AN ABSTRACT OF THE THESIS OF

Gilbert L. Buller for the degree of Master of Science in Soil Science presented on December 18, 1998. Title: Aggregation, Bulk Density, Compaction, and Water Intake Responses to Winter Cover Cropping in Willamette Valley Vegetable Production.

Abstract approved: Richard P. Dick

Richard P. Dick

Many agricultural sustainability issues are related to biological processes which are central to the ecological function of soils. Soil physical properties are the architecture in which these processes are carried out. Cover crops hold promise as one of the techniques which can ameliorate poor soil structure and improve bulk density and water intake. In addition, integrating cover crops into the production cycle may improve cash crop quality and yield. A multi-disciplinary research project was initiated in July 1996 to compare the effects of winter fallow and winter cover crops in Willamette Valley vegetable production. This thesis addresses soil physical properties which are important for plant water relations, root growth, and microbial habitat. Responses in soil physical properties to these treatments were measured in six farm fields and two research stations. At a seventh farm site, conventional tillage was compared with minimum tillage. A third component of this research was to identify early indicators of change in soil quality trajectory. Lower bulk densities and enhanced water intake were observed in research plots and farm fields with cover crops when compared to fallow. As part of this research, a procedure was developed to pre-treat soil samples to equalize water content before determining aggregate size distribution. A simple technique was developed to obtain a subsample of specified mass that contained the same percentage of aggregate size fractions found in the parent sample. The dry aggregate size distribution procedure measured aggregate size fractions (1.00 - 2.00, 0.50 - 1.00, 0.25 - 0.50, 0.106 - 0.25, and < 0.106 mm) on soil samples pretreated to equalize soil sample water content at -1300 kPa. Cover cropping increased 1.00 - 2.00 mm aggregates ($P = 0.05$) in farm fields. Water stable aggregation improved at the Oregon State University Vegetable Farm (Corvallis, OR) research plots where cover crops have been part of the management plan since 1993. Aggregate size increase occurred in the farm fields after one winter cover crop and appeared to precede an increase in water stable aggregation. The results suggest that dry aggregate size distribution may be a useful early predictor of a change in soil quality.

AGGREGATION, BULK DENSITY, COMPACTION, AND WATER INTAKE RESPONSES TO WINTER COVER CROPPING IN WILLAMETTE VALLEY VEGETABLE PRODUCTION

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented December 18, 1998
Commencement June 1999

Master of Science thesis of Gilbert L. Buller presented on December 18, 1998

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Gilbert Buller

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ACKNOWLEDGMENTS

I am grateful to the following people for their assistance:

To Dr. Richard Dick for the opportunity to study, to contribute, and to be part of a multi-disciplinary research team.

To the Soil Quality Institute, NRCS, for funding the research project and providing financial support for my Research Assistantship.

To the people who readily agreed to serve on my thesis defense committee for their suggestions and critical evaluation: Dr. Larry Boersma, Dr. John Luna, Dr. Mina McDaniel, and Dr. Cathy Seybold.

To Joan Sandeno for her skill, good humor, and dedication in facilitating my research work and editing the manuscript.

To Bob Christ for his willingness to help in any way I needed.

To John Cliff for easing my frustration with SigmaPlot.

To my officemates Hudson Minshew and Mary Schutter for their friendship and creating a good office atmosphere.

To Evelyne Ndiaye, officemate and fellow researcher for her friendship, sense of humor, and determination; for her inquisitiveness about colloquialisms; and for the mutual search to understand statistics and the vagaries of American culture and academia.

To the women in my life: Ellen, my daughter, who shines with her own special light; Jan, my wife of 26 years, who has supported me emotionally through the ups and downs of being in graduate school at this stage in life, and who has provided the bulk of the family income during this time; and Helen, my mother, whose prayers and faith in me have never wavered.

CONTRIBUTION OF AUTHORS

Gilbert Buller conducted research, and designed and wrote each manuscript. Dr. Cathy A. Seybold was involved in the development of the research concepts and project framework. Dr. Richard P. Dick was engaged in research development and project format and analyzed each manuscript.

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INTRODUCTION

Agricultural production harnesses biological processes to provide food and fiber for human sustenance. Although many producers view themselves as stewards of a vital natural resource, they are rewarded primarily for short-term economic success. Much of the past academic and commercial research has been devoted to making producers more efficient. This emphasis has neglected or placed little value on other sustainability issues which are now the subject of much debate: the destruction of rural society and culture, consumer anxiety about pesticide residues in food, animal welfare, soil erosion and the pollution of surface and ground water.

Many of the sustainability problems are questions of biology. Biological soil processes are central to the ecological function of soils. Soil biotic activity controls the degradation and cycling of complex organic compounds and is the driving force in the evolution and maintenance of soil structure (Dick, 1992). Soil physical properties like aggregation, bulk density, and water intake describe and define the architecture in which biological processes take place. To solve sustainability problems, the demands of the biological component of agricultural production must be met. Continued reliance on chemical solutions to biological problems will prolong soil degradation.

Anecdotal observation and scientific inquiry are providing impetus to: (1) more clearly define soil quality; (2) identify quantifiable indicators of soil health; and (3) apply effective means to improve and maintain soil quality. Cover crops and green manures hold promise as one of the techniques to improve soil physical properties and to ameliorate poor soil conditions like slow water intake and nutrient leaching. Improved cash crop yield may be a benefit of incorporating cover crops into the production cycle (Ball-Coelho and Roy, 1997).

CHAPTER 1

LITERATURE REVIEW

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SOIL QUALITY AND COVER CROP DYNAMICS

Soil Quality

Soil is composed of air, water, mineral matter and organic matter. It functions as: (1) a medium for plant growth; (2) a habitat for soil organisms; (3) a recycling system for nutrients and organic wastes; (4) a system for water supply and purification; and (5) an engineering medium (Brady and Weil, 1996). Soil is a thin layer of dynamic and living material covering the earth's mantel and represents the difference between survival and extinction for most terrestrial creatures. It is a natural resource that is nonrenewable within an individual human's life span (Jenny, 1980).

Webster's Seventh New Collegiate Dictionary (Merriam, 1967) defines quality in part as "the attribute of an elementary sensation that makes it fundamentally unlike any other sensation." The olfactory sensation of a freshly tilled old timer's garden or the tactile sensation of a handful of soil with good tilth are subjective indicators of what soil quality entails. Doran and Parkin (1994) defined soil quality as "The capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health." Increasing awareness of the association between human health and welfare and the health of the soil has provoked soil scientists to investigate soil parameters that can be used as indicators of soil quality (Haberern, 1992).

Observations ranging from the simple to the complex made by layman and scientist alike provide ample evidence and support for developing indices and tools to assess the condition of managed soils. More importantly, the demands of worldwide human population growth and the encroachment of suburban and industrial development onto prime agricultural soil magnify the significance of the need to move from the identification and assessment of soil quality to the practical implementation of strategies and methods that will improve and maintain this life-giving resource. Therefore, the indices and tools used to assess and improve soil quality must be useable to farmers and managers as well as scientists and policy makers. In addition, practical soil investigations require rapid and inexpensive field methods (Coote and Ramsey, 1983).

Early indicators of changes in soil quality include biological, chemical and physical characteristics that respond to management practices. Shifts in biological activity can be detected by properties such as microbial biomass, carbon mineralization, β-glucosidase activity, calico cloth decomposition and fluorescein diacetate hydrolysis. Chemical indicators include inorganic nitrogen, phosphorus and exchange cations, pH, electrical conductivity, total organic carbon, total nitrogen and cation exchange capacity. Aggregate size distribution, aggregate stability, bulk density, compaction, and water intake are physical characteristics of interest.

Cover Crops

Most soils classified as Mollisols formed under the influence of a mixture of native grasses that together with the soil and soil fauna provided the foundation for many of the highest yielding agricultural areas. High organic matter accumulation occurred under prairie grasses; many studies have documented the attributes of freshly broken sod and the decline in organic matter commensurate with continuous tillage and crop production (Jenny, 1941; Gupta and Germida, 1988; Naidu et al., 1996; Saviozzi et al., 1997).

Sanford (1982) defines a cover crop as "A close-growing crop grown primarily for the purpose of protecting and improving soil between periods of regular crop production or between trees and vines in orchards and vineyards," and a green manure as "Any crop grown for the purpose of being turned under while green or soon after maturity for the purpose of soil improvement." Enhanced soil structure, reduced soil erosion, increased water intake and holding capacity, enriched fertility, and suppression of pests including pathogens, insects, and weeds have been ascribed to cover crops (Rodgers and Giddens, 1957; Blevins et al., 1990; Lal et al., 1991). Research also has shown the ability of cover crops to capture and hold remaining nitrogen from cash crop production and keep nitrate concentrations in groundwater below the 10 ppm EPA standard (Brandi-Dohrn et al., 1997; Minshew, 1999). Vegetable row crop farmers in the Willamette Valley of Oregon report improved soil tilth when grass seed is included in the rotation (D. McGrath, Oregon State Univ. Extension, 1996, personal communication); grass seed is a sod-type crop typically in place for three years and functions as a cash crop.

A USDA funded project in the Willamette Valley of Oregon entitled "Influences of alternative vegetable systems on arthropods/soil biological dynamics and soil quality trajectory" was designed to quantify the effects of cover crops on soil quality in vegetable crop production. Also known as the Soil Quality Project, the project compared winter fallow and winter cover crops at two research sites as well as several farm fields. Studies were undertaken to measure soil physical characteristics likely to change with increased biological activity due to the effect of cover crops: aggregate size distribution (ASD), bulk density (BD), soil compaction (CMP), water intake (WI), and water stable aggregation (WSA).

SOIL PHYSICAL PROPERTIES

Soil Aggregation

Aggregation is the binding of the primary soil particles sand, silt and clay into structural units. Flocculation of clay particles is an important process in the formation of a stable microaggregate $< 250\ \mu m$ and a prerequisite for water stable aggregation. Bridges between polyvalent cations and the surface of clay particles, hydroxy polymers, or carboxyl groups are considered to be the most important interactions (Tisdall and Oades, 1982). A single fragment of humified organic matter may be bonded to more than one clay particle or several fragments of humified organic matter may be bonded to a single clay particle (Edwards and Bremner, 1967).

Several decades of research on the rhizosphere have established that roots affect soil microbial activity, soil aggregate formation and aggregate stability. In modern agricultural soils, the roots of growing crops exert a strong influence on the soil microflora, stimulating microbial development in the rhizosphere (Rovira, 1959), and releasing organic materials known as exudates or mucilage which are important stabilizing agents in agricultural soils (Harris et al., 1966; Allison, 1973; Russell, 1973). In addition to the stabilization of aggregates, mucilage is a source of soil carbon and a zone of acidification, cation exchange, nutrient uptake and ion selectivity (Oades, 1978).

The presence of microorganisms influences root exudation by altering the permeability and metabolism of root cells, and by changing some of the material released from roots (Bowen and Rovira, 1976). When plant mucilage decomposes, most of it is replaced by microbial mucilage, resulting in more thorough contact between clay and organic materials (Blevins et al., 1970; Foster and Rovira, 1976). Sorption of fine clay particles on mucilages or microbial debris is considered to be the initial step in aggregation and the rhizosphere is the region in the soil where this occurs (Oades, 1978). A reciprocal relationship exists between soil biota and soil structure. As more structural aggregates are formed by soil biotic activity, more habitable pore space is created for the soil life (Jastrow and Miller, 1991).

Organic binding agents have been classified by Tisdall and Oades (1982) as transient (primarily polysaccharides), temporary (roots and fungal hyphae), and persistent (aromatic compounds associated with polyvalent metal cations, and strongly sorbed polymers). Subsequent research employing scanning electron microscopy has shown large amounts of temporary binding agents in undisturbed soils compared to cultivated soils indicating that greater concentrations of organic matter and hyphae contributed to structural stability in undisturbed soils and conversely, a reduction of these agents caused greater sensitivity to dispersion in cultivated soils (Naidu et al., 1996).

Lime, crop rotation, type of crop, and season affect soil aggregation. Microbial gums disappear quite rapidly in the fall when they become a food source for other microorganisms that are responding to less food supply from crop roots (Rennie et al., 1954). Inclusion of a legume in crop rotation has been reported to significantly increase aggregate size and stability compared to continuous corn (Webber, 1965). Perennial ryegrass improved the aggregate stability of a sandy loam soil and different crops had varying effects on this soil property (Reid and Goss, 1981).

Aggregate size distribution

Soil structure is the arrangement of particles and associated pores in soils across a size range. Aggregate size distribution (ASD) is a measure of this arrangement. The formation of soil structure includes physical forces such as freeze-thaw cycles, wetting-drying cycles, shrink-swell due to water content changes, tillage and movement of larger soil fauna (Oades, 1993). Change in ASD is minimal in sands and maximal in clays, since the expansive properties of soils are controlled by the clay content (Unger, 1982; Ben-Hur and Shainberg, 1989). Previous research has identified soil texture (Chepil, 1953; Lyles and Woodruff, 1960), calcium carbonate (Chepil, 1954), and organic matter content (Chepil, 1955) as variables in aggregate size distribution. A crop rotation study by Angers (1992) showed aggregate mean weight diameter (MWD) fluctuating with the type of crop. Tillage can have a significant effect on ASD (Angers et al., 1993) and variation induced by season and climate have been reported (Anderson and Wendhardt, 1966; Bisal and Nielsen, 1967; Perfect et al., 1990).

The hierarchical organization of soil aggregate structure was proposed by Tisdall and Oades (1982). Two sizes of aggregates were described based on differences in binding agents and stability. The primary soil particles (sand, silt, clay) combine to form microaggregates ($< 250\ \mu m$) and are held together by polysaccharides and organo-mineral complexes. They are strongly resistant to destruction by rapid wetting and mechanical disturbance (Gijsman, 1996). Fine roots and fungal hyphae bind microaggregates together forming macroaggregates (> 250 μm) which are affected by agricultural management (Miller and Jastrow,1992; Naidu et al., 1996; Tisdall et al., 1997).

Aggregate stability

The transient, temporary, and persistent classification developed by Tisdall and Oades (1982) is based on soil aggregate resistance to breakdown due to wetting and tillage. Resistance to breakdown is primarily a function of binding agent strength and secondarily of aggregate size. Efficient crop production depends on soil structure composed of aggregates > 1 mm which do not slake when wetted. Unstable aggregates slake into smaller units when rapidly wetted (Emerson, 1977). Macroaggregate stability therefore is central to maintaining desirable soil structure for optimum crop production.

Soil structure is altered by crop type and tillage intensity. Different effects on soil structure occur due to organic matter composition and additions, diverse rooting patterns and rhizosphere processes, and provision for soil surface protection (Broersma et al., 1996). Aggregation increases in proportion to the amount and type of perennial crops used in rotation (Harris et al.,1966; Lynch and Bragg, 1985; Baldock and Kay, 1987), by using no or low tillage rather than conventional cultivation techniques (Zobeck and Popham, 1990; Angers et al., 1993), and in response to winter cover versus winter fallow (Miller and Dick, 1995).

Bulk Density, Compaction and Water Intake

Bulk density is the mass of a unit volume of soil (Mg m^{-3}), and the volume includes solids and pores. Total porosity or percent pore space is calculated from bulk density. Pore space and soil texture are determinants of water intake and storage. Sandy soils generally have less pore space and higher bulk densities than fine-textured soils like silt loams and clays. Soil structure and the degree of looseness or compactness affect bulk density. Bulk density is a factor in the specific heat capacity, thermal conductivity, and thermal diffusivity of the soil (Hillel, 1982).

The bulk densities of agricultural soils are typically from 1.1-1.6 Mg m^{-3}, and root growth is greatly impaired when bulk density exceeds this range (Brady and Weil, 1996). A model for growth-limiting bulk densities as related to soil texture was developed by Daddow and Warrington (1983). Agricultural activity has been reported to increase bulk density and reduce pore size through compaction of the soil and the resultant loss of soil structure. Wheel traffic compaction eliminated the effect of tillage on bulk density in a study that compared moldboard plowing and conservation tillage (Voorhees and Lindstrom, 1984). Wheel compaction increased bulk density in the upper 15 cm from 1.3 to 1.6 Mg m^{-3} , and total porosity decreased from 51 to 41 percent, resulting in a loss of more than 1 cm of water storage capacity in the top soil profile (Voorhees, 1986).

