AGROFORESTRY AND GRASS BUFFERS FOR IMPROVING SOIL HYDRAULIC PROPERTIES AND REDUCING RUNOFF AND SEDIMENT LOSSES FROM GRAZED PASTURES

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by

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The undersigned, appointed by the Dean of the Graduate School, have examined the dissertation entitled

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presented by

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a candidate for the degree of

DOCTOR OF PHILOSOPHY

and hereby certify that, in their opinion, it is worthy of acceptance.

Stephen H. Anderson (Chair)

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Allen L. Thompson

To My Dearest Mom and Dad

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AGROFORESTRY AND GRASS BUFFERS FOR IMPROVING SOIL HYDRAULIC PROPERTIES AND REDUCING RUNOFF AND SEDIMENT LOSSES FROM GRAZED PASTURES

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ABSTRACT

Agroforestry buffers, a system of land use in which harvestable trees or shrubs are grown among or around crops or on pastureland, have been proposed for improving water quality in watersheds. The objectives of this study were (i) to evaluate saturated hydraulic conductivity (K_{sat}) and water retention for soils managed under rotationally-grazed pasture (RG), continuously grazed pasture (CG), grass buffers (GB), and agroforestry buffers (AgB); (ii) to compare differences in computed tomography (CT)-measured macropore (>1000-μm diam.) and coarse mesopore (200- to 1000-μm diam.) parameters for AgB, GB, RG and CG treatments, and to examine relationships between CT-measured pore parameters and K_{sat} ; (iii) to compare the influence of AgB and GB systems under rotationally stocked (RG) and continuously stocked (CG) pasture systems on water infiltration measured using ponded infiltration and tension infiltration methods; (iv) to evaluate differences in root length density (RLD) and root and soil carbon content within GB, AgB, RG and CG treatments; and (v) to model runoff and sediment losses for grazed pasture watersheds with and without AgB buffers. Pasture and GB areas included red clover (*Trifolium pretense* L.) and lespedeza (*Kummerowia stipulacea* Maxim.)

planted into fescue (*Festuca arundinacea* Schreb.) while AgB included Eastern cottonwood trees (*Populus deltoids* Bortr. ex Marsh.) planted into fescue. Soil bulk density was 12.6% higher for the pasture treatments compared to buffer treatments. Soil water content at high soil water potentials (0 and -0.4 kPa) was greater in the buffer treatments relative to pasture treatments for the 0-10 cm soil depth. Soil macroporosity (>1000 µm diam.) was 5.7, 4.5, and 3.9 times higher, respectively, for the AgB, GB, and RG treatments compared to the CG treatment for the 0-10 cm soil depth. Buffer treatments had greater macroporosity (>1000-µm diam.), coarse (60- to 1000-µm diam.) and fine mesoporosity (10 to 60 µm diam.) but lower microporosity (< 10 µm diam.) compared to pasture treatments. The K_{sat} for the buffer treatments was 16.7 times higher compared with pasture treatments. The CT-measured soil macroporosity was 13 times higher (0.053 m^3m^{-3}) for the buffer treatments compared to the pasture treatments (0.004 m^3m^{-3}) for the surface 0-10 cm soil depth. Buffer treatments had greater CT-measured macroporosity (0.019 m^3m^{-3}) compared to pasture (0.0045 m^3m^{-3}) treatments. The CT-measured pore parameters (except macropore circularity) were positively correlated with K_{sat}. Quasi-steady state infiltration rates (q_s) and field-saturated hydraulic conductivity (K_{fs}) for buffers were about 30 and 40 times higher compared to pasture treatments, respectively. Green-Ampt and Parlange models appeared to fit measured data with r^2 values ranging from 0.91 to 0.98. The infiltration rate in 2007 for the GB treatment was the highest (221 mm h^{-1}) and for the CG treatment was the lowest (3.7 mm h^{-1}). Estimated sorptivity (S) and saturated hydraulic conductivity (K_s) parameters were higher for buffer areas compared to the stocked pasture areas. Grazing reduced the infiltration rate for the pasture treatments. Buffer treatments had 4.5 times higher RLD as compared to pasture treatments. The AgB treatment had the highest (173.5 cm/100 cm^3) and CG had the lowest (10.8 cm/100 cm^3) RLD. Root carbon was about 3% higher for the buffers compared to RG treatment. Soil carbon was about 115% higher for the buffers compared to pasture treatments. This study illustrates that agroforestry and grass buffers maintained higher values for soil hydraulic properties compared to grazed pasture systems. The CT-study illustrates the benefits of agroforestry and grass buffers for maintaining soil pore parameters critical for soil water transport. Results from the infiltration study conclude that the buffer areas have higher infiltration rates which imply lower runoff compared to pasture areas. The root study implies that establishment of agroforestry and grass buffers on grazed pasture watersheds improves soil carbon accumulation and root parameters which enhance soil physical and chemical properties, thus improving the environmental quality of the landscape. The Agricultural Policy Extender (APEX) model was used to simulate runoff and sediment losses from the AgB watersheds and control (CW) watersheds. The model was calibrated from 2002 to 2005 and was validated from 2005 to 2008. The r^2 and NSE values for the calibration and validation period of the runoff varied from 0.52 to 0.78 and 0.51 to 0.74, respectively. The model did not predict sediment loss very well (NSE values were less than 0.19) because of insufficient measured events. The measured runoff was 36% lower for AgB watersheds compared to CW watersheds. The measured sediment loss for the AgB watersheds was about 49% lower compared to CW watersheds. The model was run for long-term scenario analyses from 1999 to 2008. The runoff decreased 24% when the buffer width was doubled. The runoff from the AgB watersheds was 9.8% lower with double stocking densities compared to CW watersheds with double stocking densities. Results of these studies indicate that establishment of agroforestry and grass buffers on grazed pasture watersheds improve soil hydraulic properties, pore parameters, soil carbon sequestration and water quality indices and thus contribute to enhance overall environmental quality.

CHAPTER 1

INTRODUCTION

Agroforestry, a conservation land management practice where trees and agricultural crops or grasses are grown simultaneously on the same landscape or managed with cattle (e.g. silvopastoral practice, the practice of combining forestry and grazing of domesticated animals in a mutually beneficial way), is being promoted as an alternative management system that can diversify income and improve environmental quality and environmental benefits (Gold and Hanover, 1987; Garrity, 2004). These practices provide diversified productivity and better maintenance of soil fertility and carbon sequestration compared to more conventional annual cropping systems (Schroth et al., 2001). Additionally, these practices, containing both tree and grass components, may sequester more carbon than grass only systems and affect nutrient cycling, root distribution patterns and depths, and alter litter quality and deposition (van Noordwijk et al., 1996; Cadisch and Giller, 1997; Berg and McClaugherty, 2003; Sharrow and Ismail, 2004).

Agroforestry and grass buffers help in reducing nonpoint source pollution (NPSP) from row crop areas by improving soil hydraulic properties and decreasing surface runoff, and utilizing nutrients (Gilliam, 1994; Udawatta et al., 2002; Abu-Zreig et al., 2003; Blanco et al., 2004; Seobi et al., 2005; Lovell and Sullivan, 2006). Microbial diversity and enzymatic activity are higher in conservation buffer areas, thus improving mineralization of nutrients, nutrient cycling, and degradation of chemicals (Mungai et al., 2005; Udawatta et al., 2008a).

Extensive deep root systems of the trees effectively participate in trapping runoff, sediments and the nutrients from the watersheds (Udawatta et al., 2002). Growth and distribution of deep root systems of the plants/trees depend on various factors such as the plant or tree species, amount of available water, soil type, and soil properties. The growth and decay of large and deep tree roots create channels and subsequently result in a greater proportion of larger pores (macropores) that enhance soil hydraulic properties compared to a cropping system (Meek et al., 1992; Cadisch et al. 2004).

The soil macropores created by decayed roots of the buffers (such as agroforestry and grass buffers) will allow surface water to enter easily into the soil and hence increase the water infiltration compared to soils which are without buffers (Rachman et al., 2005). Other researchers Obi (1999) and Mishra et al. (2003) have also reported that root penetration and root decay of the tree roots in the soil profile create many large and small pores; these roots add organic matter and improve soil hydraulic properties. Increased soil porosity under buffers was also reported by various other researchers, such as, Udawatta et al. (2008b), Seobi et al. (2005), and Rachman et al. (2005).

Soil porosity, which can be influenced by buffer management, is an important parameter which is related to transport and storage of water and nutrients in the soil. Hence, it is essential to understand and quantify the soil pore characteristics. Porosity can be measured by traditional water retention methods (Anderson et al., 1990) but these methods do not provide information about the spatial distribution of pores (Gantzer and Anderson, 2002).

In contrast, X-ray CT scanning has been shown by various researchers to be useful for measuring soil microstructure (Phillips and Lannutti, 1997; Alshibli et al., 2000). These techniques have provided promising results for measuring the shape, distribution, and arrangement of soil pores within the soil (Udawatta et al., 2008b).

Research also shows that CT-measured pore parameters are highly correlated with soil water movement and management practices (Udawatta et al., 2008c).

In addition to use within row crop production systems to improve soil properties, agroforestry buffers can also be established on the edge of pastures with fencing around the buffer area to prevent disturbance of the buffer by grazing animals. In these buffer systems where the tree and grass buffer areas are left undisturbed by grazing animals, soil properties may be different compared to pasture areas which are disturbed by animal traffic.

Rotational grazing, in which the pasture area is subdivided into equally sized smaller paddocks, encourages uniform forage consumption and manure distribution, and decreases compacted and eroded areas (Warren et al., 1986; Turner et al., 1997). This type of grazing has also been shown to improve the productivity of cattle compared to conventional grazing (Warren et al., 1986) as well as soil properties.

To assess long-term benefits of soil conservation practices, simulation models have often been used in the past. Models can provide long-term simulations on the effects of best management practices to assist in selection of appropriate conservation approaches. Models calibrated and validated with measured runoff, sediment and nutrient losses from watersheds have been used to assist policy makers in selecting conservation practices and allocating resources. In a study comparing paired watersheds with and without agroforestry buffers, the Agricultural Policy Environmental Extender (APEX) model was calibrated and used to simulate runoff and sediment loss by Farrand et al. (2002). The APEX model is useful to assess effectiveness of filter strips or buffers in controlling sediment and runoff and other pollutants from an area (Arnold et al., 1998).

Objectives

The purpose of this study was to evaluate soil hydraulic properties, root growth, runoff, sediment, and nutrient losses for soils managed under rotationally-grazed pasture (RG), continuously grazed pasture (CG), grass buffers (GB), and agroforestry buffers (AgB). The objectives of this study were evaluated in five sub-studies as outlined below. Objectives were developed separately for each study.

Study 1. This study was entitled "soil hydraulic properties as influenced by agroforestry and grass buffers under grazed pasture systems" with the specific objectives being measurement and comparison of bulk density, saturated hydraulic conductivity, soil water retention, and pore size distributions among agroforestry buffer, grass buffer, rotationally grazed pasture and continuously grazed pasture treatments.

Study 2. This study was entitled "agroforestry and grass buffer influences on CT-measured macropores under grazed pasture systems" with specific objectives being (i) comparison of the effects of agroforestry (AgB) and grass buffer (GB) systems associated with rotationally grazed pasture (RG) and continuously grazed pasture (CG) systems on CT-measured macropore (>1000-μm diam.) and coarse mesopore (200- to 1000-μm diam.) parameters and (ii) examination of relationships between CT-measured pore parameters and saturated hydraulic conductivity (K_{sat}).

Study 3. The study was entitled "water infiltration influenced by agroforestry and grass buffers for a grazed pasture system" with the specific objective being comparison of water infiltration parameters among agroforestry and grass buffers in relation to rotationally and continuously stocked pastures.

Study 4. The study was entitled "root length density and carbon content influenced by agroforestry and grass buffers under grazed pasture systems in a Hapludalf" with the specific objective being evaluation of differences in root length density, root and soil carbon content within grass buffer (GB), agroforestry buffer (AgB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) treatments.

Study 5. The last study was entitled "APEX model simulation of runoff and sediment losses from agroforestry buffers for watersheds under pasture management" with the specific objective being to simulate runoff and sediment losses from watersheds with agroforestry buffers compared to watersheds without buffers (control).

All the five studies were written independently in the format of journal manuscripts for publication purposes. Study 1 is published in *Journal of Soil and Water Conservation*, Study 2 is accepted for publication in *Soil Science Society of America Journal*, Study 3 had been submitted to *Journal of Soil and Water Conservation* for peer review, and Study 4 had been submitted to *Agroforestry Systems* for peer review.

References

Abu-Zreig, M., R.P. Rudra, H.R. Whitely, M.N. Lalonde, and N.K. Kaushik. 2003. Phosphorus removal in vegetated filter strips. J. Environ. Qual. 32:613-619.

Alshibli, K.A., S. Sture, N.C. Costes, M.L. Frank, M.R. Lankton, S.N. Batiste, and R.A. Swanson. 2000. Assessment of localized deformations in sands using X-Ray computed tomography. Geotech. Test. J. 23:274-299.

Anderson, S.H., C.J. Gantzer, and J.R. Brown. 1990. Soil physical properties after 100 years of continuous cultivation. J. Soil Water Conserv. 45:117-121.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large Area Hydrologic Modeling and Assessment, pt.1, Model Development. J. Amer. Water Res. Assoc. 34:73-89.

Berg, B., and C. McClaugherty. 2003. Plant litter: decomposition, humus formation, carbon sequestration. Springer, Germany.

Blanco-Canqui, H., C. J. Gantzer, S.H. Anderson, E.E. Alberts, and A.L. Thompson. 2004. Grass barrier and vegetative filter strip effectiveness in reducing runoff, sediment, nitrogen, and phosphorus loss. Soil Sci. Soc. Am. J. 68:1670-1678.

Cadisch, G., and K.E. Giller. 1997. Driven by nature: plant litter quality and decomposition. CAB International, Oxford, pp 409.

Farrand, D.T., R.P. Udawatta, and H.E. Garrett. 2002. Predicting environmental benefits of Agroforestry practices in northern Missouri using APEX. Agronomy abstracts 2002. Annual meetings. Indianapolis, Indiana, Nov. 10-14, 2002. American Society of Agronomy, 677, South Segoe Road, Madison, Wisconsin 53711.

Gantzer, C.J., and S.H. Anderson. 2002. Computed tomographic measurement of macroporosity in chisel-disk and no-tillage seedbeds. Soil Tillage Res. 64:101-111.

Garrity, D.P. 2004. Agroforestry and the achievement of the millennium development goals. p. 5-17. *In* P.K.R. Nair, M.R. Rao, and L.E. Buck (eds) New vistas in agroforestry, A compendium for the 1st World Congress of Agroforestry. Kluwer Academic Publishers, New York.

Gilliam, J.W. 1994. Riparian wetlands and water quality. J. Environ.Qual. 23:896-900.

Gold, M.A., and J.W. Hanover. 1987. Agroforestry systems for temperate zones. Agrofor. Syst. 5:109-121.

Lovell, S.T., and W.C. Sullivan. 2006. Environmental benefits of conservation buffers in the United States: Evidence, promise, and open questions. Agric. Ecosyst. Environ. 112:249-260.

Meek, B.D., E.R. Rechel, L.M. Carter, W.R. DeTar, and A.L. Urie. 1992. Infiltration rate of a sandy loam soil: effects of traffic, tillage, and plant roots. Soil Sci. Soc. Am. J. 56: 908-913.

Mishra, A., S.D. Sharma, and G.H. Khan. 2003. Improvement in physical and chemical properties of sodic soil by 3, 6 and 9 year old plantation of Euculyptus tereticornis biorejuvenation of sodic soil. For. Ecol. Manage. 184:115-124.

Mungai, N.W., P.P. Motavalli, R.J. Kremer, and K.A. Nelson. 2005. Spatial variation of soil enzyme activities and microbial functional diversity in temperate alley cropping systems. Biol. Fertil. Soils 42:129-136.

Obi, M.E. 1999. The physical and chemical responses of a degraded sandy clay loam soil to cover crops in southern Nigeria. Plant Soil 211:165-172.

Phillips, D.H., and J.J. Lannutti. 1997. Measuring physical density with X-ray computed tomography, NDT & E Int 30:339-350.

Rachman, A., S.H. Anderson, and C.J. Gantzer. 2005. Computed-tomographic measurement of soil macroporosity parameters as affected by stiff-stemmed grass hedges. Soil Sci. Soc. Am. J. 69:1609-1616.

Schroth, G., J. Lehmann, M.R.L. Rodrigues, E. Barros, and J.L.V. Macedo. 2001. Plant-soil interactions in multistrata agroforestry in the humid tropics. Agrofor. Syst. 53:85-102.

Seobi, T., S.H. Anderson, R.P. Udawatta, and C.J. Gantzer. 2005. Influence of grass and agroforestry buffer strips on soil hydraulic properties for an Albaqualf. Soil Sci. Soc. Am. J. 69:893-901.

Sharrow, S.H., and S. Ismail. 2004. Carbon and nitrogen storage in agroforests, tree plantations, and pastures in western Oregon, USA. Agrofor. Syst. 60:123-130.

Turner, L.W., C.W. Absher, and J.K. Evans. 1997. Planning fencing systems for intensive grazing management. p. 1-12. University of Kentucky Cooperative Extention Service Pub. ID-74, Lexington, KY.

Udawatta, R.P., C.J. Gantzer, S.H. Anderson, and H.E. Garrett. 2008b. Agroforestry and grass buffer effects on high resolution X-ray CT-measured pore characteristics. Soil Sci. Soc. Am. J. 72:295-304.

Udawatta, R.P., J.J. Krstansky, G.S. Henderson, and H.E. Garrett. 2002. Agroforestry practices, runoff, and nutrient loss: a paired watershed comparison. J. Environ. Qual. 31:1214-1225.

Udawatta, R.P., R.J. Kremer, B.W. Adamson, and S.H. Anderson. 2008a. Variations in soil aggregate stability and enzyme activities in a temperate agroforestry practice. Appl. Soil Ecol. 39:153-160.

Udawatta, R.P., S.H. Anderson, C.J. Gantzer, and H.E. Garrett. 2008c. Influence of prairie restoration on CT-measured soil pore characteristics. J. Environ. Qual. 37:219-228.

van Noordwijk, M., G. Lawson, A. Soumare, J.J.R. Groot, and K. Hairiah. 1996. Root distribution of trees and crops: competition and/or complementarity. p.319-364. *In*: Ong CK and Huxley P (eds) Tree-crop interactions: a physiological approach. CAB International, Oxford.

Warren, S.D., W.H. Blackburn, and C.A. Taylor, J.R.1986. Soil hydrologic response to number of pastures and stocking density under intensive rotation grazing. J. Range Manage. 39:500-504.

CHAPTER 2

LITERATURE REVIEW

Agroforestry Systems

Agroforestry is a land management practice where tree species and agriculture crops are grown simultaneously in the same area for economical and environmental benefits (Gold and Hanover, 1987). Agroforestry buffers include trees which are grown either on the edges of fields or along streambanks in riparian zones. Agricultural crops or pastures are often grown together with these tree buffers. These buffers improve soil and water quality and generate additional income when nut bearing trees or ornamental shrubs are incorporated (Kang et al., 1984; Alavalapati et al., 2004; Udawatta et al., 2005). Buffers can enhance flora and fauna in an area by providing a better environment for wildlife habitat (Lovell and Sullivan, 2006). Additionally, agroforestry practices improve the socioeconomic and environmental sustainability both in tropical and temperate regions (Garrett et al., 2000; Alavalapati and Nair, 2001; Nair, 2001). They can provide products that serve household needs or that can be sold. These include construction materials, fuel wood, fruit and medicinal products (Oldfield, 1988; Kappelle and Juarez, 1994). These land management practices can improve soil quality, and air quality, and increase aesthetic value of land, in addition to providing food, wood products, and fodder for cattle (Alavalapati et al., 2004). In addition, trees sequester carbon by absorbing carbon dioxide from the atmosphere (Montagnini and Nair, 2004).

In agroforestry systems, trees intercept solar radiation, and reduce soil temperature, thus enhancing favorable conditions for microbial decomposition and nutrient cycling (Crawford, 1998). These systems, by intercepting solar radiation, help in reducing high temperatures which can help reduce heat stress for crops and/or animals (Jose et al., 2004). According to Stamps and Linit (1998), agroforestry is a potentially useful technology for reducing pest problems because tree and crop combinations provide greater diversity and complexity than row crop systems.

Influence of Buffers on Nonpoint Source Pollution

Nonpoint source pollution (NPSP) is mainly caused by sediment, nutrient and pesticide runoff and snowmelt over and through the ground. Nonpoint source pollution occurs due to soil and nutrient losses from the landscape with water runoff; these sediments and nutrients can be deposited in streams and lakes. This NPSP is a major challenge in the United States that affects water quality and negatively impacts aquatic ecosystems (Dosskey, 2001). Rainfall and snowmelt can transport sediments, nutrients, and pesticides; these pollutants are affected by land disturbance that can occur naturally, by animals or by human activities. This polluted runoff water mixes with streams and lakes as well as groundwater that decreases water quality. The major nutrients lost in runoff are nitrogen and phosphorus. These nutrients affect algal growth in lakes and rivers and may lead to eutrophication that reduces water quality and destroys aquatic habitat. Excessive runoff water caused by some management systems becomes a major cause of erosion and nonpoint source pollution (Seobi et al., 2005). Researchers have worked on trying to control nonpoint source pollution using buffers and other conservation practices. The purpose of buffers is to reduce sediments and nutrients in runoff water that can end up in lakes and streams.

Agroforestry buffer practices can help in the reduction of NPSP, surface runoff, and sediment losses from row crop areas by improving soil hydraulic properties and reducing surface runoff (Gilliam, 1994; Udawatta et al., 2002; Abu-Zreig et al., 2003; Lovell and Sullivan, 2006). Increasing amounts of nutrients or chemical fertilizers in the soil may enhance the potential for their loss, leading to groundwater contamination and NPSP from the agricultural areas (Nair and Graetz, 2004).

Several practices have been recommended to reduce NPSP such as contour strip cropping which may reduce runoff velocity and soil loss (Martin et al., 1976; Schwab et al., 1993), and grass and agroforestry buffer practices which also reduce surface runoff, sediment and nutrient losses (Udawatta et al., 2002). Filter strips of permanent vegetation reduce runoff and trap sediment which decrease NPSP (Lowrance and Sheridan 2005). These vegetative buffers have been widely studied in agricultural settings and have reduced nutrient losses from agricultural lands (Baker et al., 2000). The 'nutrient-capture' functions of agroforestry buffers are being exploited in phytoremediation of contaminated sites (Rockwood et al., 2004) and explored in the rehabilitation of heavily fertilized agricultural systems in North America (Nair and Graetz, 2004).

Runoff

A good understanding on mechanisms that affect and enhance runoff is needed to develop runoff control measures. Researchers showed that knowing factors that affect runoff can assist selection of the best conservation practices such as agroforestry buffers, grass buffers, vegetative filter strips that might help reduce runoff from a land area (Dabney et al., 1995; Gao et al., 2002).

Agroforestry practices provide many environmental benefits, such as increased soil fertility, reduced soil erosion, and reduced surface runoff (De la Cruz and Vergara 1987; Muschler and Bonnemann 1997). A study conducted by Udawatta et al. (2002) to evaluate the effects of buffer strips on sediment, runoff and nutrient losses showed that buffers reduced surface water runoff, sediments and nutrients (total P, total N) two years after grass and tree buffers were established as compared to a control watershed with no buffer strips. These researchers also found that grass and agroforestry buffer strips reduced water runoff by about 9%.

Vegetative buffers provide a natural filter for reducing surface runoff, sediment, and nutrient losses from an area. With greater slopes, a larger amount of loss of these pollutants may occur because of increased water velocity. When the soil is left bare with no residue, soil erosion is increased and water infiltration is lowered which enhances runoff. Vegetative buffers assist in maintaining soil cover which helps retain soil particles with their extensive root systems; these may increase water infiltration and reduce runoff.

The runoff loss from the watersheds contains various pollutants such as total N and P, HPO_4^{2-} and $H_2PO_4^-$, NO_3^- and NH_4^+ which affect the soil and water quality. Nitrogen (primarily NO_3^- and NH_4^+) lost in water runoff may lead to eutrophication in bodies of water at concentrations as low as 1 mg L^{-1} (Walker and Branham, 1992). Excessive nutrient levels cause an abundance of algae and aquatic plant blooms which deplete oxygen from the water and may cause the death of plants and fish (Moss et al., 2006). Dissolved reactive phosphorus (DRP), a term that refers to HPO_4^{2-} and $H_2PO_4^-$, is believed to contribute to the eutrophication of water bodies of water at concentrations as low as 25 mg L^{-1} (Walker and Branham, 1992). Hence, it is indeed important to reduce the runoff from areas to protect the soil and water quality. Agroforestry practices have proven to be effective in reducing runoff. Additionally, uptake of nutrients by trees can reduce fertilizer and pesticide runoff into nearby streams (Zinkhan and Mercer, 1997), which improves the water quality of streams.

Sediment Losses

The effectiveness of buffers depends on various factors, such as type of soil, type of vegetation, slope, soil permeability, climatic conditions, and buffer vegetation as well as buffer parameters. The width of the buffers plays a major role in reducing runoff and sediment losses; the greater the width, the more the runoff velocity is reduced and the more sediment can be trapped. Desbonnet et al. (1994) reported that, on the average, 50 percent or more of sediments and attached pollutants are trapped by a 4.6-m vegetative buffer system. Moss et al. (2006) reported that vegetative buffers in which grass vegetation was the primary material used, also referred to as vegetative filter strips (USDA-NRCS, 1997), may help to reduce the movement of sediments (Barfield et al., 1979; Hayes et al., 1979), nutrients (Gross et al., 1990) and pesticides (Baird et al., 2000; Baker et al., 2000).

Buffers which are planted on the down slope edges of watersheds trap sediments with their extensive stem and root systems and also by reducing the runoff water velocity (Udawatta et al., 2002). Lee et al. (2003) and Lowrance et al. (2002) reported that buffers can remove up to 97% of sediments in runoff before entering into a stream if these buffers are properly maintained. In another study conducted by Lowrance and Sheridan (2005), they found that permanent vegetative filter strips of the riparian zones reduce runoff and sediment losses and improve the water quality of the streams.

In a recent study of a riparian buffer strip in central Iowa, Lee et al. (2003) reported that switch grass (*Panicum virgatum*) buffers removed 95% of sediments, 80% of total N, 62% of nitrate-N, 78% of total P, and 58% of phosphate-P compared to no buffer. This switch grass buffer was effective in removing sediment and sediment-bound nutrients.

Influence of Buffers and Grazing on Soil Properties

Agroforestry buffers can also be used in combination with pastures with fencing to prevent disturbance of the buffers by grazing animals. In these types of buffer systems where tree and grass buffer areas are left undisturbed by grazing animals, soil properties might be different compared to grazed pasture areas which are disturbed by cattle. Donkor et al. (2001) reported that soil physical properties under frequent short duration grazing by wapiti (*Cervus elaphus canadensis*) were significantly different compared to moderate grazing in pasture areas. Other researchers have also reported that soil bulk density, pore size distribution and resistance to root penetration are some of the physical properties altered by compaction (Da Silva et al., 2003).

Daniel et al. (2002) observed that livestock grazing for 10-years increased soil compaction in the surface 0- to 10-cm soil depth. Soil compaction significantly increased with increased stocking densities from 12.5 to 50 cows ha^{-1} as compared to ungrazed plots. These ungrazed plots or buffers may have lower soil bulk density, higher soil porosity and increased infiltration compared to grazed pasture areas. Moreover, data show that uneven grazing in pasture areas enhances soil erosion by increased surface runoff from areas with lower infiltration due to compaction from continuous cattle traffic (Radke and Berry, 1993; Daniel et al., 2002; Wheeler et al., 2002). Soil organic matter and bulk density are greatly influenced by grazing, and other soil properties are directly or indirectly affected by these properties (Donkor et al., 2001; Daniel et al., 2002).

Soil compaction, whether due to machinery traffic (Raghavan et al., 1990; Soane and van Ouwerkerk, 1994; Hamza and Anderson, 2005) or by cattle grazing, is a well recognized problem in many parts of the world. The extent of the soil compaction problem is a function of soil type and water content (Chan et al., 2006). Soil compaction affects water, heat, and gas exchange (Linn and Doran, 1984), root penetration (Taylor et al., 1966), and consequently crop production (Hakansson et al., 1988). Compaction induced by vehicle traffic has adverse effects on a number of key soil properties such as bulk density, mechanical impedance, porosity and hydraulic conductivity (Radford et al., 2000; Hamza and Anderson, 2005). All of these factors can potentially reduce root penetration, water extraction and plant growth (Kirkegaard et al., 1992; Passioura, 2002). From a management point of view, it is useful to identify the processes responsible for changes in soil physical properties so that farming systems and practices can be adopted to either ameliorate, avoid or minimize soil compaction and reduce the subsequent risk of poor agronomic performance (Chan et al., 2006). Soil compaction can be reduced by using rotational grazing practices, where cattle are allowed to graze in an area for a specific period of time and then rested for a certain period **(**Turner et al., 1997**).**

Soil Organic Matter

Soil organic matter (SOM) is one of the important ecosystem components in both natural ecosystems and in intensively-managed agricultural systems (Paul, 1984). The SOM is also considered to be an important soil quality indicator variable because it acts as an environmental buffer by absorbing or transforming potential pollutants (Sikora and

Stott, 1996). Addition of soil organic carbon due to grass planted in tree buffer areas can reduce compaction and increase the infiltration rate of the soil. Radke and Berry (1993) reported that crop residues which cover the ground increased the infiltration rate by reducing compaction from rainfall impact and reducing soil sealing; the soil evaporation rate also decreased. Plant (alfalfa, *Medicago sativa* L.) roots and shoots contribute to fresh organic matter inputs into the soil profile, which promote soil aggregation (Angers and Caron, 1998).

Soil organic matter promotes aggregation of soil particles which increases porosity and reduces bulk density. Soil pores and organic matter are often considered together while different forms of organic matter play an important role in the formation of pores and soil structure stabilization (Kay and Van den Bygaart, 2002). In these aggregated soils, water movement is controlled by the presence of inter-aggregate pores where water flows faster than in intra-aggregate pores (Horn, 1990). Soil organic matter includes different organic compounds from easily-mineralizable plant residues to more complex products from biotic and abiotic transformation processes or microbial biomass (Stevenson, 1994; Rethemeyer, 2004). Buffers may change organic matter distribution and its accessibility.

Soil Bulk Density

Soil compaction is often measured in terms of soil density, water infiltration, or air-filled porosity. Various researchers have reported in previous studies that soil bulk density affects water, heat, and gas exchange (Grable and Siemer, 1968; Warkentin, 1971; Willis and Raney, 1971; Linn and Doran, 1984), root penetration (Taylor et al., 1966; Kirkegaard et al., 1992; Passioura, 2002), and consequently crop production

(Hakansson et al., 1988; Kirkegaard et al., 1992; Passioura, 2002). One of the most frequently used measures of compaction is soil bulk density (BD; Abu-Hamdeh, 2003). Hence it is very important to know the BD of an area. Jones (1983) found a bulk density value above 1.54 Mg m^{-3} limits plant (*Gossypium spp*., *Zea mays*., *Pisum sativum*, and *Sorghum X drummondii*) root growth for clay soils. The BD of undisturbed buffers (without grazing) and grazed pasture areas is significantly different as the grazed areas receive compaction by cattle (Abdel-Magid et al., 1987).

