

# Effective Management of Western Snowberry

Llewellyn L. Manske PhD  
Range Scientist

North Dakota State University

Dickinson Research Extension Center

Report DREC 06-3043

Western snowberry colonies invade and expand in grazingland managed by traditional grazing practices because of the reduced competitive abilities of the grass plants. Enlarging western snowberry colonies use increasing quantities of ecosystem natural resources of soil water, mineral nitrogen, and sunlight to produce biomass that is not nutritious forage for livestock or wildlife. Depending on the shrub's stem density and whether the location is in the moist or dry portions of the mixed grass prairie, the proper stocking rate of a pasture is reduced by about one animal unit for each 1.5 to 5.0 acres of land with western snowberry colonies.

Aerial stems of western snowberry are relatively easy to kill to the ground with single burning, mowing, or herbicide application treatments. The rhizomes and crowns are not easily killed and have biological mechanisms and processes that enable the shrub to survive aerial stem removal and to completely replace the aerial stem density and biomass by the third growing season following the treatment.

Development and implementation of management practices that effectively reduce western snowberry colony size and stem density require the understanding of how the shrub grows, when phenological growth stages occur, when the shrub has vulnerable periods in its life cycle, and when treatments can deplete the nonstructural carbohydrate reserves or damage the capabilities of the rhizomes and crowns for vegetative regeneration of aerial stems.

## Growth and Development

Western snowberry, *Symphoricarpos occidentalis* Hook. (a member of the honeysuckle family, Caprifoliaceae), is a native deciduous cool-season shrub that forms large colonies. This biologically successful shrub is widely distributed throughout most of the interior of North America, and it grows at the transitional boundaries of a great variety of plant communities and vegetation types on a wide variety of soils. In grasslands, it can grow in colonies as the only woody plant in association with Kentucky bluegrass and other shade-tolerant plants.

The size of western snowberry colonies can range from a small number of stems covering a few square feet to extensive growths covering hundreds of acres. Typical colonies range from 22 to 82 yards in diameter. Stem height of western snowberry tends to be greater towards the center of the colony, with a range from 16 to 45 inches. Stem density of western snowberry colonies varies considerably, with average density ranging from 39 to 62 stems/sq. yard. Typically, the lowest densities occur at the periphery of a colony, at about 28 stems/sq. yard. Canopy cover of typical western snowberry colonies ranges from 12% to 93%.

Western snowberry has an extensive interconnected rhizome system with clusters of stem bases at about 1.0- to 3.0-foot intervals. The cumulative rhizome length can be 4.4 times greater than the cumulative live aerial stem length. Rhizomes grow at a soil depth from 0.75 to 14 inches below ground. The protection the soil provides for the belowground plant parts contributes to their longevity of about 40 years. Nodes develop on the rhizomes about every 0.5 to 1.0 inch. The nodes are sites with meristematic tissue that forms into growing points for opposite pairs of roots that have unequal growth in length and opposite pairs of lateral buds that have the potential to develop vegetatively into long or short rhizome branches.

The growth of rhizome buds is regulated by apical dominance of a lead aerial stem through the production of inhibitory hormones that block or suppress the activity of growth hormones. When a lead stem is killed or damaged by unfavorable environmental conditions or by management treatments, the production of inhibitory hormones is reduced or stopped, and the growth hormones activate meristematic tissue in rhizome buds; the activation results in the development of several new rhizomes and sucker stems. The long length of the rhizome between adjacent stem base clusters reflects the distance from which hormones produced by lead stems can regulate or influence growth activity of rhizome lateral buds.

Rhizomes and rhizome branches grow horizontally away from their original growing point

for a distance, usually about 3 feet or a little less; turn upward; and develop into an erect aerial stem. Rhizome buds near a vertical stem base appear to have greater viability and can develop into long rhizomes, short rhizomes, or additional erect stems forming clusters of stem bases. These sections of vertical and horizontal rhizomes with several nodes actively producing rhizomes and aerial stems are rhizome crowns.

Aerial stems that western snowberry produces vegetatively from meristematic buds are suckers. Rhizome suckers develop from upturned rhizomes or rhizome branches, and crown suckers develop near stem base clusters. During the second year of growth, stems are young stems. During the third and subsequent years, stems are mature stems.

