetation type. (See Appendix C for scientific names.)

Site	Mature	Woody	Herbaceous
Nerstrand North	Sugar Maple	Gooseberry	Enchanter's Nightshade
Nerstrand South	Sugar Maple	Dogwood	Nodding Trillium
Norway Valley	Sugar Maple	Sugar Maple	Jack-in-the-Pulpit
Heath Creek	Sugar Maple	Basswood	Wild Ginger
Cannon River - West	White Oak	Sugar Maple	Common Violet
Cannon River - East	Sugar Maple	Gooseberry	Wild Ginger
Most Common Overall	Sugar Maple	Sugar Maple	Wild Ginger

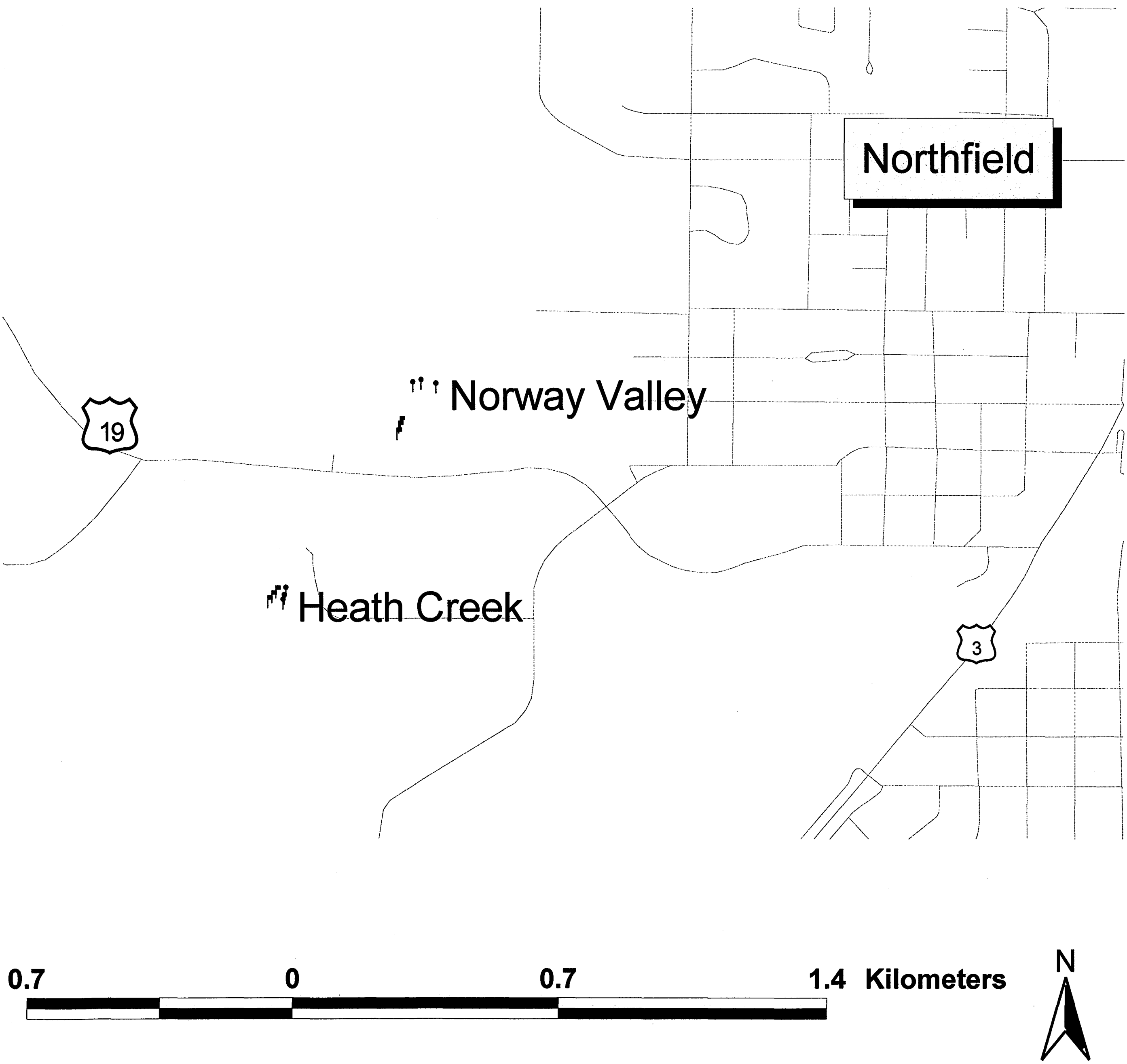
Table 7: Comparison of community similarity values between both sites at each location. Community similarity was calculated using the Jaccard coefficient (CCj=C/S), where S is the number of species in both sites, C is the number of species in common in both sites, and CCj is the community similarity value.