Rotational grazing, in which the pasture is subdivided into smaller paddocks with animals allowed to graze areas in sequence, encourages uniform consumption and decreases compacted and eroded areas (Warren et al., 1986; Turner et al., 1997). This grazing management system improves cattle productivity compared to conventional grazing (Henning et al., 2000) and also creates less compaction to the soil. Grazed pasture areas become compacted by the continual traffic of large domestic animals. Radke and Berry (1993) reported that farm implements and animals cause compaction of the soil and increase soil bulk density and reduce the infiltration rate.

One of the main impacts of grazing on soil hydraulic properties in some areas is due to increased BD which increases surface runoff (Daniels et al., 2002; Wheeler et al., 2002) and nutrient losses. Soil compaction due to cattle traffic has been noticed as a major cause for reduced infiltration rates (Alados et al., 2004; Tate et al., 2004). Various researchers have reported that cultivated fields and grazed pastures have generally higher soil bulk density than those of native grassland or forest soils (Meek et al., 1992; Taboada and Lavado, 1993; Jaiyeoba, 1995). Bulk density is required to estimate, evaluate, and calculate many other physical soil properties, such as porosity, water retention, heat capacity, and compressibility (Ruehlmann and Körschens, 2009). The SOM is one of the most dominating factors affecting soil bulk density (Heuscher et al., 2005).

Soil bulk density is highly affected by the water content under grazed pasture systems. Under intensively grazed pasture systems, with water content above field capacity, soil bulk density increases. Larger pores fill with water as the soil water content increases, and the air-water interface and the capillary suction both decrease which drastically reduces forces holding aggregates together in an open structure (Akram and Kemper, 1979). Subsequently, wetter aggregates tend to disintegrate under gravitational forces and the particles settle into more dense formations (Akram and Kemper, 1979). This is one of the reasons why soil bulk density is higher under continuously grazed and rotationally grazed areas compared with undisturbed buffer areas.

Influence of Buffers and Grazing on Soil Hydraulic Properties

Soil hydraulic properties primarily refer to hydraulic conductivity and water retention characteristics, where hydraulic conductivity includes both saturated and unsaturated processes (Jiang, 2007). Various researchers have studied buffers and their beneficial effects on soil hydraulic properties (Seobi et al., 2005; Udawatta et al., 2008a). These soil properties exhibit high spatial and temporal variability (Jiang, 2007).

Agroforestry buffers establish deep root systems which increase the proportion of macropores and improve the soil hydraulic properties as compared to a row crop system (van Noordwijk et al., 1991; Allaire-Leung et al., 2000; Rasse et al., 2000; Cadisch et al., 2004; Udawatta et al., 2006). Water can easily move through these macropores and increase water infiltration (Rachman et al., 2005) as compared to soils with fewer macropores. These soil hydraulic properties may be different between buffers (with no cattle grazing) and grazed pasture systems. Cattle grazing in these grazed pasture areas can cause compaction of soil and thereby increase soil bulk density and reduce soil hydraulic properties such as water infiltration (Radke and Berry, 1993).

Saturated Hydraulic Conductivity (K_{sat})

Hydraulic conductivity is a critical parameter for the evaluation of subsurface water flow which affects surface sediment and nutrient transport; this parameter also describes how easily a geologic medium can transmit groundwater (Xiang et al., 1997; Qian et al., 2007). Saturated hydraulic conductivity (K_{sat}) is influenced by macropores created by decayed roots. These macropores enhance K_{sat} and subsequently enhance water and chemical infiltration into soils (Logsdon and Jaynes, 1996; Mohanty et al., 1997; Mohanty et al., 1998; Shouse and Mohanty, 1998). The spatial variation, size, and interconnectedness of biological and structural macropores play a key role in determining the rate of influx (hydraulic conductivity) through soils (Gupta et al., 2006).

Land management practices (e.g agroforestry, grass buffer and grazed pasture systems) greatly influence soil hydraulic properties such as K_{sat} (Jiang et al., 2007). Undisturbed buffers such as agroforestry and grass buffers may have higher K_{sat} values as compared to grazed pasture systems due to the deep, perennial root systems of trees. Cattle grazing decreases macropores which affect K_{sat} especially within the surface 0-10 cm soil depth with less damage to these macropore structures below the 10 cm soil depth, as grazing mainly impacts the surface 0-10 cm soil depth (Singleton and Addison, 1999; Drewry, 2003).

In a research study, conducted on northeast Missouri claypan soils, Seobi et al. (2005) reported 14 and three times increased K_{sat} values with agroforestry and grass buffers, respectively, compared to row-crop areas. These researchers also reported that grass buffers and agroforestry buffers after six years can store more water in the upper 30 cm soil layer as compared to a row crop treatment. Vegetative covers have been found to increase soil organic carbon content which increases the K_{sat} of the soil.

Pore Size Distribution

The pore size distribution (PSD) of a soil greatly affects the movement of fluids and dissolved substances, and hence impacts the thermal and mechanical properties of soils (Leij et al., 2002). The PSD also influences K_{sat} and soil water retention. Very often four classes of pore sizes are used which include: macropores (>1000 µm effective diam.), coarse mesopores (60- to 1000-µm effective diam.), fine mesopores (10- to 60-µm effective diam.) and micropores (< 10 µm effective diam.; Anderson et al., 1990). Macropores are responsible for rapid flow in old root or worm channels, whereas, mesopores conduct soil matrix flow (Luxmoore, 1981). Matrix flow in mesopores can contribute to relatively rapid water flow within the soil profile without macropores being filled up (Wilson and Luxmoore, 1988). Micropores correspond to the part of soil matrix flow that is driven by changes in matric pressure.

The PSD can be calculated using the capillary rise equation to estimate effective pore size classes (Jury et al., 1991) from water retention data. In the laboratory, pore size distribution can be determined by measuring water outflow at selected pressures and then using the following relationship:

$$r = -2\ \sigma \cos\theta_{n} / (\rho g h)$$

where r is the equivalent pore radius (L), σ is the surface tension of water (M T^{-2}), θ_c is the contact angle between water and connected pore walls, ρ is the density of water (M L^{-3}), g is gravitational acceleration (L T^{-2}), and h is the soil water pressure head (L).

Management practices which increase soil macropores usually increase the infiltration rate since these pores are mainly responsible for higher infiltration rates. Rasiah and Aylmore (1998) reported that macropore characteristics such as shape, size and orientation, and size distribution affect the rate, flow and retention of water in the soil. Soil macroporosity (or air-filled macroporosity) is a sensitive indicator of soil compaction (Ball et al., 2007) and soil quality. These large pores are important for general soil health, gas and water movement and crop and pasture growth. Drainage following rainfall occurs primarily within the macropores, which are only able to remain filled under low matric tension (Azooz et al., 1996). In contrast, under dry soil conditions, transmission of water only occurs across a matric gradient through small pores (Azooz et al., 1996). Hence PSD of the soil of an area gives an idea about soil water storage and water transmission. Higher concentrations of macropores allow more water to infiltrate into the ground. Although macropores constitute only a small percentage of total porosity, they have a major influence on saturated flow (Luxmoore et al., 1990); hence, it is important to characterize these pores within soils. Pore continuity in macropores induces preferential flow especially near saturation compared to the more tortuous pore system within aggregates (Beven and Germann, 1982).

Soil pore size distribution and structure are affected by land management practices such as buffers and tillage management which influence water storage and transmission (Azooz et al., 1996). Grazing management influences the PSD especially within the surface 0-10 cm soil depth (Singleton and Addison, 1999; Drewry, 2003). Installing buffers at the downslope of the watersheds helps in reducing runoff from these grazed areas.

Soil Water Retention

Water retained in soils at a particular tension is highly dependent upon the pore size distribution. Crop residues left on the soil surface may improve the PSD and hence improve soil water retention (Azooz et al., 1996). Agroforestry and grass buffers increase water retention in soils compared to gazed pasture systems by leaving more crop and root residues within the soil surface layer; these residues also reduce soil water evaporation and runoff (Blevins, 1971; Azooz et al., 1996). These buffers create better soil structure through well-preserved pore networks enhanced by their extensive root channels. They also provide a favorable environment for the formation of better soil structure. It is well documented by various researchers (e.g. Hill et al., 1985; Mapa et al., 1986; Hill, 1990; Soebi et al., 2005) that management effects on soil water retention are mainly at higher (less negative) matric potentials ranging from 0 to -100 kPa (Hillel, 1998). However, Seobi et al. (2005) reported statistical differences among row crop, grass buffer, and tree buffer treatments only from 0 to -1.0 kPa.

The soil water retention curve is affected by soil compaction. Most of the change in the shape of water retention curves and pore size distributions occurs at water potentials higher than field capacity (Startsev and McNabb, 2001). Higher soil water content at saturation due to increased soil porosity for grass hedges was reported by Rachman et al. (2004) for a Monona silt loam soil. Smaller slopes for soil water retention curves for row crop and deposition zones treatments were found compared to the grass hedge treatment (Rachman et al., 2004). These smaller slopes of water retention curves were attributed to higher soil bulk density (Rachman et al., 2004).

Influence of Buffers and Grazing on Water Infiltration

Soil water infiltration and flow dynamics are significant factors for crop growth, nutrient cycling, and contaminant transport (Anderson et al., 2009). Infiltration is influenced by various factors such as antecedent soil wetness (van Es, 1993; Azooz and Arshad, 1996), canopy cover (Pluhar et al., 1987), and pore structure and continuity (Ankeny et al., 1990; Vepraskas et al., 1991). The aboveground stems and roots of perennial plants can reduce the runoff velocity and enhance sedimentation and water infiltration (Dillaha et al., 1989; Schmitt et al., 1999; Seobi et al., 2005). Watersheds containing agroforestry and grass buffer strips increased soil macroporosity and enhanced water infiltration which contributes to reductions in NPSP from these watershed areas (Schmitt et al., 1999; Seobi et al., 2005).

It has been well documented in the literature that the growth and decay of large and deep roots of agroforestry and grass buffers increase the proportion of macropores and improve soil hydraulic properties compared to row crop systems (van Noordwijk and Brouwer, 1991; Allaire-Leung et al., 2000; Rasse et al., 2000; Cadisch et al., 2004). Buffers improve water infiltration and control N removal from surface runoff in some soils (Lowrance and Sheridan 2005). In a study performed by Bharati et al. (2002), it was shown that a multispecies riparian buffer had five times higher soil infiltration rates compared to grazed and cultivated fields. For example, the pores (especially macropores) formed by perennial alfalfa (*Medicago sativa* L.) roots are the major cause of increasing water infiltration in compacted no-till soils (Meek et al., 1990).

Grazing has been shown to have adverse affects on infiltration (Radke and Berry, 1993; Daniel et al., 2002; Wheeler et al., 2002). Even in soils with permanent vegetation (pastures), compaction from grazing cattle can damage soil pores and affect water infiltration. In continuously grazed areas with high stocking densities, cattle can damage soils and vegetation if cattle are allowed to graze an area for too long (Sheath and Boom, 1997; Betteridge et al., 1999). Subsequently, these grazed areas enhance runoff because of higher BD values and lower infiltration rates compared to ungrazed (such as undisturbed buffers) areas (Radke and Berry, 1993; Daniel et al., 2002; Wheeler et al., 2002). However, rotationally stocked pastures have been shown to minimize the effects of livestock grazing on water infiltration (Warren et al., 1986b).

Computed Tomography Analysis of Soil Properties

Soil porosity is essential for water, gas and nutrient transport in soils, all of which are necessary for plant growth. Water transmission and storage depend on the geometry and size distribution of soil pores as these pores provide room for gas transport and space for plant root growth (Eynard et al., 2004). Agricultural management practices alter the soil pore volume and size distribution in space and time and ultimately modify the hydraulic properties of the soil (Eynard et al., 2004). Hence, the evaluation of soil porosity is very important to examine how management changes these parameters and to determine best management practices to improve water and soil quality.

The literature shows various methods to estimate porosity in soils; a few of those are (i) water retention methods (Anderson et al., 1990) (ii) thin section analysis (Van Golf-Recht, 1982), and (iii) Boyle’s law porosimetry (American Petroleum Institute, 1960). These methods are time consuming and some are destructive. Additionally, these procedures do not provide information about the spatial distribution of pores (Gantzer and Anderson, 2002). Furthermore, porosity determined by traditional methods lacks information on geometrical pore characteristics (Udawatta et al., 2006). In contrast to traditional pore characterization methods, X-ray computed tomography (CT) methods are rapid, non-destructive and provide information on the spatial distribution of soil pores and their characteristics.

X-ray CT analysis was first introduced in early 1970's by Hounsfield (1972; 1973) for medical imaging and has received increased attention since that time. This method is now used frequently in the field of soil science for examining solute movement (Anderson et al., 2003), porosity (Anderson et al., 1988; Rachman et al., 2005), pore continuity (Grevers and de Jong, 1994; Udawatta et al., 2008a), fractal dimension of porosity (Rasiah and Alymore, 1998; Gantzer and Anderson, 2002), and plant root development (Tollner et al., 1994); in addition, this method can obtain non-destructive measurements of water content and dry bulk density (Petrovic et al., 1982; Crestana et al., 1985; Hopmans et al., 1992). X-ray CT scanning has given promising results for measuring the shape, distribution, and arrangement of soil particles within the soil.

Various workers have shown that CT is a better procedure compared to traditional methods and also provides a finer resolution on a millimeter- to micrometer-scale (Gantzer and Anderson, 2002; Akin and Kovscek, 2003; Carlson et al., 2003). Carlson et al. (2003) reported that the best advantage of CT is its ability to quickly and nondestructively image the interior of a three-dimensional object. The CT techniques also can provide three-dimensional structure of soil pores which is not possible with traditional methods (Udawatta et al., 2008a).

CT-measured pore parameters have been related to saturated hydraulic conductivity by Udawatta et al. (2008b). In these studies, porosity, number of macropores, fractal dimension of macropores and K_{sat} have been shown to hold strong relationships. In another study, Udawatta et al (2008a) showed that pore continuity, pore path length and pore tortuosity can be used to discriminate agroforestry buffer, grass buffer and crop soils.

Root Growth and Its Distribution

Plant root growth and its distribution depend on various factors such as soil type and soil properties (Sudmeyer et al., 2004), plant species (Jama et al., 1998), amount of nutrients and available water. Roots reduce soil erosion by binding soil particles with their extensive root network, and reduce rainfall energy with their associated above ground plant canopy. Root exudates may also increase soil cohesion through biochemical reactions and bind soil particles together (Thorne et al., 1997) which minimize the effects of water velocity and reduce soil erosion. Larger root lengths per unit volume can bind soil particles more tightly and prevent soil erosion. In a study conducted by Kamyab (1991), it was concluded that soil erosion rates are inversely related to root length density and root volume. Additionally, soil erodibility was significantly influenced by the root length density of fine roots. Other researchers found that soil erosion decreased linearly with soil biomass (Wynn et al., 2004). Roots also stabilize streambanks by increasing the strength of streambank soils, allowing them to be more resistant to soil erosion and bank failure (Abernethy and Rutherfurd, 2001; Mamo and Bubenzer, 2001). It is believed that root systems of woody and herbaceous plants physically bind streambank soils in place, and increase soil shear strength (Coppin and Richards, 1990; Thorne et al., 1997).

Large applications of nitrogen fertilizers in row crop areas may contaminate surface and subsurface water through nitrate runoff and leaching (Bonilla et al., 1999; Ng et al., 2000). Growing trees in these agricultural crop areas (called agroforestry systems) helps in nutrient uptake and reduces nutrient losses. In agroforestry systems, tree roots help capture nutrients before and after a crop is planted and harvested which would increase the total resource use efficiency of the system (van Noordwijk et al., 1996). These systems, where tree and crop roots occupy different soil depths, enhance the level of nutrient (specifically nitrogen) uptake and reduce losses from soils, compared to only row crop roots which are more localized and have shallow rooting depths (Buresh and Tian, 1997; Nair et al., 1999; Jose et al., 2004). Various other researchers have also reported that the tree root system intercepts percolating nutrients, which is due to the rapid mineralization and leaching from high precipitation and temperature (Lehman, 2003). These processes reduce excessive nutrient losses by leaching in wet tropical climates (van Noordwijk et al., 1996). This deep tree root system extracts pollutants from storm water (Szabo et al., 2001) and directs the precipitation into the soil through trunk flow (Johnson and Lehmann, 2006).

For different climates (temperate zone, humid tropics, and semiarid tropics), it has been well documented in the literature that the tree-root density is higher within the top 0-30 cm soil depth as compared to subsurface (below 30 cm) soil depths (Itimu, 1997; Lehmannn et al., 1998; Imo and Timmer, 2000; Jose et al., 2000). In temperate alley cropping systems of maize (*Zea mays* L.) and black walnut (*Juglans nigra*) or red oak (*Juglans nigra*), Jose et al. (2000) found that the root density for all the plant species was higher at the surface 0-30 cm of soil depth and thereafter root density decreased. Higher root length densities (or surface area) are an indicator of the potential for exploitation of water and most nutrients from the soil zone (van Noordwijk et al., 1994).

Tree roots generally have extensive deep root systems which can extract nutrients and water from deeper soil horizons while shallow roots of row crops or grasses are unable to reach such depths and hence do not compete with crop or grass roots for nutrient and water uptake (Jonsson et al., 1988). Schenk and Jackson (2002) compared more than 3000 records of root systems and reported that annual plants had minimum root length, grasses had intermediate root length and trees had the highest root length. In a Coland soil (fine-loamy, mixed, mesic Cumulic Haplaquoll), Tufekcioglu et al. (1999) observed higher number of fine roots, larger number of roots penetrating into subsoil horizons, and higher soil respiration rates in a multi-species riparian buffer (*Populus euroamericana Eugenei)* system compared to a row crop (corn, *Zea mays* L., and soybean, *Glycine max* L.) area. They also reported in a similar study that these buffer systems added more organic matter to the soil profile and provided better conditions for nutrient sequestration within these buffer systems.

Model Simulation of Runoff, Sediment and Nutrient Losses

To assess long-term benefits of soil conservation practices, simulation models are often used**.** Models can provide long-term simulations of the effects of best management practices and assist in selecting appropriate conservation approaches (Wang et al., 2008).

Watershed studies typically take relatively long time periods to detect differences due to changes in annual weather patterns, and time for establishment of plants, especially where trees are involved. Due to monitoring costs and variable weather patterns, it is often difficult to assess management effects on environmental quality. This difficulty can be overcome by using simulation models which have been calibrated with measured data. For example, model calibration and validation with measured runoff, sediment and nutrient losses from watersheds have been used to assist policy makers in selecting conservation practices and allocating resources.

There are several models that are currently being used to simulate management effects: SWAT (Soil and Water Assessment Tool), WEPP (Water Erosion Prediction Project), EPIC (originally the Erosion Productivity Impact Calculator; now the Environmental Policy Integrated Climate), and APEX (Agricultural Policy Extender) (Singh and Frevert, 2006). All these models require significant inputs such as weather, precipitation, soil properties, land management, vegetation and landscape data to run the model effectively.

Wang et al. (2006) reported that watershed models such as CREAMS (a field-scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems; Knisel, 1980), ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria; Kiniry et al., 1992), APEX (Williams and Izaurralde, 2005), and SWAT (Soil and Water Assessment Tool; Arnold et al., 1998) have been developed to assess effects of changes in land use, land cover, different management practices and weather conditions on soil and water erosion on small and large watershed scales. These researchers also reported that these models generally use a daily time step.

The Agricultural Policy Extender (APEX) is one of the models which are suitable for small watersheds or field-scale simulations and is an extension of the EPIC model (Williams, 1990; Williams and Sharpley, 1989). This model was developed in the 1990's to address environmental problems associated with livestock and other agricultural production systems on a small scale, on the whole farm or on small watershed areas (Gassman et al., 2005). The APEX model has components for routing water, sediments, nutrients, and pesticides across landscapes and channel systems to a watershed outlet (Wang et al., 2008). Because of its strength in simulating agricultural management systems, the APEX model is used for cultivated cropland (Wang et al., 2006).

The APEX model was developed from several earlier mature and well tested models (Wang et al., 2008). A few examples of components of the APEX model as reported by Wang et al (2008) include: (i) the soil carbon cycling submodel taken from the Century model (Parton et al., 1993; 1994) as developed by Izaurralde et al. (2006), (ii) the pesticide component was derived from the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987), and (iii) the plant competition component was derived from Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model (Kiniry et al., 1992).

The APEX model uses different management practices, cropping systems, soil properties, and climate data and contains a database of more than 60 crops including vegetables, a few grass and tree species for simulation of runoff, sediment and nutrient losses (Wang et al., 2006). Harman et al. (2004) reported that the APEX model simulates different cropping and management practices and their environmental effects on a whole farm scale, which is a larger scale of simulation compared to the EPIC model. In central Texas, Harman et al. (2004) evaluated atrazine use in corn and sorghum (*Sorghum bicolor*) production on 66,000 ha for the Aquilla watershed using the APEX model to compare effects of conservation practices on runoff. In Missouri, Farrand et al. (2002)

used the APEX model to calibrate the paired watershed study at the Greenley Research Center to predict environmental benefits of tree and grass buffer practices.

The APEX model has been used to simulate agroforestry practices such as riparian buffers (buffers placed near the stream), shelterbelts, and farm analysis throughout Missouri and nearby states (FAPRI, 2002). This model simulates runoff and sediment loss from small farms (up to 2500 km^2 area), feeding areas, crop fields, or buffer strips or parts of larger watersheds with a variety of soil, climate, landscape, crop rotation and management combinations (Gassman et al., 2005). The APEX model has also been used to evaluate government policy effects on soil erosion in the USA and simulate soil erosion (sheet and rill) caused by wind and water (Wang et al., 2006).

Grazing on pastures is an important agricultural practice in the USA (Line et al., 2000). Pollutants from these grazed pasture areas can be washed away to nearby streams (Line et al., 2000) and affect the water quality of the streams. Introduction of rotational grazing has become an important practice to assist in reducing contaminants into streams. The APEX model also has the grazing component and the effect of practices such as rotational grazing or continuously grazing can be observed with this model.

Installation of undisturbed buffers such as agroforestry buffers, and grass buffers, vegetative filter strips on the downslope end of grazed pasture areas of watersheds can be effective in improving soil hydraulic properties and help in reducing surface runoff and nutrients (Daniels and Gilliam, 1996). The APEX model simulates runoff and nutrient losses from grazed pasture areas. This model may simulate the effects of buffers, filter strips, grassed waterways, intensive grazing management and also land application of manure removed from feedlots (Wang et al., 2008).

References

Abdel-Magid, A.H., M.J. Trlica, and R.H. Hart. 1987. Soil and vegetation responses to simulated trampling. J. Range Manage. 40:303-306.

Abernethy, B., and I.D. Rutherfurd. 2001. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. Hydrol. Processes 15:63-79.

Abu-Hamdeh, N.H. 2003. Effect of compaction and deep tillage on soil hydraulic and aeration properties and wheat yield. Comm. Soil Sci. Plant Analysis. 34:2277–90.

Abu-Zreig, M., R.P. Rudra, H.R. Whitely, M.N. Lalonde, and N.K. Kaushik. 2003. Phosphorus removal in vegetated filter strips. J. Environ. Qual. 32:613-619.

Akin, S., and A.R. Kovscek. 2003. Computed tomography in petroleum engineering research. p. 215: 23-38. *In* F. Mess, R. Swennen, M. Van Geet, and P. Jacobs (ed.) Application of X-ray Computed Tomography in the Geosciences. The Geological Society, London. UK.

Akram, M., and W.D. Kemper. 1979. Infiltration of soils as affected by the pressure and water content at the time of compaction. Soil Sci. Soc. Am. J. 43:1080-1086.

Alados, C.L., A. ElAich, V.P. Papanastasis, H. Ozbek, T. Navarro, H. Freitas, M. Vrahnakis, D. Larrosi, and B. Cabezudo. 2004. Change in plant spatial patterns and diversity along the successional gradient of Mediterranean grazing ecosystems. Ecol. Modell. 180:523-535.

Alavalapati J.R.R., and P.K. Nair. 2001. Socioeconomic and institutional perspectives of agroforestry. p. 71–81. *In* M.Palo and J. Uusivuori (ed.) World Forests, Society, and Environment-Markets and Policies. Kluwer, Dordrecht, The Netherlands.

Alavalapati, J.R.R., R.K. Shrestha, G.A. Stainback, and J.R. Matta. 2004. Agroforestry development: An environmental economic perspective. Agrofor. Syst. 61:299-310.

Allaire-Leung, S.E., S.C. Gupta, and J.F. Moncrief. 2000. Water and solute movement in soil as influenced by macropore characteristics: Macropore continuity. J. Contam. Hydrol. 41:283-301.

American Petroleum Institute. 1960. API recommended practice for core analysis procedures. Rep. 40. American Petroleum Institute. Dallas, Texas.

Anderson, S.H., C.J. Gantzer, and J.R. Brown. 1990. Soil physical properties after 100 years of continuous cultivation. J. Soil Water Conserv. 45:117-121.

Anderson, S.H., C.J. Gantzer, J.M. Boone, and R.J. Tully. 1988. Rapid nondestructive bulk density and soil-water content determination by computed tomography. Soil Sci. Soc. Am. J. 52:35-40.

Anderson, S.H., H. Wang, R.L. Peyton, and C.J. Gantzer. 2003. Estimation of porosity and hydraulic conductivity from x-ray CT-measured solute breakthrough. p. 135-149. *In* F. Mess, R. Swennen, M. Van Geet, and P. Jacobs (ed.) Application of X-ray Computed Tomography in the Geosciences. Geological Society of London Spec. Pub. 215. Geological Society of London, London.

Anderson, S.H., R.P. Udawatta, T. Seobi, and H.E. Garrett. 2009. Soil water content and infiltration in agroforestry buffer strips. Agrofor. Syst.75:5-16.

Angers, D.A., and J. Caron. 1998. Plant-induced changes in soil structure: Processes and feedbacks. Biogeochemistry 45:55-72.

Ankeny, M.D., T.C. Kaspar, and R. Horton. 1990. Characterization of tillage and traffic effects on unconfined infiltration measurements. Soil Sci. Soc. Am. J. 54:837–840.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large Area Hydrologic Modeling and Assessment, pt.1, Model Development. J. Amer. Water Res. Assoc. 34:73-89.

Azooz, R.H., and M.A. Arshad. 1996. Soil infiltration and hydraulic conductivity under long-term no-tillage and conventional tillage systems. Can. J. Soil Sci. 76:143–152.

Azooz, R.H., M. A. Arshad, A.J. Franzluebbers. 1996. Pore size distribution and hydraulic conductivity affected by tillage in northwestern Canada. Soil Sci. Soc. Am. J. 60:1197-1201.

Baird, J.H., N.T. Basta, R.L. Huhnke, G.V. Johnson, M.E. Payton, D.E. Storm, C.A. Wilson, M.D. Smolen, D.L. Martin, and J.T. Cole. 2000. Best management practices to reduce pesticide and nutrient runoff from turf. p. 268–293. *In* J.M. Clark and M.P. Kenna (ed.) Fate and management of turfgrass chemicals. American Chemical Society, Washington, DC.

Baker, J.L., S.K. Mickelson, K. Arora, and A.K. Misra. 2000. The potential of vegetated filter strips to reduce pesticide transport. p. 272–287. *In* T.R. Steinheimer et al. (ed.) Agrochemical movement: Perspective and scale. American Chemical Society, Washington, DC.

Ball, B.C., C.A. Watson, and J.A. Baddeley. 2007. Soil physical fertility, soil structure and rooting conditions after ploughing organically managed grass/clover swards. Soil Use Manage. 23:20-27.

Barfield, B.J., E.W. Tollner, and J.C. Hayes. 1979. Filtration of sediment by simulated vegetation, I. Steady state flow and homogenous sediment. Trans. ASAE 22:540-545.

Betteridge, K., A.D. Mackay, D.J. Barker, T.G. Shepherd, P.J. Budding, B.P. Devantier, and D.A. Costall. 1999. Effect of cattle and sheep treading on surface configuration of a sedimentary hill soil. Aust. J. Soil Res. 37:743-760.

Beven, K., and P. Germann. 1982. Macropores and water flow in soils. Water Resour. Res. 18:1311–1325.

Bharati, L., K.H. Lee, T.M. Isenhart, and R.C. Schultz. 2002. Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. Agrofor. Syst. 56: 249-257.

Blevins, R.L., D. Cook, S.H. Phillips, and R.E. Phillips. 1971. Influence of no-tillage on soil moisture. Agron. J. 63:593–596.

Bonilla, C.A., J.F. Muñoz, and M. Vauclin. 1999. Opus simulation of water dynamics and nitrate transport in a field plot. Ecol. Modell. 122:69-80.

Buresh R.J., and Tian G. 1997. Soil improvement by trees in sub-Saharan Africa. Agrofor. Syst. 38:51–76.

Cadisch, G., P. de Willigen, D. Suprayogo, D.C. Mobbs, M. van Noordwijk, and E.C. Rowe. 2004. Catching and competing for mobile nutrients in soils. p. 171-192. *In* M. van Noordwijk, G. Cadisch and C.K. Ong (ed.) Below ground interactions in tropical agroecosystems. CABI, Wallingford, UK.

Carlson, W.D., T. Rowe, R.A. Ketcham, and M.W. Colbert. 2003. Application of high resolution x-ray computed tomography in petrology, meteoritics, and palaeontology. p. 7-22. *In* F. Mess, R. Swennen, M. Van Geet, and P. Jacobs (ed.) Application of X-ray Computed Tomography in the Geosciences. The Geological Society, London. UK.

Chan, K.Y., A. Oates, A.D. Swan, R.C. Hayes, B.S. Dear, and M.B. Peoples. 2006. Agronomic consequences of tractor wheel compaction on a clay soil. Soil Tillage Res. 89:13-21.

Coppin, N.J., and I.G. Richards. 1990. Use of vegetation in civil engineering. Butterworths, London.

Crawford, M. 1998. Benefits of agroforestry. Agroforestry Research Trust. http://members.aol.com//Agroforestry/afbens.html

Crestana, S., S. Mascarenshas and R.S. Pozzi-Mucelli. 1985. Static and dynamic three-dimensional studies of water in soil using computed tomographic scanning. Soil Sci. 140:326-332.

Da Silva, A.P., S. Imhoff, and M. Corsi. 2003. Evaluation of soil compaction in an irrigated short-duration grazing system. Soil Tillage Res. 70:83-90

Dabney, S.M., L.D. Meyer, W.C. Harmon, C.V. Alonso, and G.R. Foster. 1995. Depositional patterns of sediments trapped by grass hedges. Trans. ASAE 38:1719-1729.

Daniel, J.A., K. Potter, W. Altom, H. Aljoe, and R. Stevens. 2002. Long-term grazing density impacts on soil compaction. Trans. ASAE 45:1911-1915.

Daniels, R. B., and J. W. Gilliam. 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Sci. Soc. Am. J. 60:246-251.

De la Cruz, R.E., and N.T. Vergara. 1987. Protective and ameliorative roles of agroforestry: An overview. p. 3-30. *In* N.T. Vergara and N.D. Briones (ed.) Agroforestry in the Humid Tropics. Environment and Policy Institute, Southeast Asian Regional Center for Graduate Study, Honolulu, Hawaii.

Desbonnet, A, P. Pamela, L. Virginia, and W. Nicholas. 1994. Vegetated Buffers in the Coastal Zone: A Summary Review and Bibliography. Coastal Resource Center, Technical Report 2064. University of Rhode Island, Graduate School of Oceanography. USA.