Sucker stems grow rapidly during the first growing season. Stem nodes comprising opposite pairs of growing points with meristematic tissue develop on sucker stems about every 1.0 to 2.0 inches. Opposite pairs of leaves are produced at each node along the entire sucker stem. Lateral branches do not appear during the first year unless the lead apical meristem is damaged. During the second year of growth, pairs of lateral twigs appear from nodes that were the previous year's leaf axils along the upper portions of the stem. Nodes along the lower portions of the stem do not develop twigs. New leaves develop as opposite pairs at the nodes of only the current year's twigs, not on older twig material. Successive twigs growing from the previous year's leaf axils create a branch network that becomes more complex with each growing season. The age of intact stems can be determined from the pattern of twig branches.

Aerial stems, which live to the maximum age of about 13 years, do not survive as long as rhizomes and clusters of stem bases, which are protected by a layer of soil. Portions of mature stems may die each year. This decadence of aerial stems is most likely the result of unfavorable environmental conditions rather than a symptom of reduced vigor of aging stems.

### **Phenological Growth Stages**

Western snowberry starts growing in mid to late April, when there are at least 14 hours of daylight. Rapid twig elongation and leaf growth and expansion occur at the same time and continue until late May or early June, when pinkish flower buds appear at the twig tips. By early June, the twigs have reached about 75% of full growth, and the leaves are

near full expansion. Twigs continue growing at a slower rate, and by mid June they have completed about 95% of their annual growth. Flower buds continue to appear in the leaf axils until about late June. The shrub starts the anthesis growth stage when the first flowers begin opening at the twig tips around mid June; subsequent new flowers open at lower leaf axils through July and sometimes into mid August. The slightly fragrant flowers are insect pollinated and open during the night or early morning. After fertilization, the fruits fill and ripen during mid July to late August. Leaf senescence can occur any time the plant is in water stress, but it usually occurs during late August to October. Many of the leaves remain attached to the stems over the winter. The greenish white mature fruits are the feature for which "snowberry" was named. The stalk of the fruit does not have an abscission layer and most fruits remain attached to the stems all winter. The fruits that have not been consumed by an animal drop to the ground during the following spring or summer. Each fruit contains two nutlets, but about half of the nutlets are defective. The nutlets have a complex double-dormancy mechanism that must be satisfied before germination can occur. Germination rate is low because only about 1% of the nutlets reaching the soil are viable. Mortality of seedlings is high because they have few defenses against insects, diseases, water stress, and competition from other plants. Seedlings probably do not become mature stems in and around existing colonies. For seedlings to develop into adult plants, the nutlets must be transported inadvertently in the digestive tracts of animals to habitat sites that have sufficient soil water, few insects, low quantities of disease organisms, and little or no competition from dense grasses or canopy cover of shrubs. Western snowberry establishment by seed is rare.

### **Nutrient Content**

Western snowberry fruits are consumed by numerous types of birds and mammals. A few nutlets pass unharmed through the digestive tracts of some animals. About 10.7% of the nutlets force-fed to domesticated chickens passed intact. Pheasants, grouse, large herbivores, and livestock are known to pass intact nutlets. Rabbits and mice are known to pass only nutlet fragments.

A wide variety of animals consumes portions of western snowberry shoots. Several insects chew parts of leaves and stems. Mice and other rodents girdle stems. Rabbits browse the stems. Wild ungulates and domesticated cattle, sheep, and goats browse the leaves and twigs. Western snowberry,

however, is not important as food for wildlife. The nutrient content of western snowberry twigs, leaves, and fruits does not meet the requirements for in vitro dry matter digestibility, crude protein, and phosphorus of wild ungulates during fall and winter. The energy content and crude protein content of western snowberry fruits do not meet the nutrient requirements of sharp-tailed grouse during fall and winter.

### **Nonstructural Carbohydrate Cycle**

Carbon is important to plants for energy transport and storage and as cellulose-based structural materials used in growth. Plants capture and fix carbon from atmospheric carbon dioxide during the process of photosynthesis. The assimilated carbon forms into various simple sugars and starches that are collectively called carbohydrates. The surplus carbohydrates that are not used as energy or for structural growth are stored as nonstructural carbohydrates. The quantity of stored nonstructural carbohydrates is related to plant growth and reproduction, with cycles of drawdown and replenishment following a typical pattern each growing season. A sharp drawdown in carbohydrate reserves occurs during the rapid growth of early spring, from mid April to early June. The lowest carbohydrate levels occur for about 10 days between late May and early June. Rapid replenishment occurs during the flowering stage, from early June to mid July. A second drawdown period occurs during fruit fill, between mid July and early August. A second replenishment period occurs between mid August and early September. A gradual third drawdown occurs during pre-winter root growth and bud development, from early September to late October.