Crops can respond to soil compaction with increased production of root exudates (Barber and Gunn, 1974; Boeuf-Tremblay et al., 1995), resulting in less microbial diversity and increased populations of opportunistic bacteria (Ikeda et al., 1997). Other morphological changes include restriction of root extension and shoot growth, and modification of root pattern and diameter (Dexter, 1986; Lipiec et al., 1991; Taylor and Brar, 1991; Kooistra et al., 1992). Nutrient restriction caused by soil compaction was shown to induce physiological changes in corn and barley (Lindberg and Pettersson, 1985; Wolkowski, 1990; Dolan et al., 1992).

Water entry into the soil is called infiltration or intake and can be described by the principle of saturated hydraulic conductivity (K_s). In a narrow sense, K_s is the ease with which the soil pores permit water movement (Brady and Weil, 1996). In practical applications, it is usually thought of as the rate at which a quantity of water flows through a uniformly saturated soil profile. Water intake rates are measures of saturated hydraulic conductivity.

Water intake is an integrative index for the previously discussed soil physical properties because it is directly related to bulk density (Babalola, 1978; Patel and Singh, 1981), soil structural stability (Tisdall and Adem, 1986), and pore structure (Ankeny et al., 1990 Boggs; et al., 1997). The relationship of organic matter and water intake is not as clear; Wischmeier and Mannering (1965) found that of the variables they tested, organic matter was most closely correlated with intake, while a later study (De Kimpe et al., 1982) concluded that in some instances, organic matter had little effect on K_s. No published reports were found which simultaneously studied water intake and the organic matter fraction affected by soil management described by Cambardella and Elliott (1992).

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CHAPTER 2

BULK DENSITY, COMPACTION, AND WATER INTAKE: IN-FIELD MEASUREMENTS OF COVER CROP AND TILLAGE EFFECTS IN VEGETABLE ROW CROP PRODUCTION

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Prepared for

Soil Science Society of America Journal

ABSTRACT

Agricultural producers are interested in adopting more sustainable systems but they need quantification that these systems can improve soil quality and nutrient efficiency while maintaining or increasing crop yields. Improved soil physical properties are important to growers for ease of tillage, seed bed preparation, water use efficiency, and root growth. An improved system utilizing a winter cover crop following summer vegetable crops was tested for its effects on bulk density, compaction and water intake. Simplified procedures were used to quickly measure these soil physical characteristics. Enhanced water intake ($P < 0.1$) and reduced bulk density ($P < 0.05$) under cover crops were demonstrated in research plots and commercial fields where cover crop/fallow comparisons were made. Minimum tillage reduced bulk density ($P < 0.05$) in a commercial field conventional tillage/minimum tillage paired comparison experiment. Dependable soil compaction testing awaits further refinement of devices that simultaneously record soil water content and cone penetration resistance.

INTRODUCTION

Indices and tools to assess soil quality are needed as demand increases for the intensification of agricultural production. Practical soil investigations require rapid and inexpensive field methods that are useful to farmers and managers as well as scientists and policy makers (Coote and Ramsey, 1983). Early indicators of change in soil quality trajectory will assist agricultural producers as they implement strategies that simultaneously meet food and fiber demand and maintain the productive quality of the soils they manage.

The Oregon Long-term Soil Quality Project began in July 1996 to investigate the effects of winter cover crops in summer vegetable row crop production. Inter-disciplinary in nature, the project investigated above-and below-ground fauna and biological, chemical, and physical soil characteristics. These were tested as possible early indicators of change in soil quality following implementation of different soil management techniques i.e., winter cover crop in place of winter fallow and minimum tillage rather than conventional tillage.

Bulk density and water intake are inversely related soil physical properties of importance to crop production and soil quality (Babalola, 1978; Patel and Singh, 1981). Vegetable row crop production in the Willamette Valley of Oregon is governed to a large extent by vegetable processors who schedule planting and harvest dates to maximize production throughout the growing season. To meet these schedules, producers often must perform tillage and harvesting operations when soil water content is too high which results in a reduction in soil structure and water intake and an increase in compaction and bulk density. Soil compaction from tillage and production activity increases bulk density, reduces water intake, and can create perched water tables resulting in less than optimal plant growth conditions (Voorhees, 1986; Ikeda et al., 1997).

Establishment of a winter cover crop is one technique of interest that producers can use to improve soil quality, reduce nutrient leaching, and mitigate soil compaction. Enhanced soil structure, reduced soil erosion, increased water intake and holding capacity, enriched fertility, and suppression of pests including pathogens, insects, and weeds have been ascribed to cover crops (Rodgers and Giddens, 1957; Blevins et al., 1990; Lal et al., 1991). We hypothesized that compared to winter fallow, a winter cover crop would reduce bulk density and compaction and increase water intake due to more vegetative cover, additional rhizosphere stimulation of biological activity, and greater C inputs. One Oregon State University research station and seven commercial vegetable fields were included for study.

MATERIALS AND METHODS

Experimental Sites

All research sites are located in the Willamette Valley of western Oregon. The climate is characterized by moist, cool winters with warm, dry summers and average annual rainfall of 1040 mm. Soils in the project are primarily Mollisols and soil textures are loam variants (Table 2.1).

Winter fallow and winter cover crop treatments were established after harvest of the summer vegetable crop. The treatments were in place during the winter and ended when field preparation began for the new vegetable crop. Crops produced for economic consideration were irrigated summer vegetables and a variety of cover crops was used. The Vegetable/Winter Interseeded Cover Crop Study located at Oregon State University Vegetable Research Station (VF), Corvallis, Oregon, was established in 1993. The experimental design was a randomized complete block with two treatments, winter fallow and mixed legume/cereal winter cover crop replicated four times (Table 2.2).

Table 2.1. Taxonomy and selected characteristics for soils in the Soil Quality Project.

Site	Classification			Clay	Silt	Sand	pH	Total C	Water content
	Series	Family	Subgroup						-1500 kPa
				------- kg kg^{-1} -------				g kg^{-1}	kg kg^{-1}
DI	Amity	Fine-silty, mixed, mesic	Argiaquic Xeric Argialboll	26	67	7	5.9	17.7	0.12
GR	Newberg	Coarse-loamy mixed, mesic	Fluventic Haploxeroll	19	50	31	6.0	32.6	0.14
	Cloquato	Coarse-silty mixed, mesic	Cumulic Ultic Haploxeroll	16	38	46	6.2	20.2	0.12
HA	Chehalis	Fine-silty, mixed, mesic	Cumulic Ultic Haploxeroll	27	59	14	6.1	14.4	0.14
HE	Saturn	Fine-loamy over fragmental, mixed, mesic	Fluventic Haplumbrept	32	47	21	6.4	35.1	0.15
LU	Aloha	Fine-silty, mixed, mesic	Aquic Xerochrept	20	70	10	6.7	12.9	0.09
PE	Woodburn	Fine-silty, mixed, mesic	Aquultic Argixeroll	22	69	9	6.4	13.1	0.11
VF	Chehalis	Fine-silty, mixed, mesic	Cumulic Ultic Haploxeroll	26	52	22	5.9	16.5	0.14
KE	Newberg	Coarse-loamy mixed, mesic	Fluventic Haploxeroll	24	53	23	5.7	19.3	0.14
	Chehalis	Fine-silty, mixed, mesic	Cumulic Ultic Haploxeroll	25	56	19	5.6	19.2	0.14

Table 2.2. Winter cover and summer vegetable crop rotation at farm and research station experiment sites.*

Site	1996	1997		1998	
	Summer vegetable	Winter cover	Summer vegetable	Winter cover	Summer vegetable
DI	Sweet corn†	Annual ryegrass††	Cauliflower	Barley, oat	Sweet corn
GR	Sweet corn	Barley, common vetch‡‡	Sweet corn	Barley, common vetch	Sweet corn
HA	Wheat‡	None	Green bean†††	Annual ryegrass, common vetch	Sweet corn
HE	Cauliflower§	None	Sweet corn	Oat, common vetch	Green bean
KE	Barley¶	Oat§§	Green bean	Barley	Sweet corn
LU	Cauliflower	Oat	Sweet corn	Barley, common vetch	Cauliflower
PE	Cauliflower	Common vetch	Sweet corn	None	Grass seed
VF	Broccoli#	Annual ryegrass, buckwheat¶¶, oat, red clover##	Sweet corn	Annual ryegrass, buckwheat, oat, red clover	Green bean

*Grower sites under cultivation since early 1900's except GR which was under forest vegetation before 1996; VF winter cover cropping began in 1993 and summer vegetable was broccoli in 1994 and 1995.

†*Zea mays* L., ‡*Triticum aestivum* L., §*Brassica oleracea* L., ¶*Hordeum vulgare* L., #*Brassica oleracea* L., ††*Secale cereale* L., ‡‡*Vicia sativa* L., §§*Avena sativa* L., ¶¶*Fagopyrum esculentum L.*, ##*Trifolium pratense* L., †††*Phaseolus vulgaris* L.

Each of six commercial vegetable producers designated one field to be part of the project; they are Dickman (DI), Grover (GR), Hamlin (HA), Hendricks (HE), and Pearmine (PE) Farms, and Lucht-Northwest Transplants (LU). Each field (Table 2.2) was a block in a randomized complete block experiment (Farms). Steve Campbell, Natural Resource Conservation Service, mapped the fields in detail. After summer vegetable harvest, each field was split into a winter cover crop and winter fallow treatment. Five sampling sites were established on each treatment and paired by soil type and texture. All sites were marked and located with a Global Positioning System (GPS) receiver.

A tillage trial was conducted with a seventh commercial vegetable producer. The Kenagy (KE) site was similarly designed, but the field was split into conventional tillage and minimum tillage treatments for the summer crop. In spring 1996, a cover crop of barley (*Hordeum vulgare* L.) was planted with a no-till drill on the entire field. After harvest, the barley stubble was disced twice and oat (*Avena sativa* L.) cover crop was planted on the whole field. Flooding in December killed the cover crop; barley was planted in spring 1997 as a cover crop and terminated chemically. On the conventional tillage part of the field, the cover crop was mowed and disced twice. A spring-tooth harrow was used before planting the summer vegetable crop. On the minimum tillage part of the field, a no-till drill was used to plant the summer crop directly into the barley stubble. After harvest of the summer crop, a cover crop was planted for the winter. In 1998, a strip tillage planting system was used on the entire field to plant the summer vegetable crop directly into the cover crop which had been chemically killed. In the minimum tillage part of the field, fertilizer was banded; in the conventional tillage part of the field, fertilizer was broadcast and incorporated with a rototiller.

Soil Procedures

Procedures to measure bulk density, compaction, and water intake were done six to twelve days after the summer vegetable crop was planted. Measurements were made in one non-traffic interrow and one traffic interrow. Composite measurements were calculated from the non-traffic interrow and traffic interrow measurements, and were based on crop planter width and tractor tire width (Tables 2.3 and 2.4) by using these formulae:

$$\text{Non-traffic weighting} = (\text{planter width} - \text{tractor tire width}) / (\text{planter width}) \quad [1]$$

$$\text{Traffic weighting} = (\text{tractor tire width}) / (\text{planter width}) \quad [2]$$

$$\text{Composite measurement} = (\text{non-traffic weighting}) \times (\text{non-traffic interrow measurement}) + (\text{traffic weighting}) \times (\text{traffic interrow measurement}) \quad [3]$$

Bulk Density and Compaction

Soil compaction was measured with a Dickey-John penetrometer (Dickey-John Corporation, Auburn, IL) and soil bulk density was measured with a Troxler nuclear density gauge (Troxler Electronic Laboratories Inc., Research Triangle Park, NC). A test area a little larger than the density gauge template (20 x 35 cm) was prepared by filling uneven soil surfaces with soil aggregates < 2 mm. The template was used as a

Table 2.3. 1997 vegetable planting parameters and dates of in-field measurements.

Site	Procedure date	Vegetable	Planter rows	Planter row spacing (cm)	Non-traffic weighting	Traffic weighting†
DI	6/07	Cauliflower	4	102	0.8250	0.1750
GR	6/29	Sweet corn	6	76	0.8444	0.1556
LU	5/23	Sweet corn	4	91	0.8056	0.1944
PE	5/17	Sweet corn	6	76	0.8444	0.1556
VF	6/20	Sweet corn	4	76	0.7667	0.2333
KE	6/13	Green bean	4	76	0.7667	0.2333

† 71 cm total tractor tire width in all cases.

Table 2.4. 1998 vegetable planting parameters and dates of in-field measurements.

Site	Procedure date	Vegetable	Planter rows	Planter row spacing (cm)	Non-traffic weighting	Traffic weighting†
DI	6/24	Sweet corn	6	76	0.8444	0.1556
GR	4/25	Sweet corn	6	76	0.8444	0.1556
HA	6/15	Sweet corn	4	91	0.8056	0.1944
HE	4/30	Green bean	8	61	0.8542	0.1458
LU	7/28	Cauliflower	4	102	0.8250	0.1750
VF	6/16	Green bean	4	76	0.7667	0.2333
KE	6/30	Sweet corn	4	76	0.5000‡	0.5000

† 71 cm total tractor tire width in all cases.
‡ No evidence of tractor tires; data from two measurements weighted evenly.

guide for the penetrometer. Compaction measurements were taken with a 1.27 cm diameter cone tip at 5 cm increments from 5 cm to 30 cm. With the template still in place, the hole left by the penetrometer was enlarged to 1.9 cm to accept the density gauge source rod; the template was removed and the density gauge was set in its place. Bulk density readings were recorded at the same depth increments as compaction. No consistent pattern between bulk density and compaction readings were observed.

The density gauge gives an average bulk density reading from the soil surface to the depth at which the source rod is set. These average gauge density readings were converted to get average bulk density for each 5 cm increment using this equation:

$$\text{mean bulk density for depth n - 1 to n} = \{\text{n}a_{\text{n}} - (\text{n} - 1)a_{\text{n}-1}\}/\,2 \qquad [4]$$

where n is 1, 2, 3, 4, 5 and 6 for 5, 10, 15, 20, 25 and 30 cm depth increments respectively, and a is the gauge reading in Mg m^{-3}.

Water Intake

Falling head water intake was measured using a single aluminum ring 30 cm in diameter and 30 cm high set 15 cm into the soil. One liter of water was added to the ring to saturate the soil. When freestanding water was no longer visible, 250 mL of water was added to the ring and the time was recorded. When freestanding water was again no longer visible, the time was recorded. This was repeated until two consecutive elapsed times were the same. If freestanding water was gone in under 1 min, 500 mL was added to the ring instead of 250 mL. If freestanding water remained after 10 min, subsequent tests were done with 125 mL or 50 mL. Intake rates were calculated by entering field recordings of water volume and elapsed time into this equation:

$$\text{cm h}^{-1} = (a / \pi r^2) / (t_1 - t_0) \qquad [5]$$

where a is the volume of water added to the ring, r is the ring radius, and t is time.

Data Analysis

The project began in July 1996, after the summer vegetable crops were planted. This eliminated the opportunity to gather baseline data for these procedures. At the beginning of the project, cooperating farmers agreed to split their fields into the two treatments for at least two years. However, this was not possible in all cases due to farm management priorities, resulting in one year of data for PE (1997), HA (1998) and HE (1998). Analysis of bulk density and water intake data for the Farms was done for year one (all farm sites with one year of winter cover crop), and year two (all farm sites with two years of winter cover crop). Year one included data from all farm sites, and year two included data from the DI, GR and LU sites. Data were collected for year one and year two at the conventional tillage/minimum tillage and research sites. Analysis of the bulk density and compaction data at each depth increment yielded no consistent results. For bulk density, the unconverted density gauge reading for 30 cm (0-30 cm average) was analyzed. For compaction, incremental depth data for each sampling point was averaged. Analysis of the averaged data is presented and discussed. Paired t-tests for each commercial site and analysis of variance (ANOVA) for Farms and VF research station were done using SAS statistical software (SAS Institute, 1988).