Dillaha, T.A., R.B. Reneau, S. Mostaghimi, and D. Lee. 1989. Vegetative filter strips for agricultural nonpoint-source pollution control. Trans. ASAE 32:513–519

Donkor, N.T., J. V. Gedir, R. J. Hudson, E.W. Bork, D. S. Chanasyk, and M. A. Naeth. 2001. Impacts of grazing systems on soil compaction and pasture production in Alberta. Can. J. Soil Sci. 82:1-8.

Dosskey, M.G. 2001. Toward quantifying water pollution abatement in response to installing buffers on crop land. Environ. Manage. 28:577-598.

Drewry, J.J. 2003. Dairy grazing strategies to minimise soil pugging and compaction in Waikato. Proc. of New Zealand Grassland Association. 65:99-103.

Eghball, B., J.E. Gilley, L.A. Kramer, and T.B. Moorman. 2000. Narrow grass hedge effects on phosphorus and nitrogen in runoff following manure and fertilizer application. J. Soil Water Conserv. 55:172-176.

Eynard, A., Schumacher, T.E., Lindstrom, M.J., and Malo, D.D. 2004. Porosity and pore-size distribution in cultivated Ustolls and Usterts. Soil Sci. Soc. Am. J. 68:1927-1934.

FAPRI, 2002. Food and Agricultural Policy Research Institute, College of Agriculture, Food and natural Resources, University of Missouri, Columbia, MO 65211.

Farrand, D.T., R.P. Udawatta, and H.E. Garrett. 2002. Predicting environmental benefits of Agroforestry practices in northern Missouri using APEX. Agronomy abstracts

2002. Annual meetings. Indianapolis, Indiana, Nov. 10-14, 2002. American Society of agronomy, 677, South Segoe Road, Madison, Wisconsin 53711.

Gantzer, C.J., and S.H. Anderson. 2002. Computed tomographic measurement of macroporosity in chisel-disk and no-tillage seedbeds. Soil Tillage Res. 64:101-111.

Gao, Q., L. Ci, and M. Yu. 2002. Modeling wind and water erosion in northern China under climate and land use changes. J. Soil Water Conserv. 57:47-55.

Garrett, H.E., W.J., Rietveld and R.F. Fisher. 2000. North American Agroforestry: An Integrated Science and Practice. American Society of Agronomy, Madison, Wisconsin., 402 p.

Gassman, P.W., J.R. Williams, V.W. Benson, R.C. Izaurralde, L.M. Hauck, C.A Jones, J.D. Atwood, J.R. Kiniry, and J.D. Flowers. 2005. Historical development and applications of the EPIC and APEX Models. Working paper 05-WP 397. Centre for Agricultural and Rural Development, Iowa State University, Ames, Iowa.

Gilliam, J.W. 1994. Riparian wetlands and water quality. J. Environ. Qual. 23:896-900.

Gold, M.A., and J.W. Hanover. 1987. Agroforestry systems for temperate zones. Agrofor. Syst. 5:109-121.

Grable, A.R., and E.G. Siemer. 1968. Effects of bulk density, aggregate size, and soil water suction on oxygen diffusion, redox potentials, and elongation of corn roots. Soil Sci. Soc. Am. Proc. 32:180–186.

Grevers, M.C.J., and E. de Jong. 1994. Evaluation of soil-pore continuity using geostatistical analysis of macroporosity in serial sections obtained by computed tomography scanning. p. 73-86. *In* F. Mess, R. Swennen, M. Van Geet, and P. Jacobs (ed.) Application of x-ray Computed Tomography in the Geosciences. The Geological Society, London. UK

Gross, C.M., J.S. Angle, and M.S. Welterlen. 1990. Nutrient and sediment losses from turfgrass. J. Environ. Qual. 19:663–668.

Gupta, S.D., B.P. Mohanty, and J.M. Kohne. 2006. Soil hydraulic conductivities and their spatial and temporal variations in a Vertisol. Soil Sci. Soc. Am. J. 70:1872-1881.

Hakansson, I., W.B. Voorhees, and H. Riley. 1988. Vehicle and wheel factors influencing soil compaction and crop response in different traffic regimes. Soil Tillage Res. 11:239-282.

Hamza, M.A., and W.K. Anderson. 2005. Soil compaction in cropping systems. A review of the nature, causes and possible solutions. Soil Tillage Res. 82:121–145.

Harman, W.L., E. Wang, and J.R. Williams, 2004. Reducing atrazine losses: Water quality implications of alternative runoff control practices. J. Environ. Qual. 33:7-12.

Hayes, J.C., B.J. Barfield, and R.I. Barnhisel. 1979. Filtration of sediment by simulated vegetation, II. Unsteady state flow and non homogeneous sediment. Trans. ASAE 22:1063–1067.

Henning, J., Lacefield, G., Rasnake, M., Burris, R., Johns, J., Johnson, K., and Turner, L. 2000. Rotational grazing. Cooperative Extension Service. University of Kentucky. 1-16.

Heuscher, S.A., C.C. Brandt, and P.M. Jardine. 2005. Using soil physical and chemical properties to estimate bulk density. Soil Sci. Soc. Am. J. 69:51–56

Hill, R.L. 1990. Long-term conventional and no-tillage effects on selected soil physical properties. Soil Sci. Soc. Am. J. 54:161-166.

Hill, R.L., R.Horton, and R.M. Cruse. 1985. Tillage effects on soil water retention and pore size distribution of two Mollisols. Soil Sci. Soc. Am. J. 49:1264-1270.

Hillel, D. 1998. Environmental soil physics. Academic Press. San Diego, CA.

Hopmans, J.W., T. Vogel and P.D., Koblik. 1992. X-ray tomography of soil water distribution in one-step outflow experiments. Soil Sci. Soc. Am. J. 56:355-362.

Horn, R., 1990. Aggregate characterization as compared to soil bulk properties. Soil Tillage Res. 17:265-289.

Hounsfield, G.N. 1972. A method of and apparatus for examination of a body by radiation such as X- or gamma-radiation. British Patent No 1.283.915. London. UK.

Hounsfield, G.N. 1973. Computerized transverse axial scanning (tomography). Part 1. Description of system. Br. J. Radiol. 46:1016-1022.

Imo, M. and V.R. Timmer. 2000. Vector competition analysis of a Leucaena-maize alley cropping system in western Kenya. For. Ecol. Manage. 126:255–268.

Itimu, O.A. 1997. Nitrogen dynamics and root distribution of *Gliricidia sepium* and *Senna spectabilis* in maize (*Zea mays*)-based alley cropping systems in Malawi. Ph.D. Dissertation. Department of Biological Sciences, Wye College, University of London, UK.

Izaurralde, R.C., Williams, J.R., McGill, W.B., Rosenberg, N.J., 2006. Simulating soil C dynamics with EPIC: Model description and testing against long-term data. Ecol. Modell. 192:362–384.

Jaiyeoba, I.A. 1995. Changes in soil properties related to different land uses in part of the Nigerian semi-arid savannah. Soil Use Manage. 11:84-89.

Jama, B.A., J.R. Buresh, J.K. Ndufa, and K.D. Shepherd. 1998. Vertical distribution of roots and soil nitrates: Tree species and phosphorus effects. Soil Sci. Soc. Am. J. 62:280–286.

Jiang, P. 2007. Variability of soil hydraulic properties and estimation of plant-available water on clay pan-soil landscapes**.** Ph.D Dissertation. Univ. of Missouri-Columbia, Columbia, USA.

Johnson, M.S., and J. Lehmann. 2006. Double-funneling of trees: Stem flow and root-induced preferential flow. Ecoscience 13:324–333.

Jones, C.A. 1983. Effect of soil texture on critical bulk densities for root growth. Soil Sci. Soc. Am. J. 47:1208-1211.

Jonsson, K., L. Fidjeland, J.A. Maghembe, and P. Hogberg. 1988. The vertical distribution of fine roots of five tree species and maize in Morogoro, Tanzania. Agrofor. Syst. 6:63-69.

Jose S., A.R. Gillespie, J.R. Seifert, D.B. Mengel, and P.E. Pope. 2000. Defining competition vectors in a temperate alley cropping system in the mid-western USA. 3. Competition for nitrogen and litter decomposition dynamics. Agrofor. Syst. 48:61–77.

Jose, S., A.R. Gillespie and S.G. Pallardy. 2004. Interspecific interactions in temperate agroforestry. Agrofo. Syst. 61:237–255.

Jury, W.A., W.R. Gardner, and W.H. Gardner. 1991. Soil physics. 5^{th} ed. John Wiley and Sons, Inc., New York.

Kamyab, I. 1991. Streambank stability prediction for C6 stream type reconstruction. Ph.D. Dissertation. Univ. of Nevada, Reno.

Kang, B.T., G.F. Wilson, and T.L. Lawson. 1984. Alley cropping: A stable alternative to shifting cultivation. Int. Inst. Tropical Agric., Ibadan, Nigeria.

Kappelle, M. and M.E. Juarez. 1994. The Los Santos forest reserve: A buffer zone vital for the Costa Rican La Amistad Biosphere Reserve. Environ. Conserv. 21:166–169.

Kay, B.D. and A.J. Van den Bygaart. 2002. Conservation tillage and depth stratification of porosity and soil organic matter. Soil Tillage Res. 66:107-118.

Kiniry, J.R., R. Blanchet, J.R. Williams, V. Texier, C.A. Jones, and M. Cabelguenne. 1992. Sunflower simulation using EPIC and ALMANAC Models. Field Crops Res. 30:403–423.

Kirkegaard, J.A., H.B. So, R.J. Troedson, and E.S. Wallis. 1992. The effect of compaction on the growth of pigeonpea on clay soils. I. Mechanisms of crop response and seasonal effects on a Vertisol in a sub-humid environment. Soil Tillage Res. 24:107–127.

Knisel, W.G., 1980. CREAMS: A field scale model for chemical, runoff, and erosion from agricultural management systems: Conservation Research Report, no. 26, US Department of Agriculture, Washington, D.C., 640 p.

Lee, K.H., T.M. Isenhart, and R.C. Schultz. 2003. Sediment and nutrient removal in an established multi-species riparian buffer. J. Soil Water Conserv. 58:1-8.

Lehmann, J. 2003. Subsoil root activity in tree-based cropping systems. Plant and Soil 255:319-331.

Lehmann, J., I. Peter, C. Steglich, G. Gebauer, B. Huwe, and W. Zech. 1998. Belowground interactions in dryland agroforestry. For. Ecol. Manage 111:157–169.

Leij, F.J. Teamrat A. Ghezzehei, and Dani Or. 2002. Analytical models for soil pore-size distribution after tillage. Soil Sci. Soc. Am. J. 66:1104-1114.

Leonard, R.A., Knisel, W.G., Still, D.A., 1987. GLEAMS: Groundwater loading effects of agricultural management system. Trans. ASAE 30:1403–1418.

Line, D.E., W.A. Harman, G.D. Jennings, E.J. Thompson, and D.L. Osmond. 2000. Nonpoint-source pollutant load reductions associated with livestock exclusion. J. Environ. Qual. 29:1882–1890.

Linn, D.M. and J.W., Doran. 1984. Effect of water-filled pore space on carbon dioxide and nitrous oxide production in tilled and non-tilled soils. Soil Sci. Soc. Am. J. 48:1267–1272.

Logsdon, S.D., and D.B. Jaynes. 1996. Spatial variability of hydraulic conductivity in a cultivated field at different times. Soil Sci. Soc. Am. J. 60:703–709.

Lovell, S.T. and Sullivan, W.C. 2006. Environmental benefits of conservation buffers in the United States: Evidence, promise, and open questions. Agric. Ecosyst. Environ. 112:249-260.

Lowrance, R., and J.M. Sheridan. 2005. Surface runoff water quality in a managed three zone riparian buffer. J. Environ. Qual. 34:1851–1859.

Lowrance, R., and S.R. Crow. 2002. Implementation of riparian buffer systems for landscape management. p. 145-158. *In* L. Ryszkowski (Ed.) Landscape ecology in Agroecosystems Management. CRC Press, Washington, DC.

Luxmoore, R.J. 1981. Micro-, meso-, and macroporosity of soil. Soil Sci. Soc. Am. J. 45:671–672.

Luxmoore, R.J., P.M. Jardine, G.V. Wilson, J.R. Jones, and L.W. Zelazny.1990. Physical and chemical controls of preferred path flow through a forested hillslope. Geoderma 46:139-154.

Mamo, M., and G.D. Bubenzer. 2001. Detachment rate, soil erodibility and soil strength as influenced by living plant roots. Part II: Field study. Trans. ASAE 44:1175–1181.

Mapa, R.B., R.E. Green, and L. Santo. 1986. Temporal variability of soil hydraulic-properties with wetting and drying subsequent to tillage. Soil Sci. Soc. Am. J. 50:1133-1138.

Martin, J.H., K.W. Bruland, and W.W. Broenkow. 1976. Cadmium transport in the California current, p. 159-l84. *In* H. L. Windom and R. A. Duce (ed.), Marine Pollutant Transfer. Heath.

Meek, B.D., E.R. Rechel, L.M. Carter, W.R. DeTar, and A.L.Urie. 1992. Infiltration rate of a sandy loam soil: effects of traffic, tillage, and plant roots. Soil Sci. Soc. Am. J. 56:908-913.

Meek, B.D., W.R. De Tar, D. Rolph, E.R. Rechel, and L.M. Carter. 1990. Infiltration rate as affected by an alfalfa and no-till cotton cropping system. Soil Sci. Soc. Am. J. 54:505–508.

Mohanty, B.P., R.S. Bowman, J.M.H. Hendrickx, and M.Th. van Genuchten. 1997. New piecewise-continuous hydraulic functions for modeling preferential flow in an intermittent flood-irrigated field. Water Resour. Res. 33:2049–2063.

Mohanty, B.P., T.H. Skaggs, and M. Th van Genuchten. 1998. Impact of saturated hydraulic conductivity on the prediction of tile flow. Soil Sci. Soc. Am. J. 62: 1522-1529.

Montagnini, F., and P.K.R. Nair. 2004. Carbon sequestration: An underexploited environmental benefit of agroforestry systems Agrofor. Syst. 61:281–295.

Moss, J.Q., G.E. Bell, M.A. Kizer, M.E. Payton, H. Zhang, and D.L. Martin. 2006. Reducing nutrient runoff from golf course fairways using grass buffers of multiple heights. Crop Sci. 46:72–80.

Muschler, R.G., and A. Bonnemann. 1997. Potentials and limitations of agroforestry for changing land-use in the tropics: experiences from Central America. For. Ecol. Manage. 91:61–73

Nair, P.K.R. 2001. Agroforestry. In our fragile world: Challenges and opportunities for sustainable development, Forerunner to The Encyclopedia of Life Support Systems, Chapter 1.25: 375– 393. UNESCO, Paris, France & EOLSS, UK.

Nair, P.K.R., R.J. Buresh, D.N. Mugendi, and C.R. Latt. 1999. Nutrient cycling in tropical agroforesty systems: Myths and science. p. 1–31. In L.E. Buck, J.P. Lassoie and E.C.M. Fernandes (ed.), Agroforestry in Sustainable Agricultural Systems. CRC Press. LLC, Boca Raton, Florida, USA.

Nair, V.D., and D.A. Graetz. 2004. Agroforestry as an approach to minimizing nutrient loss from heavily fertilized soils: The Florida experience. Agrofor. Syst. 61:269–279.

Ng, H.Y.F., C.F. Drury, V.K. Serm, C.S. Tan, and J.D. Gaynor. 2000. Modeling and testing of the effect of tillage, cropping and water management practices on nitrate leaching in clay loam soil. Agric. Water Manage. 43, 111–131.

Oldfield, S. 1988. Buffer zone management in tropical moist forests: Case studies and guidelines. IUCN, Gland, Switzerland and Cambridge, UK.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel. 1994. A general model for soil organic matter dynamics: Sensitivity to litter chemistry, texture and management. p. 147–167. *In*: Quantitative Modeling of Soil Forming Processes, SSSA Spec. Public. No. 39, Madison, WI.

Parton, W.J., J.M.O. Scurlock, D.S. Ojima, T.G. Gilmanov, R.J. Scholes, D.S. Schimel, T. Kirchner, J.C. Menaut, T. Seastedt, M.E. Garcia, A. Kamnalrut, and J.I. Kinyamario. 1993. Observations and modelling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem Cycles 7:785–809.

Passioura, J.B. 2002. Soil conditions and plant growth. Plant Cell Environ. 25:311–318.

Paul, E.A. 1984. Dynamics of organic matter in soils. Plant Soil 76:275– 285.

Petrovic, A.M., J.E. Siebert, and P.E. Rieke. 1982. Soil bulk density analysis in three dimensions by computed tomographic scanning. Soil Sci. Am. J. 46:445-450.

Pluhar, J.J., R.W. Knight, and R.K. Heitschimdt. 1987. Infiltration rates and sediment production as influenced by grazing systems in the Texas Rolling Plains. J. Range Manage. 40:240-243.

Qian, J., H. Zhan, S. Luo, and W. Zhao. 2007. Experimental evidence of scale-dependent hydraulic conductivity for fully developed turbulent flow in a single fracture. Journal of Hydrology. 339:206-215.

Rachman, A., S.H. Anderson, and C.J. Gantzer. 2005. Computed-tomographic measurement of soil macroporosity parameters as affected by stiff-stemmed grass hedges. Soil Sci. Soc. Am. J. 69:1609-1616.

Rachman, A., S.H. Anderson, C.J. Gantzer, and E.E. Alberts. 2004. Soil hydraulic properties influenced by stiff-stemmed grass hedge systems. Soil Sci. Soc. Am. J. 68:1386-1393.

Radford, B.J., B.J. Bridge, R.J. Davis, D. McGarry, U.P. Pillai, J.F. Rickman, P.A. Walsh, and D.F. Yule. 2000. Changes in the properties of a Vertisol and responses of wheat after compaction with harvester traffic. Soil Tillage Res. 54:155–170.

Radke, J.K and E.C. Berry.1993. Infiltration as a tool for detecting soil changes due to cropping, tillage and grazing livestock. Am. J. Alternative Agric. 8:164-174.

Raghavan, G.S.V., P. Alvo, and E. McKyes. 1990. Soil compaction in agriculture: A view toward managing the problem. Adv. Soil Sci.11:1–32.

Rasiah, V., and L.A.G. Alymore. 1998. The topology of pore structure in cracking clay soil: I. The estimation of numerical density. J. Soil Sci. 39:303-314.

Rasse, D.P., A.J.M. Smucker, and D. Santos. 2000. Alfalfa root and shoot mulching effects on soil hydraulic properties and aggregation. Soil Sci. Soc. Am. J. 64:725-731.

Rethemeyer, J. 2004. Organic carbon transformation in agricultural soils: Radiocarbon analysis of organic matter fractions and biomarker compounds. Ph.D. Dissertation, Christian- Albrechts University, Kiel.

Rockwood, D.L., C.V., Naidu, D.R., Carter, M., Rahmani, T.A., Spriggs, C., Lin, G.R., Alker, J.G., Isebrands, and S.A. Segrest. 2004. Shortrotation woody crops and phytoremediation: Opportunities for agroforestry? p. 51-64. *In*: P.K.R. Nair, M.R. Rao, and L.E. Buck (Ed.). New Vistas in Agroforestry: A compendium for the 1st World Congress of Agroforestry, 2004. Volume 1: Advances in Agroforestry. Dordrecht: Kluwer Academic Publishers.

Ruehlmann, J., and M. Körschens. 2009. Calculating the effect of soil organic matter concentration on soil bulk density. Soil Sci. Soc. Am. J. 73:876-885

Schenk, H.J., and R.B. Jackson. 2002. The global biogeography of root systems. Ecol. Monogr. 72:311-328.

Schmitt, T.J., M.G. Dosskey, and K.D. Hoagland. 1999. Filter strip performance and processes for different vegetation, widths, and contaminants. J. Environ. Qual. 28:1479-1489.

Schwab, G.O., D.D. Fangmeier, W.J. Elliot, and R.K. Frevert. 1993. Soil and water conservation engineering, 4th ed. John Wiley & Sons, United States of America. p. 396.

Seobi, T., S.H. Anderson, R.P. Udawatta, and C.J. Gantzer. 2005. Influence of grass and agroforestry buffer strips on soil hydraulic properties for an Albaqualf. Soil Sci. Soc. Am. J. 69:893-901.

Sheath, G.W., and C.J. Boom. 1997. Impact of cattle grazing systems on treading damage and forage supply. Proc. New Zealand Grassland Association 59:87-92.

Shouse, P.J., and B.P. Mohanty. 1998. Scaling of near-saturated hydraulic conductivity measured using disc infiltrometers. Water Resour. Res. 34:1195–1205.

Sikora, L., and D. Stott. 1996. Soil organic carbon and nitrogen. p. 157-167. In W. Doran and A. Jones (ed.) Methods for Assessing Soil Quality, vol 49, SSSA, Madison, WI.

Singh, V.P., and D.K. Frevert. 2006. Watershed Models.CRC press. Taylor and Francis. Boca Raton, FL.

Singleton, P.L., and B. Addison. 1999. Effects of cattle treading on physical properties of three soils used for dairy farming in the Waikato, North Island, New Zealand. Aust. J. Soil Res. 37: 891-902.

Soane, B.D., and C. van Ouwerkerk. 1994. Soil compaction problems in world agriculture. p. 1-21. *In*: B.D. Soane and C. van Ouwerkerk, (Ed.), Soil Compaction in Crop Production. Elsevier Science.

Stamps, W.T., and M.J. Linit. 1998. Plant diversity and arthropod communities: implications for temperate agroforestry. Agrofor. Syst. 39:73–89.

Startsev, A.D., and D. H. McNabb. 2001. Skidder traffic effects on water retention, pore-size distribution, and van Genuchten parameters of boreal forest soils. Soil Sci. Soc. Am. J. 65:224–231.

Stevenson, F.J. 1994. Humus chemistry: Genesis, composition, reactions. J. Wiley & Sons, New York.

Sudmeyer, R.A., J. Speijers, and B.D. Nicholas. 2004. Root distribution of *Pinus pinaster*, *P. radiata*, *Eucalyptus globulus* and *E. kochii* and associated soil chemistry in agricultural land adjacent to tree lines. Tree Physiol. 24:1333-1346.

Szabo, A., A. Osztoics, and F. Szilagyi. 2001. Natural wastewater treatment in Hungary. Water Sci. Technol. 44:331–338.

Taboada, M.A., and R.S. Lavado. 1993. Influence of cattle trampling on soil porosity under alternate dry and ponded conditions. Soil Use and Manage. 9:139-143.

Tate, K.W., D.M. Dubley, N.K. McDougald, and M.R. George. 2004. Effect of canopy and grazing on soil bulk density. J. Range. Manage. 57: 411-417.

Taylor, H.M., G.M. Robertson, and J.J. Parker. 1966. Soil strength-root penetration relations for medium and coarse textured soil materials. Soil Sci. 102:18-22.

Thorne, C., I. Amarasinghe, J. Gardiner, C. Perala-Gardiner, R. Sellin, M. Greaves, and J. Newman. 1997. Bank protection using vegetation with special reference to willows: Project record. Eng. And Phys. Sci. Res. Council and Environ. Agency, Swindon, UK.

Tollner, E.W., C. Murphy, and E.L. Ramseur. 1994. Techniques and approaches for documenting plant root development with X-ray computed tomography. p. 115-134 *In*: S.H. Anderson and J.W. Hopmans (ed.) Tomography of Soil-Water-Root processes. SSSA Special Publication Number 36. Amer. Soc. Agron., Madison, WI, USA.

Tufekcioglu, A., J.W. Raich, T.M. Isenhart, and R.C. Schultz. 1999. Fine root dynamics, coarse root biomass, root distribution, and soil respiration in a multispecies riparian buffer in central Iowa, USA. Agrofor. Syst. 44:163–174.

Turner, L.W., C.W. Absher and J.K. Evans. 1997. Planning fencing systems for intensive grazing management. University of Kentucky. College of Agriculture. p.1-11.

Udawatta, R.P., J.J. Krstansky, G.S. Henderson, and H.E. Garrett. 2002. Agroforestry practices, runoff, and nutrient loss: A paired watershed comparison. J. Environ. Qual. 31:1214-1225.

Udawatta, R.P., P. Nygren, and H.E. Garrett. 2005. Growth of three oak species during establishment of an agroforestry practice for watershed protection. Can. J. For. Res. 35:602-609.

Udawatta**,** R.P., S.H. Anderson, C.J. Gantzer, and H.E. Garrett. 2006. Agroforestry and grass buffer influence on macropore characteristics: A computed tomography analysis. Soil Sci. Soc. Am. J. 70: 1763-1773.

Udawatta, R.P., C.J. Gantzer, S.H. Anderson, and H.E. Garrett. 2008a. Agroforestry and grass buffer effects on high resolution X-ray CT-measured pore characteristics. Soil Sci. Soc. Am. J. 72: 295-304.

Udawatta, R.P., S.H. Anderson, C.J. Gantzer, and H.E. Garrett. 2008b. Influence of prairie restoration on CT-measured soil pore characteristics. J. Environ. Qual. 37: 219-228.

USDA-NRCS. 1997. National handbook of conservation practices. Item number 0120-A. USDA-NRCS, U.S. Gov. Print. Office, Washington, DC.

van Es, H.M. 1993. Evaluation of temporal, spatial and tillage induced variability for parameterization of soil infiltration. Geoderma 60:187-199.

van Golf-Recht, T.D. 1982. Fundamentals of fractured reservoir engineering. Elsevier, Amsterdam, The Netherlands.

van Noordwijk M, G. Lawson, J.J.R. Groot, and K. Hairiah. 1996. Root distribution in relation to nutrients and competition. p. 319-364. *In*: C.K. Ong and P.A. Huxley (Ed.). Tree-Crop Interactions - a Physiological Approach. CAB International, Wallingford, UK.

van Noordwijk M., and G. Brouwer. 1991. Review of quantitative root length data in agriculture p. 515-525. *In*: H Persson and B.L. McMichael (ed.) Plant Roots and their Environment. Elsevier, Amsterdam. The Netherlands.

van Noordwijk, M., H. M. Widianto, and K. Hairiah. 1991. Old tree root channels in acid soils in the humid tropics: Important for crop root penetration, water infiltration and nitrogen management. Plant and Soil 134: 37-44.

van Noordwijk, M., L.Y. Spek, and P. De Willingen. 1994. Proximal root diameters as predictors of total root system size for fractal branching models. I. Theory. Plant and Soil, 164: 107-118.

Vepraskas, M.J., A.G. Jongmans, M.T. Hoover, and J. Bouma. 1991. Hydraulic conductivity of saprolite as determined by channels and porous groundmass. Soil Sci. Soc. Am. J. 55:932–938.

Walker, W.J., and B. Branham. 1992. Environmental impacts of turfgrass fertilization. p. 105–219. In J.C. Balogh and W.J. Walker (ed.) Golf course management and construction: Environmental issues. Lewis Publ., Chelsea, MI.

Wang, E., C. Xin, J.R. Williams, and C. Xu. 2006. Predicting Soil Erosion for Alternative Land Uses. J. Environ. Qual. 35:459-467.

Wang, X., P.W. Gassman, J.R. Williams, S. Potter, and A.R. Kemanian. 2008. Modeling the impacts of soil management practices on runoff, sediment yield, maize productivity, and soil organic carbon using APEX. Soil Tillage Res. 101:78–88.

Warkentin, B.P. 1971. Effects of compaction on content and transmission of water in soils. p. 126-153. *In*: K.K. Barnes et al. (ed). Compaction of Agricultural Soils. Am. Soc. Agric. Eng., St. Joseph, Mich.

Warren, S.D., M.B. Nevill, W.H. Blackburn, and N.E. Garza. 1986a. Soil response to trampling under intensive rotation grazing. Soil Sci. Soc. Am. J. 50:1336-1341.

Warren, S.D., W.H. Blackburn, and C.A. Taylor Jr. 1986b. Soil hydrologic response to number of pastures and stocking density under intensive rotation grazing. J. Range Manage. 39:500-504.

Wheeler, M.A., M.J. Trlica, G.W. Frasier, and J.D. Reeder. 2002. Seasonal grazing affects on soil physical properties of a mountain riparian community. J. Range Manage. 55:49-56.

Williams, J.R. 1990. The erosion-productivity impact calculator (EPIC) model: A case history. Phil. Trans. Royal Soc. London 329: 421-428.

Williams, J.R., and A.N. Sharpley. 1989. EPIC-Erosion/productivity impact calculator: 1. Model documentation. Technical Bulletin No. 1768. Washington, D.C.: USDA Agricultural Research Service.

Williams, J.R., and R.C. Izaurralde. 2005. The APEX model. BRC Rep. 2005-02. Blackland Res. Center, Texas A&M Univ., Temple, TX.

Willis, W.O., and W.A. Raney. 1971. Effects of compaction on content and transmission of heat in soils. p. 165-177. *In*: K.K. Barnes et al. (ed.) Compaction of Agricultural Soils. Am. Soc. Agric. Eng., St. Joseph, Mich.

Wilson, G.V., and R.J. Luxmoore. 1988. Infiltration, macroporosity distributions on two forested watersheds. Soil Sci. Soc. Am. J. 52, 329-335.

Wynn, T.M., S. Mostaghimi, J.A. Burger, A.A. Harpold, M.B. Henderson, and L.A. Henry. 2004. Variation in root density along stream banks. J. Environ. Qual. 33:2030-2039.

Xiang, J., B.R. Scanlon, W.F. Mullican III, L. Chen, and R.S. Goldsmith. 1997. A multistep constant-head borehole test to determine field saturated hydraulic conductivity of layered soils. Adv. Water Resour. 20:45-57.

Zinkhan, J.C., and D.E. Mercer. 1997. An assessment of agroforestry systems in the southern USA. Agrofor. Syst. 35:303-321.

CHAPTER 3

SOIL HYDRAULIC PROPERTIES INFLUENCED BY AGROFORESTRY AND GRASS BUFFERS FOR GRAZED PASTURE SYSTEMS

ABSTRACT

Agroforestry buffers have been introduced in temperate areas to improve water quality and diversify farm income. The objective of this study was to evaluate saturated hydraulic conductivity and water retention for soils managed under rotationally-grazed pasture (RG), continuously grazed pasture (CG), grass buffers (GB), and agroforestry buffers (AgB). Pasture and GB areas included red clover (*Trifolium pretense* L.) and lespedeza (*Kummerowia stipulacea* Maxim.) planted into fescue (*Festuca arundinacea* Schreb.) while AgB included Eastern cottonwood trees (*Populus deltoids* Bortr. ex Marsh.) planted into fescue. Water retention data were measured at -0.4, -1.0, -2.5, -5.0, -10, -20, and -30 kPa soil water pressures using 76 mm diam. by 76 mm long cores from the 0-10, 10-20, 20-30, and 30-40 cm depths. Soil bulk density was 12.6% higher for the RG and CG treatments (1.41 and 1.45 g cm^{-3}) than the GB and AgB treatments (1.25 and 1.29 g cm^{-3}). Soil water content at high soil water potentials (0 and -0.4 kPa) was greater in the buffer treatments relative to the other treatments for the 0-10 cm soil depth. Soil macroporosity (>1000 μm diam.) was 5.7, 4.5, and 3.9 times higher, respectively, for the AgB, GB, and RG treatments compared to the CG treatment for the 0-10 cm soil depth. Buffer treatments had greater macroporosity (>1000-μm diam.), coarse (60- to 1000-μm diam.) and fine mesoporosity (10 to 60 μm diam.) but lower microporosity (< 10 μm diam.) compared to RG and CG treatments. Saturated hydraulic conductivity values for GB and AgB treatments were 16.7 times higher (56.95 vs.61.33 mm hr^{-1}) compared with

RG and CG (3.98 vs. 3.11 mm hr^{-1}). This study illustrates that agroforestry and grass buffers maintained higher values for soil hydraulic properties compared to grazed pasture systems.