### **Biological Management**

The persistence and abundance of a species in a community is determined by that species' competitive ability to acquire aboveground and belowground resources. Western snowberry and native grasses compete for sunlight, mineral nitrogen, and soil water. The taller aerial stems of the shrub shade sunlight from the grass understory, reducing the quantity of light reaching the grass canopy by 70% to 80%. The quantity of light reaching the grass plants is below the light saturation point of most native grassland species, and the shading reduces grass biomass production severely. Shading has a greater effect on warm-season grasses because of their higher light compensation point than on cool-season species. Effects from shading by dense aerial stems can completely eliminate the understory vegetation.

Implementation of traditional grazing practices that are antagonistic to the biological requirements of grass plants and the biogeochemical processes in grassland ecosystems weakens the competitive abilities of grasses and facilitates the encroachment and enlargement of western snowberry colonies. Less than healthy grasses have diminished competitive abilities; these grass plants relinquish quantities of belowground resources in proportion to the reduced competitiveness. The additional resources then become available for western snowberry growth and facilitate the enlargement and spread of the colonies and the increase in stem density. Increases in aerial stem canopy cover improve the competitiveness of the shrubs for the aboveground resource of sunlight.

Healthy grass plants are superior competitors for soil water and mineral nitrogen; these grass plants reduce the quantity of belowground resources available for western snowberry and thereby retard or reverse the shrub's encroachment into grazinglands. Grass competition for belowground resources reduces the quantity of western snowberry vegetative buds with activated meristematic tissue, reduces the growth rates of developing rhizome suckers, and causes a relatively high mortality rate of young sucker stems. The effect of competition from grasses causes a decrease in the density of rhizome and crown suckers, young stems, and total aerial stems and a decrease in the canopy cover of western snowberry colonies. Implementation of biologically effective management, like the twice-over rotation system, that is designed to meet the biological requirements of the plants and to coordinate two grazing periods with grass growth stages, activates the defoliation resistance mechanisms in grazed grass plants. The coordinated defoliation stimulates biological and ecological processes within grass plants and the ecosystem so that beneficial changes to plant growth, soil organisms, and biogeochemical cycles in the ecosystem result. The increase in vegetative reproduction by tillering from axillary buds contributes to the development of greater grass basal cover and to the production of greater herbage weight. The increase in activity of the soil organisms in the rhizosphere supplies the plant with greater quantities of nutrients to support additional growth. The result is a healthy, dense, productive grass population that is highly competitive for belowground resources and creates the strongest possible biological barrier to western snowberry encroachment.

Biologically effective management practices improve the health and competitive abilities of the

native grass plants but do not remove the aerial stems and reduce the size of preexisting western snowberry colonies. Additional management practices that use burning, mechanical, and chemical methods are needed to diminish existing colonies of western snowberry on grazinglands.

### **Burning Management**

Western snowberry aerial stems are sensitive to fire, and even if they are not completely consumed by the fire, the stems usually die to ground level. Because of the protection provided by soil, the belowground rhizomes and rhizome crowns with clusters of stem bases are usually not damaged by fire. The belowground parts have large quantities of buds that have the potential to develop into new aerial sucker stems.

Historically, fire has been an environmental factor on mixed grass prairie, with an estimated fire return interval of 5 to 10 years on the moist portions and around 25 years on the dry portions. Both lightning-set fires and Indian-set fires have influenced how western snowberry responds to prescribed burning. Most lightning-set fires occurred in July and August, and a large portion of the Indian-set fires occurred between July and early November. The Northern Plains has probably had considerably more late season fires, occurring after mid July, than spring or early summer fires.

Western snowberry top growth is usually removed completely by fire if sufficient fine fuel is present; however, spring burns result in great quantities of sucker stems, which become visible about two weeks following the burn, and because carbohydrate stores can be completely replenished by the new plant material in one growing season, spring burns do not decrease stem frequency even after 24 years. Shrub stem densities recover during the first and second growing season following a burn treatment, and during the third growing season following burning, stem densities on burn treatments are similar to stem densities on the unburned reference areas.