Soil water content has a direct effect on compaction (Hillel, 1982) and thus on penetrometer resistance. The nuclear density gauge can determine percent moisture, but no meaningful correlation was found between compaction and density gauge moisture data. Therefore the compaction data obtained are useful only for comparison within a single site and for the day on which the testing was done.

RESULTS

Compaction

No significant cover crop treatment effect on soil compaction was measured at any of the project research sites except at HE (Table 2.5). The difference noted is confounded by nonuniform summer crop planting at the time of measurement. Planting acreage and dates for vegetable growers are controlled by the vegetable industry which resulted in two planting dates at this site. The first planting included all five fallow sampling points and one cover crop sampling point. The second planting ten days later included the four remaining cover crop sampling points. All three soil parameters were tested at all ten sampling points eight days after the first planting. A confounding effect from the time difference in planting this close to the time of testing may explain the significant difference in compaction at this site since the four cover crop sampling points received less tillage at the time of testing. The lack of significant compaction data from the other sites in the project was primarily a function of the penetrometer design. The device used for this project has an analog gauge with too few subdivisions. Soil water content is a critical factor in soil resistance to penetration, and timely, reliable water content determination when compaction was measured was not feasible.

Table 2.5. Means for bulk density and penetrometer resistance after tillage and cover crop-fallow treatments.

Site	Year	Bulk density		Penetrometer resistance	
		Conventional	Improved	Conventional	Improved †
		Mg m^{-3}		kPa	
DI	1997	1.449	1.418	644	592
	1998	1.419	** 1.315	1137	874
GR	1997	1.375	1.416	1259	1442
	1998	1.270	1.361	973	913
HA	1998	1.495	1.511	1166	1210
HE‡	1998	1.455	1.361	1003	* 765
LU	1997	1.515	1.533	1625	1715
	1998	1.418	1.415	1433	1323
PE	1997	1.489	1.511	1040	1038
Farms	1997	1.463	1.459		
	1998	1.361	1.364		
VF	1997	1.433	1.392	1098	957
	1998	1.486	* 1.460	855	864
KE	1997	1.244	1.249	976	933
	1998	1.396	* 1.344	1374	1254

† For KE conventional is conventional tillage and improved is minimum tillage; for all other sites conventional is fallow and improved is cover crop.

‡ See text for discussion of confounding factor.

*, ** Pairs within a site and year for bulk density or penetrometer resistance are significantly different at $P < 0.05$ and 0.01, respectively.

Bulk Density

At the KE tillage site, bulk density showed no significant difference in 1997. In 1998, minimum tillage bulk density was significantly lower ($P < 0.05$) than conventional tillage bulk density. Winter cover crops have been part of the management plan at the VF research site since 1993 and there was a trend toward lower bulk density with cover crops, but this was not significant ($P < 0.1$) for 1997. In 1998, bulk density was significantly lower at $P < 0.05$ in the cover crop treatments than in the fallow treatments at the VF site (Table 2.5).

There was no significant difference either year in bulk density due to fallow and cover crop treatments when ANOVA was done across all farms. However, paired comparisons within individual fields showed an interesting trend at the DI site. After one year of cover cropping, no significant effect on bulk density was found, but there was a statistical difference after two years (Table 2.5). No cover crop effect on bulk density was seen at the GR, HA, LU, and PE sites. Bulk density at the HE site appears to show favorable response to cover crop treatment. The same confounding effect from a nonuniform summer vegetable planting date as described for the compaction results at this site likely contributed to the significant difference in bulk density as well. Inclusion of this site in the Farms analysis did not substantially alter the ANOVA results or overall means for bulk density.

Water Intake

At the KE site, water intake was lower in 1998 than in 1997 for both tillage regimes. In 1998, water intake for the minimum tillage was significantly lower than for the conventional tillage (Fig. 2.1). The 1997 data show water intake marginally higher in the cover crop plots ($P < 0.2$) at the VF research site. In 1998 there was less water intake than 1997 among all plots, but a significant treatment effect was observed on non-traffic and composite intake rates. Fig. 2.2 shows the depressed intake rate caused by wheel traffic and a slight mitigation of this in the cover crop plots.

No significant differences between cover crop and fallow treatments for water intake were noted at the HA and PE sites which had winter cover crops only one season (Fig. 2.3). Water intake at the DI site was not significantly different the first year, but improved dramatically after two cover crop treatments (Fig. 2.4). Water intake at the GR site appears to conform to the expected effect of cover crop treatment. After the first year, water intake was lower in the cover crop treatment, and it was slightly higher the second year, but statistical significance is lacking. The confounding effect of a non-uniform planting of the summer vegetable crop most likely affected the apparent water intake difference at the HE site. The difference was not significant.

Farms ANOVA for water intake did not change substantially by including the HE site, but the overall fallow and cover crop means were higher. Water intake at the LU site was significantly greater on the cover crop side of the field after the first year of data collection. Field preparation after termination of the second cover crop included subsoiling to break a tillage induced compaction layer. This likely introduced a confounding factor because data collection for the second year was done after the subsoiling. The second year intake rate for the cover crop side was marginally lower than the first year and the fallow side was somewhat higher, but a significant difference in water intake was lacking the second year at the LU site.

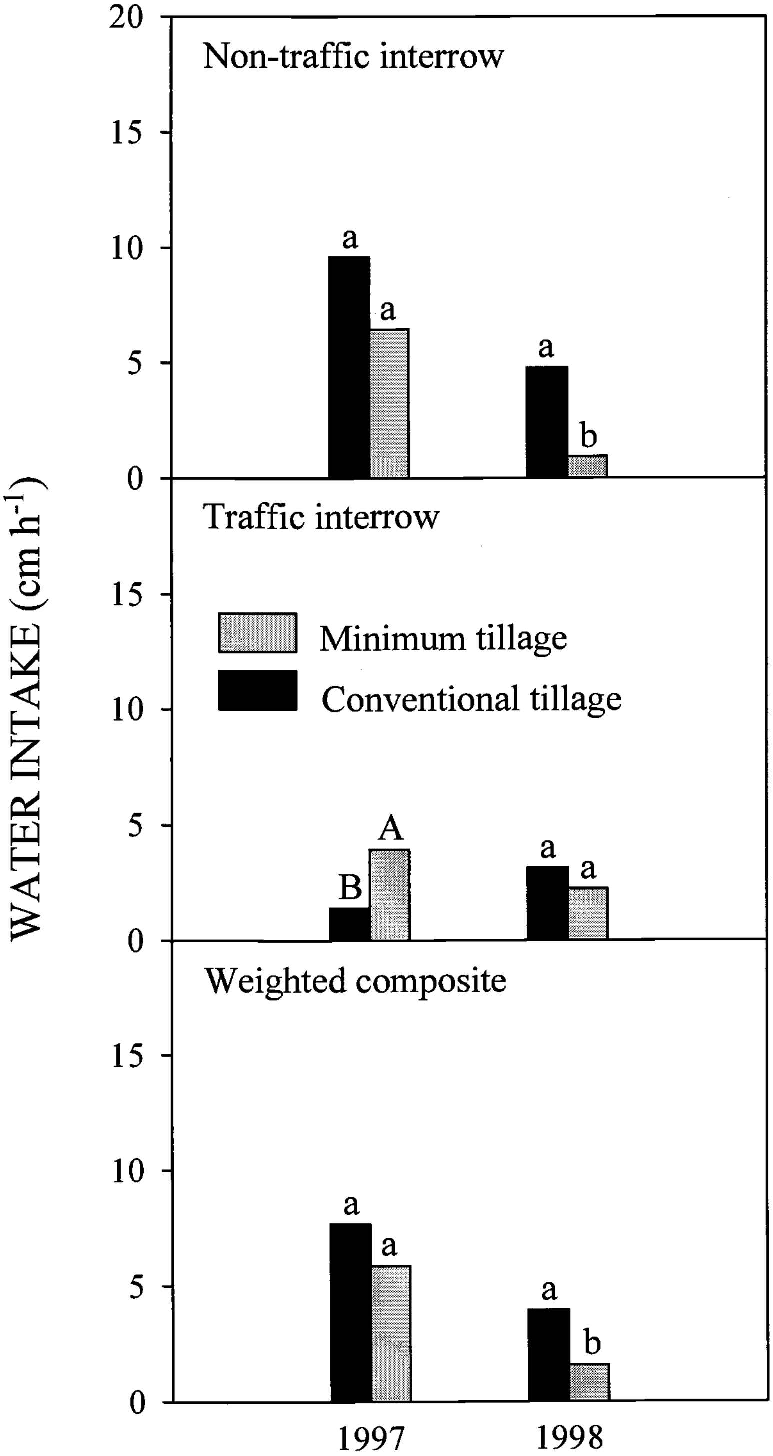

Fig. 2.1. KE site tillage effects on water intake in non-traffic interrows, traffic interrows, and weighted composite. Bars within a year with different lower case or upper case letters are significantly different at $P < 0.1$ and 0.05, respectively.

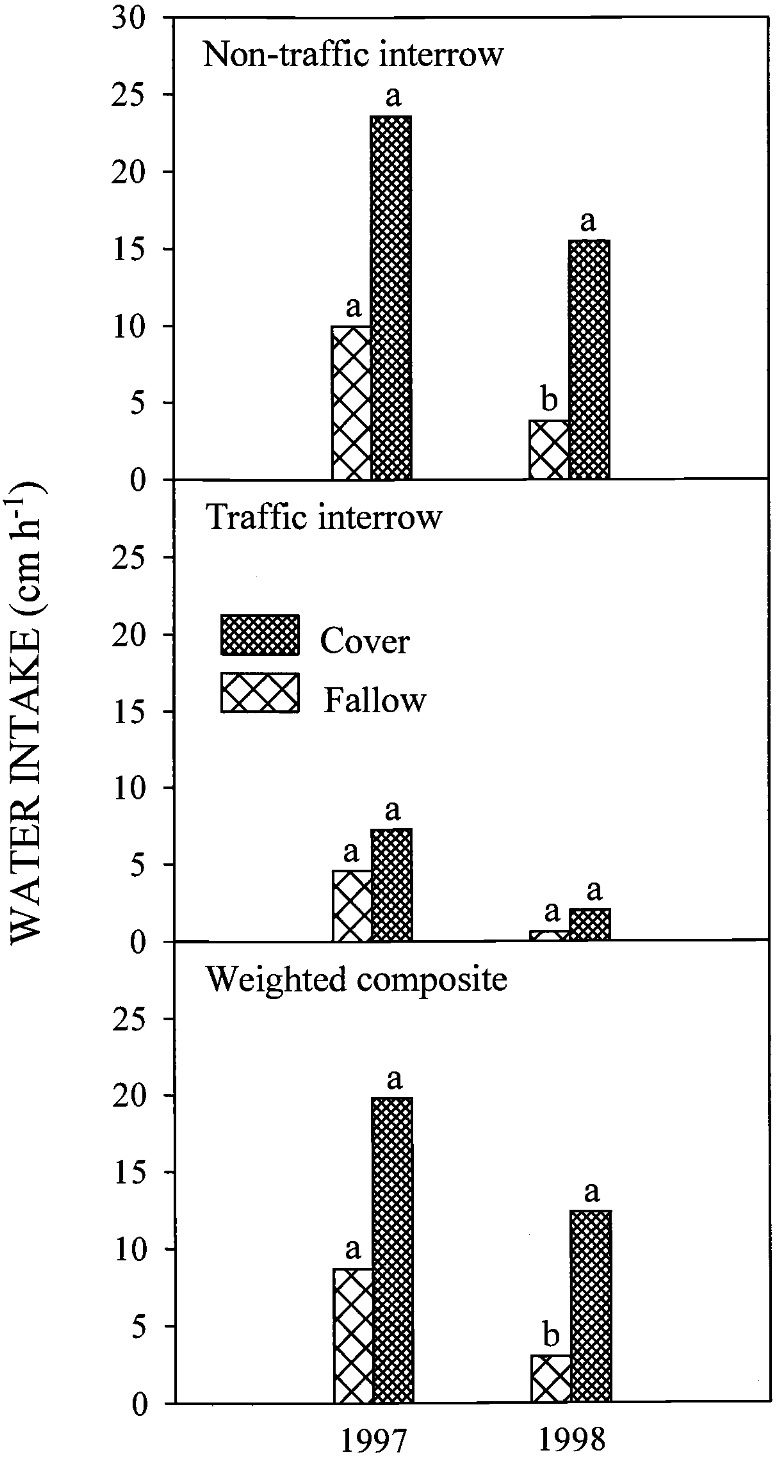

Fig. 2.2. Winter cover crop and winter fallow effects on water intake in non-traffic interrows, traffic interrows, and weighted composite at VF research station. Bars within a year with different lower case letters are significantly different at $P < 0.1$.

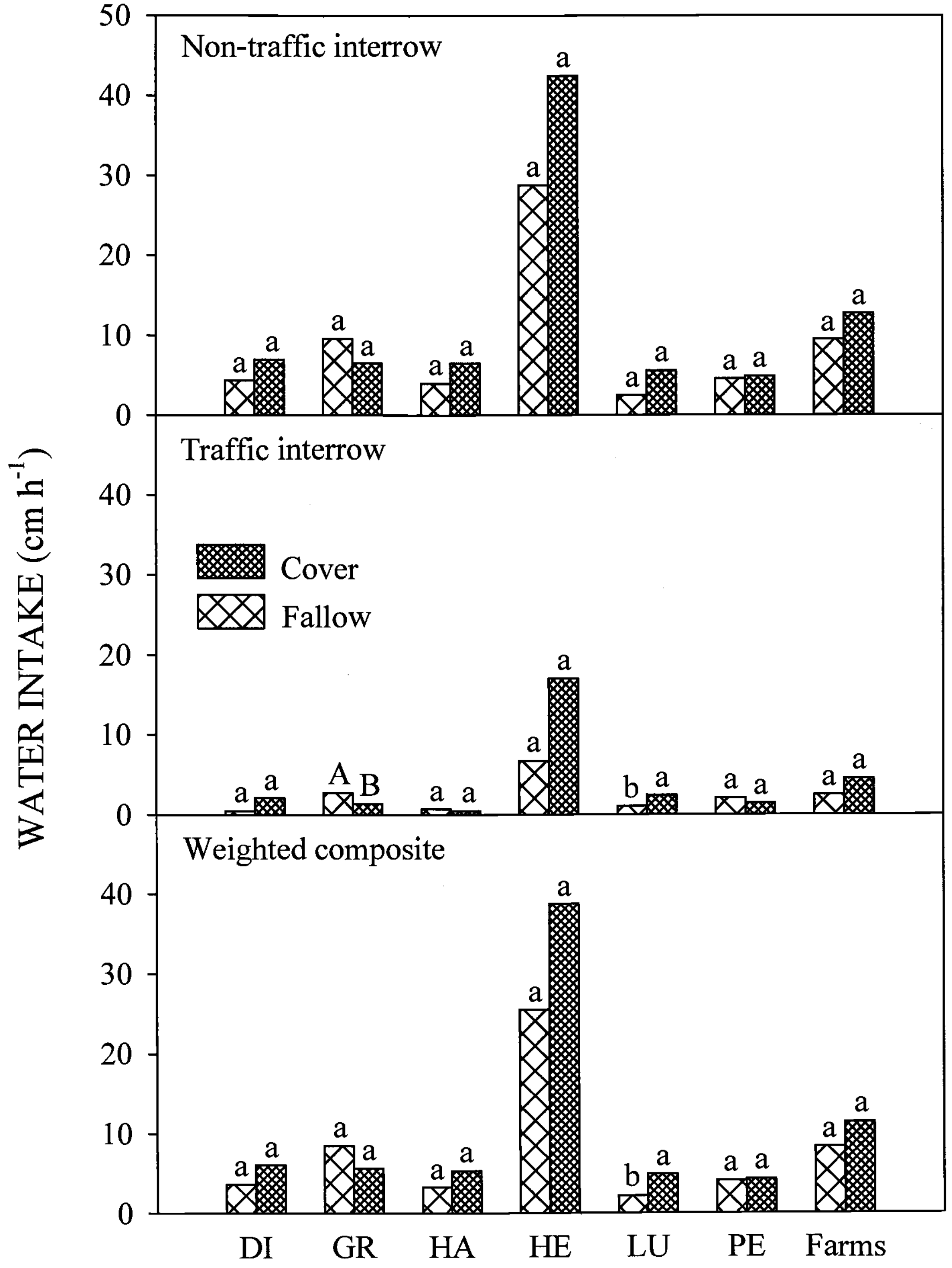

Fig. 2.3. Water intake in farm fields after one year of winter cover crop and winter fallow treatments in non-traffic interrows, traffic interrows, and weighted composite. Bars with different lower case or upper case letters are significantly different at $P < 0.1$ and 0.05, respectively.