Keywords: agroforestry buffer, grass buffer, pore size distribution, saturated hydraulic conductivity, soil water retention.

Introduction

Agroforestry buffers are being adopted to improve environmental quality and diversify income. Agroforestry is a land management where trees and agriculture crops are grown simultaneously on the same landscape for economic and environmental benefits (Gold and Hanover, 1987). Agroforestry practices are now receiving more attention in temperate climatic regions due to their environmental benefits (Lovell and Sullivan, 2006). Buffers have been shown to improve carbon sequestration, soil quality, and soil health (Kang et al., 1984). These buffers include trees which are grown either on the edges of fields, along streambanks in riparian zones, or upland cropping areas. Agricultural crops or pastures are grown in alleys between tree buffers or in upland areas.

Agroforestry and grass buffers help in reducing nonpoint source pollution (NPSP) from the row crop areas by improving soil hydraulic properties and decreasing surface runoff (Gilliam, 1994; Udawatta et al., 2002; Abu-Zreig et al., 2003; Seobi et al., 2005; Lovell and Sullivan, 2006). A study conducted by Udawatta et al. (2002) in northeast Missouri found that established agroforestry buffer practices with row crop production reduced surface runoff and total phosphorus losses during a three-year study. Research also shows that microbial diversity and enzymatic activity are higher in conservation buffer areas thus improving mineralization, nutrient cycling, and degradation of chemicals (Mungai et al., 2005). Root penetration and root decay in the soil profile create many small and larger pores and add organic matter which improves soil structure under agroforestry buffers (Obi, 1999; Mishra et al., 2003).

Agroforestry buffers can also be established on the edge of pastures with fencing around the buffer area to prevent disturbance of the buffer by grazing animals. In these buffer systems where the tree and grass buffer areas are left undisturbed by grazing animals, soil properties may be different compared to pasture areas which are disturbed by animal traffic. Undisturbed buffers may have lower soil bulk density, increased soil porosity and increased soil infiltration than grazed buffers, and trap sediment thus reducing stream sediment loads (Blanco et al., 2004). Cultivated fields and grazed pastures have generally greater soil bulk density than those of native grassland or forest soils (Jaiyeoba, 1995; Meek et al., 1992; Taboada and Lavado, 1993). These buffers can also reduce concentrations of some pathogenic microorganisms like *Cryptosporidium parvum*, which cause waterborne diseases transmitted between domestic animals and humans in grassland watersheds with extensive cattle grazing (Tate et al., 2004b). Vegetative buffers remove these waterborne microbial pathogens through overland flow infiltration, subsurface filtration and adsorption (Harter et al., 2000; Atwill et al., 2002; Trask et al., 2004).

Uneven grazing in pastures enhances soil erosion by increased surface runoff from areas with lower infiltration due to compaction from high animal traffic (Radke and Berry, 1993; Daniel et al., 2002; Wheeler et al., 2002). In a study conducted by Radke and Berry (1993), it was found that farm implements and animals cause soil compaction which results in an increase in the bulk density and a decrease in infiltration.

With rotational grazing, in which the pasture area is subdivided, animals are briefly concentrated on smaller paddocks which encourages uniform forage consumption and manure distribution, and decreases compacted and eroded areas (Warren et al., 1986; Turner et al., 1997). Rotational grazing has also been shown to improve the productivity of cattle compared to conventional grazing (Warren et al., 1986).

Few studies have evaluated changes in soil hydraulic properties due to establishment of agroforestry and grass buffers in grazed pasture management systems. The purpose of this study was to compare the effects of agroforestry and grass buffers on soil hydraulic properties compared to grazed pastures. The objective of the study was to measure and compare bulk density, saturated hydraulic conductivity, soil water retention, and pore size distributions among agroforestry buffer, grass buffer, rotationally grazed pasture and continuously grazed pasture treatments.

Materials and Methods

Experimental Site and Management. The experimental site is located at the Horticulture and Agroforestry Research Center (HARC) in New Franklin, Missouri (39°02'N, 92°46'W, 195 m amsl). The study site was established in 2000 to compare the influence of grass and agroforestry buffers on runoff water quality. Prior to establishment, most of the area was in tall fescue grass (*Festuca arundinacea* Schreb.) for three years. The pasture areas and buffers were reseeded with tall fescue (*Festuca arundinacea* Schreb;

Kentucky 31) in 2000. The pastures were seeded into the fescue with red clover (*Trifolium pretense* L.) and lespedeza (*Kummerowia stipulacea* Maxim.) in 2003. Eastern cottonwood trees (*Populus deltoids* Bortr. ex Marsh.) were planted into the fescue to create the agroforestry buffers in 2001. Trees were planted 3 m (9.8 ft) apart within four rows which were also 3 m apart. At sampling, trees were an average 7.6 m (25 feet) high with 15 cm (6 inch) diameter at breast height.

Soils at the site are Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs). The annual precipitation of the experimental site for the last 50 years (1956-2006 year) is 967 mm; mean temperature in July is 25.6°C (77.9°F) and mean temperature in January is -2.1°C (35.78°F). The selected soil physical and chemical properties of the study area are shown in Table 3.1.

Before introducing cattle for grazing, the bulk density in the pasture and buffer areas was measured in November 2002 for the 0-10 and 10-20 cm soil depths with 9 replicate samples. Values for pasture areas were 1.23 ± 0.083 and 1.34 ± 0.11 g cm^{-3} for the 0-10 and 10-20 cm depths, respectively, while values for the buffer areas were 1.17 ± 0.10 and 1.33 ± 0.12 g cm^{-3}, respectively.

Four-wire fences were installed around the watershed when the study was established. Fences were also installed between the pasture area and the agroforestry and grass buffer areas when the study was established to prevent cattle access to the buffers. Grazing was initiated at the site on April 6 and stopped on November 9, 2005; grazing was reinitiated on March 27 and stopped on October 24, 2006. Each year, beef cows were introduced in the watershed area with weights between 450 kg (992.08 lb) to 590 kg

(1102.31 lb). The number of cattle for the small watershed (0.8 ha, 2.0 ac) was three. Eighty-five percent of the grazing area (0.64 ha, 1.6 ac) of the watershed was divided into six smaller rotationally grazed paddocks which contained single wire electric fences for cattle management. The other 15% of the grazing area was continuously grazed. The stocking rate was 5.26 AU/ha (2.13 AU/ac) and stocking density was 31.6 AU/ha (12.8 AU/ac) with a site production capacity of 31.6 AUM/ha (12.8 AUM/ac). The cows were moved between paddocks on each Monday and Thursday with each paddock being grazed for 3.5 days and rested for 17.5 days. In 2005 and 2006, cows were removed on July 19 to August 25 and August 15 to September 21, respectively.

Treatments and Sampling Procedures. Study treatments were agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG), and continuously grazed pasture (CG) with six replications per treatment. The GB and AgB buffer treatments were fenced from the pasture area and did not receive any cattle grazing. The RG treatment was rotationally grazed with six fenced areas (paddocks) within the small watershed. The CG pasture treatment was continuously grazed by cattle with no rest.

Intact soil samples were collected using a core sampler (76 mm diam. and 76 mm length) on 18 to 22 May 2006 from the four treatments. Continuously grazed pasture (CG) samples were taken from six replicate continuously grazed areas and rotationally grazed pasture (RG) samples were taken from six replicate rotationally grazed areas. Agroforestry buffer (AgB) samples were taken from soil under six replicate trees, three each from two tree rows in the agroforestry buffer area. These samples were taken a distance of 20 cm from the base of tree trunks in the agroforestry buffer. Grass buffer (GB) samples were taken from six replicate grass buffer areas. Four sampling depths were used for all treatments which included 0-10, 10-20, 20-30 and 30-40 cm. Soil cores were labeled, trimmed, sealed in plastic bags, transported to the laboratory and stored at 4°C (39.2°F) until measurements were taken.

Laboratory Analyses. Laboratory analyses included saturated hydraulic conductivity, soil water retention and bulk density. Saturated hydraulic conductivity was measured using the constant head or falling head methods (Klute and Dirksen, 1986). Water retention was measured at 0, -0.4, -1.0, -2.5, -5.0, -10.0, -20.0, and -30.0 kPa soil water pressures (Klute and Dirksen, 1986).

Pore size distributions were calculated using the capillary rise equation to estimate effective pore size classes (Jury et al., 1991) from the water retention data. Four classes of pore sizes were used: macropores (>1000 µm effective diam.), coarse mesopores (60- to 1000-µm effective diam.), fine mesopores (10- to 60-µm effective diam.) and micropores (< 10 µm effective diam.; Anderson et al., 1990). Total porosity was determined using the soil water content value at 0 kPa soil water pressure.

Soil cores were saturated with a dilute salt solution **(**$CaCl_2$; 6.24 g L^{-1} and $MgCl_2$; 1.49 g L^{-1}) to retain soil structure and the constant head or falling head methods were used to measure saturated hydraulic conductivity. Saturated hydraulic conductivity was collected after eliminating visible pores and the space between soil and the core wall by applying bentonite slurry with a syringe (Blanco-Canqui et al., 2002). The purpose of applying the bentonite slurry was to block bypass flow in the core. The same soil cores were used for determining bulk density. Bulk density was determined by the core method given by Blake and Hartge (1986). Soil cores were dried at 105°C (221°F) until constant weight was obtained (about 48 hours).

Statistical Analysis. A test for homogeneity of variance was conducted to evaluate the variability within the different treatments for each soil hydraulic property due to the systematic arrangement of treatments. Analysis of variance (ANOVA) was further conducted with SAS using the GLM procedure when variances within treatments were homogeneous (SAS Institute, 1999). Single degree-of-freedom contrasts were also determined and were conducted as follows: *buffers vs. pastures*, *grass buffer vs. agroforestry buffer*, and *continuously grazed pasture vs. rotationally grazed pasture*. An estimate for the least significant difference (Duncan's LSD) between treatments at the same depth or different depths was obtained using the Mixed procedure in SAS. Statistical differences were declared significant at the $\alpha = 0.05$ level.

Results and Discussion

Bulk Density. Soil bulk density was different ($P<0.01$) among the treatments (Table 3.2). Significant differences were found for two contrasts: 'buffers vs. pastures' and 'grass buffer vs. agroforestry buffer' (Table 3.2). Buffer treatments (1.27 g cm^{-3}) had 11.2% lower soil bulk density than pasture treatments (1.43 g cm^{-3}). The GB treatment had slightly lower bulk density compared to the AgB treatment (Table 3.2). The GB treatment had 13.8 and 11.3% lower bulk density compared to the CG and RG treatments.

The bulk density in the pasture and buffer areas was measured during November 2002 prior to initiation of the grazing treatments for the 0-10 and 10-20 cm soil depths.

Initial values for pasture areas were 1.23 ± 0.083 and 1.34 ± 0.11 g cm^{-3} for the 0-10 and 10-20 cm depths, respectively, while values for the buffer areas were 1.17 ± 0.10 and 1.33 ± 0.12 g cm^{-3}, respectively. It is apparent that no significant differences occurred among the pasture and buffer areas prior to grazing initiation. After grazing was initiated, the pasture treatments showed significant increase in soil bulk density for upper two depths. Thus, the buffer treatments were able to maintain the initial bulk density values at these two depths.

Soil bulk density changed with soil depth ($P<0.01$; Table 3.2). Bulk density generally increased with soil depth for the buffer treatments and was relatively unaffected by soil depth for the CG treatment (Fig. 3.1A). The pasture treatments had higher bulk density as compared to the buffer treatments for the first two depths (Fig. 3.1A). Similar to our results, Greenwood and McKenzie (2001) also reported higher compaction of the upper 5 to 15 cm soil layer under pasture areas. The lowest bulk density for the 0-10 cm depth was found under the AgB (1.04 g cm^{-3}) treatment while the highest bulk density for this depth was found under the CG (1.45 g cm^{-3}) treatment. Interactions between treatment and soil depth were also found ($P<0.01$; Table 3.2).

The higher soil bulk density value in the CG treatment was due to the fact that the area was continuously grazed by cattle during the grazing season. Similar to our results, Radke and Berry (1993) observed that cattle traffic caused compaction of the soil and increased the soil bulk density and reduced the infiltration rate. Daniel et al. (2002) studied grazing effects on soil compaction under rangeland management in the tall-grass prairie region of Oklahoma. They assessed soil compaction 10 years after grazing treatments were initiated and reported that long–term livestock grazing increased soil bulk density, but only in the upper 10 cm. While Daniel et al. (2002) showed that long-term grazing impacts occurred near the soil surface; our study also showed that compaction can increase soil bulk density near the surface after two years of cattle grazing.

Comparing bulk density under trees and grass areas for the surface 15 cm, Messing et al. (1997) in low and high clay content soils and Seobi et al. (2005) in a high clay subsoil Putnam silt loam soil showed that soil bulk density was lower under trees than grass areas. The lower soil bulk density values under agroforestry and grass buffer treatments is due to root penetration and root decay in the soil profile which creates many pores and adds organic matter which improves the soil structure (Obi, 1999; Mishra et al., 2003). Literature shows that cultivated fields and grazed pastures have generally greater soil bulk density than those of native grassland or forest soils (Jaiyeoba, 1995; Meek et al., 1992; Taboada and Lavado, 1993). For a Typic Tropohumults soil, Fisher (1995) reported that deep rooted and heavy litter tree species lowered soil bulk density as compared with a grazed pasture treatment.

Soil Water Retention. Soil water retention was significantly affected by treatment ($P<0.05$) for six of the eight soil water pressures measured: 0.0, -0.4, -1.0, -10.0, -20.0, and -30.0 kPa pressures (Table 3.3). Soil water content was higher for the buffer vs. pasture treatments at the first three pressures measured, but lower at the last three pressures. The different slopes as a function of pressure were attributed to compaction for pasture treatments relative to buffer treatments. Additionally, water retained was lower ($P<0.05$) for the CG vs.RG treatments ($P<0.05$) and the AgB vs. GB treatments ($P<0.01$) at the 0.0, -0.4, and -1.0 kPa pressures (Table 3.3, Fig. 3.2). The soil water content was 10, 8.8, and 5.7% higher under buffer treatments compared to pasture treatments at 0.0, -0.4 and -1.0 kPa pressures, respectively.

At lower pressures (-10.0, -20.0 and -30.0 kPa), buffer treatments released more soil water compared to the pasture treatments which was attributed to compaction differences. Results show that the CG treatment retained less water at high pressures and more water at low pressures which resulted in flatter slopes for the water retention curves for this treatment relative to the others (Fig. 3.2A-D). This was probably due to changes in the pore size distribution for the CG treatment which affects air-filled porosity (Bruand and Cousin, 1995).

Volumetric water content at 0.0, -0.4 and -1.0 kPa water pressures under the GB treatment was found to be 0.56, 0.51 and 0.48 $m^3\ m^{-3}$, respectively, with the AgB treatment having values of 0.53, 0.48, 0.45 $m^3\ m^{-3}$. No differences were observed for other pressures between these two treatments. Higher soil water content was attributed to higher macroporosity in the GB treatment which was about 1.9, 26, 104% higher than AgB,RG and CG treatments, respectively.

Soil water retention also changed with soil depth ($P<0.010$, Table 3.3), generally decreasing slightly with soil depth. Interactions between treatment and soil depth were also significant ($P<0.05$) at all soil water pressures.

da Silva et al.(2004) reported that plant growth increased with increased air-filled porosity with a value of 10% air-filled porosity (saturation value minus -10 kPa value) being critical for root growth. In our study, we found that the continuously grazed pasture has 8% air-filled porosity which was below the critical limit for root growth; while the air-filled porosity for the GB and AgB treatments was on an average of 17 and 15%. The lower air-filled porosity was due to the higher bulk density for the continuously grazed pasture treatment.

Soil water retained at high soil water pressures for the buffer treatments was higher due to increased soil macroporosity. Higher soil water content at saturation due to increased soil porosity for grass hedges was reported by Rachman et al. (2004) for a Monona silt loam soil. They also reported smaller slopes for the soil water retention curve for the row crop and deposition zones which were attributed to higher soil bulk density; similar findings were observed in this study with the CG treatment which had a higher soil bulk density (Fig. 3.2A-D).

Pore Size Distributions. Pore size classes were affected by treatment ($P<0.05$) for all size classes (Table 3.4). Contrasting buffer vs. pasture treatments was significant ($P<0.01$) for all pore size classes. Buffer treatments had higher macroporosity and mesoporosity but lower microporosity compared to the pasture treatments. Additionally, differences ($P<0.05$) in total porosity and fine mesoporosity were found between the CG and RG treatments and in total porosity and coarse mesoporosity between the GB and AgB treatments. Buffers had 11, 54, 89 and 62% higher total porosity, macroporosity, coarse mesoporosity and fine mesoporosity compared with pasture treatments but 5% lower microporosity for all depths. Microporosity was nearly the same for all treatments. The values for macroporosity and coarse mesoporosity in the 0 to 10 cm depth were 0.035 and 0.067 m^3/m^3 higher, respectively, for the combined buffer treatments relative to the combined pasture treatments. These increases will have a strong influence on water transport in these systems.

Total porosity, fine mesoporosity and microporosity changed with soil depth (Table 3.4, Fig. 3.3). The treatment by depth interaction was also found to be significant ($P<0.05$) for total porosity, coarse mesoporosity, fine mesoporosity and microporosity (Fig. 3.3).

An 8.4% decrease in total porosity, a 28% increase in fine mesoporosity, and a 10% decrease in microporosity occurred between the first two depths averaged across treatments (Table 3.4). The total porosity, fine mesoporosity, and microporosity values slightly increased between the second and third depths probably due to the slight decrease in soil bulk density between these two layers. The decreased value of total porosity from the first to the second depth is due to the increase in the soil bulk density from the first to the second depth; whereas increased fine mesoporosity was probably due to the fact that increased bulk density did not affect this size class. Differences in pore classes were not much different at lower depths because differences in bulk density were smaller.

Agroforestry buffers establish deep root systems which increase the proportion of macropores and improve the soil hydraulic properties as compared to a row crop system (van Noordwijk et al., 1991; Rasse et al., 2000; Allaire-Leung et al., 2000; Cadisch et al., 2004). Water can easily enter in these macropores and hence increase infiltration (Rachman et al., 2005). This study showed increased macroporosity for the agroforestry buffer area relative to pasture areas and slightly higher values for the grass buffer area compared to the agroforestry area. For clay soils studies by Seobi et al. (2005), the situation is slightly different. Seobi et al. (2005) reported that clay content increased with soil depth which increased soil microporosity and decreased macroporosity. These claypan soils generally have fewer macropores and hence a much lower infiltration rate which can create higher runoff. Higher values for macroporosity were observed in the current study compared to those observed by Seobi et al. (2005).

Saturated Hydraulic Conductivity. The K_{sat} values were found to be different among the treatments (Table 3.2). The K_{sat} for both buffer treatments (59.2 mm h^{-1}) was 16.7 times higher as compared to the pasture treatments (3.54 mm h^{-1}; Table 3.2). Saturated conductivity for the AgB treatment was 15.4 and 19.7 times higher as compared to the RG and CG treatments, respectively. Significant differences were found between buffers vs. pastures but not for the other two contrasts. Higher K_{sat} values were found for the tree buffer treatment compared to grass buffer and row crop treatments by Udawatta et al. (2006) for a Putnam silt loam soil. Higher K_{sat} values in the buffer treatments were probably due to lower soil bulk density and higher macroporosity values.

The K_{sat} values significantly decreased with increasing soil depth (Table 3.2; Fig. 3.1B). The K_{sat} values generally decreased with increasing soil depth with the highest values occurring in the surface 0-10 cm layer (79.2 mm h^{-1}). The buffers had higher K_{sat} values as compared to the pasture treatments at all soil depths; however, significant differences occurred only for the 0-10 cm soil depth. The highest K_{sat} (182 mm h^{-1}) value for the study was found at the 0-10 cm soil depth under AgB management which was 4.7, 12.2, and 19.7 times higher as compared to the 10-20, 20-30, and 30-40 cm depths for this treatment. In contrast, the lowest K_{sat} (0.097 mm h^{-1}; Fig. 3.1B) value for the study was also found at the 0-10 cm depth under the CG treatment which was more than three orders of magnitude lower than the value for the AgB treatment at this same depth. The interactions between the treatment and soil depth factors were also significant ($P<0.01$; Table 3.2).

These differences in treatment K_{sat} values would significantly change the time to ponding during rainfall. For example with an 80 mm/hr rainfall rate, the time to ponding estimated using mean K_{sat} values predicted time to ponding of 0.03 hr for the pasture areas in contrast with 1.8 hr for the buffer areas.

Saturated hydraulic conductivity depends on the pore size distribution and continuity of the pore system. Higher macroporosity was attributed to higher K_{sat} values for buffer treatments (Rachman et. al., 2004). Seobi et al. (2005) also reported increased saturated hydraulic conductivity with agroforestry and grass buffers for claypan soils in northeastern Missouri. The differences were attributed to lower values of bulk density and increased levels of macroporosity and coarse mesoporosity. They also reported that grass buffers and agroforestry buffers after six years can store more water in the upper 30 cm soil layer as compared to a row crop treatment.

Summary and Conclusions

This study was conducted to evaluate the effects of agroforestry and grass buffers on soil hydraulic properties relative to pasture management. Results showed the effects of different grazing systems (RG and CG) on soil bulk density, soil water retention curves, pore size distributions and soil saturated hydraulic conductivity compared to selected buffer systems (GB and AgB). Soil bulk density was lower for the buffer treatments as compared to pasture treatments. Bulk density values averaged across soil depth were higher for the RG and CG treatments, 1.41 and 1.45 g cm^{-3}, compared to the GB and AgB treatments, 1.25 and 1.29 g cm^{-3}. Buffers had significantly higher water retained for the 0.0, -0.4, and -1.0 kPa pressures compared to pasture treatments, but lower water retained at -10.0, -20.0, and -30.0 kPa pressures. Soil water content at high soil water potentials (0, -0.4, and -1.0 kPa) was greater in the RG area compared to the CG area.

Soil macroporosity (>1000 μm diam.) was 2.1 times higher for the buffer treatments compared to the pasture treatments for the 0-10 cm soil depth. Results showed that the GB and AgB treatments had greater total porosity, macroporosity, coarse mesoporosity (60 to 1000 μm diam.) and fine mesoporosity (10 to 60 μm diam.) but lower microporosity (< 10 μm diam.) compared to the RG and CG treatments. Soil saturated hydraulic conductivity values averaged across soil depth for the GB and AgB treatments were 57.0 and 61.3 mm hr^{-1}, while the values for the RG and CG treatments were 3.98 and 3.11 mm hr^{-1}. Higher K_{sat} values were probably related to the significantly higher total porosity and soil macroporosity found for the buffer treatments.

This study illustrates the benefits of agroforestry and grass buffers for maintaining soil hydraulic properties compared to grazed pasture systems. Results from this study showed that non-grazed buffers had somewhat higher values for soil hydraulic properties compared to grazed pastures. In the buffer treatments, soil water retention at high pressures, total porosity, macroporosity, mesoporosity, and saturated hydraulic conductivity were higher compared to pasture management but had lower soil bulk density. This study shows that soil hydraulic properties which are related to infiltration were higher with buffer treatments and lower with grazed pasture areas; this implies that buffers will probably have higher infiltration and subsequently lower surface runoff compared to grazed pastures systems.

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References Cited

Abu-Zreig, M., R.P. Rudra, H.R. Whitely, M.N. Lalonde, and N.K. Kaushik. 2003. Phosphorus removal in vegetated filter strips. Journal of Environmental Quality 32:613-619.

Alados, C.L., A. ElAich, V.P. Papanastasis, H. Ozbek, T. Navarro, H. Freitas, M. Vrahnakis, D. Larrosi, and B. Cabezudo. 2004. Change in plant spatial patterns and diversity along the successional gradient of Mediterranean grazing ecosystems. Ecological Modeling 180:523-535.

Allaire-Leung, S.E., S.C. Gupta, and J.F. Moncrief. 2000. Water and solute movement in soil as influenced by macropore characteristics: I. Macropore continuity. Journal of Contaminant Hydrology 41:283–301.

Anderson, S.H., C.J. Gantzer, and J.R. Brown. 1990. Soil physical properties after 100 years of continuous cultivation. Journal of Soil and Water Conservation 45:117-121.

Atwill, E.R., L. Hou, B.M. Karle, T. Harter, K.W. Tate, and R.A. Dahlgren. 2002. Transport of *Cryptosporidium parvum* oocysts through vegetated buffer strips and estimated filtration efficiency. Applied and Environmental Microbiology 68:5517–5527.

Blake, G.R., and K.H. Hartge. 1986. Bulk density. p. 363-375. *In* A. Klute (ed.) Methods of soil samples. Part 1. 2nd ed. Agronomy Monograph 9, American Society of Agronomy, Madison, WI.

Blanco-Canqui, H., C.J. Gantzer, S.H. Anderson, E.E. Alberts, and A.L. Thompson. 2004. Grass barrier and vegetative filter strip effectiveness in reducing runoff, sediment, nitrogen, and phosphorus loss. Soil Science Society of America Journal 68:1670-1678.

Blanco-Canqui, H., C.J. Gantzer, S.H. Anderson, E. E. Alberts, and F. Ghidey. 2002. Saturated hydraulic conductivity and its impact on simulated runoff for claypan soils. Soil Science Society of America Journal 66:1596-1602.

Bruand, A., and I. Cousin. 1995. Variation of textural porosity of a clay-loam soil during compaction. European Journal of Soil Science 46:377–385.

Cadisch, G., P. de Willigen, D. Suprayogo, D.C. Mobbs, M. van Noordwijk, and E.C. Rowe. 2004. Catching and competing for mobile nutrients in soils. p. 171-191. *In* M. van Noodwijk , G. Cadisch, and C.K. Ong (*ed.*) Below-ground interactions in tropical agroecosystems. CABI, Wallingford, UK.

da Silva, A., Silvia, I., and Kay, B. 2004. Plant response to mechanical resistance and air-filled porosity of soils under conventional and no-tillage system. Scientia Agricola (Piracicaba, Braz.), 61:451-456.

Daniel, J.A., K. Potter, W. Altom, H. Aljoe, and R. Stevens. 2002. Long-term grazing density impacts on soil compaction. Transactions of ASAE 45:1911-1915.

Fisher, R.F. 1995. Amelioration of degraded rainforest soils by plantations of native trees. Soil Science Society of America Journal 59:544-549.

Gilliam, J.W. 1994. Riparian wetlands and water quality. Journal of Environmental Quality 23:896-900.

Gold, M.A., and J.W. Hanover. 1987. Agroforestry systems for temperate zones. Agroforestry Systems 5:109–121.

Greenwood, K.L., and B.M. McKenzie. 2001. Grazing effects on soil physical properties and the consequences for pasture: A review. Australian Journal of Experimental Agriculture 41:1231–1250.

Harter, T., S. Wagner, and E.R. Atwill. 2000. Colloid transport and filtration of *Cryptosporidium parvum* in sandy porous media (soils and groundwater). Environmental Science and Technology 34:62–70.

Jaiyeoba, I.A. 1995. Changes in soil properties related to different land uses in part of the Nigerian semi-arid savannah. Soil Use and Management 11:84-89.

Jury, W.A., W.R. Gardner, and W.H. Gardner. 1991. Soil physics. John Wiley & Sons, New York.

Kang, B.T., G.F. Ilson, and T.L. Lawson. 1984. Alley cropping: A stable alternative to shifting cultivation. International Institute of Tropical Agriculture, Ibadan, Nigeria.

Klute, A., and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. p. 687-734 *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agronomy Monograph 9, American Society of Agronomy, Madison, WI.

Lovell, S.T., and W.C. Sullivan. 2006. Environmental benefits of conservation buffers in the United States: Evidence, promise, and open questions. Agriculture, Ecosystems and Environment 112:249-260.

Meek, B.D., E.R. Rechel, L.M. Carter, W.R. DeTar., and A.L. Urie. 1992. Infiltration rate of a sandy loam soil: effects of traffic, tillage, and plant roots. Soil Science Society of America Journal 56:908-913.

Messing, I., A. Alriksson, and W. Johansson. 1997. Soil physical properties of afforested and arable land. Soil Use and Management 13:209-217.

Mishra, A., S.D. Sharma, and G.H. Khan. 2003. Improvement in physical and chemical properties of sodic soil by 3, 6 and 9 year old plantation of *Euculyptus tereticornis* biorejuvenation of sodic soil. Forest Ecology and Management 184:115-124.

Mungai, N.W., P.P. Motavalli, R.J.Kremer, and K.A.Nelson. 2005. Spatial variation of soil enzyme activities and microbial functional diversity in temperate alley cropping systems. Biology and Fertility of Soils Journal 42: 129–136

Obi, M.E. 1999. The physical and chemical responses of a degraded sandy clay loam soil to cover crops in southern Nigeria. Plant and Soil 211:165-172.

Rachman, A., S.H. Anderson, and C.J. Gantzer. 2005. Computed-tomographic measurement of soil macroporosity parameters as affected by stiff-stemmed grass hedges. Soil Science Society of America Journal 69:1609-1616.

Rachman, A., S.H. Anderson, C.J. Gantzer, and E.E. Alberts. 2004. Soil hydraulic properties influenced by stiff-stemmed grass hedge systems. Soil Science Society of America Journal 68:1386–1393.

Radke, J.K, and E.C. Berry. 1993. Infiltration as a tool for detecting soil changes due to cropping, tillage and grazing livestock. American Journal of Alternative Agriculture 8:164-174.

Rasse, D.P., A.J.M. Smucker, and D. Santos. 2000. Alfalfa root and shoot mulching effects on soil hydraulic properties and aggregation. Soil Science Society of America Journal 64:725-731.

SAS Institute. 1999. SAS user's guide. Statistics. SAS Inst., Cary, NC.

Seobi, T., S.H. Anderson, R.P. Udawatta, and C.J. Gantzer. 2005. Influence of grass and agroforestry buffer strips on soil hydraulic properties for an Albaqualf. Soil Science Society of America Journal 69:893-901.

Taboada, M.A., and R.S. Lavado. 1993. Influence of cattle trampling on soil porosity under alternate dry and ponded conditions. Soil Use and Management 9:139-143.

Tate, K.W., D.D. Dudley, N.K. McDougald, and M.R. George. 2004a. Effects of canopy and grazing on soil bulk density on annual rangeland. Journal of Range Management 57:411-417.

Tate, K.W., M.D.G.C. Pereira, and E.R. Atwill.2004b. Efficacy of vegetated buffer strips for retaining *Cryptosporidium parvum.* Journal of Environmental Quality 33:2243-2251.

Trask, J.R., P.K. Kalita, M.S. Kuhlenschmidt, R.D. Smith, and T.L.Funk. 2004. Overland and near-surface transport of *Cryptosporidium parvum* from vegetated and nonvegetated surfaces. Journal of Environmental Quality 33:984–993.

Turner, L.W., C.W. Absher, and J.K. Evans. 1997. Planning fencing systems for intensive grazing management. p. 1-12. University of Kentucky Cooperative Extention Service Pub. ID-74, Lexington, KY.

Udawatta, R.P., S.H. Anderson, C.J. Gantzer, and H.E. Garrett. 2006. Agroforestry and grass buffer influence on macropore characteristics: A computed tomography analysis. Soil Science Society of America Journal 70:1763-1773.