Site	S	C	CCj
Nerstrand North	38	14	0.37
Nerstrand South			
Norway Valley	35	5	0.14
Heath Creek			
Cannon River - West	43	11	0.26
Cannon River - East			

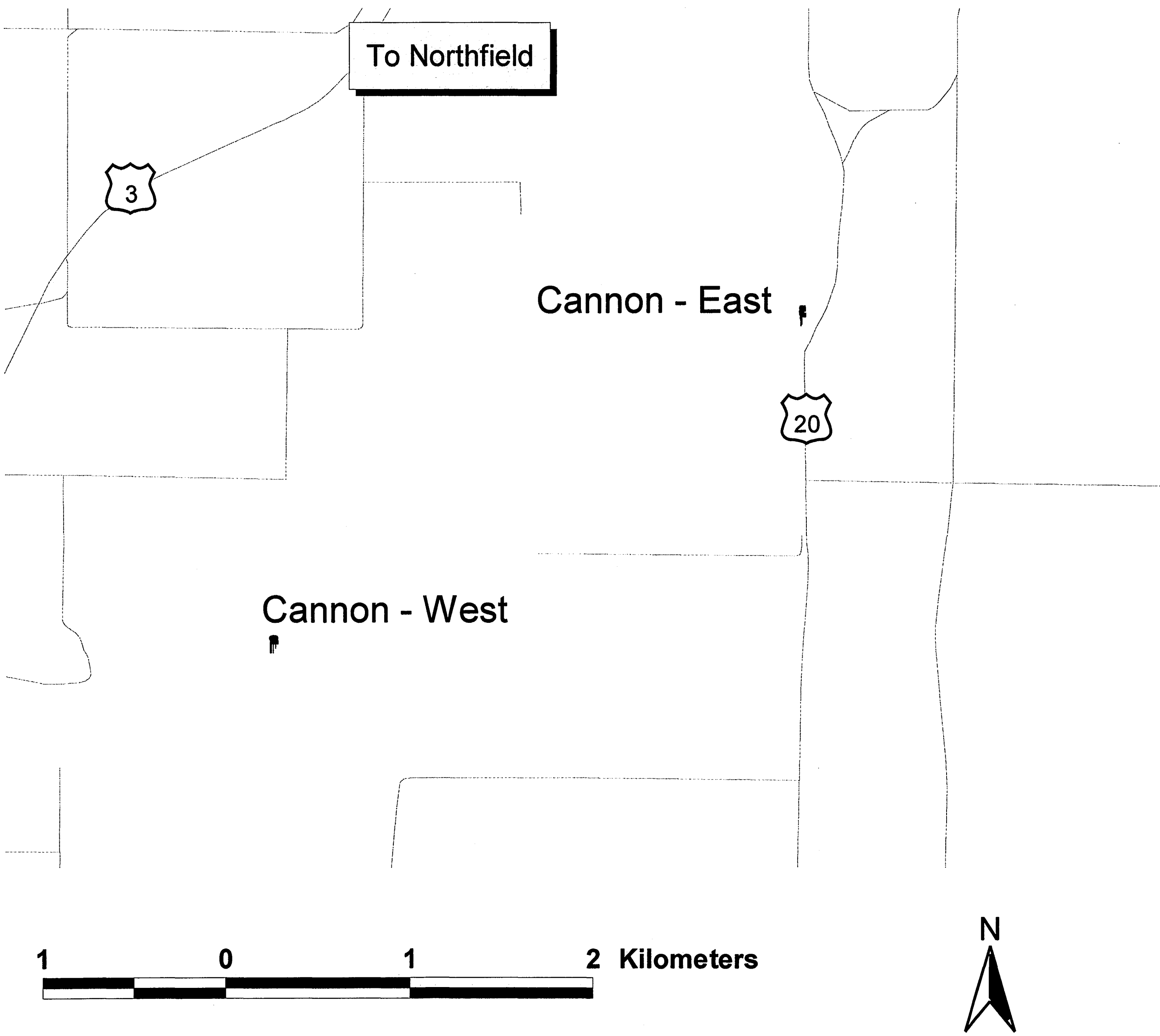
Appendix A: Locations of Plots Sampled in Rice County



Plot Locations in Nerstrand Big Woods State Park



Plot Locations at St. Olaf College



Plot Locations at Cannon River Wilderness Area