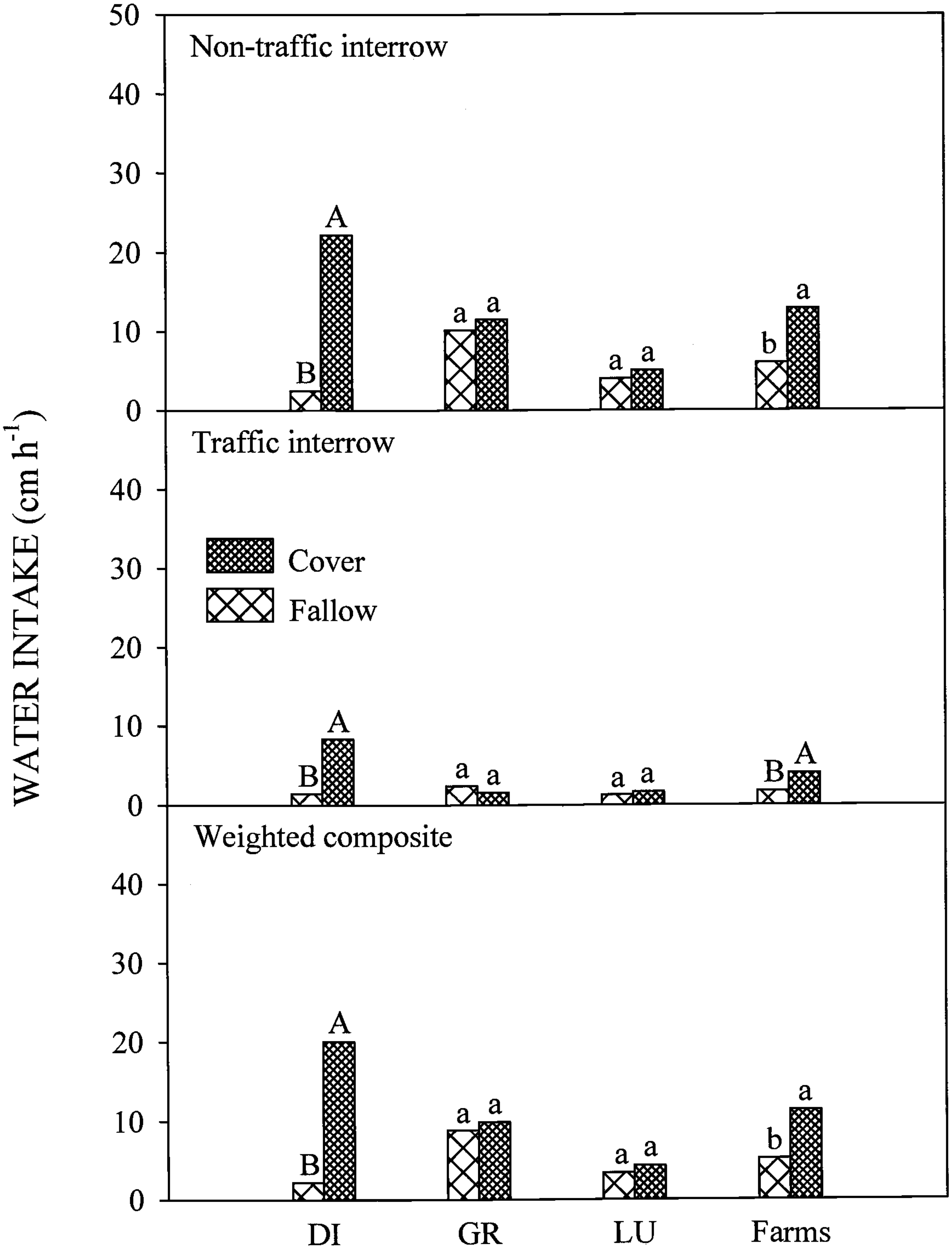

Fig. 2.4. Water intake in farm fields after two years of winter cover crop and winter fallow treatments in non-traffic interrows, traffic interrows, and weighted composite. Bars with different lower case or upper case letters are significantly different at $P < 0.1$ and 0.05, respectively.

DISCUSSION

Increased water intake is one reason for tillage, and the results of the tillage trial suggest minimum tillage may reduce water intake. Total lower porosity in no-till has been cited (Ehlers, 1975), but Sauer et al. (1990) reported that ponded infiltration in no-till was equal to or greater than it was in tilled soils. Increased numbers of earthworm burrows connected to the soil surface and a more stable soil structure were credited for this observation. Lower intake for the minimum tillage may not be problematic if attention is given to irrigation rates and because most rainfall in the Willamette Valley is distributed over a nine-month period. At this tillage trial site, adverse effects of slower intake like rill erosion are reduced by a winter cover crop. The significant reduction ($P < 0.05$) in bulk density in the minimum tillage side of the field at this site stands in contrast to other studies in which bulk density initially increased upon implementation of no-till (NeSmith and McCracken, 1994; Crovetto, 1998).

The water intake results for the first year of the Farms study reflect the often reported spatial variability of soil physical properties (Russo and Bresler, 1981; Coote and Ramsey, 1983; Trangmar et al., 1985; Tsegaye and Hill, 1998). Farms study coefficients of variability (CV's) ranging from 7 to 104 are similar to what other researchers have found. With data fluctuations of this magnitude, it is worth noting that all sites in this study except GR had higher means for water intake in the cover crop side of the field (Fig. 2.4). Interpretation of the results for the GR site require historical perspective. This field came into row crop production just prior to initiation of the project and had been under forest vegetation for about 80 years. Heavy machinery and large log trucks were used to harvest and remove the trees and stumps. Not all of the tree roots were removed from the subsurface soil profiles and slash was piled and burned on site. This activity could have affected the first year results, although the CV's were comparable to other sites in the Farms study.

The year two Farms cover crop water intake was significantly higher ($P < 0.1$) compared to the fallow. The DI site accounts for this, but the remaining Farms sites for year two (GR and LU) trend in this direction. The lack of statistical significance in the year two data at the GR site may be a cover crop effect since the first year data showed water intake in the fallow side of the field was greater ($P < 0.15$). The VF research station water intake results exhibit the same year to year pattern as the Farms. These two studies together suggest that winter cover crops can improve water intake.

Where significant treatment effects in the cover crop/fallow sites occurred for both water intake and bulk density (DI and VF research site), the winter cover crop caused lower bulk density and higher water intake. Cover crop biomass is less dense than soil solids, and its incorporation into the soil would tend to reduce soil bulk density, at least temporarily (Hillel, 1982). Decomposing plant material from cover crops is a source of soil organic matter which lowers soil bulk density and has been cited as a factor in increased intake and rainfall retention (Reicosky and Forcella, 1998).

Based on the cover/fallow treatments, a negative correlation ($r = -0.27$, $P < 0.05$, $n = 54$) between the Farms year one water infiltration and average bulk density data, is indicative of an inverse relationship between these two parameters. The same correlation improved for the year two Farms data ($r = -0.41$, $P < 0.05$, $n = 28$). This is consistent with results reported elsewhere (Patel and Singh, 1981; Dunn and Phillips, 1991; Dabney, 1998). Cover crops can increase macroporosity through root growth or by providing habitat and protection for burrowing soil fauna (Tomlin et al., 1995). When porosity increases, bulk density goes down; when macroporosity increases, infiltration and drainage of water increase (Hillel, 1982).

Cover crop roots can also improve water infiltration and bulk density through their effect on aggregate size and stability. Roots and associated fungi have been shown to be primary factors in the creation of aggregates > 250 µm (Tisdall and Oades, 1982; Jastrow, 1996). Larger aggregates do not pack as tightly as smaller ones, thus improving macroporosity. Cover crop biomass absorbs the kinetic energy of raindrops, reducing the detachment and rearrangement of soil particles that can cause surface sealing (Eastman, 1986; Römkens et al., 1990), allowing soil pores to remain open. Less soil erosion occurs because the plant biomass slows the flow of runoff in heavy rainfall (Parsons, 1949; Brill and Neal, 1950).

Even though the compaction data are not significant, it is likely that if porosity and water intake have increased measurably, compaction has probably been reduced. This can benefit the succeeding summer vegetable crop by enhancing seedling emergence and providing a healthier environment for new crop roots (Ikeda et al., 1997).

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CHAPTER 3

AGGREGATE SIZE DISTRIBUTION FOR MULTI-DISCIPLINARY SOIL RESEARCH

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Prepared for

Soil Science Society of America Journal

ABSTRACT

Distribution of aggregates into each size fraction can be affected significantly by the handling of soil samples, by soil sample water content, and by subsampling methods. Furthermore, it is often desirable to perform several procedures on one soil sample. Methods of handling and treating soil samples before determining dry aggregate size distribution are not standardized and can limit the usefulness of samples for other procedures, e.g. biological measurements. We found that variation in soil sample water content at the time of sieving caused unacceptable variation in aggregate size distribution, even after the sample was air dried before doing the distribution. On a silty clay loam soil, the largest aggregate fraction was > 53 percent at a water potential of -10^4 kPa and < 43 percent at -1.3×10^3 kPa ($P < 0.01$). In addition, it was found that subsampling methods also caused variation in aggregate size distribution. Consequently, a modified pretreatment aggregate size distribution procedure was developed. This method involved adjustment of soil sample water content (pretreatment) to a specified amount followed by sieving (2 mm), air drying, and aggregate size distribution. A simple technique was developed to obtain a subsample of specified mass that contained the same percentages of aggregate size fractions found in the parent sample. This technique reduced coefficients of variability within the 1 to 2 mm size fraction an average of 84 percent; the greatest CV reduction was from 21 to 1.6. A sample splitter was utilized to enable multiple uses of soil samples.

INTRODUCTION

Increasing awareness of the association between human health and welfare and the health of the soil has motivated soil scientists to investigate soil characteristics that can be used as early indicators of change in soil quality (Haberern, 1992). Soil structure can be an indicator of soil health because it controls water infiltration, root penetration, and microbial habitat. Aggregate stability and size distribution are two indices of soil structure. When organic compounds are involved in aggregate formation and stability there is evidence for an hierarchical structure of aggregates (Oades and Waters, 1991). Microaggregates ($< 250\ \mu$m) are resistant to mechanical disturbance (Tisdall and Oades, 1982), but the organic agents that bind microaggregates into macroaggregates $> 250\ \mu$m are disrupted by cultivation, resulting in organic matter loss and a downward shift in aggregate size (Elliott, 1986). Agricultural management practices like cover cropping improve soil quality by rebuilding macroaggregates (Rodgers and Giddens, 1957; Blevins et al., 1990; Lal et al., 1991).

One method of observing changes in soil structure is to measure changes in aggregate size distribution (ASD). If sampling procedure is kept constant, ASD is a sensitive measure of soil structural differences (Kemper and Rosenau, 1986). Allmaras et al. (1965) noted that secondary aggregates are created by field sampling, preparation before sieving, and aggregate distribution. None of the published ASD procedures satisfy the need for a multiple-use soil sample handling protocol responsive to all the procedural demands of the soil biological, chemical, and physical methods that are often desirable for multi-disciplinary studies on soils. One of the earliest procedures assumed that the entire sample retrieved from the field would be used and that soil samples would be air dried (Chepil and Bisal, 1943). More recent studies have continued this practice (Allmaras et al., 1965; Broersma et al., 1996). Another dry ASD procedure used a portion of a sample that was sieved when moist and air dried before distribution (Gijsman and Thomas, 1995). Studies that have cited water content at the time of sampling as an influence on structural stability indices either used a part of the air dried samples for distribution (Carter et al., 1994) or were methods for wet ASD (Rasiah et al., 1992; Caron et al., 1992). Studies that used only a part of the soil sample did not note the method of subsampling and this raises questions about the validity of the results.

Standardized methods of subsampling and soil sample water content adjustment or pretreatment are needed; these factors can have a major impact on aggregate distribution and variability within aggregate fractions among replicate samples. Previously published ASD procedures equalize soil sample water content by air drying the sample before sieving or aggregate size distribution. Sieving air-dried soil requires considerable effort, and if many samples are to be tested, sieving samples at the right water content is more efficient.

The objective of this study was to develop a simple, low-cost method of obtaining representative subsamples and a standardized pretreatment protocol to reduce variability and enable multiple uses of soil samples. To do this, it was important to ascertain the effect on dry aggregate size distribution of different soil sample water contents at the time of pre-distribution sieving.

MATERIALS AND METHODS

Soil sample cores were taken from 0-7.5 cm depth with a 2.5 cm diameter probe from two fallow commercial vegetable fields (Table 3.1) in the Willamette Valley in western Oregon and stored in a cooler at 4 °C. Seventy-five cores from each site provided about three kg of each soil. Pretreatment consisted of the following procedural steps. Field-moist soil was gently separated into 2.5 cm pieces. A Versa-splitter SP-2.5 (Gilson Company, Inc., Worthington, OH) was used to homogenize the soil and to remove about 100 g for gravimetric soil water content determination. Each soil was further split into three parts and treated by drying one part to -1.3×10^3 kPa, one part to -2.3×10^3 kPa, and one part to -10^4 kPa, which approximated one-half field capacity, one-third field capacity and air dry, respectively. These approximations were derived from water retention values for the same soil type (Ullery and Simonson 1977). The -1.3×10^3 kPa and -2.3×10^3 kPa treatments were dried in customized desiccators using prilled $CaCl_2$ (Dri-Z-Air, Rainier Precision, Seattle, WA). The desiccator was an air-tight Rubbermaid 3056, 5.68 L container (Rubbermaid Incorporated, Wooster,OH) which contained a stand made with plastic fluorescent light diffuser grid, cheesecloth, and plastic legs 5 cm in height to keep the soil above the $CaCl_2$. The beginning gravimetric soil water content was used to predict the combined mass of soil sample solids and water at the desired water potential, and to calculate how many grams of water were to be removed to achieve the desired water content. For each gram of water to be removed, 0.5 g of prilled $CaCl_2$ was placed in the bottom of the desiccator. The moist soil was removed periodically and weighed to ensure that it reached the proper

Table 3.1. Descriptions and selected properties of the soils used in procedure development.

Series name and Classification	Clay	Silt	Sand	Total C	pH	Water content			
						initial	water potential (kPa)		
							$-1.3\text{x}10^3$	$-2.3\text{x}10^3$	-10^4
	------ kg kg^{-1} ------			g kg^{-1}		------------------ kg kg^{-1} ------------------			
Chehalis silty clay loam Cumulic Ultic Haploxeroll	26.6	63.2	10.2	1.78	5.6	0.36	0.16	0.11	0.02
Cloquato loam Cumulic Ultic Haploxeroll	14.9	37.1	48.0	1.75	6.3	0.38	0.15	0.10	0.02

water content. When the desired gravimetric weights were reached, the treated soil samples were stored in a cooler for 48 h at 4 °C to reduce the effects of uneven drying. Pretreated samples, including the -10^4 kPa pretreatments (air dry), were passed through 4.75 mm and 2 mm sieves and air dried before further handling or aggregate size distribution.