Management strategies with four every-other-year burns are required to reduce western snowberry aboveground biomass production and shrub frequency and to increase grass biomass production. Prescribed fires during August cause the least damage to native cool- and warm-season grasses and perennial forbs. August fires remove all or most of the top growth of western snowberry and result in fewer sucker shoots the following year than spring

burns. The growth pattern and biological requirements of the herbaceous vegetation in the mixed grass prairie match the defoliation pattern of August burns more closely than burns at other periods. When the soil is not dry, August burns can be nearly nondetrimental to desirable plants and can cause considerable damage to the undesirable woody plants. Prescribed burning alone, however, will not remove western snowberry from the northern mixed grass prairie.

### **Mechanical Management**

Mechanical mowing treatments can effectively reduce western snowberry stem densities by causing depletion of stored nonstructural carbohydrate energy from repeated cutting of aerial stems at the times when the carbohydrate reserves are low. Energy reserves are reduced when vegetative sucker regrowth is produced. Repeat cutting is required to prevent replenishment of reserves when the replacement suckers produce greater quantities of carbohydrates than they use for growth. Plant growth requirements cause carbohydrate drawdown during rapid spring growth, from mid April to early June; during fruit fill, from mid July to early August; and during pre-winter root growth and bud development, from early September to late October.

The mowing height of western snowberry colonies in grazed pastures should not be close to the ground, at the height that hay is cut, but the mowing height should be raised to about 8 or 9 inches above the ground. Young and mature stems topped by cutting frequently die all the way to the ground. The cutting height should be set so most of the leaves and branches on the typical stems are removed and a relatively tall, flexible, bare stem remains. Intact mature stems are flexible and can be bent to the ground without breakage. Stems cut short are very rigid and do not bend when stepped on. Short, rigid, sharp stems can be serious problems for cattle walking through mowed western snowberry colony areas. The stiff stems can puncture the sole of the hoof, causing an injury open to infection that can possibly result in hoof rot.

Single annual mowing treatments do not reduce stem numbers, because the regrowth of sucker stems can replenish the carbohydrate reserves during one growing season. Double mowing treatments can be effective at reducing stem numbers when mowing periods are conducted for maximum carbohydrate depletion. The seasonal low carbohydrate reserves for western snowberry occur from the period of rapid growth until near the start of flowering, between May

and mid June. The first mowing treatment conducted during the last week in May through the third week in June should cause considerable depletion of stored carbohydrates. Growth of sucker shoots should continue to deplete carbohydrate reserves for nearly six weeks, until the new sucker stems develop about ten leaf pair. A second mowing treatment conducted sometime during late July through August is needed to prevent full carbohydrate replenishment. Mowing in late July or August causes a substantial amount of winter injury to late-season lateral bud sprouts on the stem bases. Double mowing treatments will need to be repeated two, three, or more seasons, depending on the quantity of stored carbohydrates of western snowberry colonies at the start of the mowing treatments.

### **Chemical Management**

Successful chemical management of western snowberry depends on terminating the regenerative capabilities of the rhizomes and the clusters of stem bases on the crowns. Two critical factors must occur in order for sufficient quantities of foliage-active herbicides to reach the site of activity in the belowground plant parts and interfere with their physiological processes. First, the herbicides must enter the leaf tissue through the stomata openings or penetrate the outer cuticle layer, be absorbed through leaf tissue by diffusion, and be moved to the vascular system within the leaf. Second, the herbicides must be translocated from the leaves downward through the phloem vascular system to the metabolically active sites of the crowns and rhizomes. During the period of rapid twig elongation, from mid April to early June, nonstructural carbohydrates move from the storage site in the rhizomes and the crowns upward through the phloem vascular system to the active growing points. The upward movement of

carbohydrates through the phloem prevents downward movement of herbicides. Herbicides can readily penetrate young western snowberry leaves during May and early June but cannot be translocated downward. Sometime between early June and mid June, the carbohydrate production by leaf photosynthesis exceeds the demands from growth, and the surplus carbohydrates are moved downward through the phloem for storage in the rhizomes and crowns. This change in direction of carbohydrate flow permits the translocation of herbicides from the leaves downward to the belowground plant parts. The leaves have continued to mature, developing a thicker cuticle layer and denser cell walls; the result is an increased resistance to herbicide penetration and absorption. The two critical factors for successful chemical management of western snowberry occur coincidentally during only a brief vulnerable stage, from about 10 June until 20 June, when herbicide penetration into leaf tissue is decreasing and herbicide translocation downward is increasing. Leaf penetration by herbicides is improved with wetting agents, and these surfactants should be added to all foliage-active herbicide spray mixtures.