Udawatta, R.P., J.J. Krstansky, G.S. Henderson, and H.E. Garrett. 2002. Agroforestry practices, runoff, and nutrient loss: a paired watershed comparison. Journal of Environmental Quality 31:1214-1225.

van Noordwijk, M., and G. Brouwer. 1991. Review of quantitative root length data in agriculture. p. 515-525. *In* Plant roots and their environment, *eds*., Persson, H., and B. L. McMichael, Amsterdam, The Netherlands: Elsevier.

Warren, S.D., W.H. Blackburn, and C.A. Taylor, JR.1986. Soil hydrologic response to number of pastures and stocking density under intensive rotation grazing. Journal of Range Management 39:500-504.

Wheeler, M.A., M.J. Trlica, G.W. Frasier, and J.D. Reeder. 2002. Seasonal grazing affects on soil physical properties of a mountain riparian community. Journal of Range Management 55:49-56.

Table 3.1. Selected physical and chemical properties for the Menfro silt loam soil of the study area.

Soil Horizon	Soil Depth	Sand	Silt	Clay	CEC†	OC‡	EC§	-----pH-----	
	cm	-------- g kg^{-1}---------			cmol kg^{-1}	g kg^{-1}	dS m^{-1}	$CaCl_2$	H_2O
A	0-10	37	638	325	22.7	21.0	0.23	6.4	5.1
AB	10-20	38	639	322	21.9	9.0	0.18	6.4	5.1
Bt_1	20-45	40	641	319	21.2	6.1	0.13	6.4	5.1

†CEC, Cation exchange capacity

‡OC, Organic carbon

§EC, Electric conductivity

Table 3.2. Geometric means of saturated hydraulic conductivity (K_{sat}) and arithmetic means of bulk density for the continuously grazed pasture (CG), rotationally grazed pasture (RG), grass buffer (GB), and agroforestry buffer (AgB) treatments and soil depths, and the analysis of variance.

Treatment	K_{sat}	Bulk density
	mm h^{-1}	g cm^{-3}
Treatment mean		
Continuously grazed pasture (CG)	3.11	1.45
Rotationally grazed pasture (RG)	3.98	1.41
Grass buffer (GB)	57.0	1.25
Agroforestry buffer (AgB)	61.3	1.29
Depth mean		
0- to 10-cm	79.2	1.25
10- to 20-cm	21.2	1.39
20- to 30-cm	10.9	1.37
30- to 40-cm	14.1	1.38
	Analysis of variance P > F	
Treatment	<0.010	<0.010
Buffers vs. Pastures	<0.010	<0.010
GB vs. AgB	0.753	0.047
CG vs. RG	0.951	0.059
Depth	<0.010	<0.010
Treatment by Depth	<0.010	<0.010

†Means with different level for a soil property are significantly different at the 0.05 probability level.

Table 3.3. Average soil water content as a function of soil water pressure (0.0 to -30 kPa) for the continuously (cont.) grazed pasture, rotationally (rot.) grazed pasture, grass buffer, and agroforestry buffer treatments and soil depths, and the analysis of variance

	Soil water pressure (kPa)							
	0.0	-0.4	-1.0	-2.5	-5.0	-10.0	-20.0	-30.0
	$m^3\ m^{-3}$							
Treatment mean								
Cont. grazed pasture (CG)	0.48	0.45	0.43	0.42	0.41	0.40	0.40	0.39
Rot. grazed pasture (RG)	0.51	0.46	0.45	0.43	0.41	0.40	0.39	0.38
Grass buffer (GB)	0.56	0.51	0.48	0.43	0.41	0.39	0.38	0.37
Agroforestry buffer (AgB)	0.53	0.48	0.45	0.42	0.40	0.38	0.37	0.36
Depth mean								
0- to 10-cm	0.55	0.50	0.47	0.44	0.43	0.42	0.41	0.40
10- to 20-cm	0.50	0.46	0.44	0.41	0.39	0.38	0.37	0.36
20- to 30-cm	0.51	0.47	0.45	0.42	0.40	0.39	0.38	0.37
30- to 40-cm	0.53	0.48	0.46	0.42	0.40	0.38	0.37	0.36
	Analysis of variance P > F							
Treatment	<0.010	<0.010	<0.010	0.088	0.163	0.018	<0.010	<0.010
Buffers vs. Pastures	<0.010	<0.010	<0.010	0.150	0.119	<0.010	<0.010	<0.010
GB vs. AgB	<0.010	<0.010	<0.010	0.140	0.102	0.134	0.208	0.225
CG vs. RG	<0.010	0.049	0.029	0.102	0.773	0.452	0.195	0.150
Depth	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010
Treatment by Depth	<0.010	<0.010	0.048	<0.010	<0.010	<0.010	<0.010	<0.010

Table 3.4. Total pores, macropores, coarse mesopores, fine mesopores, and micropores for the continuously (cont.) grazed pasture, rotationally (rot.) grazed pasture, grass buffer and agroforestry buffer treatments and soil depths, and the analysis of variance.

Treatment	Total Pores	Macropores (>1000 µm)	Coarse Mesopores (60- to 1000-µm)	Fine Mesopores (10- to 60-µm)	Micropores (<10 µm)
	----------	----------	$m^3\ m^{-3}$	----------	----------
Treatment mean					
Cont. grazed pasture (CG)	0.477	0.026	0.042	0.018	0.392
Rot. grazed pasture (RG)	0.505	0.042	0.052	0.029	0.382
Grass buffer (GB)	0.562	0.053	0.100	0.039	0.370
Agroforestry buffer (AgB)	0.529	0.052	0.078	0.037	0.363
Depth mean					
0- to 10-cm	0.550	0.049	0.071	0.025	0.404
10- to 20-cm	0.504	0.046	0.063	0.032	0.363
20- to 30-cm	0.511	0.042	0.068	0.034	0.368
30- to 40-cm	0.509	0.035	0.070	0.032	0.371
		Analysis of variance P > F			
Treatment	<0.010	0.028	<0.010	<0.010	<0.010
Buffers vs. Pastures	<0.010	<0.010	<0.010	<0.010	<0.010
GB vs. AgB	<0.010	0.950	<0.010	0.287	0.224
CG vs. RG	<0.010	0.092	0.053	<0.010	0.150
Depth	<0.010	0.133	0.193	<0.010	<0.010
Treatment by Depth	<0.010	0.128	<0.010	0.014	<0.010

† Means with different level for a soil property are significantly different at the 0.05 probability level.

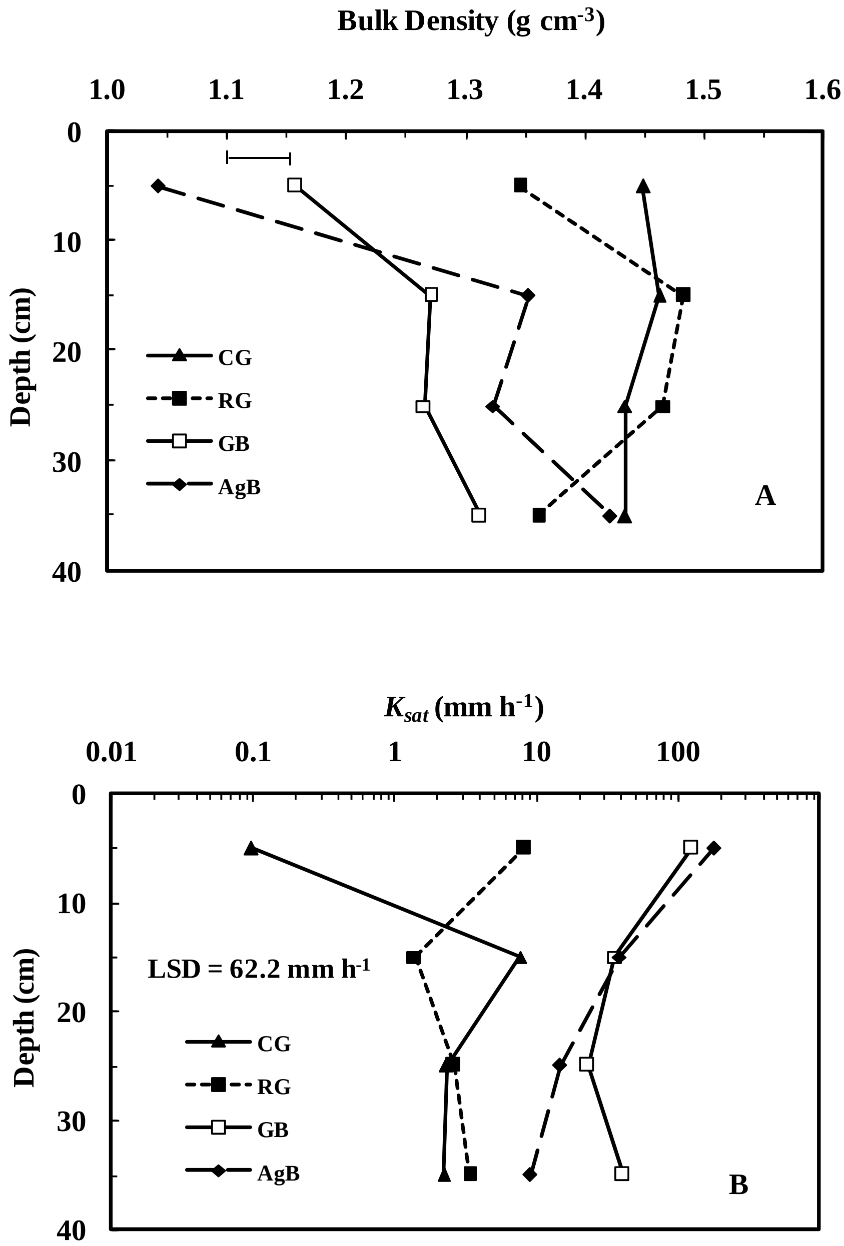

Fig. 3.1.Bulk density (A) and saturated hydraulic conductivity (B) for continuously grazed pasture (CG), rotationally grazed pasture (RG), grass buffer (GB), and agroforestry buffer (AgB) treatments influenced by soil depth. The bar indicates the LSD (0.05) value for bulk density (A). The LSD (0.05) value for K_{sat} is listed on the graph due to log scale (B).

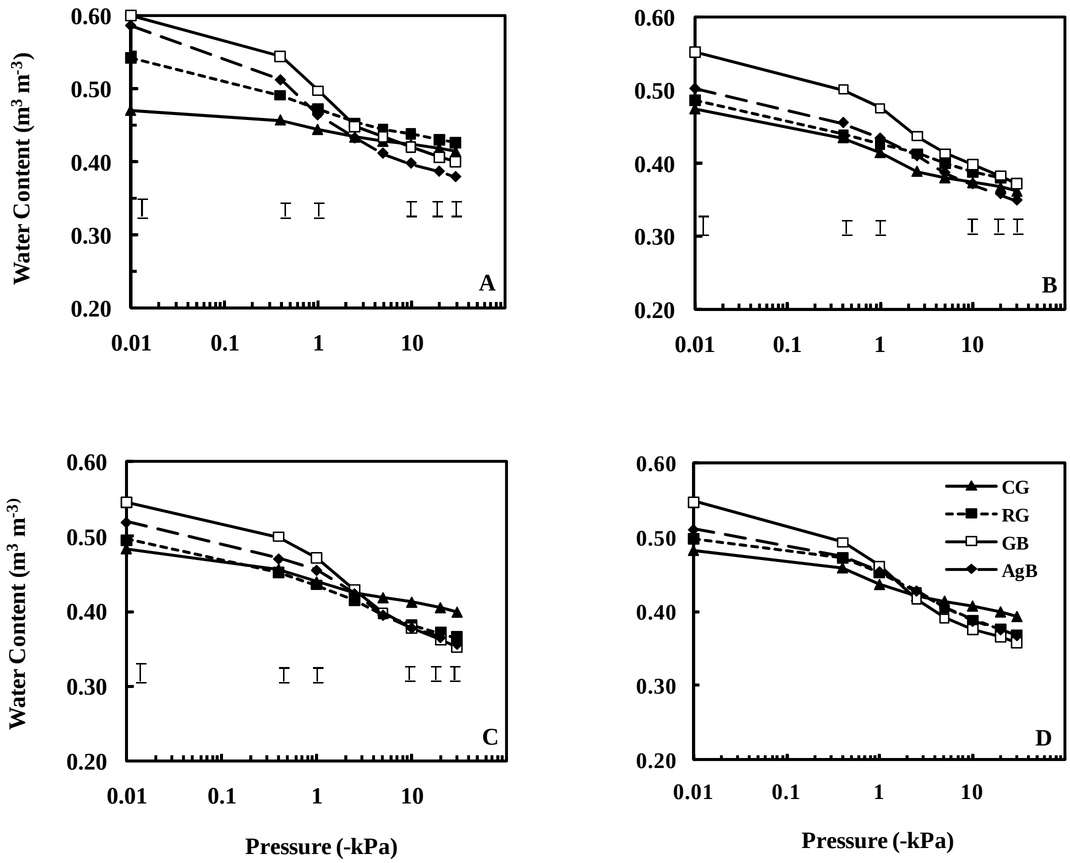

Fig. 3.2. Soil water retention curves for continuously grazed pasture (CG), rotationally grazed pasture (RG), grass buffer (GB), and agroforestry buffer (AgB) treatments for 0-10 cm (A), 10-20 cm (B), 20-30 cm (C), and 30-40 cm (D) depths. Bars indicate LSD (0.05) values and are presented at pressures when significant differences occurred among the treatments.

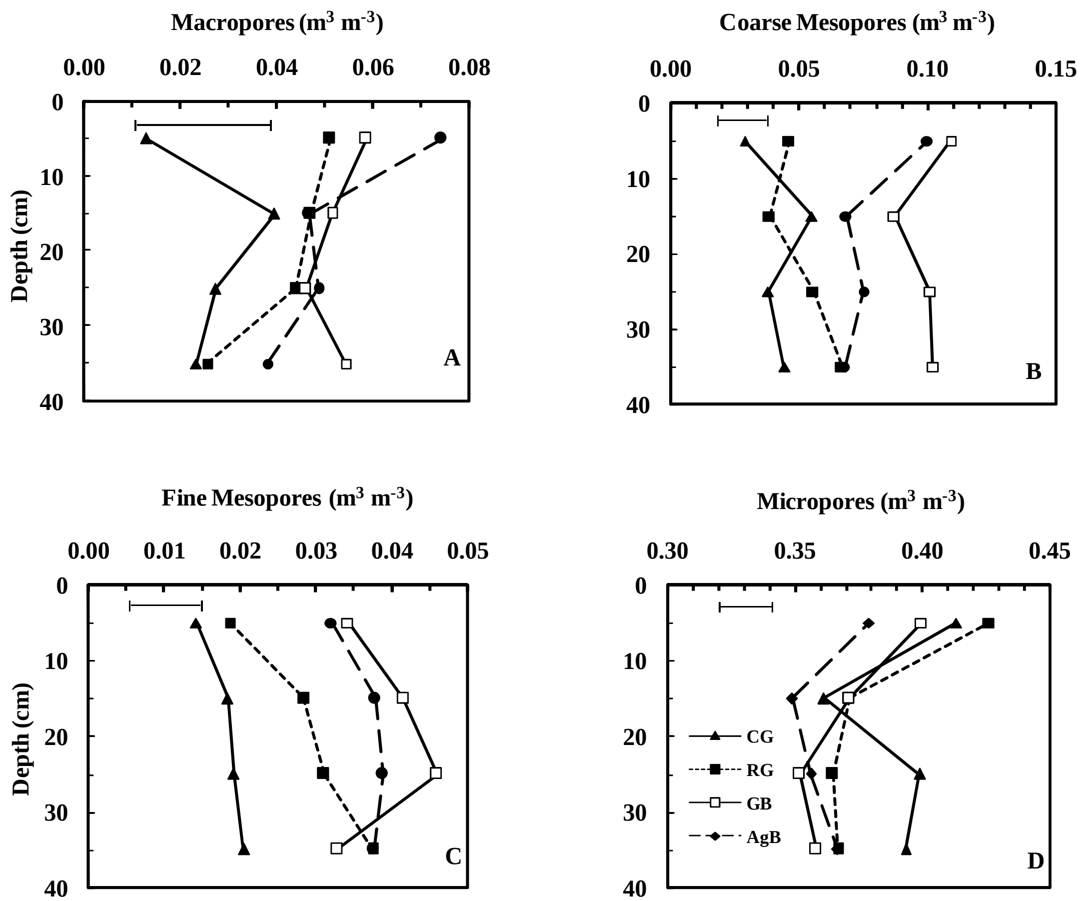

Fig. 3.3. Porosity values for continuously grazed pasture (CG), rotationally grazed pasture (RG), grass buffer (GB), and agroforestry buffer (AgB) treatments influenced by soil depth. Pore size classes include macropores (> 1000-µm diam; A), coarse mesopores (60- to 1000-µm diam.; B), fine mesopores (10- to 60-µm diam.; C), and micropores (< 10-µm diam.; D). Bars indicate LSD (0.05) values and are presented for pore-size classes with significant differences among treatments.

CHAPTER 4

AGROFORESTRY AND GRASS BUFFER INFLUENCES ON CT-MEASURED MACROPORES UNDER GRAZED PASTURE SYSTEMS

ABSTRACT

Agroforestry buffers, which include trees, grass, and shrubs, have been proposed for improving water quality in watersheds. The objectives of the study were to compare differences in macropore (>1000-µm diam.) and coarse mesopore (200–1000-µm diam.) parameters measured by computed tomography (CT) within agroforestry buffer (AgB) and grass buffer (GB) systems associated with rotationally grazed pasture (RG) and continuously grazed pasture (CG) systems, and to examine relationships between CT-measured pore parameters and saturated hydraulic conductivity (K_{sat}). Pasture and GB areas included red clover (*Trifolium pratense* L.) and Korean lespedeza [*Kummerowia stipulacea* (Maxim.) Makino] planted into fescue (*Festuca arundinacea* Schreb.), while AgB included eastern cottonwood trees (*Populus deltoides* W. Bartram ex Marshall ssp. *deltoides*) planted into fescue. Soils at the site were Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalf). Intact soil cores were collected from the four treatments at five soil depths. Five equally spaced images were acquired from each core and were analyzed with Image-J software. The CT-measured soil macroporosity was 13 times higher (0.053 $m^3 m^{-3}$) for the buffer treatments than the pasture treatments (0.004 $m^3 m^{-3}$) for the surface 0- to 10-cm soil depth. Buffer treatments had greater macroporosity (0.02 $m^3 m^{-3}$) than RG (0.005 $m^3 m^{-3}$) or CG (0.004 $m^3 m^{-3}$) treatments. The K_{sat} values for buffer treatments were five times higher than pasture treatments. Soil bulk density was 5.6% lower for the buffer treatments than the pasture treatments. The

CT-measured pore parameters (except macropore circularity) were positively correlated with K_{sat}. This study illustrates the benefits of agroforestry and grass buffers for maintaining soil pore parameters critical for soil water transport.

Abbreviations: AgB, agroforestry buffer; CG, continuously grazed pasture; CT, computed tomography; GB, grass buffer; K_{sat}, saturated hydraulic conductivity; NPSP, nonpoint source pollution; RG, rotationally grazed pasture

INTRODUCTION

Agroforestry buffers have been recently introduced to improve environmental quality and diversify farm income. Agroforestry is a land management practice where trees and agricultural crops are grown simultaneously on the same landscape for economical and environmental benefits (Gold and Hanover, 1987). Agroforestry and grass buffers help in reducing nonpoint-source pollution from the row crop areas by improving soil hydraulic properties and reducing surface runoff (Udawatta et al., 2002; Abu-Zreig et al., 2003; Seobi et al., 2005). These buffers increase the soil porosity relative to row crop land management under tilled or no-till practices (Bharati et al., 2002; Seobi et al., 2005). The establishment of buffers in pasture areas has been shown to decrease soil bulk density and increase soil porosity (Kumar et al., 2008). Grass roots and tree roots persist longer than row crop roots, which may result in larger, longer, and more continuous pores spreading into subsurface horizons (Udawatta et al., 2008a).

Soil porosity is a very important parameter that is related to transport and storage of water and nutrients in the soil. Hence, it is essential to understand soil pore characteristics. Water transmission and storage depend on the geometry and size distribution of soil pores (Eynard et al., 2004). This pore network, especially the pore size distribution and connectivity of the pores, is believed to control soil hydraulic properties (Vogel, 2000; Perret et al., 2000; Pierret et al., 2002). Different management practices alter the soil pore volume and size distribution in space and time and ultimately modify the hydraulic properties of the soil (Eynard et al., 2004).

Porosity can be estimated by traditional water retention methods (Anderson et al., 1990), thin-section analysis (van Golf-Recht, 1982), and Boyle's law porosimetry (American Petroleum Institute, 1960). Gantzer and Anderson (2002) reported that these procedures do not provide information about the spatial distribution of pores. Additionally, although macropores constitute only a small percentage of the total porosity, they have a major influence on saturated flow (Luxmoore et al., 1990). These traditional methods are time consuming and some are destructive. Moreover, porosity determined by traditional methods lacks information on pore characteristics (Udawatta et al., 2006). In contrast, x-ray CT methods are faster, nondestructive, and provide information on spatial distributions of soil pores and their characteristics.

An x-ray image is a picture of the x-ray linear attenuation coefficients of an object, which is related to the density of the object (Phillips and Lannutti, 1997). In recent years, x-ray CT analysis methods, first introduced in the early 1970s by Hounsfield (1973, 1977) for medical imaging, have received increased attention in soil and earth sciences. It is now being used more frequently in the field of soil science for examining solute movement (Anderson et al., 2003), porosity (Anderson et al., 1988; Rachman et al., 2005), pore continuity (Grevers and de Jong, 1994), the fractal dimension of porosity (Rasiah and Alymore, 1998; Gantzer and Anderson, 2002), and plant root development

(Tollner et al., 1994) and to obtain nondestructive measurement of water content and dry bulk density (Petrovic et al., 1982; Crestana et al., 1985; Hopmans et al., 1992). This technique can also be used for studying soil structure (Rogasik et al., 1999), measuring soil microstructure (Phillips and Lannutti, 1997; Alshibli et al., 2000), and determining the shape, distribution, and arrangement of soil pores within the soil (Udawatta et al., 2008b). This technique also has been applied to characterize pore continuity and tortuosity (Udawatta et al., 2008b). According to Tollner et al. (1994), x-ray CT scanning can provide aggregate size data consistent with traditional testing.

Computed tomography procedures have advantages compared with traditional methods since these procedures provide a finer resolution on a millimeter to micrometer scale (Gantzer and Anderson, 2002). The nondestructive nature of CT scanning allows the same soil sample to be scanned at different times. Carlson et al. (2003) reported that the best advantage of CT is its ability to quickly and nondestructively image the interior of a three-dimensional object. Computed tomography techniques can provide the three-dimensional structure of soil pores. Another advantage of x-ray CT scanning is its ability to quantitatively measure soil bulk density and water content distributions in undisturbed soil samples (Heijs et al., 1995).

The objectives of this study were to compare the effects of AgB and GB systems associated with RG and CG systems on CT-measured macropore (>1000-µm diam.) and coarse mesopore (200–1000-µm diam.) parameters, and to examine the relationships between CT-measured pore parameters and K_{sat}.

MATERIALS AND METHODS

Study Area and Management

The experimental site is located at the Horticulture and Agroforestry Research Center in New Franklin, MO (39°02′ N, 92°46′ W, 195 m above mean sea level). The study site was established in 2000 to compare the effects of grass and agroforestry buffers on runoff water quality (Kumar et al., 2008). The pasture areas and buffers were reseeded with tall fescue in 2000. The pastures were also seeded with red clover and Korean lespedeza into the fescue in 2003. Four rows of eastern cottonwood trees were planted into the fescue to create the agroforestry buffers in 2001. Trees were planted at 3 m within and between rows. At sampling, the average height of the trees was 7.6 m, with 0.15 m diameter at breast height. Additional information about the study site can be found in Kumar et al. (2008).

Soils at the site are Menfro silt loam. The average annual precipitation of the experimental site for the last 50 yr (1956–2006) is 967 mm; the mean temperature in July is 25.6°C and the mean temperature in January is −2.1°C. The GB and AgB treatments were fenced from the pasture areas, preventing access by the cattle (*Bos taurus*). The RG treatment was rotationally grazed with six fenced areas (paddocks) within the small watershed. The CG treatment was continuously grazed by cattle.

Grazing was initiated at the site in late March or early April and discontinued in late October or early November each year. During late July or early August, the cattle were removed for about 1 mo due to poor grass growth. The pasture treatment sites had been grazed for 3 yr before sampling. Each year, beef cows with weights between 450 kg and

590 kg were introduced into the pasture area. The number of cattle for the small watershed (0.8 ha) was three. Eighty-five percent of the grazing area (0.64 ha) of the watershed was divided into six smaller rotationally grazed paddocks with a single-wire electric fence for cattle management. The other 15% of the grazing area was continuously grazed. The stocking rate was 5.26 animal units ha^{-1} and the stocking density was 31.6 animal units ha^{-1}, with a site production capacity of 31.6 animal unit mo ha^{-1}. The cows were moved between paddocks on each Monday and Thursday, with each paddock being grazed for 3.5 d and rested for 17.5 d.

Sample Collection

Soil cores were removed from the AgB, GB, RG, and CG treatment areas to determine management effects on CT-measured macropore properties. The dimensions of sampling Plexiglas rings were 76.2 mm long and 76.2 mm in diameter, with a 3.2-mm-thick wall. Intact 120 soil cores were collected from five soil depths (0–50 cm in 10-cm increments) per treatment with six replications per treatment on 6 and 7 June 2007. The CG treatment samples were taken from six replicate, continuously grazed areas and RG samples were taken from six replicate, rotationally grazed areas. The AgB samples were taken from soil under six replicate trees, three each from two tree rows in the agroforestry buffer area. These samples were taken at a distance of 20 cm from the base of the tree trunks in the agroforestry buffer. The GB samples were taken from six replicate grass buffer areas. Soil cores were labeled, trimmed, sealed in plastic bags, transported to the laboratory, and stored at 4°C until measurements were taken.

Scanning and Image Analysis

Soil cores were saturated with a dilute salt solution (6.24 g $CaCl_2$ L^{-1} and 1.49 g $MgCl_2$ L^{-1}) to retain soil structure. After 24 h, weights were recorded and samples were then drained at 35-cm tension for 24 h using a glass-bead tension table, which removed water from pores >85-μm equivalent cylindrical diameter to enhance the image contrast between air-filled pores and soil solids. These cores were scanned using a Siemens Somaton Plus 4 Volume Zoom x-ray CT scanner (Siemens Corp., New York) to acquire CT scan images. The scanner used in the current study is basically for medical purposes. The scan system parameters were set to 125 kV, 400 mA, and 1.5 s scan time. Soil cores were positioned horizontally on the scanner stage so that the x-ray beam was perpendicular to the longitudinal axis. Five images were acquired from each core at the following scan depths from the core surface: 1.7, 2.8, 3.9, 5.0, and 6.1 cm. The pixel resolution was 0.19 by 0.19 mm. The width or "slice" thickness was 0.5 mm, producing a volume element (voxel) size of 0.018 mm^3. A total of 600 images were analyzed in this study.

The images were analyzed using the Image J version 1.27 software (Rasband, 2002) to examine the treatment effects on pore size distributions and pore characteristics. The software is a public domain image-processing program that can calculate the area and voxel value statistics of selected areas defined by the user (Gantzer and Anderson, 2002). Note that CT estimates of porosity near the lower resolution of the scanner will have a partial volume effect and have less precision.

The macropore and mesopore characteristics analyzed included the total number of pores, number of macropores, number of coarse mesopores, total porosity (macroporosity plus coarse mesoporosity), macroporosity (>1000-μm diam.), and coarse mesoporosity (200–1000-μm diam.). In addition, the circularity and fractal dimensions of macropores were analyzed. The circularity of macropores is estimated by dividing the product of the area of the pore and 4π by the pore perimeter squared (Tuller et al., 1999). The macroporosity and mesoporosity at each scan depth were calculated from the total area of all macropores and mesopores isolated in the image at a given depth divided by the cross-sectional area (2500 mm^2) of the selected region on the soil core image.

The Region of Interest tool was used to select a rectangular region of 50- by 50-mm area to exclude voids near the core walls and minimize the effects of beam hardening. The Threshold tool was used to partition pores from solids after converting the image into an eight-bit gray-scale image. The threshold value selected to analyze all images was 40 (range 0–255). The values lower than the threshold value were identified as the air-filled pores and the values greater than the threshold value were identified as non-pore (Fig. 4.1). The Analyze Particles tool was used to measure the statistics of individual pores. The fractal dimension of macropores was determined with 0 to 100 threshold values to better populate the low-porosity samples with pores (Gantzer and Anderson, 2002). For all images, the fractal dimension was obtained as the slope of the log–log plot of measured box counts as a function of box size.

Saturated Hydraulic Conductivity and Bulk Density

After scanning, the saturated hydraulic conductivity and dry bulk density were determined on all 120 soil cores. Saturated hydraulic conductivity was measured using the constant-head method (Klute and Dirksen, 1986) after eliminating visible pores and the space between the soil and the core wall by applying a bentonite slurry with a syringe to block bypass flow in the core (Blanco-Canqui et al., 2002). The same soil cores were used for determining bulk density as described by Blake and Hartge (1986). The soil cores were dried at 105°C until a constant weight was obtained (about 48 h).

Statistical Analysis

A test for homogeneity of variance was conducted to evaluate the variability within the different treatments due to the systematic arrangement of treatments. Analysis of variance was further conducted with SAS using the GLM procedure when variances within treatments were homogeneous (SAS Institute, 1999). Single degree of freedom contrasts were also determined and were conducted as follows: buffers vs. pastures, GB vs. AgB, and RG vs. CG. The differences in pore characteristics among scans along the soil core were statistically compared to evaluate depth and management influences using PROC MIXED (SAS Institute, 1999). An estimate for the least significant difference (Duncan's LSD) between treatments at the same depth or different depths was obtained using the MIXED procedure in SAS. Statistical differences were declared significant at the $\alpha = 0.05$ level.

RESULTS AND DISCUSSION

Number of Pores, Macropores, and Coarse Mesopores Measured by Computed Tomography

The number of CT-measured pores, macropores, and coarse mesopores were significantly greater in buffer areas than grazed pastures ($P < 0.01$; Table 4.1). Significant differences were found for two contrasts: buffers vs. pastures and GB vs. AgB (Fig. 4.2;

Table 4.1). The buffer treatments had a greater total number of pores (140% higher at 69), macropores (245% higher at 19), and coarse mesopores (100% higher at 51), averaged across all 25 scan depths on a 2500-mm^2 scan area, compared with the average of the pasture treatments. In contrast, the CG treatment had the lowest values of all these parameters.

Two terms for depth were used to explain the CT-measured pore characteristics—depth zone and scan depth—and to distinguish between the five depth zones or soil core depths (0–10, 10–20, 20–30, 30–40, and 40–50 cm) and the 25 scan depths (five scans per soil depth zone at 1.7, 2.8, 3.9, 5.0, and 6.1 cm from the top of the core), respectively. The soil depth zone significantly affected the CT-measured total number of pores, macropores, and coarse mesopores ($P < 0.01$; Table 4.1). For all three parameters, the total number of pores decreased with increasing soil depth zone (Fig. 4.2). The total number of pores and macropores significantly decreased between the first and second depth zones. A 33, 43, and 29% decrease in the total number of pores, macropores, and coarse mesopores, respectively, occurred from the first to the second soil depth zone. Similar trends were also observed between the second and third depth zones but the percentage decrease was smaller, and beyond the third depth zone differences were not significant (Table 4.1; Fig. 4.2). Significant interactions between treatment and soil depth zone were also found ($P < 0.01$; Fig. 4.2; Table 4.1) due to the decreasing number of pores with depth zone for the buffer treatments, while the values in the pasture treatments had small changes with depth zone.