Subsampling of each of the six pretreatments was done by two different methods. One method used a funnel (funnel method) with a 1.25 cm opening and #3029 candy molds (Apollo Corp.,Tulsa, OK) each of which held about 5 g of soil. The whole soil sample was passed through the funnel and spread slowly and evenly over a predetermined area containing 15 molds. The soil in the molds was weighed to 70 g. The other method (scoop method) used a lab scoop to get a 70 g subsample from the whole sample. Each method was done four times for each pretreatment of both soils, resulting in 48 subsamples.

The 70 g subsample size and sieve-shaking time were determined according to directions of the sieve-shaker distributor (ELE International, 1995). Sieve-shaking time was 1 min for the Chehalis silty clay loam and 2 min for the Cloquato loam. For aggregate size distribution, each subsample was placed in the top of a nest of sieves with screen sizes of 1, 0.5, 0.25, 0.106 mm, and a receiver cup, and placed on a Ro-Tap Sieve Shaker Model B (Tyler Industrial Products, Mentor, OH). This device, originally designed for 20.33 cm diameter sieves, was modified to accept 7.5 cm diameter sieves.

The aggregates retained on each sieve screen and in the receiver cup were weighed and divided by the subsample mass to calculate the fraction of aggregates in each size. Fractions are stated as percentages in the tables. Mean weight diameter

(MWD) was calculated for each subsample according to White (1993). Using SAS statistical software (SAS Instutite, Cary, NC), coefficients of variability (CV's) for each aggregate size fraction and MWD were calculated from four replications of the aggregate size distribution on each pretreatment for both subsampling methods and both soil types. Treatment means separation were tested by Least Significant Difference ($P < 0.01$).

RESULTS AND DISCUSSION

The same general order of percentage of aggregates in the 1 to 2 mm size class resulting from different pretreatment were seen with -10^4 kPa > -2.3×10^3 kPa > -1.3×10^3 kPa. The reverse pattern was observed in the smaller class sizes (Fig 3.1). Regardless of pretreatment, Chehalis silty clay loam had higher MWD than Cloquato loam ($P < 0.001$). This was expected because textural difference and clay content in particular, are factors in forming stable aggregates (Edwards and Bremner, 1967; Tisdall and Oades, 1982; Perfect et al., 1995).

When soil is disturbed by sieving, bonds between soil particles are broken and aggregate strength is lowered. Clay particles especially are displaced from an equilibrium position of low free energy to high free energy. A soil with low free energy is stronger than a soil with high free energy. As the soil particles rearrange and free energy is reduced, aggregate strength increases. The amount of change depends on soil water content. A deficiency of water in the electric double-layer occurs at low water content, reducing particle-particle repulsion. As a result the soil is strongly flocculated,

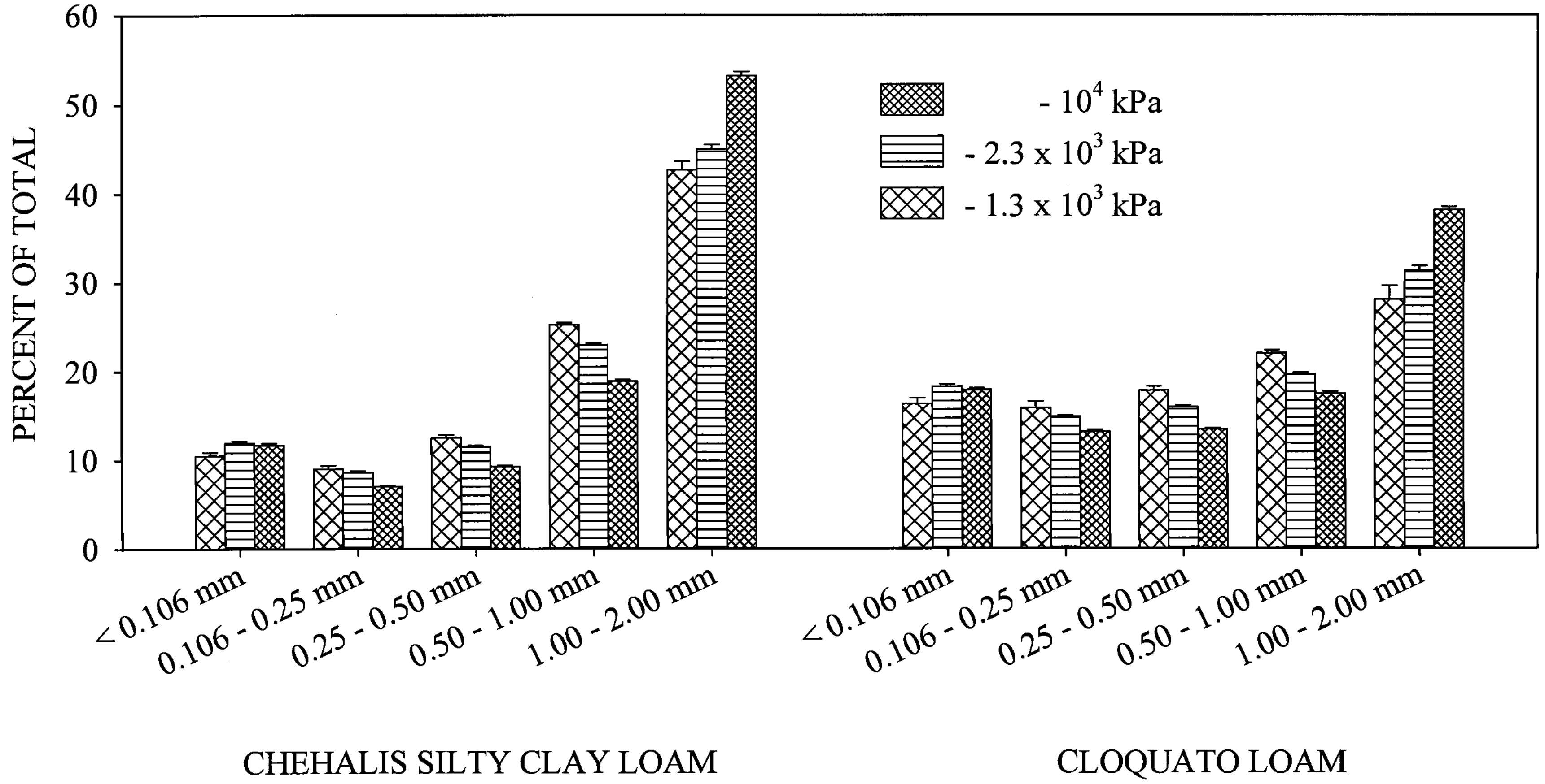

Fig. 3.1. Percentage of total aggregates in five class sizes resulting from three water content pretreatments before 2 mm sieving of two soils. Error bars are standard deviations; $n = 4$.

giving greater strength to dry soil compared to wet soil. Particle rearrangement is accompanied by changes in pore size distribution, causing a change in the matric potential of the soil water. As soil dries, tension in the retreating meniscuses displaces water molecules between particles, bringing them into direct contact. A wide range of amorphous gels, ions, and molecules can diffuse toward this particle-particle contact and cement these bonds. These processes are described as age-hardening and cementation by Dexter et al. (1988) and Uehara and Jones (1976).

Compared to the scoop method, subsamples obtained with the funnel method had CV's that were always lower in MWD and all aggregate size classes in both soil types (Tables 3.2 and 3.3). Reductions in CV's averaged 84 percent. These results indicate that the scoop method does not provide an adequate means of obtaining a representative subsample for determining aggregate size distribution. This is in agreement with a powder sampling comparison which tested the reliability of five subsampling techniques to give representative subsamples of sand and a sugar/sand mix (Allen and Khan, 1970). The authors state three essential requirements of a good subsampling device: (1) the whole of the sample should pass through the device; (2) the subsample should be taken from a moving sample stream; and (3) a preference for taking the whole stream for short intervals of time rather than part of the stream all of the time. The funnel method meets all three of these criteria and provides subsampling accuracy that is comparable to rifflers (Table 3.4). Rifflers cost up to US $5000 compared to less than US $10 for a funnel and candy molds. The low cost and simple methodology of the funnel method enables widespread adoption of this approach.

Table 3.2. Aggregate size distribution percentages and MWD means for two subsampling methods and three soil water tension treatments on Chehalis silty clay loam; coefficients of variability are in parentheses.

Aggregate size class	Funnel method†			Scoop method‡		
mm	-10^4 kPa	-2.3×10^3 kPa	-1.3×10^3 kPa	-10^4 kPa	-2.3×10^3 kPa	-1.3×10^3 kPa
	---------------------	---------------------	-----------%	----------------------	---------------------	---------------------
1.000 - 2.000	53.22a (0.9)	45.00b (1.1)	42.66c (2.2)	51.93A (12.2)	48.15A (11.9)	44.84A (12.7)
0.500 - 1.000	18.86c (0.9)	22.98b (0.7)	25.25a (0.8)	19.25C (6.7)	23.08B (2.3)	25.40A (3.8)
0.250 - 0.500	9.25c (1.4)	11.47b (1.2)	12.52a (2.2)	9.58A (16.4)	10.52A (15.1)	11.88A (13.2)
0.106 - 0.250	6.97b (1.6)	8.56a (2.4)	9.00a (3.8)	7.30A (20.8)	7.57A (22.6)	8.22A (21.9)
< 0.106	11.68a (1.8)	11.93a (1.9)	10.51b (3.6)	11.93A (16.5)	10.67A (18.2)	9.63A (20.7)
MWD§	0.7909a (0.6)	0.7198b (0.8)	0.7505b (1.5)	0.7783A (8.5)	0.7566A (8.4)	0.7333A (8.6)

† Funnel method values within rows followed by a different lower case letter are significant at the 0.01 probability level.

‡ Scoop method values within rows followed by a different upper case letter are significant at the 0.01 probability level.

§ MWD is an index and has no units.

Table 3.3. Aggregate size distribution percentages and MWD means for two subsampling methods and three soil water tension treatments on Cloquato loam; coefficients of variability are in parentheses.

Aggregate size class	Funnel method†			Scoop method‡		
mm	-10^4 kPa	-2.3×10^3 kPa	-1.3×10^3 kPa	-10^4 kPa	-2.3×10^3 kPa	-1.3×10^3 kPa
	%					
1.000 - 2.000	38.14a (0.9)	31.30b (1.7)	28.03c (5.6)	32.24A (13.1)	33.97A (8.6)	35.52A (17.5)
0.500 - 1.000	17.43c (1.2)	19.59b (0.9)	21.98a (1.4)	17.72C (2.8)	19.83B (2.2)	22.81A (3.4)
0.250 - 0.500	13.39c (1.0)	15.94b (1.1)	17.82a (2.6)	15.06A (7.6)	15.22A (5.4)	16.59A (8.3)
0.106 - 0.250	13.13c (1.4)	14.86a (0.9)	15.82a (4.7)	15.08A (11.3)	13.74A (9.3)	13.64A (17.9)
< 0.106	17.88a (1.1)	18.28a (1.3)	16.31b (4.2)	19.88A (8.8)	17.21AB (7.2)	14.40B (18.3)
MWD§	0.6094a (0.7)	0.5450b (1.1)	0.5245b (3.7)	0.5433A (9.3)	0.5771A (6.2)	0.5806A (12.1)

† Funnel method values within rows followed by a different lower case letter are significant at the 0.01 probability level.

‡ Scoop method values within rows followed by a different upper case letter are significant at the 0.01 probability level.

§ MWD is an index and has no units.

Table 3.4. Statistical parameters for selected subsampling devices.

Subsampling method	Standard deviation	Variance	*n*
	%	%	
Cone and quartering†	6.81	46.4	16
Scoop†	5.14	26.4	16
Table†	2.09	4.37	16
Chute riffler†	1.01	1.02	16
Spinning riffler†	0.125	0.016	16
Scoop method Chehalis	5.68	32.2	4
Scoop method Cloquato	5.69	32.4	4
Funnel method Chehalis	0.948	0.898	4
Funnel method Cloquato	1.56	2.43	4

†From Allen and Kahn (1970).

Scoop method variation may be greater than the treatment differences expected in agricultural soil research. Pretreatment effects in each soil type and in most of the aggregate size fractions were not significant with the scoop method. The funnel method detected significant differences ($P < 0.01$) between pretreatments within each soil type in most of the aggregate size fractions and in MWD (Tables 3.2 and 3.3).

Samples with different pretreatment at pre-distribution sieving had large differences within aggregate size classes (Tables 3.2 and 3.3). The MWD tends to go down as soil water content increases. This compares with Caron et al. (1992) who reported low water content associated with increased stability, and with Rasiah et al. (1992) who showed weakened stability with increasing water content. These relationships corresponded to antecedent water content, the water content at the time of sampling. By equalizing soil sample water content before sieving, air drying, and aggregate distribution, we found that sieving was easier and ASD variability was reduced. In addition, we developed a simple and inexpensive subsampling technique that has excellent statistical precision.

It is recommended that soil samples from the field be handled gently, homogenized and divided using a splitter to obtain a portion for testing antecedent water content and to preserve part of the sample for other procedures. The portion of the sample for ASD should be pretreated to equalize the water content of all samples before sieving. It is also recommended that sieving be done at -2.3×10^{-3} kPa (approximately one-third field capacity) since this resulted in consistently lower CV's (Tables 3.2 and 3.3). In addition, using only a 4.75 mm sieve would be sufficient rather than both the 4.75 mm and 2 mm sieves used in this study.

The results of our study show the importance of pretreatment and sample handling on ASD. This has important implications for field-based experiments and for monitoring soil quality. First, the correct subsampling approach greatly reduces ASD variability which will increase the chances of showing significant treatment effects and more accurately reflect soil quality trajectory as measured by ASD. Secondly, soil water content must be constant among tested soil samples to accurately reflect time and treatment effects on aggregate size distribution.

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CHAPTER 4

AGGREGATE SIZE DISTRIBUTION AND STABILITY UNDER WINTER COVER CROP AND WINTER FALLOW IN SUMMER IRRIGATED VEGETABLES

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Prepared for

Soil Science Society of America Journal

ABSTRACT

Winter cover crop in place of winter fallow is a management practice that can improve soil quality. A vital component of soil quality is the extent and stability of aggregation which is important for water relations and plant growth. The effects on aggregation in vegetable systems with winter cover crops were compared to systems with winter fallow. The study was conducted in replicated plots and in six paired farm fields; each farm represented a block in a randomized complete block experiment. Water stable aggregation (WSA) was tested using the single sieve method. Dry aggregate size distribution (ASD) was measured (1.00 - 2.00, 0.50 - 1.00, 0.25 - 0.50, 0.106 - 0.25, and < 0.106 mm) on soil samples pretreated to equalize soil sample water content at -1300 kPa. Cover cropping increased 1.00 - 2.00 mm aggregates ($P < 0.05$) in farm fields and water stable aggregates ($P < 0.1$) in the research plots. Aggregate size increase appeared to precede the stabilization of aggregates, suggesting that dry ASD may be a useful early predictor of change in soil quality trajectory.

INTRODUCTION

The size distribution and stability of aggregates are important indicators of soil quality. Structural aggregates develop during soil formation and strongly influence soil behavior and productivity. Water infiltration and storage, resistance to erosion, seedling emergence and root penetration, aeration, and the soil biota are affected by the size, strength, and stability of soil aggregates. Testing the capacity of aggregates to resist breakdown in water is an estimate of the ability of soil to maintain the above attributes (Kemper and Rosenau, 1986).

Efficient crop production depends on soil structure composed of aggregates > 1 mm which do not slake when wetted or disintegrate with tillage (Tisdall and Oades, 1982). In the same paper, these researchers proposed a hierarchical organization of soil aggregate structure based on transient, temporary, and persistent aggregate binding agents that engender phases of stability. Primary soil particles combine to form microaggregates (< 250 μm) and are held together by polysaccharides and organo-mineral complexes. They are strongly resistant to destruction by rapid wetting and mechanical disturbance (Gijsman, 1996). Fine roots and fungal hyphae bind microaggregates together forming macroaggregates which are affected by agricultural management (Naidu et al., 1996; Tisdall et al., 1997). The hierarchical model divides microaggregates from macroaggregates at 250 μm.