Implementing management practices that effectively reduce western snowberry colony size and stem density using biological, burning, mechanical, and chemical methods requires an understanding of how the plant grows, its strong characteristics, and its weaknesses and periods of vulnerability.

### **Acknowledgment**

I am grateful to Amy M. Kraus for assistance in preparation of this manuscript. I am grateful to Sheri Schneider for assistance in production of this manuscript.

## References

- Adams, B.W., and A.W. Bailey. 1983.** Effect of mowing on energy reserves of western snowberry. Agriculture and Forestry Bulletin (Special Issue). p. 72-75.
- Anderson, H.G., and A.W. Bailey. 1980.** Effects of annual burning on grassland in the aspen parkland of east-central Alberta. Canadian Journal of Botany 58:985-996.
- Anderson, M.L., and A.W. Bailey. 1979.** Effects of fire on a *Symphoricarpos occidentalis* shrub community in central Alberta. Canadian Journal of Botany 57:2819-2823.
- Bailey, A.W., and M.L. Anderson. 1980.** Fire temperatures in grass, shrub, and aspen forest communities of central Alberta. Journal of Range Management 33:37-40.
- Bowes, G.G. 1991.** Long-term control of aspen poplar and western snowberry with dicamba and 2,4-D. Canadian Journal of Plant Science 71:1121-1131.
- Bowes, G.G., and D.T. Spurr. 1995.** Improved forage production following western snowberry (*Symphoricarpos occidentalis* Hook.) control with metsulfuron methyl. Canadian Journal of Plant Science 75:935-940.
- Bowes, G.G., and D.T. Spurr. 1996.** Control of aspen poplar, balsam poplar, prickly rose, and western snowberry with metsulfuron-methyl and 2,4-D. Canadian Journal of Plant Science 76:885-889.
- Evans, K.E., and D.R. Dietz. 1974.** Nutritional energetics of sharp-tailed grouse during winter. Journal of Wildlife Management 38:622-629.
- Ferrell, M.A. 1986.** Evaluation of herbicides for control of western snowberry. Western Society of Weed Science-Research Progress Report. p. 38.
- Ferrell, M.A. 1992a.** Control of western snowberry (*Symphoricarpos occidentalis* Hook.) with various herbicides. Western Society of Weed Science-Research Progress Report. p. I-75.
- Ferrell, M.A. 1992b.** Control of western snowberry (*Symphoricarpos occidentalis* Hook.) with metsulfuron. Western Society of Weed Science-Research Progress Report. p. I-76.
- Ferrell, M.A., and T.D. Whitson. 1987.** Herbicide control evaluations on western snowberry. Western Society of Weed Science-Research Progress Report. p. 53.
- Gorder, M.M., L.L. Manske, and T.L. Stroh. 2004.** Grazing treatment effects on vegetative tillering and soil rhizospheres of western wheatgrass. NDSU Dickinson Research Extension Center. Range Research Report DREC 04-1056. Dickinson, ND. 13p.
- Great Plains Flora Association. 1986.** Flora of the Great Plains. University of Kansas, Lawrence, KS.
- Johnson, J.R., and G.E. Larson. 1999.** Grassland plants of South Dakota and the Northern Great Plains. South Dakota State University. B 566 (rev.). Brookings, SD.
- Kirby, D.R., G.M. Sturn, and T.A. Ransom-Nelson. 1988.** Effects of grazing on western snowberry communities in North Dakota. Prairie Naturalist 20:161-169.
- Kochy, M. 1999.** Grass-tree interactions in western Canada. Ph.D. Dissertation. University of Regina. Regina, Saskatchewan, Canada.
- Kochy, M., and S.D. Wilson. 2000.** Competitive effects of shrubs and grasses in prairie. Oikos 91:385-395.
- Krueger, J.K., and D.J. Bedunah. 1988.** Influence of forest site on total nonstructural carbohydrate levels of pinegrass, elk sedge, and snowberry. Journal of Range Management 41:144-149.
- Li, X., and S.D. Wilson. 1998.** Facilitation among woody plants establishing in an old field. Ecology 79:2694-2705.