Buffers had about 71% of the total pores for the profile within the 0- to 10-cm soil surface depth and the remaining 29% within the 10- to 50-cm depth zones. In contrast, pastures had only 39% of the total pores for the profile within the 0- to 10-cm depth and the remaining 61% in the subsurface layers. The GB treatment area had the highest total number of pores (159, 96, 61, 64, and 78) and number of macropores (44, 26, 15, 16, and 21) for the five depth zones, respectively, while the CG treatment had the lowest total number of pores (17, 32, 27, 28, and 25, respectively) and number of macropores (4, 7, 4, 6, and 3, respectively). Similar trends were found for the coarse mesopores for these treatments. It should be noted that soil core sampling for the AgB treatment resulted in collecting only the fine (diameter <2 mm) roots, which resulted in slightly smaller pore characteristics. An increase in the pore parameters between the first and second depth zones for the CG treatment was attributed to surface compaction in this treatment.

Generally, the total number of pores and macropores decreased with soil depth zone. Pachepsky et al. (1996) reported that management practices mostly affect the number and area of large elongated pores. The greater total number of pores and macropores under the buffer areas can be attributed to greater root development and the addition of the organic matter, which improved the soil physical properties in the buffer areas compared with the grazed pasture treatment areas.

Porosity, Macroporosity, and Coarse Mesoporosity Measured by Computed Tomography

The CT-measured porosity (macroporosity plus coarse mesoporosity), macroporosity, and coarse mesoporosity were significantly influenced by the AgB, GB, RG, and CG treatments ($P < 0.01$; Table 4.1; Fig. 4.3). Significant differences were found for two contrasts: buffers vs. pastures and GB vs. AgB ($P < 0.01$; Table 4.1). The buffers had higher porosity (0.026 $m^3 m^{-3}$, 271% higher), macroporosity (0.019 $m^3 m^{-3}$, 322% higher), and coarse mesoporosity (0.006 $m^3 m^{-3}$, 140% higher) than the pasture treatments (0.007, 0.0045, and 0.0025 $m^3 m^{-3}$, respectively). All three parameters were found to be the highest for the GB treatment. The porosity for the GB treatment was about 1.9, 4.2, and 5.7 times higher than the AgB, RG, and CG treatments, respectively. In addition, macroporosity for the GB treatment was about 2, 5.2, and 6.5 times higher while coarse mesoporosity was 2, 2.7, and 4 times higher than the AgB, RG, and CG treatments, respectively.

Soil depth zones also influenced porosity, macroporosity, and coarse macroporosity (Table 4.1). Averaged across all the treatments, all three parameters decreased from the first to fourth depth zones (Table 4.1). Porosity decreased linearly with soil depth ($r = -0.82$). Similar trends were found for macroporosity ($r = -0.82$) and coarse mesoporosity ($r = -0.83$). The greatest differences among depth zones for porosity, macroporosity, and coarse mesoporosity were observed between the 0- to 10- and 10- to 20-cm depth zones.

A decrease in the values of porosity, macroporosity, and coarse mesoporosity was observed from the first to second depth zones for the AgB (77, 79, 82%, respectively) and GB (57, 63, 25%, respectively) treatments, whereas an increase in the values of these parameters was observed in the RG (86, 150, 50%) and CG (100, 75, and 200%) treatments for similar depth zones (Fig. 4.3). This was probably caused by cattle grazing on the pasture treatments. Interactions between treatment and soil depth zone were also found ($P < 0.010$; Table 4.1; Fig. 4.3).

Previous studies in Iowa and Missouri showed that grass, tree, and native prairie improved CT-measured porosity and macroporosity (Rachman et al., 2005; Udawatta et al., 2006, 2008a). The porosity values determined in Kumar et al. (2008) were different than those of the current study but the trend was similar. The porosity values determined in Kumar et al. (2008) were used to calculate the porosity resolved with the CT method. On average, the fraction of total porosity resolved with the CT technique varied from 2 to 5%.

The data from the current study showed that the CG treatment had the lowest porosity and macroporosity, which will probably contribute to more surface runoff from this area. In contrast, the buffer treatments had higher porosity and macroporosity values, which will allow better infiltration of water and hence less runoff.

Fractal Dimension of Macropores Measured by Computed Tomography

Fractal theory has been applied to characterize particle and aggregate distributions in soils. The fractal dimension of macropores was significantly affected among the four treatments ($P < 0.01$; Table 4.1). The fractal dimension of macropores ranged from 1.08 (CG treatment) to 1.41 (GB treatment). Significant differences were found for two contrasts: buffers vs. pastures and GB vs. AgB (Table 4.1). The higher fractal dimension values for the surface 0- to 10-cm depth observed in the AgB (1.53) and GB (1.62) treatments may suggest more macroporosity and hence a higher probability of preferential water flow due to large and more elongated pores compared with the RG and CG treatments. Similar results were also reported by Udawatta et al. (2008b) for native prairie areas. The fractal dimension is related to the number of macropores and their size distribution since it measures the space-filling nature of the macropores (Rachman et al., 2005). The fractal dimension of macropores increased from the first to the second depth zone (1.08 to 1.21 and 1.06 to 1.08 for the RG and CG treatments, respectively); with further depth, values decreased. The CG treatment lowered the fractal dimension for the first depth zone; hence, values for this treatment increased from the first to second depth.

The soil depth zone also influenced the fractal dimension of the macropores ($P < 0.01$). The fractal dimension decreased with soil depth (Table 4.1), as did macroporosity. Significant interactions between treatment and soil depth were also found ($P < 0.010$; Fig. 4.4). The fractal dimension and macroporosity for each scan depth averaged across the six replicates were found to be positively correlated, with coefficients of determination ranging from 0.51 for CG, 0.54 for RG, 0.72 for GB, and 0.81 for AgB treatments (Fig. 4.5). The relationships between fractal dimension and macroporosity were similar to the results of Rachman et al. (2005), who found that the relationships between the fractal dimension and macroporosity were positively related and the r^2 was highest for the buffer (grass hedge). Similar trends were found in the current study, where r^2 was highest for the buffers compared with grazed pasture areas and the relationship was positive.

Largest Pore Area and Macropore Circularity Measured by Computed Tomography

Solute and water transport in soils are significantly affected by pore size, shape, and distribution. The largest pore from each scan image within each treatment was evaluated. The area of the CT-measured largest pore was significantly different among all treatments ($P < 0.01$; Table 4.1). Significant differences were found only for the buffers vs. pastures contrast ($P < 0.02$; Table 4.1). The GB treatment had the largest (9.07 mm^2)

pore, followed by the AgB treatment (7.33 mm^2). The GB treatment had about 1.2, 1.6, and 2.5 times higher largest pores than the AgB, RG and CG treatments, respectively.

The CT-measured circularity was significantly different among all the treatments ($P < 0.01$; Table 4.1). Significant differences were found only for the buffers vs. pastures contrast ($P < 0.02$; Table 4.1). Circularity for the GB treatment was significantly lower (4.86%) than the pasture treatments. The lower circularity value in the GB treatment indicates more elongated and larger pores. This implies that the GB treatment had more irregular pores. The average profile values of circularity for the AgB, GB, RG, and CG treatments were 0.90, 0.88, 0.92, and 0.93, respectively.

The CT-measured macropore circularity was affected by the soil depth zone ($P < 0.01$; Table 4.1). Circularity increased with soil depth but values were not significantly different after the second depth zone (Table 4.1). Our findings support previous research by Rachman et al. (2005) and Udawatta et al. (2006, 2008a). These studies reported that circularity was lower in agroforestry and grass buffer treatments than row crop areas in Iowa and Missouri. The results of these studies and the current study indicate that continuous disturbance affects pore size and shape compared with undisturbed permanent vegetative areas. The circularity value differences in these three studies and the current study can be attributed to soil type, management, and sampling depth.

Correlation of Pore Parameters and Saturated Hydraulic Conductivity

An evaluation of soil bulk density and saturated hydraulic conductivity is presented before correlation analysis of properties. Soil bulk density was different among the treatments ($P < 0.01$; Table 4.2). Buffer treatments (1.35 g cm^{-3}) had 5.6% lower soil bulk density than pasture treatments (1.43 g cm^{-3}). Soil bulk density changed with soil depth zone ($P < 0.01$; Table 4.2). Bulk density generally increased with soil depth for the buffer treatments, whereas for the CG treatment bulk density was unaffected after the second soil depth zone (Fig. 4.6). Interactions between treatment and soil depth were also found ($P < 0.01$; Fig. 4.6). The current study supports findings reported in previous research (Kumar et al., 2008).

The K_{sat} values were found to be different among the treatments (Fig. 4.6; Table 4.2). The buffer treatments had the highest (75.8 mm h^{-1}) K_{sat}, averaged across depths, while the two grazed pasture treatments had the lowest K_{sat} (15 mm h^{-1}; Table 4.2). Studying soil physical properties on the same study area, Kumar et al. (2008) attributed these differences to the roots of the vegetation and the absence of cattle. The K_{sat} was about 31 times higher in the buffers than the grazed pasture systems for the 0- to 10-cm soil depth zone. The K_{sat} values significantly decreased with increasing soil depth zone (Table 4.2; Fig. 4.6).

The K_{sat} values generally decreased with increasing soil depth zone. The K_{sat} values for the AgB and GB treatments decreased from the first to second depth zone (85.7 and 73.0%, respectively), whereas for the RG and CG treatments, the K_{sat} increased for these depth zones (142.6 and 295.1%, respectively). The highest percentage decrease was for the CG treatment, which experienced continuous cattle traffic. Interactions between the treatment and soil depth factors were also significant ($P < 0.01$; Table 4.2; Fig. 4.6). These differences were attributed to differences in soil macroporosity and bulk density (Kumar et al., 2008).

For correlation analysis, averages of the five scan depths per core were used as core parameters for each property. Nine CT-measured pore parameters (total number of pores, number of macropores, number of coarse mesopores, porosity, macroporosity, coarse mesoporosity, area of the largest pore, circularity of macroporosity, and fractal dimension of the macropores) along with bulk density were regressed with K_{sat} (Table 4.3). All CT-measured pore parameters except circularity were positively correlated with K_{sat}. Circularity was negatively correlated due to more circular pores being present among the pasture treatments, which had lower K_{sat} values. The correlation for all the parameters was found to be statistically significant ($P < 0.001$).

Among the nine CT-measured pore parameters, macroporosity explained 58% of the variation in saturated hydraulic conductivity (Table 4.3). The porosity (57.9%) and total number of pores (51.7%) ranked second and third, respectively, after macroporosity. The number of macropores plus porosity was the best two-parameter combination and accounted for 63% of the variation in K_{sat}. The number of macropores plus macroporosity was the second best two-parameter combination (Table 4.3). Regression analysis showed that macroporosity and porosity ranked the best when evaluating single parameters. Dosskey et al. (2007) reported that increased macroporosity should increase infiltration and reduce the sediment transport capacity of the runoff water. Our findings imply that the buffers, which had higher porosity and macroporosity, will infiltrate more water and allow less runoff.

In the current study, macroporosity was the best single parameter to predict K_{sat}. Udawatta et al. (2008a) reported that the CT-measured number of macropores was the best single variable explaining 43% of the variation in K_{sat} ($n = 96$). Udawatta and

Anderson (2008) reported that the fractal dimension of macropores was the best parameter explaining 75% of the variation in logK_{sat} (n = 120). In another study, Rachman et al. (2005) reported a correlation between K_{sat} and CT-measured macroporosity of 0.95 (n = 6). These studies illustrate a good correlation between CT-measured pore parameters and K_{sat}. Differences among the studies are attributed to differences in soils and treatments.

In summary, one of the purposes for using buffers at the study site was to reduce surface runoff by increasing the soil porosity within the buffers, which indeed enhance infiltration and reduce runoff. In some settings, enhanced soil porosity is not a desired outcome with buffers, since this effect will enhance water flow through the soil system, which can negatively impact shallow groundwater quality. These issues should be kept in mind when using buffers similar to those investigated in this study.

CONCLUSIONS

This study evaluated the hypothesis that buffers would influence the CT-measured soil pore parameters in pasture systems. Agroforestry and grass buffer treatments had a greater total number of pores, number of macropores, number of coarse mesopores, porosity, macroporosity, coarse mesoporosity, area of largest pore, and fractal dimension of macropores compared with grazed pasture treatments. The circularity of macropores, however, was found to be lower in the buffer treatments than pasture treatments. The buffer treatments also had lower soil bulk density values (5.6%) and higher K_{sat} values (five times higher) than the pasture treatments. Preventing cattle grazing in the buffer areas lowered the soil bulk density and increased the K_{sat}.

Most CT-measured pore parameters within the buffer treatments decreased significantly between the first and second depth zones (0–10 and 10–20 cm), while values in these depth zones either increased slightly or stayed the same for the pasture treatments. All CT-measured pore parameters except circularity were positively correlated with K_{sat}. Increased macroporosity in the buffer areas will probably increase soil water infiltration, increase gas exchange, and reduce runoff and nonpoint-source pollution. Additionally, buffer areas might help prevent surface runoff and serve as a sediment trap. Also, buffers negatively enhance the groundwater flow. Differences in pore parameters were attributed in part to differences in root growth and development among the treatments. For improved infiltration, buffer zones should be managed to prevent cattle traffic for better maintenance of soil pore characteristics.

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REFRENCES

Abu-Zreig, M., R.P. Rudra, H.R. Whitely, M.N. Lalonde, and N.K. Kaushik. 2003. Phosphorus removal in vegetated filter strips. J. Environ. Qual. 32: 613-619.

Alshibli, K.A., S. Sture, N.C. Costes, M.L. Frank, M.R. Lankton, S.N. Batiste, and R.A. Swanson. 2000. Assessment of localized deformations in sands using X-ray computed tomography. Geotech. Test. J. 23: 274-299.

American Petroleum Institute. 1960. API recommended practice for core analysis procedures. Rep. 40. American Petroleum Institute. Dallas, Texas.

Anderson, S.H., C.J. Gantzer, and J.R. Brown. 1990. Soil physical properties after 100 years of continuous cultivation. J. Soil Water Conserv. 45: 117-121.

Anderson, S.H., C.J. Gantzer, J.M. Boone, and R.J. Tully. 1988. Rapid nondestructive bulk density and soil-water content determination by computed tomography. Soil Sci. Soc. Am. J. 52: 35-40.

Anderson, S.H., H. Wang, R.L. Peyton, and C.J. Gantzer. 2003. Estimation of porosity and hydraulic conductivity from X-ray CT-measured solute breakthrough. p. 135-149. In F. Mess, R. Swennen, M. Van Geet, and P. Jacobs (ed.). Application of X-ray Computed Tomography in the Geosciences. Geological Society of London Spec. Pub. 215. Geological Society of London, UK.

Bharati, L., K.H. Lee, T.M. Isenhart, and R.C. Schultz. 2002. Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. Agrofor. Syst. 56: 249-257.

Blake, G.R., and K.H. Hartge. 1986. Bulk density. p. 363-375. In A. Klute (ed.) Methods of soil samples. Part 1. 2nd ed. Agron. Monogr.9.ASA and SSSA, Madison, WI. USA.

Blanco-Canqui, H., C.J. Gantzer, S.H. Anderson, E.E. Alberts, and F. Ghidey. 2002. Saturated hydraulic conductivity and its impact on simulated runoff for claypan soils. Soil Sci. Soc. Am. J. 66: 1596-1602.

Carlson, W.D., T. Rowe, R.A. Ketcham, and M.W. Colbert. 2003. Application of high resolution X-ray computed tomography in petrology, meteoritics, and palaeontology. p. 7–22. In F. Mess et al. (ed.) Application of X-ray computed tomography in the geosciences. The Geological Society, London. UK.

Crestana, S., S. Mascarenshas, and R.S. Pozzi-Mucelli. 1985. Static and dynamic three-dimensional studies of water in soil using computed tomographic scanning. Soil Sci. 140: 326-332.

Dosskey, M.G., K.D. Hoagland, and J.R. Brandle. 2007. Change in filter strip performance over ten years. J. Soil Water Conserv. 62: 21–32.

Eynard, A., T.E. Schumacher, M.J. Lindstrom, and D.D. Malo. 2004. Porosity and pore-size distribution in cultivated Ustolls and Usterts. Soil Sci. Soc. Am. J. 68: 1927-1934.

Gantzer, C.J., and S.H. Anderson. 2002. Computed tomographic measurement of macroporosity in chisel-disk and no-tillage seedbeds. Soil Tillage Res. 64: 101-111.

Gold, M.A., and J.W. Hanover. 1987. Agroforestry systems for temperate zones. Agrofor. Syst. 5: 109–121.

Grevers, M.C.J., and E. de Jong. 1994. Evaluation of soil-pore continuity using geostatistical analysis of macroporosity in serial sections obtained by computed tomography scanning. p. 73-86. In. F. Mess, R. Swennen, M. Van Geet, and P.

Jacobs (ed.) Application of X-ray Computed Tomography in the Geosciences. The Geological Society, London. UK.

Heijs, A.W.J., J. Delange, J.F.T. Schoute, and J. Bouma. 1995. Computed-tomography as a tool for non-destructive analysis of flow patterns in macroporous clay soils. Geoderma 64: 183-196.

Hopmans, J.W., T. Vogel, and P.D. Koblik. 1992. X-ray tomography of soil water distribution in one-step outflow experiments. Soil Sci. Soc. Am. J. 56: 355-362.

Hounsfield, G.N. 1973. Computerized transverse axial scanning (tomography): 1. Description of system. Br. J. Radiol. 46:1016–1022.

Hounsfield, G.N. 1977. A apparatus for examining a body by radiation such as x or gamma radiation. U.S. Patent 4052618. Date issued: 4 October.

Klute, A., and C. Dirksen. 1986. Hydraulic conductivity and diffusivity: Laboratory methods. p. 687-734 In A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA SSSA, Madison, WI. USA.

Kumar, S., S.H. Anderson, L.G. Bricknell, R.P. Udawatta, and C.J. Gantzer. 2008. Soil hydraulic properties influenced by agroforestry and grass buffers for grazed pasture systems. J. Soil Water Conserv. 63: 224-232.

Luxmoore, R.J., P.M. Jardine, G.V. Wilson, J.R. Jones, and L.W. Zelazny.1990. Physical and chemical controls of preferred path flow through a forested hillslope. Geoderma 46: 139-154.

Pachepsky, Y., V. Yakovchenko, M.C. Rabenhorst, C. Pooley, and L.J. Sikora. 1996. Fractal parameters of pore surfaces as derived from micromorphological data: Effect of long-term management practices. Geoderma 74: 305-319.

Perret, J., S.O. Prasher, A. Kantzas, and C. Langford. 2000. A two-domain approach using CAT scanning to model solute transport in soil. J. Environ. Qual. 29: 995–1010.

Petrovic, A.M., J.E. Siebert, and P.E. Rieke. 1982. Soil bulk density analysis in three dimensions by computed tomographic scanning. Soil Sci. Am. J. 46: 445-450.

Phillips, D.H., and J.J. Lannutti. 1997. Measuring physical density with X-ray computed tomography, NDT & E International 30: 339-350.

Pierret, A., Y. Capowiez, L. Belzunces, and C.J. Moran. 2002. 3D reconstruction and quantification of macropores using X-ray computed tomography and image analysis. Geoderma 106: 247–271.

Rachman, A., S.H. Anderson, and C.J. Gantzer. 2005. Computed-tomographic measurement of soil macroporosity parameters as affected by stiff-stemmed grass hedges. Soil Sci. Soc. Am. J. 69: 1609-1616.

Rasband, W. 2002. NIH Image J. Research Service Branch, National Institute of Mental Health, National Institute of Health. Bethesda, MD, USA.

Rasiah, V., and L.A.G. Alymore. 1998. The topology of pore structure in cracking clay soil: I. The estimation of numerical density. J. Soil Sci. 39: 303-314.

Rogasik, H., J.W. Crawford, O. Wendroth, I.M. Young, M. Joschko, and K. Ritz. 1999. Discrimination of soil phases by dual energy X-ray tomography. Soil Sci. Soc. Am. J. 63: 741–751.

SAS Institute. 1999. SAS user's guide. Statistics. SAS Inst., Cary, NC.

Seobi, T., S.H. Anderson, R.P. Udawatta, and C.J. Gantzer. 2005. Influence of grass and agroforestry buffer strips on soil hydraulic properties for an Albaqualf. Soil Sci. Soc. Am. J. 69: 893-901.

Tollner, E.W., C. Murphy, and E.L. Ramseur. 1994. Techniques and approaches for documenting plant root development with X-ray computed tomography. p. 115-134 In S.H. Anderson and J.W. Hopmans (ed.) Tomography of Soil-Water-Root processes. SSSA Special Publication Number 36. Amer. Soc. Agron., Madison, WI, USA.

Tuller, M., D. Or, and L.M. Dudley. 1999. Adsorption and capillary condensation in porous media: Liquid retention and interfacial configurations in angular pores. Water Resour. Res. 35:1949–1964.

Udawatta, R.P., and S.H. Anderson. 2008. CT-measured pore characteristics of surface and subsurface soils influenced by agroforestry and grass buffers. Geoderma 145: 381-389.

Udawatta, R.P., J.J. Krstansky, G.S. Henderson, and H.E. Garrett. 2002. Agroforestry practices, runoff, and nutrient loss: a paired watershed comparison. J. Environ. Qual. 31: 1214-1225.

Udawatta**,** R.P., S.H. Anderson, C.J. Gantzer, and H.E. Garrett. 2006. Agroforestry and grass buffer influence on macropore characteristics: A computed tomography analysis. Soil Sci. Soc. Am. J. 70: 1763-1773.

Udawatta, R.P., S.H. Anderson, C.J. Gantzer, and H.E. Garrett. 2008a. Influence of prairie restoration on CT-measured soil pore characteristics. J. Environ. Qual. 37: 219-228.

Udawatta, R.P., C.J. Gantzer, S.H. Anderson, and H.E. Garrett. 2008b. Agroforestry and grass buffer effects on high resolution X-ray CT-measured pore characteristics. Soil Sci. Soc. Am. J. 72: 295-304.

Van Golf-Recht, T.D. 1982. Fundamentals of fractured reservoir engineering. Elsevier, Amsterdam, The Netherlands.

Vogel, H.J. 2000. A numerical experiment on pore size, pore connectivity, water retention, permeability, and solute transport using network models. Eur. J. Soil Sci. 51: 99–105.

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Table 4.1. Average total number of pores (pores, macropores, and coarse mesopores), total porosity (porosity, macroporosity, and coarse mesoporosity), area of the largest pore, circularity, and fractal dimension of macropores measured by computed tomography as influenced by agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG), and continuously grazed pasture (CG) treatments and soil depth and the analysis of variance. Data are means ± standard deviations, and minimum and maximum values for each parameter are given in parentheses.

	Number			Porosity					
Treatment means	Pores	Macropores	Coarse Mesopores	Porosity $m^3\ m^{-3}$	Macro-porosity $m^3\ m^{-3}$	Coarse Mesoporosity $m^3\ m^{-3}$	Area of Largest Pore mm^2	Circularity	Fractal Dimension
AgB	45 ± 10^{b}	13 ± 4^{b}	33 ± 6^{b}	0.018 ± 0.007^{b}	0.013 ± 0.005^{b}	0.004 ± 0.002^{b}	7.33 ± 2.15^{ab}	0.90 ± 0.02^{ab}	1.21 ± 0.08^{b}
	(29-57)	(5-18)	(22-39)	(0.006-0.025)	(0.004-0.017)	(0.002-0.008)	(4-9.57)	(0.88-0.94)	(1.11-1.28)
GB	92 ± 14^{a}	25 ± 6^{a}	68 ± 8^{a}	0.034 ± 0.008^{a}	0.026 ± 0.007^{a}	0.008 ± 0.001^{a}	9.07 ± 0.90^{a}	0.88 ± 0.02^{b}	1.41 ± 0.06^{a}
	(93-110)	(17-32)	(60-82)	(0.027-0.044)	(0.020-0.036)	(0.007-0.009)	(7.30-9.57)	(0.87-0.90)	(1.34-1.51)
RG	31 ± 10^{c}	6 ± 3^{c}	27 ± 6^{b}	0.008 ± 0.004^{c}	0.005 ± 0.004^{c}	0.003 ± 0.001^{c}	5.67 ± 0.40^{ab}	0.92 ± 0.03^{a}	1.14 ± 0.06^{b}
	(18-44)	(3-11)	(19-36)	(0.004-0.015)	(0.001-0.011)	(0.002-0.004)	(5.22-5.97)	(0.88-0.95)	(1.09-1.26)
CG	26 ± 4^{c}	5 ± 2^{c}	23 ± 5^{b}	0.006 ± 0.003^{c}	0.004 ± 0.003^{c}	0.002 ± 0.001^{c}	3.57 ± 0.48^{b}	0.93 ± 0.03^{a}	1.08 ± 0.06^{b}
	(20-33)	(2-8)	(18-31)	(0.003-0.010)	(0.001-0.007)	(0.001-0.003)	(3.0-4.11)	(0.88-0.96)	(1.00-1.14)
Depth (cm) means									
0-10	75 ± 11^{a}	23 ± 3^{a}	52 ± 8^{a}	0.035 ± 0.007^{a}	0.029 ± 0.029^{a}	0.007 ± 0.002^{a}	9.38 ± 2.21^{a}	0.88 ± 0.02^{a}	1.33 ± 0.08^{a}
	(56-87)	(17-26)	(36-60)	(0.22-0.045)	(0.018-0.039)	(0.004-0.011)	(5.4-11.86)	(0.84-0.90)	(1.17-1.40)
10-20	50 ± 7^{b}	13 ± 1^{b}	37 ± 7^{b}	0.017 ± 0.002^{b}	0.012 ± 0.002^{b}	0.004 ± 0.0005^{b}	6.46 ± 2.56^{b}	0.90 ± 0.02^{a}	1.21 ± 0.04^{b}
	(42-60)	(12-14)	(28-48)	(0.013-0.019)	(0.008-0.015)	(0.003-0.005)	(2.51-9.57)	(0.88-0.92)	(1.14-1.25)
20-30	40 ± 4^{c}	9 ± 3^{c}	36 ± 4^{b}	0.010 ± 0.004^{c}	0.008 ± 0.004^{bc}	0.004 ± 0.001^{bc}	5.80 ± 2.69^{b}	0.92 ± 0.02^{b}	1.15 ± 0.03^{c}
	(33-41)	(5-15)	(28-39)	(0.006-0.018)	(0.003-0.014)	(0.002-0.005)	(1.93-7.79)	(0.91-0.95)	(1.08-1.17)
30-40	38 ± 6^{c}	8 ± 2^{c}	33 ± 3^{b}	0.009 ± 0.002^{c}	0.007 ± 0.002^{c}	0.003 ± 0.0003^{c}	5.21 ± 2.83^{b}	0.93 ± 0.02^{b}	1.14 ± 0.04^{c}
	(30-48)	(4-9)	(30-37)	(0.006-0.012)	(0.003-0.009)	(0.0025-0.003)	(2.32-7.67)	(0.89-0.95)	(1.08-1.21)
40-50	38 ± 4^{c}	8 ± 2^{c}	30 ± 3^{b}	0.011 ± 0.008^{c}	0.005 ± 0.001^{bc}	0.007 ± 0.0003^{bc}	5.21 ± 2.71^{b}	0.94 ± 0.01^{b}	1.13 ± 0.03^{c}
	(32-41)	(5-10)	(27-32)	(0.005-0.010)	(0.002-0.007)	(0.0027-0.003)	(2.11-7.67)	(0.93-0.95)	(1.09-1.15)

Table 4.1 Cont.

	Analysis of Variance, P > F								
Treatment	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Buffers vs. Pastures	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.016	<0.01
GB vs. AgB	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.40	0.12	<0.01
RG vs. CG	0.36	0.52	0.31	0.63	0.78	0.10	0.31	0.51	0.10
Depth	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Treatment by Depth	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.15	<0.01

The ANOVA table represents significance levels among treatments and depths for the measured parameters. Within columns, values followed by the same letter for the treatments or the depths are not significantly different at the 0.05 probability level.

Table 4.2. Mean saturated hydraulic conductivity (K_{sat}) and bulk density for the agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG), and continuously grazed pasture (CG) treatments and soil depths and an analysis of variance. Data are means ± standard deviations, and minimum and maximum values for each parameter are given in parentheses.

	K_{sat} mm h^{-1}	Bulk Density g cm^{-3}
Treatment means		
AgB	60.2±26.7[a†] (32.0-103.8)	1.39±0.03[b] (1.34-1.42)
GB	91.5±43.4[a] (40.3-149.4)	1.32±0.02[a] (1.29-1.35)
RG	20.2±9.79[b] (9.55-34.4)	1.42±0.04[bc] (1.42-1.48)
CG	9.9±3.83[b] (3.93-14.4)	1.44±0.03[c] (1.40-1.47)
Depth (cm) means		
0-10	130.9±66.7[a] (50.8-226.3)	1.28±0.05[a] (1.21-1.32)
10-20	38.6±14.0[b] (16.8-48.8)	1.39±0.03[b] (1.33-1.40)
20-30	26.9±10.6[b] (11.8-38.9)	1.43±0.01[bc] (1.41-1.43)
30-40	19.3±4.30[b] (13.4-21.9)	1.42±0.03[bc] (1.38-1.46)
40-50	11.5±4.73[b] (6.81-18.4)	1.44±0.03[c] (1.41-1.47)
Analysis of variance P > F		
Treatment	<0.01	<0.01
Buffers vs. Pastures	<0.01	<0.01
GB vs. AgB	0.05	<0.01
RG vs. CG	0.50	0.33
Depth	<0.01	<0.01
Treatment by Depth	<0.01	<0.01

†Means with different level for a soil property are significantly different at the 0.05 probability level.

Table 4.3. Relationships between pore parameters measured by computed tomography and saturated hydraulic conductivity (K_{sat}).

Relationship	Coefficient of Determination	Significance Level
Single parameter		
K_{sat} = -0.36 + 3743.88*macroporosity	0.580	0.001
K_{sat} = -6.51 + 3166.25*porosity	0.579	0.001
K_{sat} = -30.84 + 1.58*pores†	0.517	0.001
Two parameters		
K_{sat} = 4.59 - 5.93*macropores† + 6825.76*porosity	0.635	0.001
K_{sat} = 10.9 - 3.54*macropores + 6292.15*macroporosity	0.607	0.001

†Pores = Total number of pores, macropores = Number of macropores, porosity= Total porosity.