Other researchers have proposed that the function of plant roots and fungal hyphae in the aggregation process is to initiate the macroaggregate form and within this structure, microaggregates form and are stabilized (Jastrow, 1996). Sorption of fine clay particles on mucilages or microbial debris is considered to be the initial step in aggregation and the rhizosphere is the region in the soil where this occurs (Oades, 1978). A reciprocal relationship exists between soil biota and soil structure. As more structural aggregates are formed by soil biotic activity, more habitable pore space is created for the soil life (Jastrow and Miller, 1991).

Aggregate resistance to deterioration is primarily a function of binding agent strength and secondarily of aggregate size (Tisdall and Oades, 1982). Unstable aggregates slake into smaller units when rapidly wetted (Emerson, 1977), reducing soil porosity and soil health. Macroaggregate stability therefore is central to maintaining desirable soil structure for optimum crop production and soil quality.

Soil structure is altered by crop type and tillage intensity. Different effects on soil structure occur due to organic matter composition and additions, diverse rooting patterns and rhizosphere processes, and soil surface protection (Broersma et al., 1996). Aggregation increases in proportion to how often perennial crops are used in rotation (Harris et al., 1966; Lynch and Bragg, 1985; Baldock and Kay, 1987), by using no or low tillage rather than conventional cultivation techniques (Zobeck and Popham, 1990; Angers et al., 1993), and in response to winter cover versus winter fallow (Miller and Dick, 1995).

Winter cover cropping combined with summer vegetable production moves the agroecosystem toward the optimum conditions created by native perennial grasslands. Many studies have documented the attributes of freshly broken sod and the commensurate decline in organic matter with continuous tillage and crop production (Jenny, 1941; Gupta and Germida, 1988; Naidu et al., 1996; Saviozzi et al., 1997). Enhanced soil structure, reduced soil erosion, increased water infiltration and holding capacity, enriched fertility, and suppression of pests including pathogens, insects, and weeds have been ascribed to cover crops (Rodgers and Giddens, 1957; Blevins et al., 1990; Lal et al., 1991). Research also has shown the ability of cover crops to stabilize residual fertilizer nitrogen after cash crop production and to reduce nitrate concentrations in groundwater below the 10 ppm EPA standard (Brandi-Dohrn et al., 1997; Minshew, 1999). Little information is available on the response of aggregation to winter cover cropping in irrigated vegetable production.

Cover crop effects on water stable aggregation and aggregate size distribution were studied as part of a multidisciplinary project that investigated differences between winter cover cropping and the conventional practice of winter fallow in irrigated summer vegetable row crop production in the Willamette Valley of western Oregon. The primary objective of this research was to determine if either of these structural inventories serve as early indicators of soil quality change. The second objective was to determine the effect on soil structure of integrating winter cover with summer vegetable production systems by measuring changes in aggregate size distribution and water stable aggregation. The third objective was to determine if a relationship exists between these two indices. The hypothesis tested was that aggregate size and stability would increase by replacing winter fallow with a winter cover crop.

MATERIALS AND METHODS

Experimental Sites and Designs

All fields and plots in the project are located in the Willamette Valley of western Oregon. The climate is characterized by moist, cool winters with warm, dry summers and average annual rainfall of 1040 mm. Soils in the project are primarily Mollisols and soil textures are loam variants (Table 4.1). Winter fallow and winter cover crop treatments were established after harvest of the summer vegetable crop. The treatments were in place during the winter and ended in the spring when field preparation began for the new summer crop.

Table 4.1. Taxonomy and selected characteristics for soils in the aggregation studies.

Site	Classification			Clay	Silt	Sand	Total C
	Series	Family	Subgroup				
				------- kg kg^{-1} -------			g kg^{-1}
DI	Amity	Fine-silty, mixed, mesic	Argiaquic Xeric Argialboll	26	67	7	17.7
GR	Newberg	Coarse-loamy mixed, mesic	Fluventic Haploxeroll	19	50	31	32.6
	Cloquato	Coarse-silty mixed, mesic	Cumulic Ultic Haploxeroll	16	38	46	20.2
HA	Chehalis	Fine-silty, mixed, mesic	Cumulic Ultic Haploxeroll	27	59	14	14.4
HE	Saturn	Fine-loamy over fragmental, mixed, mesic	Fluventic Haplumbrept	32	47	21	35.1
LU	Aloha	Fine-silty, mixed, mesic	Aquic Xerochrept	20	70	10	12.9
PE	Woodburn	Fine-silty, mixed, mesic	Aquultic Argixeroll	22	69	9	13.1
VF	Chehalis	Fine-silty, mixed, mesic	Cumulic Ultic Haploxeroll	26	52	22	16.5
KE	Newberg	Coarse-loamy mixed, mesic	Fluventic Haploxeroll	24	53	23	19.3
	Chehalis	Fine-silty, mixed, mesic	Cumulic Ultic Haploxeroll	25	56	19	19.2

The Vegetable/Winter Interseeded Cover Crop Study is being conducted at Oregon State University Vegetable Research Station (VF), Corvallis, Oregon, where winter cover crops were established in 1993. The experimental design was a randomized complete block with two treatments, winter fallow or mixed legume/cereal cover crop. There were four replications and one sampling area was established in each plot.

Each of six farmers designated one field to be part of the Project; they are Dickman Farms (DI), Grover Farms (GR), Hamlin Farms (HA), Hedricks Farms (HE), Lucht-Northwest Transplants (LU), and Pearmine Farms (PE). The experimental design was a randomized complete block where each field represented a block (Farms). Steve Campbell, National Resource Conservation Service, mapped the fields in detail. A part of each field was selected for a winter cover crop after harvest of the summer vegetable crop (Table 2.2) and a directly adjacent part was designated winter fallow. Five sampling points were established in the fallow side of each field and paired by soil type and texture with five sampling points in the cover crop side. Cover crop/fallow splits and sampling points in the farm fields and research plots were marked and located with a Global Positioning System (GPS) receiver.

A conventional tillage/minimum tillage paired comparison was conducted with a seventh vegetable producer. The Kenagy (KE) site was designed like the other farm sites with conventional tillage substituted for the fallow treatment and minimum tillage substituted for the winter cover crop treatment. A winter cover crop was planted over the whole field at this site.

Soil Sampling and Pretreatment

Soil samples were taken three times each growing season: in the spring before the cover crop was terminated (spring); at canopy closure of the summer vegetable crop (canopy); and within one week before harvest of the summer vegetable crop (harvest). Sampling was done at canopy and harvest in 1996 (baseline), and at spring, canopy, and harvest in 1997 and 1998. Canopy closure for broccoli and cauliflower was at the eight-to-nine leaf stage of growth; for green bean at the two-trifoliate leaf stage; and for sweet corn at the seven-to-eight leaf stage.

The Soil Quality Project began in July 1996, after the summer vegetable crops were planted. The VF research station study began in 1993; thus, baseline samples before treatment were obtained only at the farm sites in 1996 at canopy closure except at the HA and KE sites which were sampled at harvest of that year. Grass seed crops are an integral part of vegetable crop rotations and grow continuously for two to three years, which limited sampling at the PE site to 1996 and1997. Winter cover crops were not established after the summer 1997 harvest at the HA and HE sites, which limited sampling to 1996 and 1998.

Bulk soil samples composed of thirty-six, 2.5 cm diameter soil cores from 0 - 7.5 cm deep were stored in a cooler at 4° C. Field moist soil was gently divided into 2.5 cm cubes. A Versa-splitter SP-2.5 (Gilson Company, Inc., Worthington, OH) was used to mix each bulk sample and separate a 100 g subsample which was used to determine gravimetric soil water content. Each sample was further split into two parts; one part was stored at 4° C and used for water stable aggregate analysis. The second part was used for aggregate size distribution and was pretreated by drying to a water potential of about -1300 kPa. This approximates one-half field capacity based on moisture retention values (Ullery and Simonson, 1977). Soil samples were dried in customized desiccators using prilled calcium chloride (Dri-Z-Air, Rainier Precision, Seattle, WA). The desiccator was an air-tight plastic chamber which contained a stand made with plastic grid, cheesecloth, and 5 cm-high plastic legs to keep the soil above the calcium salt solution. The beginning gravimetric soil water content was used to predict the combined mass of soil sample solids and water at the desired water potential, and to calculate how many grams of water were to be removed to achieve the desired water content. For each gram of water to be removed, 0.5 g of calcium chloride was placed in the bottom of the desiccator. The moist soil was removed periodically and weighed to ensure that the it reached the proper water content. When the desired gravimetric weights were reached, the treated soil samples were stored in a cooler for 48 h at 4 °C to reduce the effects of uneven drying. Treated samples were passed through 4.75 and 2 mm sieves and air dried.

Aggregate Size Distribution

In order to get unsegregated, representative sampling for aggregate size distribution, subsamples were taken by using a funnel with a 1.25 cm opening and #3029 candy molds (Apollo Corporation, Tulsa, OK) each holding about 5 g of soil. The whole soil sample was passed through the funnel, and spread slowly and evenly over a predetermined area containing 15 molds. The soil in the molds was weighed to the appropriate test mass for each soil type. Subsample mass and sieve-shaking time were determined according to sieve-shaker manufacturer directions (ELE International, 1995). For aggregate size distribution, each subsample was placed in the top of a nest of sieves with screen sizes of 1.0, 0.5, 0.25, 0.106 mm, and a receiver cup, and placed on a Ro-Tap Sieve Shaker Model B (Tyler Industrial Products, Mentor, OH). This device, originally designed for 20.33 cm diameter sieves, was modified to accept 7.5 cm diameter sieves. The aggregates retained on each sieve screen and in the receiver cup were weighed and divided by the beginning subsample mass to calculate the fraction of aggregates in each size. Aggregate size distribution was determined on the 1997 and 1998 canopy samples. The mean weight diameter (MWD) is advantageous for making comparisons because it results in a single index instead of five size fractions. MWD was calculated using the summation equation described by Youker and McGuinness (1956) as found in White (1993):

$$\mathrm{MWD} = \sum_{i=1}^{n} X_i W_i \qquad [1]$$

where:

X_i = mean diameter of the aggregate size fraction midpoint; and,
W_i = proportion of total sample retained on sieve.

This equation overestimates MWD, and compensation can be made by substituting the raw summation into the following regression equation:

$$Y = 0.876X - 0.079 \qquad [2]$$

where:

Y = adjusted MWD; and,
X = MWD calculated in equation [1].

Water Stable Aggregation

Excessively moist soil samples from the field were dried in at 4° C to a water content that would facilitate passing them through a 2 mm sieve. After sieving and 48 h of air drying, a portion of each sample was sieved to eliminate aggregates < 1 mm. Four grams of the retained aggregates were placed on a 3.6 cm diameter sieve with a 0.250 mm stainless steel screen. Eight of these sieves can be accommodated on a sieving machine with a 1.3 cm vertical stroke and a frequency of 35 cycles min^{-1} (Kemper and Rosenau, 1986). Containers with 100 mL de-ionized water were placed on a stationary platform under the sieves. The water level in the containers just covered the soil on the sieves at the bottom of the machine stroke cycle. No premoistening of the soil was done. After cycling the samples for three minutes, the containers of water and dissolved soil aggregates were removed. A second set of containers with 100 mL dispersing solution (2 g sodium polyphosphate L^{-1}) were placed on the stationary platform and the samples were cycled through this solution until only sand particles remained on the sieve screen. Both sets of containers were oven dried overnight at 110°C and weighed.

$$\text{Percent water stable aggregate} = (\text{g soil in dispersing container} - 0.2\text{ g}) \times 100 / (\text{g soil in both containers} - 0.2\text{ g}) \qquad [3]$$

Subtraction of 0.2 g was to compensate for the mass of the dispersing solution.

Data Analysis

Data analysis for the Farms WSA data was done for baseline, year one (all producer sites with one established winter cover crop), and year two (all producer sites with two established winter cover crops). Baseline and year one analyses included data from all producer sites, and year two analysis included data from the DI, GR and LU sites. Analysis for the Farms ASD data was done for year one and year two. Aggregate size distribution means differences were analyzed for MWD and for the percentage of aggregates in the 1 to 2 mm size class. Data was analyzed for baseline, year one and year two at the conventional tillage/minimum tillage site. Paired t-tests were done for each farm site and analysis of variance (ANOVA) was done for the Farms and VF research station using SAS statistical software (SAS Institute, 1988).

RESULTS AND DISCUSSION

Water Stable Aggregation

The KE conventional tillage/minimum tillage site began with significantly higher water stable aggregation in the minimum tillage side, and by the second year the minimum tillage effect on aggregate stability became significantly more evident. The magnitude of this effect appears to be cumulative as the difference between the conventional tillage and minimum tillage WSA became greater each year (Fig. 4.1a). Several studies have shown that no-till management can improve soil aggregation (Weill et al., 1989; Carter, 1992; Beare et al., 1994). The protection and maintenance of soil organic matter is augmented in reduced tillage systems. Aggregate binding agents are derived from various organic matter fractions that tillage physically disrupts and exposes to oxidation.

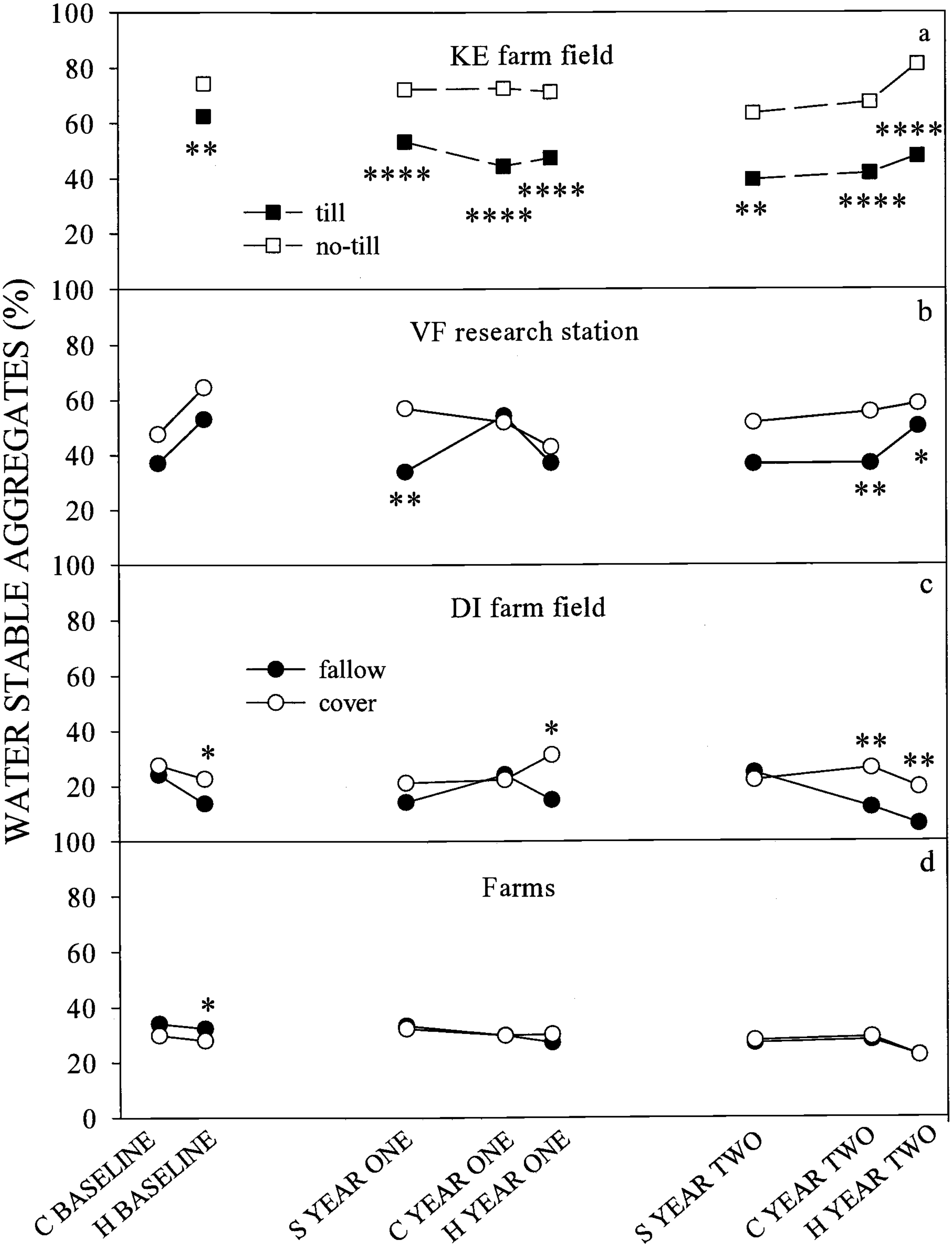

Fig. 4.1. Water stable aggregates for treatment differences at sampling times for SQP studies; spring (S), canopy closure (C), harvest (H). Presence of *, **, ***, **** indicates significant differences within a time period at $P < 0.1$, 0.05, 0.01, and 0.001, respectively.