- Manske, L.L. 1992.** Effects from prescribed burning treatments repeated every other year on shrub invaded mixed grass prairie. Report to USDI Fish and Wildlife Service. Lostwood National Wildlife Refuge. Kenmare, ND.
- Manske, L.L. 1999.** Can native prairie be sustained under livestock grazing? p. 99-108. *in* J. Thorpe, T.A. Steeves, and M. Gollop (eds.). Proceedings of the Fifth Prairie Conservation and Endangered Species Conference. Provincial Museum of Alberta. Natural History Occasional Paper No. 24. Edmonton, Alberta, Canada.
- Manske, L.L. 2000.** Management of Northern Great Plains prairie based on biological requirements of the plants. NDSU Dickinson Research Extension Center. Range Science Report DREC 00-1028. Dickinson, ND. 12p.
- Manske, L.L. 2005a.** Western snowberry biology. NDSU Dickinson Research Extension Center. Range Management Report DREC 05-1059. Dickinson, ND. 29p.
- Manske, L.L. 2005b.** Biological management of western snowberry. NDSU Dickinson Research Extension Center. Range Management Report DREC 05-1060. Dickinson, ND. 12p.
- Manske, L.L. 2005c.** Burning management of western snowberry. NDSU Dickinson Research Extension Center. Range Management Report DREC 05-1061. Dickinson, ND. 20p.
- Manske, L.L. 2005d.** Mechanical management of western snowberry. NDSU Dickinson Research Extension Center. Range Management Report DREC 05-1062. Dickinson, ND. 6p.
- Manske, L.L. 2006.** Chemical management of western snowberry. NDSU Dickinson Research Extension Center. Range Management Report DREC 06-1063. Dickinson, ND. 32p.
- Mastel, J.A. 1983.** Growth, production, utilization, and phytosociology of western snowberry (*Symphoricarpos occidentalis* Hook.) in the North Dakota badlands. M.S. Thesis. North Dakota State University. Fargo, ND.
- McCarty, M.K. 1967.** Control of western snowberry in Nebraska. *Weeds* 15:130-133.
- McMillan, C., and B.F. Pagel. 1958.** Phenological variation within a population of *Symphoricarpos occidentalis*. *Ecology* 39:766-770.
- Pelton, J. 1953.** Studies on the life-history of *Symphoricarpos occidentalis* Hook., in Minnesota. *Ecological Monographs* 23:17-39.
- Peltzer, D.A., and M. Kochy. 2001.** Competitive effects of grasses and woody plants in mixed grass prairie. *Journal of Ecology* 89:519-527.
- Ransom-Nelson, T.A. 1985.** Ecology, phytosociology, growth, and production of western snowberry (*Symphoricarpos occidentalis* Hook.) in south-central North Dakota. M.S. Thesis. North Dakota State University. Fargo, ND.
- Roel, J.C. 1983.** Growth and production characteristics of buckbrush (*Symphoricarpos occidentalis* Hook.) in south-central North Dakota. M.S. Plan B Paper. North Dakota State University. Fargo, ND.
- Romo, J.T., P.L. Grilz, R.E. Redmann, and E.A. Driver. 1993.** Standing crop, biomass allocation patterns and soil-plant water relations in *Symphoricarpos occidentalis* Hook. following autumn or spring burning. *The American Midland Naturalist* 130:106-115.
- Smith, K.A. 1985.** Prescribed burning reduces height and canopy cover of western snowberry (North Dakota). *Restoration and Management Notes* 3:86-87.

**Sturn, G.M. 1987.** Response of western snowberry (*Symphoricarpos occidentalis* Hook.) dominated communities to grazing in south central North Dakota. M.S. Thesis. North Dakota State University. Fargo, ND.

**Volesky, J.D. 1982.** Big game browse study evaluation. M.S. Thesis. North Dakota State University. Fargo, ND.

**Williamson, R.L. 1979.** Seasonal variations in the nutrient qualities of nine selected shrubs of North Dakota. M.S. Thesis. North Dakota State University. Fargo, ND.