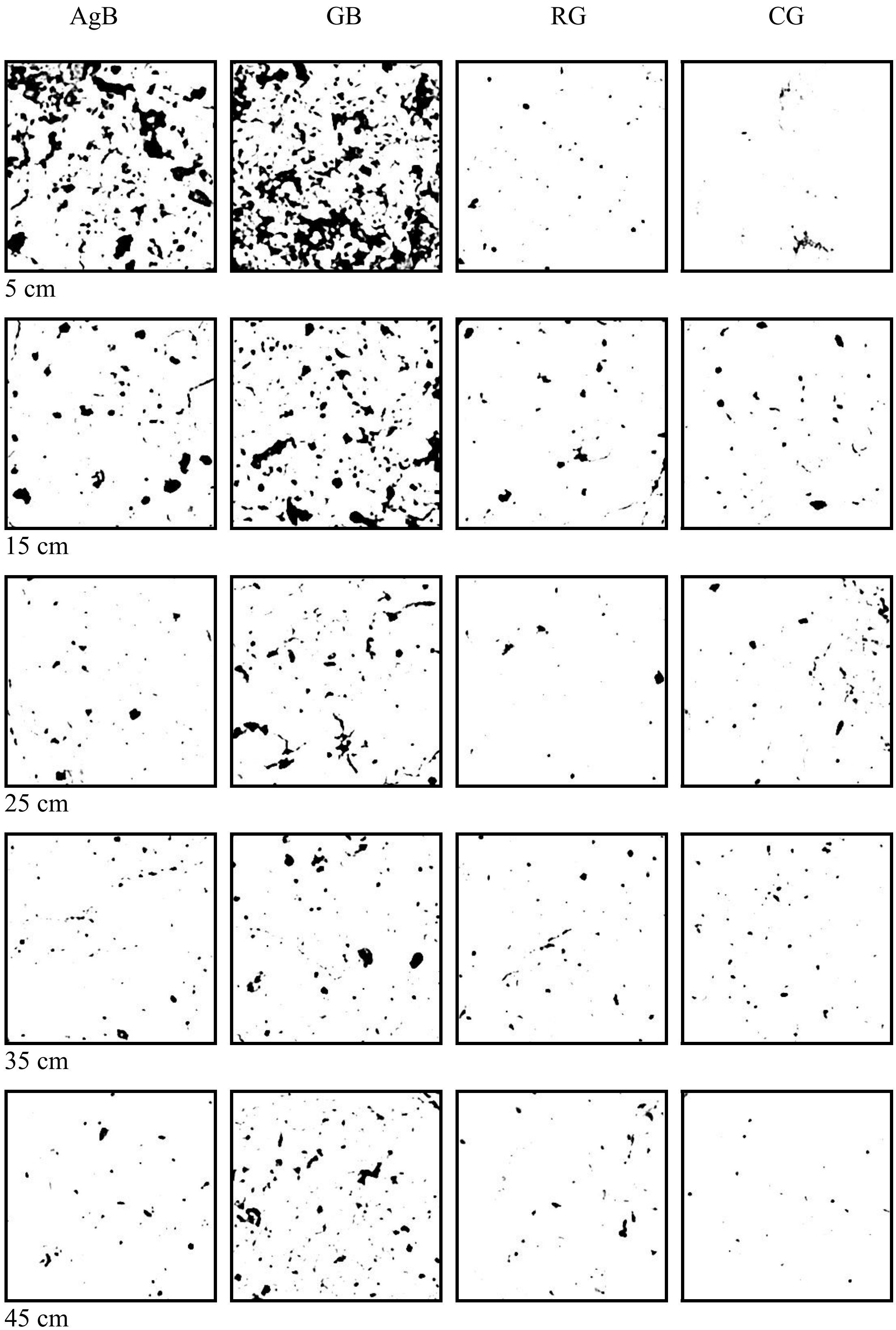
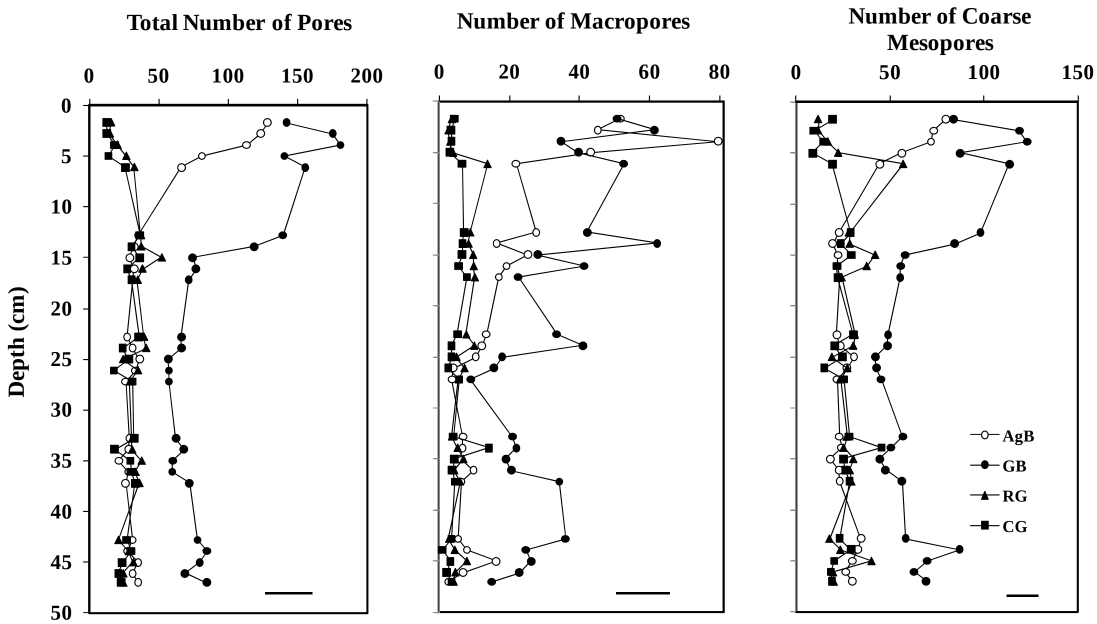


Fig. 4.1



Total Number of Pores
Number of Macropores
Number of Coarse Mesopores
0
50
100
150
200
0
20
40
60
80
0
50
100
150
0
5
10
15
20
25
30
35
40
45
50
Depth (cm)
AgB
GB
RG
CG

Fig. 4.2.

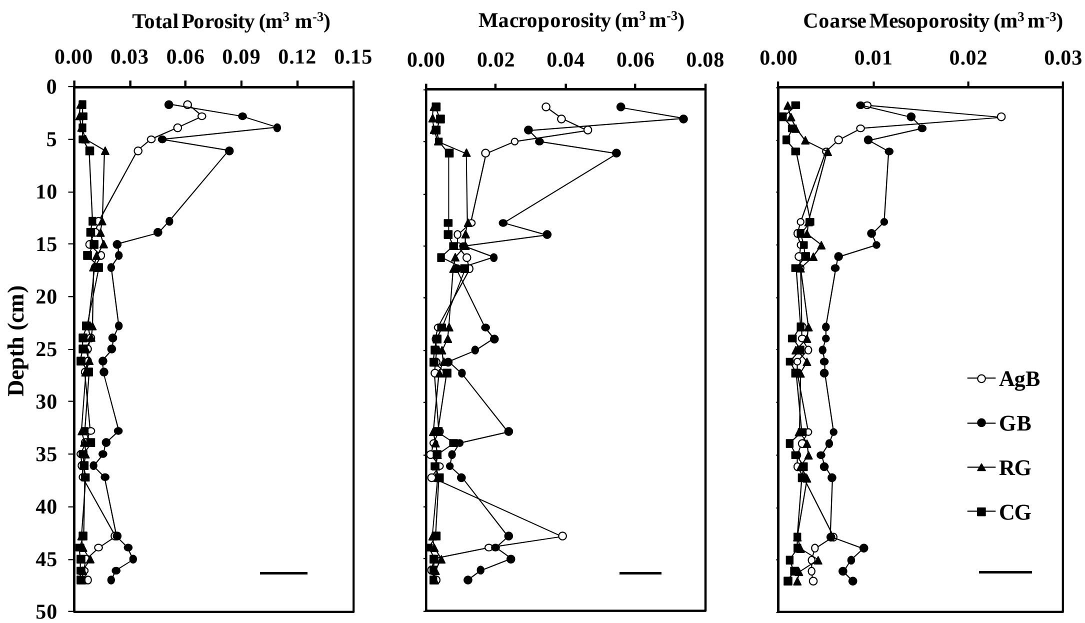

Total Porosity (m³ m⁻³)
0.00 0.03 0.06 0.09 0.12 0.15
Macroporosity (m³ m⁻³)
0.00 0.02 0.04 0.06 0.08
Coarse Mesoporosity (m³ m⁻³)
0.00 0.01 0.02 0.03
Depth (cm)
0 5 10 15 20 25 30 35 40 45 50
AgB
GB
RG
CG

Fig. 4.3.

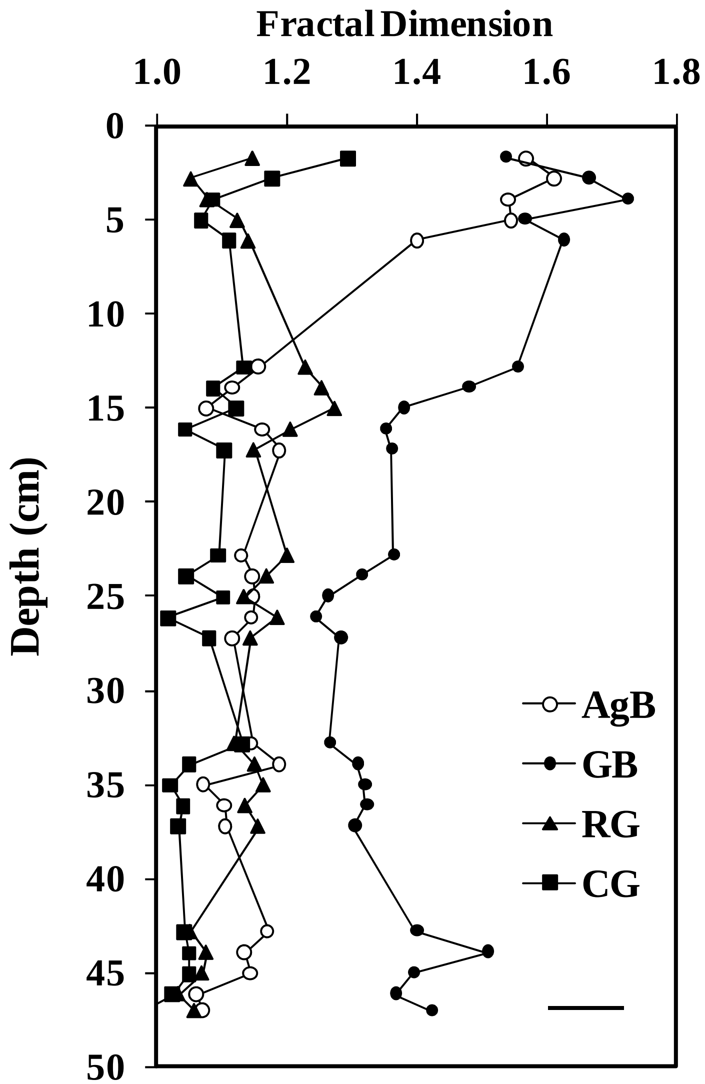

Fractal Dimension
1.0
1.2
1.4
1.6
1.8
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
AgB
GB
RG
CG

Fig. 4.4.

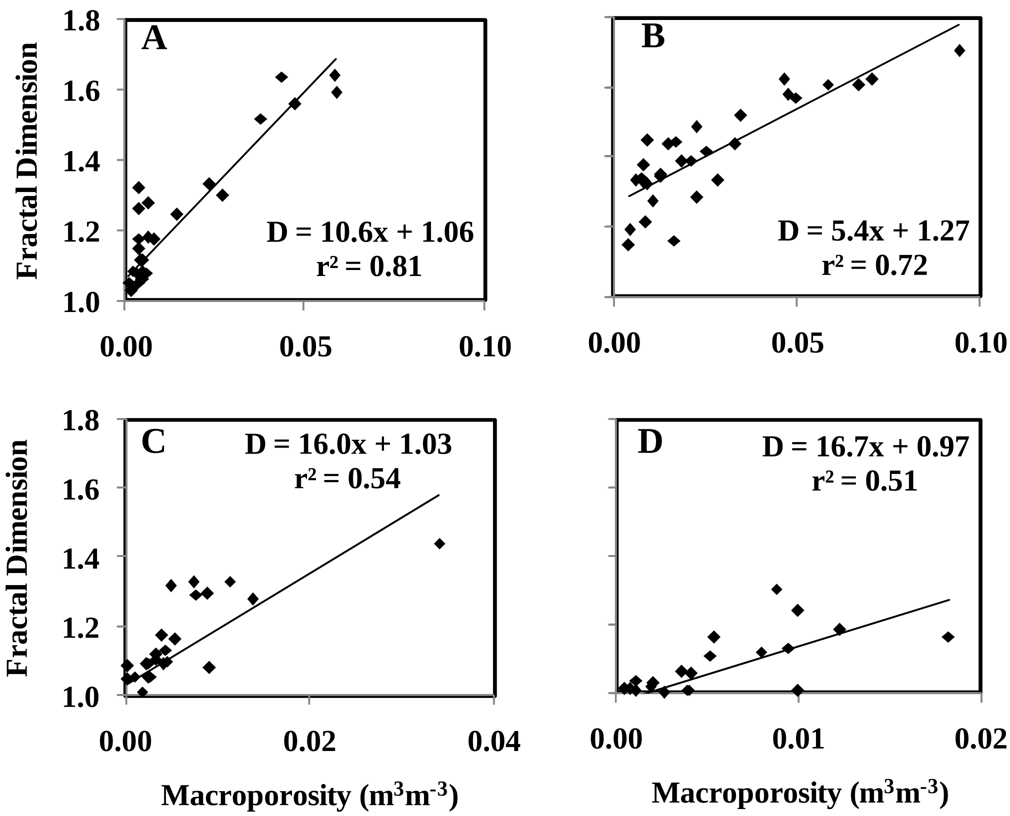
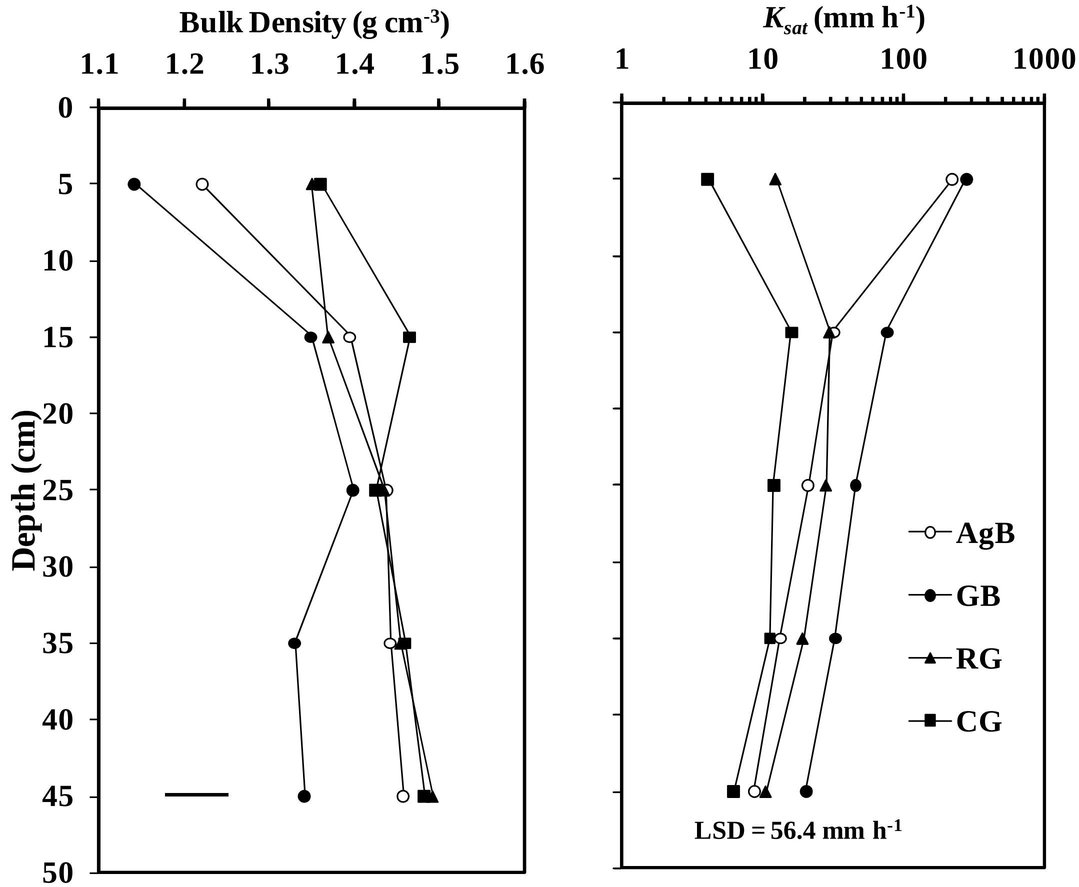

A
B
C
D
Fractal Dimension
Fractal Dimension
D = 10.6x + 1.06
r² = 0.81
D = 5.4x + 1.27
r² = 0.72
D = 16.0x + 1.03
r² = 0.54
D = 16.7x + 0.97
r² = 0.51
1.8
1.6
1.4
1.2
1.0
0.00
0.05
0.10
0.00
0.02
0.04
0.00
0.01
0.02
Macroporosity (m3m-3)
Macroporosity (m3m-3)

Fig. 4.5.



Bulk Density (g cm-3)
1.1
1.2
1.3
1.4
1.5
1.6
Depth (cm)
0
5
10
15
20
25
30
35
40
45
50
Ksat (mm h-1)
1
10
100
1000
AgB
GB
RG
CG
LSD = 56.4 mm h-1

Fig. 4.6.

CHAPTER 5

WATER INFILTRATION INFLUENCED BY AGROFORESTRY AND GRASS BUFFERS FOR A GRAZED PASTURE SYSTEM

ABSTRACT

Agroforestry (AgB) and grass (GB) buffers are often adopted as alternative resource management tools in agroecosystems for environmental and economic benefits. The objective of this study was to compare the influence of agroforestry (AgB) and grass buffer (GB) systems under rotationally stocked (RP) and continuously stocked (CP) pasture systems on water infiltration measured using ponded infiltration and tension infiltration methods. Buffers were surrounded by a fence that prevented cattle from grazing within these areas. Soils at the site are Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalf). Infiltration rates were measured using ponded ring infiltration units in 2007 and 2008 for the four treatments with six replicates. Infiltration rate as a function of tension (at 50-, 100-, and 150-mm) (1.97-, 3.94-, and 5.90-in) was also measured using a tension infiltrometer in 2007. For ponded infiltration, a single steel infiltration ring (25 cm [9.8 in] diam. and 30 cm [11.8 in] length) was vertically driven 15 cm (5.9 in) into the soil. Water infiltration parameters were estimated using Green-Ampt and Parlange infiltration equations. Quasi-steady state infiltration rates (q_s) and field-saturated hydraulic conductivity (K_{fs}) for buffers were about 30 and 40 times higher compared to pasture treatments, respectively. Green-Ampt and Parlange models appeared to fit measured data with r^2 values ranging from 0.91 to 0.98. The q_s (measured with ponded method) in 2007 for the GB treatment was the highest (221 mm h^{-1} [8.72 in h^{-1}]) and for the CP treatment was the lowest (3.7 mm h^{-1}[0.15 in h^{-1}]). For

both years, estimated sorptivity (*S*) and saturated hydraulic conductivity (K_s) parameters were higher for buffer areas compared to the stocked pasture areas. Grazing reduced the infiltration rate for the pasture (RP and CP) treatments. Results show that the buffer areas have higher infiltration rates which imply lower runoff compared to pasture areas.

Keywords: agroforestry buffer-grass buffer-Green-Ampt equation-Parlange equation-sorptivity-saturated hydraulic conductivity-water infiltration.

Introduction

Water infiltration is affected by various factors such as soil texture and structure, landscape position, management system, soil organic carbon, vegetative cover, and antecedent water content (Radke and Berry, 1993). Vegetative covers have been found to increase soil organic carbon which improves soil properties and increases water infiltration rates. Meek et al. (1992) reported that pores formed by perennial plant roots are the major cause of increasing soil water infiltration rate. Management practices which increase soil macropores usually increase the water infiltration rate. Rasiah and Aylmore (1998) reported that macropore characteristics such as shape, size and orientation, and size distribution affect the rate, flow, and retention of water in the soil.

Connolly et al. (1997) reported that reduced infiltration leads to less water stored in the soil for later use by crops and often reduces crop yields. Runoff associated with low infiltration is also the driving force for soil erosion, a serious problem for sloping lands (Freebairn et al., 1986; Radford et al., 1992). Hoof trampling by grazing cattle can damage the vegetation and soils of pasture areas with high stock densities (Betteridge et al., 1999; Sheath and Boom, 1997) if cattle are left to graze an area for too long.

Previous studies have shown that the loss of vegetative and litter cover by improperly stocking cattle allow direct raindrop impact on soils which can increase runoff from these areas (Lal and Elliot, 1994; Thurow et al., 1988; Warren et al., 1986a). The increased kinetic energy in downhill water flow on moderate and steep slopes may have greater capacity to damage the soil surface and hence increase soil erosion (Russell et al., 2001). Installing grass or agroforestry buffers at the down slope end of pastures can decrease runoff flow rates and reduce sediment transport.

Agroforestry and grass buffers establish deep root systems which increase the proportion of macropores and improve the soil hydraulic properties as compared to row crop systems (Allaire-Leung et al., 2000; Cadisch et al., 2004; Rasse et al., 2000; van Noordwijk and Brouwer, 1991). The channels formed by decayed roots subsequently form the macropores which creates an environment conducive to high soil water flow rates. Water can easily enter these macropores and have greater infiltration rates compared to soils without these buffers and macropores (Rachman et al., 2005). In a study performed by Bharati et al. (2002), it was shown that a multispecies riparian buffer had five times higher soil infiltration rates compared to grazed and cultivated fields. Seobi et al. (2005) also reported increased saturated hydraulic conductivity with agroforestry and grass buffers for claypan soils. The same study showed that grass buffers and agroforestry buffers stored more water than the adjacent row crop areas.

Agroforestry and grass buffers are sometimes used in combination with pastures. In these buffer systems where the tree and grass buffer areas are left undisturbed by grazing animals, soil properties are different compared to pasture areas (Kumar et al. 2008). Uneven grazing in continuously stocked pastures has been shown to lower water infiltration rates because of soil compaction in certain areas (Daniel et al., 2002; Radke and Berry, 1993; Wheeler et al., 2002). However rotationally stocked pastures, where rest periods are provided to allow forage to recover between grazing events, have been shown to be important in minimizing the effects of livestock grazing on water infiltration rates (Warren et al., 1986b).

Few studies have been conducted to evaluate the impact of agroforestry and grass buffers on water infiltration rates compared to stocked pasture systems. The purpose of this study was to compare the effects of agroforestry and grass buffers on water infiltration relative to rotationally and continuously stocked pastures. The specific objective of the study was to compare water infiltration parameters among agroforestry and grass buffers in relation to rotationally and continuously stocked pastures.

Materials and Methods

Experimental site and management. The experimental site was located at the Horticulture and Agroforestry Research Center (HARC) near New Franklin, Missouri (39°02'N, 92°46'W, 195 m (640 ft) above mean sea level). The study site was established in 2000 to compare the influence of grass and agroforestry buffers on runoff water quality.

The pasture areas and grass buffers were seeded with Kentucky 31 tall fescue [*Lolium arundinaceum* (Schreb.) Darbysh. = (*Schedonorus arundinaceus* (Schreb.) Dumort.]. Red clover (*Trifolium pratense* L.) and Korean lespedeza [(*Kummerowia stipulacea* Maxim.) Makino] were over-seeded in February 2003 (Kumar et al., 2008). Eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) trees were planted in 2001 into the fescue for areas designated to be agroforestry buffers. Within the agroforestry buffers, trees were planted 3 m (9.8 ft) apart within four rows which were also 3 m (9.8 ft) apart. On average, trees were 7.6 m (25 ft) high with 15 cm (6 in) diameter at breast height. Additional information about the experimental site can be found in Kumar et al. (2008).

Soils at the site are Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalf). Average annual precipitation of the site (1956-2006) was 967 mm (38.07 in); mean July temperature was 25.6°C (78.1°F) and mean January temperature was -2.1°C (28.2°F). The grass and agroforestry buffer areas were adjacent to the pasture areas, but surrounded by an electric fence to prevent access by cattle. The rotationally stocked pasture treatment had six paddocks within the watershed. The continuously stocked pasture had no subdivisions. Treatments included agroforestry buffer (AgB), grass buffer (GB), rotationally stocked pasture (RP), and continuously stocked pasture (CP).

Grazing was initiated at the site in late March/early April and discontinued in late October/early November. During late July/early August, cattle were removed for about one month due to inadequate forage. The pasture treatment sites had been grazed for three years prior to 2007, and four years prior to 2008, before the infiltration measurements were taken. Each year, three beef cows (average weight of 520 kg [1146 lb]) were introduced into the watershed (0.8 ha [2.0 ac]). Eighty-five percent of the grazing area (0.64 ha [1.6 ac]) of the watershed was divided into six rotationally grazed paddocks with a single wire electric fences for forage management. The other 15% of the grazing area was continuously grazed. The stocking density was 5.26 animal units ha^{-1}, AU ha^{-1} (2.13 AU ac^{-1}), and grazing pressure was 31.6 animal unit months ha^{-1}, AUM ha^{-1} (12.8 AUM ac^{-1}). The cows were rotated to new paddocks each Monday and Thursday with each paddock being grazed for 3.5 days and rested for 17.5 days (Kumar et al., 2008).

Ponded infiltration measurements. Water infiltration was measured using ponded ring infiltration units for the four treatments each with six replicates (total 24 times each year) in late May 2007 and early June 2008. The AgB measurements were taken under six replicate trees, three each from two tree rows in the AgB area. Infiltration measurements were taken 20 cm (7.87 in) from the base of tree trunks in the agroforestry buffer. The GB treatment measurements were taken from six grass buffer areas. The RP samples were taken from six replicate rotationally stocked areas and the CP treatment measurements were taken from six replicate continuously stocked areas.

Infiltration rates were measured using a single-ring infiltrometer (Bouwer, 1986) with 25-cm (9.84 in) inner diameter and 30-cm (11.8 in) in length. Plant residues were not removed while inserting the ring. At the time of infiltration measurements, gravimetric soil water content at depths of 0-10, 10-20, and 20-30 cm (0-3.94, 3.94-7.87, and 7.87-11.8 in) was taken from all treatments and adjusted to volumetric water content using measured bulk density values.

For the ponded infiltration measurements, a steel ring was driven 15- cm (5.90 in) into the soil. A positive head of 50- mm (1.97 in) was maintained inside the ring using a Mariotte system. Infiltration measurements were conducted for about 90 to 120 minutes.

Two infiltration models were used to fit infiltration data which include the Green-Ampt model (1911), and the Parlange et al. (1982) model. Throughout this paper, the Parlange et al. (1982) model will be referred to as the Parlange model. The Green-Ampt

(1911) infiltration model was modified by Philip (1957) for time (t) vs. cumulative infiltration (I), as follows:

$$t = \frac{I}{K_s} - \frac{\left[S^2 \ln(1 + \frac{2IK_s}{S^2})\right]}{2K_s^2} \qquad [1]$$

The physically based Parlange model for t vs. I is

$$t = \frac{I}{K_s} - \frac{S^2\left[1 - \exp(-2IK_s / S^2)\right]}{2K_s^2} \qquad [2]$$

where t (T) is time (h), I (L) is the cumulative infiltration (mm), S (L $T^{-0.5}$) is the sorptivity (mm $h^{-0.5}$), and K_s (L T^{-1}) is the saturated hydraulic conductivity (mm h^{-1}). For estimating the S and K_s parameters, the method proposed by Clothier et al. (2002) was used. Both these parameters were estimated based on cumulative infiltration. The initial S parameter is estimated from initial infiltration divided by the $(\text{time})^{-0.5}$ and the initial K_s value is the final/steady state infiltration rate (mm h^{-1}).

The method of Reynolds et al. (2002) was used to estimate field saturated hydraulic conductivity (K_{fs}). This method assumes one-dimensional water flow in the infiltration ring, and uses the following equation:

$$K_{fs} = \frac{q_s}{\left(\frac{H}{C_1 d + C_2 a}\right) + \left\{\frac{1}{\left[\alpha^* (C_1 d + C_2 a)\right]}\right\} + 1} \qquad [3]$$

where K_{fs} is the field-saturated hydraulic conductivity (mm h^{-1}), q_s is the quasi-steady infiltration rate (mm hr^{-1}), a is the radius of the infiltration ring (mm), H is the hydraulic head of ponded water in the ring (mm), d is the depth of ring insertion into the soil (mm), C_1 and C_2 are dimensionless quasi-empirical constants (C_1=0.993 and C_2=0.578 for this infiltrometer), and α* is the soil macroscopic capillary length, assumed to be equal to 0.036 mm^{-1} (0.91 in^{-1}) for the agroforestry buffer and grass buffer treatments, 0.012 mm^{-1} (0.30 in^{-1}) for the rotationally stocked pasture system, and 0.004 mm^{-1} (0.10 in^{-1}) for the continuously stocked pasture treatment (Reynolds et al., 2002). Laboratory saturated hydraulic conductivity (K_{sat}) values were taken from Kumar et al. (2010) for comparison with field K_{fs} values.

Tension infiltration measurements. After the completion of the measurements for ponded infiltration, the same rings were used for the tension infiltration measurements. Without removing the ring infiltrometer, infiltration was measured with a tension infiltrometer at 50-, 100-, 150-mm (1.97-, 3.94-, and 5.90-in) tensions. The ring was filled with a 0.5 cm (0.20 in) silica sand layer (between 0.25 and 0.42 mm [0.098 and 0.165 in] diameter). The K_s and water entry of the sand were assumed to be 283 m d^{-1} (928.48 ft d^{-1}) and 22 cm (8.66 in), respectively, based on Wang et al. (1998). A water reservoir was attached to a 20-cm (7.87 in) diameter tension infiltrometer preset at 50-mm (1.97-in) tension then gently placed in contact with the sand. Infiltration was measured for 20 minutes at 1-minute intervals. After infiltration data at 50-mm (1.97 in) tension were recorded; the tension was increased by removing the bubbling tube from the disc and then setting the tension to 100 mm (3.94 in). This procedure was repeated for the 150-mm (5.90 in) tension setting. Tension infiltration measurements were only conducted during 2007.

Statistical Analysis. A test for homogeneity of variance was conducted to evaluate the variability in infiltration measurements within the different treatments due to the systematic arrangement of treatments. Analysis of variance (ANOVA) was further conducted with SAS (SAS Institute, 1999) using the GLM procedure when variances within treatments were homogeneous. A *buffer vs. pastures* contrast was also conducted. Statistical differences were declared significant at $\alpha = 0.05$ level.

Results and Discussion

Ponded infiltration measurements. Water infiltration is a critical process affecting surface runoff and transport of dissolved nutrients (Rashidi and Seyfi, 2007). Infiltration data are often fit to models (Green-Ampt and Parlange) to represent infiltration data over time with physical parameters. Fitted parameters serve as a convenient, condensed description of data and can be used for predictive purposes (Hopmans et al., 1997). The initial infiltration rate depends on the antecedent soil water content. Hence, the sorptivity parameter (S) which is highly dependent on the initial infiltration rate is dependent on antecedent soil water content. Sorptivity is a physical parameter and is a property describing the tendency of porous material to absorb and transmit water by capillary suction (Reda Taha et al., 2001). Another physical parameter important in infiltration is the saturated hydraulic conductivity (K_s); it is related to the long-term steady infiltration rate. Both parameters (K_s and S) can be estimated to represent infiltration data; physically-based models were used since these are the simplest infiltration models. Two models (Green and Ampt; Parlange) were used to evaluate the consistency in estimated physical parameters S and K_s.

Two infiltration models were fit to infiltration data as a function of time for typical replicates for the agroforestry buffer (AgB), grass buffer (GB), rotationally stocked pasture (RP) and continuously stocked pasture (CP) treatments for 2007 (Fig.

5.1) and 2008. The Green-Ampt and Parlange models fit the measured infiltration data reasonably well with coefficients of determination (r^2) ranging from 0.91 to 0.98.