Conventional tillage was used on all plots at the VF research station. Cover crop treatment produced significantly more water stable aggregates during some sampling periods, and seasonal changes in WSA appear to be more dynamic in the fallow plots than in the cover crop plots (Fig. 4.1b). Winter cover crops provide an additional input of carbon (C) substrates compared to winter fallow, which may support a larger, more active biological community to stabilize aggregates. Cover crops provide C inputs during the fall and winter by root exudation of compounds when the rhizosphere is present and by incorporation of its biomass in the spring. Microorganisms utilize these substrates and produce polysaccharides and gums that are part of the aggregation process (Foster and Rovira, 1976; Jastrow and Miller, 1991). Furthermore, roots can enmesh soil particles to form aggregates (Oades, 1978).

Individual fields in the Farms experiment with only one year of cover cropping showed no effect on water stable aggregation. After two winter cover crops, the DI site showed significantly more WSA in the cover crop portion of the field the last two sampling periods (Fig. 4.1c). The difference in this site at the baseline harvest sampling period was probably a cover crop effect from annual rye grass that was interseeded into the sweet corn in June 1996 and was well established by the time the baseline harvest soil samples were taken. Perennial ryegrass (*Lolium, perenne*) has been shown to increase aggregate stability in as little as four weeks (Reid and Goss, 1980). The extensive and diffuse root structure of ryegrass promotes aggregation in part by its symbiotic relationship with vesicular-arbuscular mycorrhizal fungi (Tisdall and Oades, 1979).

The higher WSA in the cover crop side at the baseline harvest sampling period in the DI site was offset by the five other sites in the Farms experiment (Fig. 4.1d). The WSA percentage was significantly higher in the winter fallow sides of the Farms fields at the baseline harvest sampling period. Results from the sampling periods after that showed no significant difference. This suggests an effect on WSA due to cover crops. It seems likely therefore, that more time is needed for cover cropping to improve aggregate stability. Evidence for this is shown at the VF research station where WSA was affected after five years of cover cropping. The 1997 and 1998 data represented in Fig. 4.1b correspond to the fourth and fifth winter cover crop treatments at this location. This would follow Angers et al. (1993) who reported that in a reduced tillage system it took four years before WSA significantly affected.

Aggregate Size Distribution

A significant difference in aggregate size distribution was detected after one year between conventional tillage and minimum tillage. The apparent treatment difference after year two is not significant (Table 4.2). This most likely happened because the conventional tillage treatment was less intensive the second year than the first year. Aggregate size distribution is known to be strongly affected by tillage (Kemper and Rosenau, 1986) because it physically disrupts soil aggregates, dislocates microorganism communities, and/or exposes protected organic matter to decomposition (Kandeler and Murer, 1993).

Tillage procedures were not imposed on the on-farm cover crop trials with both parts of each field receiving the same tillage; cultivation practices varied from site to

Table 4.2. Effects on aggregate size distribution in winter cover cropping versus fallow and in reduced tillage versus conventional tillage.

Site	Year	MWD			1.00 - 2.00 mm size class		
		Conventional		Improved	Conventional		Improved †
						%	
DI	1997	0.7440	**	0.8325	27.84	**	35.08
	1998	0.8704		0.7927	37.49		35.36
GR	1997	0.7738		0.7326	34.00		31.82
	1998	0.7349		0.7076	31.98		29.49
HA	1998	0.8590		0.8894	38.56		41.28
HE	1998	0.8960		0.9140	41.90		42.96
LU	1997	0.7890		0.8129	34.08		36.43
	1998	0.8007	*	0.8370	33.51	**	36.92
PE	1997	0.7809	***	0.8331	32.62	***	37.44
Farms	1997	0.8097	*	0.8337	35.21	**	37.37
	1998	0.7915		0.7791	33.84		33.92
VF	1997	0.8105		0.8270	34.63		35.18
	1998	0.8546		0.8782	38.58		40.43
KE	1997	0.8111	*	0.8791	35.10	*	40.69
	1998	0.8394		0.8659	37.68		40.35

† For KE, conventional is conventional tillage and improved is minimum tillage; for all other sites conventional is fallow and improved is cover crop.

*, **, *** Significantly different within MWD or size class pairs at the 0.1, 0.05 and 0.01 probability levels, respectively.

site. Nevertheless, year one cover crop treatment effects on ASD were statistically significant for the Farms experiment (Table 4.2). Cover crop MWD means were higher than the fallow MWD means in five of the six sites. The sixth site (GR) came into row crop production at the same time it was included in the project. For the previous 80 years, it was under forest vegetation. Heavy machinery and large log trucks were used to harvest and remove the trees and stumps. Not all of the roots and branches were removed, and slash was piled and burned on site. Soils are naturally variable in their physical characteristics (Jury et al., 1991; Brady and Weil, 1996), and the tree harvesting activities probably increased the variability here (Smith and Waas, 1985). If this site is not included in the Farms analysis, the cover crop/fallow difference for year one would be significant at $P < 0.01$. In paired t-tests, the DI and PE sites showed higher cover crop MWD means at the 0.05 and 0.01 probability levels, respectively.

In the second year, only three farm fields continued to receive the same treatment splits as in year one. The LU site cover crop MWD was significantly greater than the fallow MWD (Table 4.2), but the results at the DI site were opposite from year one with lower MWD in the cover crop treatment. The role of roots in improving aggregation has been cited (Tisdall and Oades, 1979; Reid and Goss, 1980), but it also has been reported that in the short term, roots may reduce inter-aggregate binding by physical movement of the root tip and by root exudates (van Noordwijk et al., 1993).

While other sites showed ASD differences, the VF research station did not. The site is blocked well for soil mineral particle composition, although Steve Campbell, Natural Resources and Conservation Service agent, has documented some minor textural differences between the cover and fallow plots in three of the four blocks. These variations contributed to variation in the ASD data. Differences in clay, silt, and sand content have been reported to affect the strength of aggregates as they form (Perfect et al., 1995). Aggregate strength is a factor in ASD because soil sampling, sample pre-distribution handling, and distribution procedure sieving create secondary aggregates (Chepil, 1953; Allmaras et al., 1965).

Fig. 4.2 details the percentage of aggregates found in each size class across the Farms fields. The difference in ASD in this investigation was a decrease in the

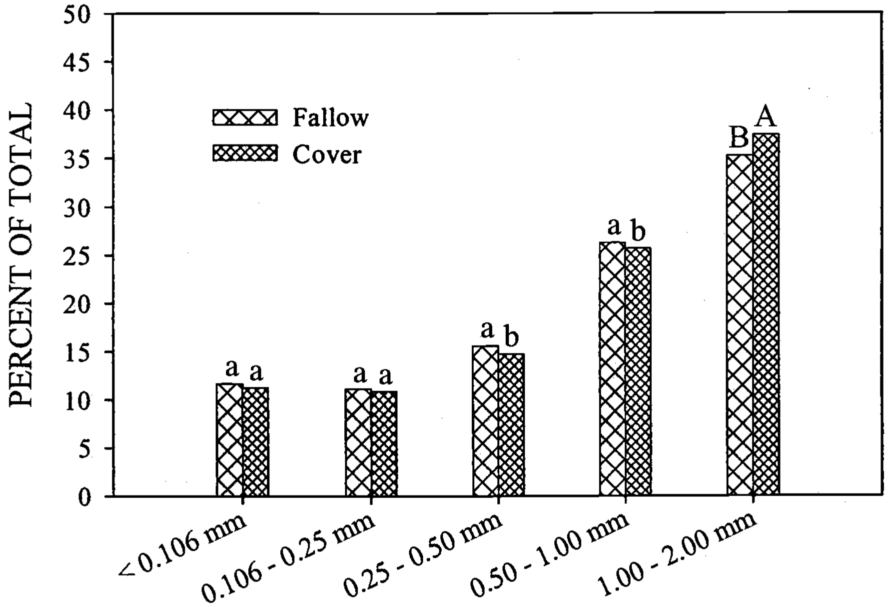

Fig. 4.2. Fallow and cover crop treatment differences in aggregate size distribution for Farms after one winter; bars with different upper or lower case letters are significantly different at $P < 0.1$ and 0.05, respectively.

percentage of aggregates in the smaller size classes and an increase in the percentage of aggregates in the 1 to 2 mm size class (Table 4.3). The increase in this size class and the decrease in the combined 0.25 to 1 mm size classes were significant ($P < 0.05$), but the decrease in the combined microaggregate size classes (< 0.25 mm) was not significant. The reductions found here in the smaller macroaggregate class sizes and the lack of significant reduction in the microaggregate size classes discount the most commonly cited aggregation theory, which delineates microaggregates from macroaggregates at 0.25 mm (250 μm).

Table 4.3. Macroaggregate and microaggregate distribution percentages and treatment gain or loss for Farms after one year of winter cover cropping.

Aggregate size class	Fallow	Cover	Significance	Gain or Loss
mm	---- kg kg^{-1} ----		P <	kg kg^{-1}
2.0 - 1.0	35.62	37.41	0.05	2.15
1.0 - 0.25	41.90	40.44	0.05	- 1.46
< 0.25	22.84	22.15	NS	- 0.69

The literature on aggregate hierarchy and formation has been evolving since Tisdall and Oades (1982) presented a four-stage model of hierarchical aggregation that, on close reading, has very little discussion of aggregates > 250 μm < 2000 μm. This and subsequent papers (Oades and Waters, 1991; Beare et al., 1994; Wright and Upadhyaya, 1998) leave the distinct impression that aggregation is a linear process beginning with the accumulation of the primary particles into microaggregates and proceeding sequentially in stair-step fashion to the formation of macroaggregates. The research underlying the model is reductionist and is more accurately an examination of disaggregation, in which aggregates are broken down into smaller and smaller units. It is assumed that aggregation is the reverse of disaggregation.

Jastrow (1996) and others have proposed that plant roots and fungal hyphae serve to physically form macroaggregates and within this structure, microaggregates form and are stabilized. Haynes and Swift (1990) advanced the view that the formation of stable aggregates occurred in two stages: an aggregation phase and a stabilization phase. A comparison of year one data showed a significant correlation between MWD and WSA canopy closure ($r = 0.44$, $P < 0.001$) and WSA harvest ($r = 0.59$, $P < 0.001$). Aggregate size distribution was done only at the canopy closure sampling; the higher ASD-WSA harvest data correlation suggests that increased aggregate size preceded aggregate stability.

The ASD procedure used in this project identified a shift in aggregate size after the first winter cover crop treatment across the Farms fields. Increases in the percentage of WSA with cover cropping may take longer periods and its response may vary with soil type. Even after five years of cover cropping at the VF research, station significant differences in WSA were not observed consistently during the last two years. Conversely, ASD may be one of the earliest indicators of change in an important soil characteristic. Additional research is needed to determine if this procedure is applicable across a range of soil types and land management strategies.

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SUMMARY

The research presented in this thesis demonstrates the effectiveness of winter cover crops to improve several soil physical properties. Enhanced water intake and reduced bulk density occurred in research plots and commercial farm fields where cover crop/fallow comparisons were made. Cover crops hold potential to increase macroporosity through root growth and by providing habitat and protection for burrowing soil fauna, which results in decreased bulk density and increased water intake.

Cover crop biomasss absorbs the kinetic energy of raindrops, reducing the detachment and rearrangement of soil particles that can cause surface sealing. Plant biomass slows the flow of water runoff, diminishing soil erosion. Cover crop roots can improve water intake and bulk density through their effect on aggregate size and stability. Roots and associated fungi are primary factors in the creation of aggregates larger than 250 μm, and these aggregates provide greater pore space than smaller ones. Cover cropping increased the amount of 1.00 to 2.00 mm size aggregates in farm fields.

A procedure to measure dry aggregate size distribution was developed in the early stages of this research. Soil sample water content was found to be a critical factor in the repeatability and reliability of aggregate size distribution. The method to pretreat soil samples to equalize water content makes possible comparisons of aggregate size distribution using soil samples with varying antecedent water contents. A simple procedure was also developed to accurately obtain subsamples with the same percentage of aggregate sizes as contained in the parent sample.

Aggregate size increase appeared to precede the stabilization of aggregates in the farm fields. More research is needed to verify if this is what happens. In this research, an increase in aggregate size was found in the farm fields after one winter of cover cropping, but the results of water stable aggregate testing showed no significant increase after two winter cover crops. A correlation of the Farms data for aggregate size distribution and water stable aggregation suggested that aggregate size increase occurred before aggregate stabilization. This was supported by the results at the OSU Vegetable Research Station experiment which has had winter cover crop treatments since 1993. Increases in water stable aggregates in these plots were consistently significant in 1997 and 1998, the fourth and fifth years after cover cropping was implemented. The aggregation studies suggest that aggregate size distribution may be a useful early predictor of change in soil quality.

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APPENDICES

Appendix A: Aggregate size distribution data for North Willamette Research and Extension Center.

Plot	Trt†	Rep	Date	Aggregate size class					MWD‡
				1.0-2.0	0.5-1.0	0.25-0.5	0.106-0.25	<0.106	
				------------------------		%		--------------------------	
2.2	C	1	97224	25.26	22.32	15.28	16.88	20.29	0.4855
4.2	Hr	1	.	.	.	.	.	.	.
9.1	Hl	1	97224	32.17	25.66	15.37	13.86	12.95	0.5904
12.2	C	2	97224	26.61	22.93	14.52	15.79	20.17	0.5030
15.1	Hl	2	97224	27.71	24.09	15.62	16.88	15.71	0.5283
20.2	Hr	2	97224	26.06	22.92	14.51	16.06	20.49	0.4962
23.2	C	3	97224	26.18	22.64	14.22	15.32	21.67	0.4944
24.1	Hl	3	97224	30.92	23.64	13.64	13.48	18.35	0.5569
29.2	Hr	3	97224	25.35	22.73	14.14	16.05	21.74	0.4850
31.2	C	4	97224	26.12	21.11	13.78	16.53	22.50	0.4844
33.2	Hr	4	97224	29.51	23.51	13.90	15.36	17.74	0.5411
39.1	Hl	4	97224	30.88	23.62	13.81	13.81	17.90	0.5572
2.2	C	1	98195	36.11	23.04	13.00	12.23	15.53	0.6158
4.2	Hr	1	.	.	.	.	.	.	.
9.1	Hl	1	98195	37.36	23.73	12.49	11.34	15.10	0.6335
12.2	C	2	98195	35.61	23.56	12.73	11.97	16.14	0.6117
15.1	Hl	2	98195	36.44	23.33	12.90	11.93	15.39	0.6212
20.2	Hr	2	98195	39.13	24.34	11.81	10.39	14.31	0.6567
23.2	C	3	98195	36.06	23.83	12.90	11.40	15.79	0.6189
24.1	Hl	3	98195	40.60	24.01	11.96	10.46	12.89	0.6738
29.2	Hr	3	98195	37.73	25.37	12.57	10.76	13.56	0.6478
31.2	C	4	98195	36.29	23.91	12.79	11.59	15.37	0.6222
33.2	Hr	4	98195	37.63	23.90	12.46	11.47	14.51	0.6380
39.1	Hl	4	98195	39.31	24.60	12.30	10.80	12.97	0.6624

† Treatment.

‡ Mean weight diameter.

Appendix B: Bulk density data for North Willamette Research and Extension Center.

Plot	Treatment	Rep	Date	Depth (cm)					
				5	10	15	20	25	30
				------------------------Mg m^{-3} ------------------------					
Non-traffic interrow									
2.2	C	1	97151	1.445	1.537	1.347	1.411	1.515	1.523
4.2	Hr	1	97151	1.382	1.594	1.524	1.588	1.617	1.421
9.1	Hl	1	97151	1.438	1.552	1.528	1.550	1.477	1.521
12.2	C	2	97151	1.470	1.534	1.406	1.430	1.435	1.539
15.1	Hl	2	97151	1.391	1.519	1.356	1.438	1.356	1.448
20.2	Hr	2	97151	1.466	1.554	1.486	1.474	1.435	1.579
23.2	C	3	97151	1.443	1.569	1.428	1.504	1.291	1.507
24.1	Hl	3	97151	1.476	1.506	1.368	1.394	1.271	1.439
29.2	Hr	3	97151	1.425	1.555	1.442	1.398	1.455	1.389
31.2	C	4	97151	1.321	1.523	1.413	1.527	1.411	1.577
33.2	Hr	4	97151	1.447	1.535	1.482	1.524	1.432	1.526
39.1	Hl	4	97151	1.471	1.577	1.488	1.484	1.505	1.583
Traffic interrow									
2.2	C	1	97151	1.379	1.507	1.413	1.533	1.383	1.449
4.2	Hr	1	97151	1.386	1.502	1.390	1.454	1.463	1.445
9.1	Hl	1	97151	1.508	1.494	1.483	1.507	1.513	1.519
12.2	C	2	97151	1.428	1.496	1.417	1.443	1.391	1.669
15.1	Hl	2	97151	1.381	1.513	1.390	1.364	1.337	1.343
20.2	Hr	2	97151	1.504	1.542	1.409	1.429	1.411	1.465
23.2	C	3	97151	1.390	1.470	1.343	1.357	1.380	1.394
24.1	Hl	3	97151	1.412	1.510	1.440	1.518	1.485	1.611
29.2	Hr	3	97151	1.479	1.525	1.538	1.602	1.536	1.212
31.2	C	4	97151	1.388	1.514	1.412	1.418	1.483	1.449
33.2	Hr	4	97151	1.405	1.525	1.360	1.426	1.359	1.655
39.1	Hl	4	97151	1.515	1.571	1.501	1.569	1.434	1.686
Composite									
2.2	C	1	97151	1.430	1.530	1.362	1.439	1.484	1.506
4.2	Hr	1	97151	1.383	1.573	1.493	1.557	1.581	1.427
9.1	Hl	1	97151	1.454	1.538	1.518	1.540	1.485	1.521
12.2	C	2	97151	1.460	1.525	1.409	1.433	1.425	1.569
15.1	Hl	2	97151	1.389	1.518	1.364	1.421	1.352	1.424
20.2	Hr	2	97151	1.475	1.551	1.468	1.464	1.429	1.552
23.2	C	3	97151	1.431	1.546	1.408	1.470	1.312	1.481
24.1	Hl	3	97151	1.461	1.507	1.385	1.423	1.321	1.479
29.2	Hr	3	97151	1.438	1.548	1.464	1.446	1.474	1.348
31.2	C	4	97151	1.337	1.521	1.413	1.502	1.428	1.547
33.2	Hr	4	97151	1.437	1.533	1.454	1.501	1.415	1.556
39.1	Hl	4	97151	1.481	1.576	1.491	1.504	1.488	1.607

Appendix B cont.

Plot	Treatment	Rep	Date	Depth (cm)					
				5	10	15	20	25	30
				Mg m^{-3}					
Non-traffic interrow									
2.2	C	1	98162	1.202	1.506	1.357	1.387	1.348	1.504
4.2	Hr	1	98162	.	.	.	.	.	.
9.1	Hl	1	98162	1.306	1.576	1.501	1.665	1.422	1.584
12.2	C	2	98162	1.270	1.434	1.502	1.570	1.504	1.462
15.1	Hl	2	98162	1.267	1.553	1.497	1.583	1.600	1.524
20.2	Hr	2	98162	1.289	1.603	1.539	1.649	1.645	1.557
23.2	C	3	98162	1.357	1.545	1.550	1.472	1.476	1.432
24.1	Hl	3	98162	1.355	1.499	1.538	1.568	1.540	1.596
29.2	Hr	3	98162	1.403	1.551	1.438	1.484	1.459	1.503
31.2	C	4	98162	1.275	1.483	1.445	1.429	1.418	1.458
33.2	Hr	4	98162	1.372	1.544	1.476	1.568	1.500	1.564
39.1	Hl	4	98162	1.352	1.500	1.399	1.357	1.457	1.335
Traffic interrow									
2.2	C	1	98162	1.364	1.482	1.432	1.502	1.380	1.396
4.2	Hr	1	98162	.	.	.	.	.	.
9.1	Hl	1	98162	1.387	1.499	1.452	1.406	1.391	1.685
12.2	C	2	98162	1.403	1.477	1.332	1.396	1.267	1.327
15.1	Hl	2	98162	1.372	1.476	1.412	1.384	1.346	1.584
20.2	Hr	2	98162	1.348	1.512	1.448	1.316	1.541	1.565
23.2	C	3	98162	1.348	1.480	1.351	1.373	1.348	1.416
24.1	Hl	3	98162	1.453	1.593	1.517	1.529	1.503	1.369
29.2	Hr	3	98162	1.491	1.619	1.582	1.516	1.527	1.481
31.2	C	4	98162	1.362	1.388	1.417	1.273	1.205	1.521
33.2	Hr	4	98162	1.413	1.509	1.542	1.400	1.436	1.550
39.1	Hl	4	98162	1.477	1.573	1.600	1.514	1.561	1.467
Composite									
2.2	C	1	98162	1.240	1.500	1.374	1.414	1.355	1.479
4.2	Hr	1	98162	.	.	.	.	.	.
9.1	Hl	1	98162	1.325	1.558	1.490	1.605	1.415	1.608
12.2	C	2	98162	1.301	1.444	1.462	1.529	1.449	1.431
15.1	Hl	2	98162	1.291	1.535	1.477	1.537	1.541	1.538
20.2	Hr	2	98162	1.303	1.582	1.518	1.571	1.621	1.559
23.2	C	3	98162	1.355	1.530	1.504	1.449	1.446	1.428
24.1	Hl	3	98162	1.378	1.521	1.533	1.559	1.531	1.543
29.2	Hr	3	98162	1.424	1.567	1.472	1.491	1.475	1.498
31.2	C	4	98162	1.295	1.461	1.438	1.393	1.368	1.473
33.2	Hr	4	98162	1.382	1.536	1.491	1.529	1.485	1.561
39.1	Hl	4	98162	1.381	1.517	1.446	1.394	1.481	1.366

Appendix C: Compaction data for North Willamette Research and Extension Center.

Plot	Treatment	Rep	Date	Depth (cm)					
				5	10	15	20	25	30
				---------------------------kPa-------------------------					
Non-traffic interrow									
2.2	C	1	97151	345	345	345	518	518	690
4.2	Hr	1	97151	.	.	.	.	.	.
9.1	Hl	1	97151	345	345	690	1208	690	345
12.2	C	2	97151	345	345	690	518	345	1035
15.1	Hl	2	97151	345	345	690	345	345	1035
20.2	Hr	2	97151	345	345	690	345	345	518
23.2	C	3	97151	345	345	345	345	345	345
24.1	Hl	3	97151	345	345	345	345	345	690
29.2	Hr	3	97151	345	345	690	345	345	690
31.2	C	4	97151	345	345	690	690	690	690
33.2	Hr	4	97151	345	345	690	690	690	690
39.1	Hl	4	97151	345	345	345	345	345	345
Traffic interrow									
2.2	C	1	97151	345	345	690	690	690	1208
4.2	Hr	1	97151	.	.	.	.	.	.
9.1	Hl	1	97151	345	690	690	690	690	1208
12.2	C	2	97151	345	345	345	345	345	690
15.1	Hl	2	97151	345	518	690	518	345	345
20.2	Hr	2	97151	345	345	345	345	345	690
23.2	C	3	97151	345	345	345	345	345	345
24.1	Hl	3	97151	345	345	690	1208	690	1208
29.2	Hr	3	97151	345	345	1380	345	345	345
31.2	C	4	97151	345	345	690	345	1208	1035
33.2	Hr	4	97151	345	345	345	345	345	1035
39.1	Hl	4	97151	345	345	1035	345	690	690
Composite									
2.2	C	1	97151	345	345	425	558	558	811
4.2	Hr	1	97151	.	.	.	.	.	.
9.1	Hl	1	97151	345	425	690	1087	690	546
12.2	C	2	97151	345	345	610	477	345	955
15.1	Hl	2	97151	345	385	690	385	345	874
20.2	Hr	2	97151	345	345	610	345	345	558
23.2	C	3	97151	345	345	345	345	345	345
24.1	Hl	3	97151	345	345	425	546	425	811
29.2	Hr	3	97151	345	345	851	345	345	610
31.2	C	4	97151	345	345	690	610	811	770
33.2	Hr	4	97151	345	345	610	610	610	770
39.1	Hl	4	97151	345	345	506	345	425	425

Appendix C cont.

Plot	Treatment	Rep	Date	Depth (cm)					
				5	10	15	20	25	30
				kPa					
Non-traffic interrow									
2.2	C	1	98162	345	690	690	690	690	690
4.2	Hr	1	98162	.	.	.	.	.	.
9.1	Hl	1	98162	690	1035	1725	1380	1380	1380
12.2	C	2	98162	345	1380	690	690	690	690
15.1	Hl	2	98162	345	690	1725	1725	1725	1725
20.2	Hr	2	98162	345	1035	1725	1380	1380	1380
23.2	C	3	98162	345	690	1380	1725	1380	1035
24.1	Hl	3	98162	345	690	1380	1725	1035	690
29.2	Hr	3	98162	345	1035	1035	690	690	690
31.2	C	4	98162	345	1035	1380	1380	1380	1035
33.2	Hr	4	98162	345	690	1035	1725	1380	690
39.1	Hl	4	98162	345	690	1380	1035	1380	1035
Traffic interrow									
2.2	C	1	98162	1035	1725	2070	2070	1725	1380
4.2	Hr	1	98162	.	.	.	.	.	.
9.1	Hl	1	98162	1035	1380	1380	1035	690	1035
12.2	C	2	98162	345	690	1035	1035	1035	690
15.1	Hl	2	98162	1380	1725	1725	1725	1725	1725
20.2	Hr	2	98162	345	690	1035	1035	1035	690
23.2	C	3	98162	345	690	690	1035	1380	1725
24.1	Hl	3	98162	690	1380	1725	1725	1380	1380
29.2	Hr	3	98162	690	1380	1725	1725	1725	1380
31.2	C	4	98162	690	1035	1035	690	690	690
33.2	Hr	4	98162	345	690	1035	1035	690	690
39.1	Hl	4	98162	345	690	690	345	690	345
Composite									
2.2	C	1	98162	506	931	1012	1012	931	851
4.2	Hr	1	98162	.	.	.	.	.	.
9.1	Hl	1	98162	770	1115	1645	1300	1219	1300
12.2	C	2	98162	345	1219	770	770	770	690
15.1	Hl	2	98162	586	931	1725	1725	1725	1725
20.2	Hr	2	98162	345	955	1564	1300	1300	1219
23.2	C	3	98162	345	690	1219	1564	1380	1196
24.1	Hl	3	98162	425	851	1460	1725	1115	851
29.2	Hr	3	98162	425	1115	1196	931	931	851
31.2	C	4	98162	425	1035	1300	1219	1219	955
33.2	Hr	4	98162	345	690	1035	1564	1219	690
39.1	Hl	4	98162	345	690	1219	874	1219	874

Appendix D: Water intake data for North Willamette Research and Extension Center.

Plot	Treatment	Rep	Date	Non-traffic	Traffic	Composite
					-----------cm h^{-1} -----------	
2.2	C	1	97151	1.47	0.43	1.23
4.2	Hr	1	97151	4.57	1.71	3.90
9.1	Hl	1	97151	0.38	0.08	0.31
12.2	C	2	97151	2.28	2.28	2.28
15.1	Hl	2	97151	0.17	1.28	0.43
20.2	Hr	2	97151	0.54	0.18	0.46
23.2	C	3	97151	0.34	2.28	0.80
24.1	Hl	3	97151	0.40	1.47	0.65
29.2	Hr	3	97151	2.28	1.71	2.15
31.2	C	4	97151	0.54	0.76	0.59
33.2	Hr	4	97151	0.11	1.47	0.42
39.1	Hl	4	97151	0.51	0.14	0.43
2.2	C	1	98162	5.14	0.12	3.97
4.2	Hr	1	.	.	.	.
9.1	Hl	1	98162	0.06	0.22	0.10
12.2	C	2	98162	0.10	0.14	0.11
15.1	Hl	2	98162	0.09	0.10	0.09
20.2	Hr	2	98162	0.07	0.18	0.09
23.2	C	3	98162	0.12	0.18	0.13
24.1	Hl	3	98162	0.69	0.07	0.54
29.2	Hr	3	98162	0.10	0.06	0.09
31.2	C	4	98162	0.10	0.27	0.14
33.2	Hr	4	98162	0.60	0.05	0.48
39.1	Hl	4	98162	4.11	0.20	3.20

Appendix E: Water stable aggregates (WSA) data for North Willamette Research and Extension Center.

Plot	Treatment	Rep	Date	WSA %	Date	WSA %	Date	WSA %
2.2	C	1	.	.	96197	21.07	96250	36.79
4.2	Hr	1	.	.	96197	28.28	96250	37.13
9.1	Hl	1	.	.	96197	27.89	96250	38.84
12.2	C	2	.	.	96197	23.30	96250	42.81
15.1	Hl	2	.	.	96197	54.34	96250	56.91
20.2	Hr	2	.	.	96197	53.05	96250	60.00
23.2	C	3	.	.	96197	17.31	96250	29.11
24.1	Hl	3	.	.	96197	25.52	96250	29.64
29.2	Hr	3	.	.	96197	14.51	96250	24.73
31.2	C	4	.	.	96197	28.47	96250	38.65
33.2	Hr	4	.	.	96197	29.55	96250	36.06
39.1	Hl	4	.	.	96197	20.83	96250	28.78
2.2	C	1	97083	25.75	97224	14.36	97259	5.96
4.2	Hr	1	.	.	.	.	.	.
9.1	Hl	1	97083	27.88	97224	19.83	97259	5.47
12.2	C	2	97083	21.37	97224	14.09	97259	5.03
15.1	Hl	2	97083	56.10	97224	34.48	97259	10.33
20.2	Hr	2	97083	43.36	97224	20.66	97259	6.32
23.2	C	3	97083	14.83	97224	17.08	97259	4.86
24.1	Hl	3	97083	20.68	97224	15.62	97259	6.69
29.2	Hr	3	97083	31.47	97224	9.05	97259	4.14
31.2	C	4	97083	42.62	97224	24.71	97259	6.54
33.2	Hr	4	97083	47.25	97224	17.57	97259	4.98
39.1	Hl	4	97083	20.26	97224	13.19	97259	3.19
2.2	C	1	98082	4.21	98195	14.87	98268	21.87
4.2	Hr	1	.	.	.	.	.	.
9.1	Hl	1	98082	9.66	98195	28.21	98268	32.34
12.2	C	2	98082	11.14	98195	21.93	98268	24.95
15.1	Hl	2	98082	23.05	98195	31.45	98268	51.48
20.2	Hr	2	98082	6.60	98195	21.70	98268	31.88
23.2	C	3	98082	3.33	98195	27.34	98268	23.48
24.1	Hl	3	98082	6.80	98195	8.76	98268	18.74
29.2	Hr	3	98082	3.42	98195	9.62	98268	12.27
31.2	C	4	98082	11.32	98195	29.90	98268	31.14
33.2	Hr	4	98082	6.92	98195	25.16	98268	31.77
39.1	Hl	4	98082	7.30	98195	13.25	98268	18.06