The K_s and S parameters estimated with the Green-Ampt model were significantly higher for the AgB and GB treatments as compared to pasture treatments for both years (Tables 5.1 and 5.2). Both parameters were also significantly higher for the GB treatment compared to AgB (except the Green-Ampt estimated K_s parameter for 2008; Table 5.1). These parameters were not significantly different between the RP and CP pasture treatments for both years. The CP treatment had the lowest numerical values for K_s and S parameters estimated by the Green-Ampt and Parlange models for 2007, but not in 2008 (Table 5.1). In 2007, the Green-Ampt estimated K_s and S parameters were about 15.6 and 13.7 times higher in the buffers compared to pastures, while values were about 8 and 15.8 times higher for buffers in 2008 as compared to pasture treatments.

The values for K_s and S parameters estimated with the Parlange model were 22.7 and 12 times higher for the buffer treatments in 2007 compared to pasture treatments, while buffers treatments were 8.7 and 12.4 times higher in 2008 relative to pasture treatments. Coefficients of variation (CV) for the fitted K_s and S parameters (Green-Ampt and Parlange models) ranged from 14.0 to 106.6 % for the four treatments in 2007 and 2008 (Table 5.1). One possible reason for the higher values for the S parameter may be due to slightly lower initial soil water content; the volumetric water content for the 0-30 cm (0-11.8 in) soil profile for the buffers was 7.7 and 13.5% lower compared to pastures in 2007 and 2008, respectively .

The quasi-steady state infiltration rate (q_s) and field saturated hydraulic conductivity (K_{fs}) were significantly different ($P < 0.01$) among the treatments (Table

5.2). The single degree contrast, *buffers vs. pastures*, was also determined. Both parameters were significantly different for the *buffers vs. pastures* contrast (P<0.01; Table 5.2). The q_s and K_{fs} values were significantly higher for GB treatment compared to other treatments in 2007 but significant differences were not observed among the other three treatments (Table 5.3). In 2008, both these parameters for the AgB and GB treatments were significantly higher as compared to pasture treatments (Table 5.3). The q_s and K_{fs} parameters were not significantly different between the RP and CP treatments for both years. The q_s and K_{fs} parameters for the buffers were about 31 and 41 times higher, respectively, as compared to pasture treatments in 2007 (Table 5.3). Similarly for 2008, the values were 14 and 19 times (Table 5.3).

The CV values for the CP treatment were found to be higher for these parameters in 2007 (81 %) and 2008 (66 %) compared to the other treatments. Similar CV values were found for the GB and RP treatments with average CV values of 63 and 55% for these years. The lowest CV values were found for the AgB treatment. The higher values of CV for the RB and CP treatments were probably due to lower mean values of q_s and K_{fs} parameters.

The buffers had better plant root and shoot growth which improved soil properties compared to grazed pasture areas. Udawatta et al (2003) found that root length density for trees in similar soils to the present study was higher compared to row crop areas. The higher amount of roots in the buffers for the current study will probably improve soil properties as roots decay and add soil organic matter. Kumar et al. (2008) reported 16.7 times higher saturated hydraulic conductivity and 11.2% lower bulk density for buffers compared to grazed pasture areas at the same site. Thus, higher infiltration is expected due to higher saturated hydraulic conductivity in the buffers. Hence, buffers were shown to improve water infiltration into the soil which would indicate less runoff from these areas compared to stocked pastures areas (RP and CP treatments).

To assess the consistency of the parameters obtained from the field infiltration data with laboratory data, comparisons were made between the K_{fs} parameter and previously measured laboratory saturated hydraulic conductivity (K_{sat}) data (Kumar et al., 2010). Laboratory data for saturated hydraulic conductivity (K_{sat}) measured in 2007 for the 0-10 cm (0- 3.94 in) soil depth (taken from Kumar et al., 2010) were correlated with K_{fs} values estimated from 2007 (Fig. 5.2). The coefficient of determination for this regression was found to be 0.56 between K_{fs} and K_{sat}. The slope of the regression was estimated to be 0.39. Bouwer (1986) and Rachman et al (2004) proposed that K_{fs} could be estimated as 0.5 x K_{sat} and 0.65 x K_{sat}, respectively. In the current study, this coefficient was estimated to be 0.4 x $K_{sat.}$ which was slightly lower than the other two studies. Rachman et al. (2004) reported that K_{fs} and K_{sat} could be related when K_{sat} was measured in small cores of 76 by 76 mm (2.99 by 2.99 in), if the potential rapid-pipe flow conduits were eliminated.

Tension infiltration measurements. Land management practices, such as buffers used in the current study, may improve water infiltration and reduce surface runoff. Buffer management practices enhance development of permanent root systems which add organic matter to the soil as well as improve soil porosity and macroporosity (Kumar et al., 2008; Udawatta et al., 2008). Macroporosity directly affects water infiltration since these pores help in transmitting water. To assess the impact of these pores, water infiltration under tension can be measured. Water infiltration under tension prevents larger pores from transmitting water. Hence, measurement of infiltration under tension is one method to assess why ponded infiltration is larger for some management systems. In the current study, the tension infiltration method was used to measure how much macropores influenced water infiltration for the treatments.

Measured infiltration rates at 50-, 100-, and 150-mm (1.97-, 3.94-, and 5.90-in) tensions for the AgB, GB, RP and CP treatments are shown in Table 5.4. Infiltration rates at 50 and 100 mm (1.97 and 3.94 in) tension were significantly affected by the treatments ($P<0.05$; Table 5.4). The infiltration rate values measured at 50 and 100 mm (1.97 and 3.94 in) were significantly higher for the GB treatment as compared to the other three treatments, while the infiltration rate at 150 mm (5.90 in) tension was significant only between GB and CP treatments (Table 5.4). The infiltration rate at 50 mm (1.97 in) tension for the GB treatment was about 2.7, 7.5, and 13 times higher compared to AgB, RP and CP treatments, respectively.

The single degree freedom contrast *buffers vs. pastures* was found to be significant at 50- and 100- mm (1.97 and 3.94 in) tensions ($P<0.05$; Table 5.4). At 150 mm (5.90 in) tension, infiltration rate differences were also found to be significant for this contrast (Table 5.4).

Infiltration rate decreased with increased applied tension with the highest decrease occurring between the 0- to the 50-mm (1.97-in) tension values. The decrease for AgB, GB, RP and CP treatments was about 99, 99, 94 and 94% between 0- to 50-mm (0- to 1.97-in) tensions. An exponential model seemed to fit the relationships for the infiltration rate decrease with tension (fitted parameters shown in Table 5.5). Estimated exponential parameter (β_1 parameter) values for the four treatments appear to indicate smaller values or a steeper decent for the buffer treatments (-0.039) compared to the pasture treatments (-0.026). Similar exponential parameter results were reported by Rachman et al. (2004) for deep loess soils in Iowa. These researchers reported the smallest values for the equation under grass hedge management (-0.034) compared to row crop management (-0.029). It has been reported in a previous study (Kumar et al., 2008) that more macropores were found in the buffer areas as compared to stocked pasture treatments. The higher number of macropores was probably responsible for conducting water under saturated conditions in the buffers (AgB and GB) compared to pastures (RP and CP; Ankeny et al., 1990). Similar results for the function used in this study were also reported by Rachman et al. (2004).

Summary/Conclusions

Infiltration measurements were taken to evaluate the effects of buffers on water infiltration under stocked pasture systems. Agroforestry and grass buffers were compared to rotationally stocked and continuously stocked pasture areas. Buffers had 30 and 14 times higher quasi-steady state infiltration (q_s) in 2007 and 2008, respectively, as compared to pasture treatments. The q_s for the GB treatment (233.2 mm h^{-1}[9.18 in h^{-1}]) was highest and for the CP treatment (6.83 mm h^{-1}[0.269 in h^{-1}]) was lowest for the two year study. The Green-Ampt and Parlange models appeared to adequately fit the measured infiltration data for the treatments as estimated using coefficients of determination. Fitted S and K_s parameters were highest for the GB treatment and lowest for the CP treatment. Tension infiltration measurements were used to illustrate the influence of macropores on water infiltration in the soil. The infiltration rate decreased more between 0 and 150 mm (0 and 5.90 in) tension for the buffer treatments compared to the pasture treatments. This was attributed to more macropores present in the buffer treatments which increased the water infiltration in the buffer areas compared to grazed pasture areas. Findings from the current study were similar for both years.

Results obtained from the current study illustrates that management practices such as grass and agroforestry buffers improve soil porosity and macroporosity and hence improved water infiltration into the soil. Grazing reduced infiltration rates for pasture areas compared to buffer areas with no cattle access. Findings of the current study show that the buffer areas had higher infiltration rates which imply lower runoff compared to pasture areas. Buffer areas were fenced which prevented cattle grazing in these areas which probably benefited infiltration.

References

Allaire-Leung, S.E., S.C. Gupta, and J.F. Moncrief. 2000. Water and solute movement in soil as influenced by macropore characteristics: I. Macropore continuity. Journal of Contaminant Hydrology. 41(3-4):283-301.

Ankeny, M.D., T.C. Kaspar, and R. Horton. 1990. Characterization of tillage and traffic effects on unconfined infiltration measurements. Soil Science Society of America Journal. 54(3):837-840.

Betteridge, K., A.D. Mackay, D.J. Barker, T.G. Shepherd, P.J. Budding, B.P. Devantier, and D.A. Costall. 1999. Effect of cattle and sheep treading on surface configuration of a sedimentary hill soil. Australian Journal of Soil Research. 37(4):743-760.

Bharati, L., K.H. Lee, T.M. Isenhart, and R.C. Schultz. 2002. Soil-water infiltration under crops, pasture, and established riparian buffer in Midwestern USA. Agroforestry Systems. 56(3):249-257.

Bouwer, M. 1986. Intake rate: Cylinder infiltrometer. p. 825–844. *In* A. Klute (ed.) Methods of soil analysis. Part 1. *2nd ed*. Agronomy Monograph No. 9. ASA and SSSA, Madison, WI. USA.

Cadisch, G., P. de Willigen, D. Suprayogo, D.C. Mobbs, M. van Noordwijk, and E.C. Rowe. 2004. Catching and competing for mobile nutrients in soils. p. 171-191. *In* M. van Noodwijk, G. Cadisch, and C.K. Ong (*ed*.) Below-ground interactions in tropical agro ecosystems. CABI, Wallingford, UK.

Clothier, B., D. Scotter, and J.P. Vandervaere. 2002. Unsaturated water transmission parameters obtained from infiltration. p. 879– 898. *In:* J.H. Dane and G.C. Topp (ed.) Part 4. Methods of Soil Analysis. Soil Science Society of America, Madison, Wisconsin. USA.

Connolly, R.D., Freebairn, D.M., and Bridge, B.J. 1997. Change in infiltration characteristics associated with cultivation history of soils in south-eastern Queensland. Australian Journal of Soil Research 35(6):1341-1358.

Daniel, J.A., K. Potter, W. Altom, H. Aljoe, and R. Stevens. 2002. Long-term grazing density impacts on soil compaction. Transactions of the American Society of Agricultural Engineers. 45(6):1911-1915.

Freebairn, D.M., G.H. Wockner, and D.M. Silburn. 1986. Effects of catchment management on runoff, water quality and yield potential from a Vertisols. Agricultural Water Management. 12(1-2):1-17.

Green, W.H., and G.A. Ampt. 1911. Studies on soil physics. Part I. The flow of air and water through soils. Journal of Agricultural Sciences. 4(1):1-24.

Hopmans, J.W., V. Clausnitzer, K.I.Kosugi, D.R. Nielsen and F. Somma.1997. Vadose zone measurement and modeling. Sci. Agric., Piracicaba. 54:22-38.

Kumar, S., S.H. Anderson, and R.P. Udawatta. 2010. Agroforestry and grass buffer influences on CT-measured macropores under grazed pasture systems. Soil Science Society of America Journal. 74:1-10.

Kumar, S., S.H. Anderson, L.G. Bricknell, R.P. Udawatta, and C.J. Gantzer. 2008. Soil hydraulic properties influenced by agroforestry and grass buffers for grazed pasture systems. Journal of Soil and Water Conservation. 63(4):224-232.

Lal, R., and W. Elliot. 1994. Erodibility and erosivity. p. 181-208. *In*: R. Lal (*ed*.). Soil Erosion Research Methods (*2nd Ed*.) Soil and Water Conservation Society, Ankeny, IA. USA.

Meek, B.D., E.R. Rechel, L.M. Carter, W.R. DeTar, A.L. Urie. 1992. Infiltration rate of a sandy loam soil: effects of traffic, tillage, and plant roots. Soil Science Society of America Journal. 56(3):908-913.

Parlange, J.Y., I. Lisle, R.D. Braddock, and R.E. Smith. 1982. The three-parameter infiltration equation. Soil Science. 133(6):337-341.

Philip, J.R. 1957. The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. Soil Science 84(3):257–264.

Rachman, A., S.H. Anderson, and C.J. Gantzer. 2005. Computed-tomographic measurement of soil macroporosity parameters as affected by stiff-stemmed grass hedges. Soil Science Society of America Journal. 69(5):1609-1616.

Rachman, A., S.H. Anderson, C.J. Gantzer, and E.E. Alberts. 2004. Soil hydraulic properties influenced by stiff-stemmed grass hedge systems. Soil Science Society of America Journal. 68(4):1386-1393.

Radford, B.J., G. Gibson, R.G.H. Nielsen, D.G., Butler, G.D. Smith, and D.N. Orange. 1992. Fallowing practices, soil water storage, plant-available soil nitrogen accumulation and wheat performance in South West Queensland. Soil and Tillage Research 22(1-2):73-93.

Radke, J.K., and E.C. Berry. 1993. Infiltration as a tool for detecting soil changes due to cropping, tillage and grazing livestock. American Journal of Alternative Agriculture 8:164-174.

Rashidi, M and K. Seyfi. 2007. Field comparison of different infiltration models to determine the soil infiltration for border irrigation method. American-Eurasian Journal of Agricultural & Environmental Sciences. 2(6):628-632.

Rasiah, V., and L.A.G. Alymore, 1998. The topology of pore structure in cracking clay soil: I. The estimation of numerical density. Journal of Soil Science. 39: 303-314.

Rasse, D.P., A.J.M. Smucker, and D. Santos. 2000. Alfalfa root and shoot mulching effects on soil hydraulic properties and aggregation. Soil Science Society of America Journal. 64(2):725-731.

Reda Taha, M.M., A. S. El-Dieb, and N. G. Shrive. 2001. Sorptivity: a reliable measurement for surface absorption of masonry brick units. Materials and Structures. 34.(8-9): 438-445.

Reynolds, W.D., D.E. Elrick, E.G. Youngs, and A. Amoozegar. 2002. Field methods (vadose and saturated zone techniques). p. 817–826. *In:* J.H. Dane and G.C. Topp (*ed.*). Methods of Soil Analysis. Part 4. Soil Science Society of America Book Series No. 5. Soil Science Society of America Madison, Wisconsin. USA.

Russell, J.R., K. Betteridge, D.A. Costall, and A.D. Mackay. 2001. Cattle treading effects on sediment loss and water infiltration. Journal of Range Management.54(2): 184-190.

SAS Institute. 1999. SAS user's guide. Statistics. SAS Inst., Cary, NC.

Seobi, T., S.H. Anderson, R.P. Udawatta, and C.J. Gantzer. 2005. Influence of grass and agroforestry buffer strips on soil hydraulic properties for an Albaqualf. Soil Science Society of America Journal. 69(3):893-901.

Sheath, G.W., and C.J. Boom. 1997. Impact of cattle grazing systems on treading damage and forage supply. Proceedings New Zealand Grassland Association 59(3):87-92.

Thurow, T.L., W.H. Blackburn, and C.A. Taylor, Jr. 1988. Some vegetation responses to selected livestock grazing strategies. Journal of Range Management. 41:108-114.

Udawatta RP and G.S. Henderson. 2003. Root distribution relationships to soil properties in Missouri oak stands: a productivity index. Soil Science Society of America Journal 67:1869-1878.

Udawatta, R.P., and S.H. Anderson. 2008. CT-measured pore characteristics of surface and subsurface soils influenced by agroforestry and grass buffers. Geoderma 145: 381-389.

van Noordwijk, M., and G. Brouwer. 1991. Review of quantitative root length data in agriculture. 515-525. *In*: Persson, H., and B. L. McMichael. Plant roots and their environment, *ed*, Amsterdam, The Netherlands: Elsevier.

Wang, D., S.R. Yates, and F.F. Ernst. 1998. Determining soil hydraulic properties using tension infiltrometers, time domain reflectometry, and tensiometers. Soil Science Society of America Journal. 62(2):318–325.

Warren, S.D., M.B. Nevill, W.H. Blackburn, and N.E. Garza. 1986a. Soil response to trampling under intensive rotation grazing. Soil Science Society of America Journal. 50(5):1336-1341.

Warren, S.D., W.H. Blackburn, and C.A. Taylor, JR.1986b. Soil hydrologic response to number of pastures and stocking density under intensive rotation grazing. Journal of Range Management 39(6):500-504.

Wheeler, M.A., M.J. Trlica, G.W. Frasier, and J.D. Reeder. 2002. Seasonal grazing affects on soil physical properties of a mountain riparian community. Journal of Range Management 55:49-56.

Table 5.1. Means and coefficients of variation (CV) for saturated hydraulic conductivity (K_s) and sorptivity (S) parameters estimated by the Green-Ampt and Parlange models in the agroforestry buffer (AgB), grass buffer (GB), rotationally stocked pasture (RP), and continuously stocked pasture (CP) treatments in 2007 and 2008 (n=6).

Treatments	2007 K_s Mean mm h^{-1}	2007 K_s CV %	2007 S Mean mm h$^{-0.5}$	2007 S CV %	2008 K_s Mean mm h^{-1}	2008 K_s CV %	2008 S Mean mm h$^{-0.5}$	2008 S CV %
Green-Ampt model								
Agroforestry buffer (AgB)	46.2^{b†}	53.0	94.6^{b}	38.4	71.6^{a}	49.1	133.0^{b}	57.9
Grass buffer (GB)	120.3^{a}	44.2	258.1^{a}	46.6	81.7^{a}	66.4	325.8^{a}	28.8
Rotationally stocked pasture (RP)	8.59^{c}	73.3	19.5b^{c}	42.8	7.90^{b}	92.2	10.8^{c}	59.2
Continuously stocked pasture (CP)	2.07^{c}	58.3	6.32^{c}	46.0	11.3^{b}	47.9	18.1^{c}	42.9
Parlange model								
Agroforestry buffer (AgB)	40.0^{b}	23.5	80.8^{b}	14.0	83.2^{b}	64.6	110.6^{b}	43.1
Grass buffer (GB)	158.7^{a}	35.5	239.9^{a}	50.7	159.8^{a}	39.9	257.8^{a}	45.7
Rotationally stocked pasture (RP)	6.75^{bc}	105.6	21.3^{b}	48.4	14.2^{c}	106.6	12.5^{c}	73.4
Continuously stocked pasture (CP)	2.00^{c}	50.9	5.17^{b}	56.2	13.8^{c}	58.4	17.1^{c}	41.0

†Means with different letters within a column are significantly different at the 0.05 probability level.

Table 5.2. Analysis of variance of the sorptivity(S), saturated hydraulic conductivity (K_s), quasi-steady state infiltration rate (q_s) and field-saturated hydraulic conductivity (K_{fs}) parameters for 2007 and 2008.

Analysis of variance P > F

2007

	Green-Ampt		Parlange			
	K_s	S	K_s	S	q_s	K_{fs}
Treatment	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Buffers vs. Pastures	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

2008

	Green-Ampt		Parlange			
	K_s	S	K_s	S	q_s	K_{fs}
Treatment	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Buffers vs. Pastures	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

Table 5.3. Means and coefficients of variation (CV) of quasi-steady state infiltration rate (q_s) and field-saturated hydraulic conductivity (K_{fs}) for the agroforestry buffer (AgB), grass buffer (GB), rotationally stocked pasture (RP), and continuously stocked pasture (CP) treatments in 2007 and 2008 (n=6).

	Year							
	2007				2008			
	q_s		K_{fs}		q_s		K_{fs}	
Treatments	Mean	CV	Mean	CV	Mean	CV	Mean	CV
	mm h^{-1}	%	mm h^{-1}	%	mm h^{-1}	%	mm h^{-1}	%
Agroforestry buffer (AgB)	80.4[b†]	14.7	59.5[b]	14.7	105.8[b]	16.6	78.2[b]	16.6
Grass buffer (GB)	221.4[a]	61.1	163.8[a]	61.1	245.0[a]	51.7	181.2[a]	51.7
Rotationally stocked pasture (RP)	6.15[b]	65.6	3.84[b]	65.6	14.8[c]	58.4	9.23[c]	58.4
Continuously stocked pasture (CP)	3.73[b]	81.0	1.58[b]	81.0	9.93[c]	65.7	4.22[c]	65.7

†Means with different within a column letters are significantly different at the 0.05 probability level.

Table 5.4. Means of infiltration rate (q_s) as a function of tension for the agroforestry buffer (AgB), grass buffer (GB), rotationally stocked pasture (RP), and continuously stocked pasture (CP) treatments in 2007 year (n=6).

	Tension, mm water		
	50	100	150
	q_s (mm h^{-1})		
Treatments			
Agroforestry buffer (AgB)	1.04^{b†}	0.32^{b}	0.21^{ab}
Grass buffer (GB)	2.77^{a}	1.45^{a}	0.40^{a}
Rotationally stocked pasture (RP)	0.37^{b}	0.21^{b}	0.12^{ab}
Continuously stocked pasture (CP)	0.21^{b}	0.14^{b}	0.06^{b}
Analysis of variance P > F			
Treatment	<0.01	<0.02	0.08
Buffers vs. Pastures	<0.01	<0.03	<0.02

†Means with different letters within a column are significantly different at the 0.05 probability level.

Table 5.5. Fitted β_0 and β_1 parameters for the exponential equation, $y = \beta_0 \exp(\beta_1 x)$, and the coefficient of determination (r^2) calculated by plotting quasi-steady state infiltration (y) vs. soil water tension (x) as a function of tension (0, 50, 100 and 150 mm) for the agroforestry buffer (AgB), grass buffer (GB), rotationally stocked pasture (RP), and continuously stocked pasture (CP) treatments in 2007 (n=6).

Treatments	β_0	β_1	r^2
Agroforestry buffer (AgB)	26.7	-0.038	0.81
Grass buffer (GB)	82.2	-0.039	0.85
Rotationally stocked pasture (RP)	3.13	-0.025	0.84
Continuously stocked pasture (CP)	1.91	-0.026	0.84

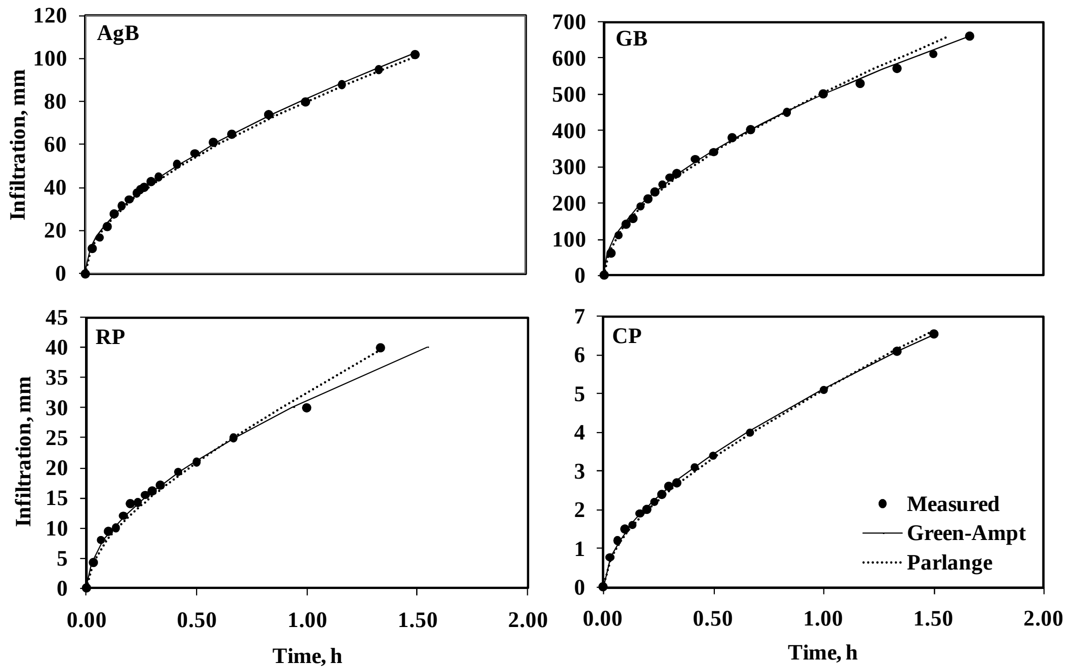


Fig. 5.1. The Green-Ampt and Parlange models fitted to measured ponded infiltration data for typical replicates under agroforestry buffer (AgB), grass buffer (GB), rotationally stocked pasture (RP), and continuously stocked pasture (CP) treatments for 2007. Please note that y-axis scale is different.

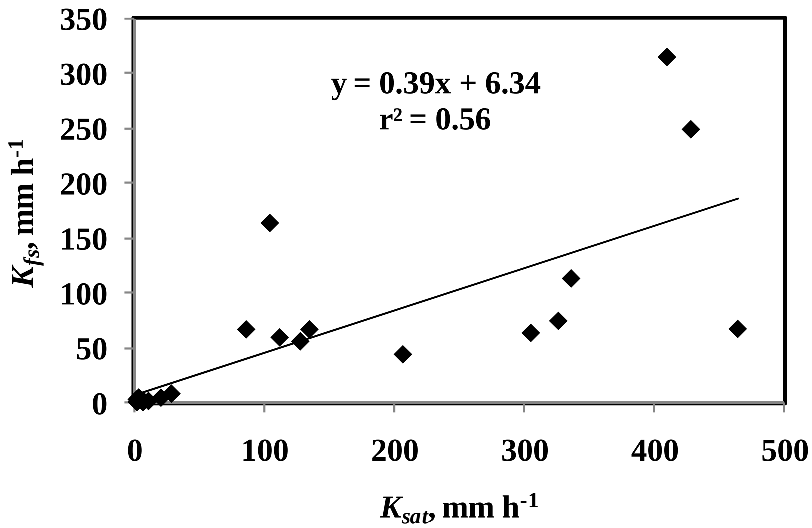


Fig. 5.2. Field saturated hydraulic conductivity (K_{fs}, 2007 data) vs. laboratory measured saturated hydraulic conductivity (K_{sat}, 2007 data; n=24).

CHAPTER 6

ROOT LENGTH DENSITY AND CARBON CONTENT INFLUENCED BY AGROFORESTRY AND GRASS BUFFERS UNDER GRAZED PASTURE SYSTEMS IN A HAPLUDALF

ABSTRACT

Enhancement of root development helps to improve soil physical properties, carbon sequestration, and water quality of streams. The objective of this study was to evaluate differences in root length density (RLD) and root and soil carbon content within grass buffer (GB), agroforestry buffer (AgB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) treatments. Pasture and GB areas included red clover (*Trifolium pretense* L.) and lespedeza (*Kummerowia stipulacea* Maxim.) planted into fescue (*Festuca arundinacea* Schreb.) while AgB included Eastern cottonwood trees (*Populus deltoids* Bortr. ex Marsh.) planted into fescue. One-meter deep soil cores were collected from each treatment in August 2007 and 2008 with a soil probe. Three soil cores were sampled at six replicate sampling positions. Soil cores were collected in plastic tubes inserted inside the metal soil probe. Soils were segregated by horizons, and roots were separated into three diameter classes (<1, 1-2, 2-3 mm) by soil horizon. Root length was determined using a flatbed scanner assisted with computer software. Buffer treatments (167 cm/100 cm^3) had 4.5 times higher RLD as compared to pasture treatments (37.25 cm/100 cm^3). The AgB treatment had the highest (173.5 cm/100 cm^3) RLD and continuously grazed pasture had the lowest (10.8 cm/100 cm^3) value. Root carbon was about 3% higher for the buffers compared to RG treatment. Soil carbon was about 115% higher for the buffers compared to pasture treatments. Results from this study imply that establishment of agroforestry and grass buffers on grazed pasture watersheds improve

soil carbon accumulation and root parameters which enhance soil physical and chemical properties thus improving the environmental quality of the landscape.

Keywords: agroforestry buffer, grass buffer, root carbon, root length density, soil carbon.

Introduction

In agroforestry management practices, agricultural crops along with trees and grass are grown on the same landscape for economic and environmental benefits (Gold and Hanover 1987). One of the main environmental benefits of growing trees near agricultural crops is to capture nutrients, lost from the crop root zone, by the extensive deep root system of perennial vegetation (Comerford et al. 1984; van Noordwijk et al. 1991; Sanchez 1995). Tree roots can penetrate deeper into the soil (Stone and Kalisz 1991) compared to roots of annual crops (Mekonnen et al. 1997). The extensive deep root system of the trees intercept percolating nutrients (Szabo et al. 2001; Lehman et al. 2003) and thereby reduce the impact on soil and water quality. Additionally, this vegetation brings nutrients from deeper soil horizons to the surface soil, and increases soil organic matter which is responsible for the retention and release of nutrients (Lehman et al. 2003).

A study conducted by Tufekcioglu et al. (1999) reported that roots of the buffers help in immobilizing soil water pollutants and improve soil quality. The extensive deep root system of trees more effectively reduce non-point source pollution and thereby help improve the water quality of streams and lakes (Jin et al. 2000; Udawatta et al. 2002). In this process, fine roots (< 1 mm diam.) play an important function for the uptake of water and nutrients. Fine and small roots (< 5 mm) act as the dynamic portion of belowground biomass and nutrient capital

(Tufekcioglu et al. 1999). The quantity of fine roots present in the soil profile also reduces soil erosion (Kamyab 1991). In another study conducted by O'Neill and Gordon (1994), they found that excess nitrate coming from adjacent crop fields through ground water flow might be taken up by the roots of buffer strip vegetation (Carolina poplar trees) more effectively than in roots in row crop areas (corn, *Zea mays* or soybean, *Glycine max*). This was attributed to greater live root biomass, higher root densities and greater rooting depths in poplar trees as compared to row crops.

Roots also improve soil aggregation, soil porosity (Traore et al. 2000; Wienhold and Tanaka 2000), water infiltration and soil water storage (Rasse et al. 2000; Wienhold and Tanaka 2000; Cadisch et al. 2004). The decaying roots of trees result in a greater proportion of larger pores that enhance soil hydraulic properties, preferential flow, and macropore flow compared to row crop systems (van Noordwijk et al. 1991; Allaire-Leung et al. 2000; Rasse et al. 2000; Cadisch et al. 2004). The extent of roots and rooting depth help improve soil hydraulic properties; these effects are influenced by many factors such as plant species (Jonsson et al. 1988; Stone and Kalisz 1991), provenances within a species (Vandenbeldt 1991), and subsoil resources such as soil water (Esthman et al. 1990), and soil nutrients (Atkinson 1973). Rasse et al. (2000) reported that alfalfa (*Medicago sativa* L.) root systems increased saturated hydraulic conductivity by 57%, total porosity by 1.7%, macroporosity by 1.8%, and the water recharge rate of the soil profile by 5.4% per day.

In buffer systems where tree and grass buffer areas are left undisturbed by grazing cattle, root distributions may be different compared to pasture areas which are either continuously or rotationally grazed by cattle. These undisturbed buffers have lower soil bulk density, increased soil porosity and increased soil infiltration as compared to grazed pasture areas (Kumar et al. 2008). The decreased soil bulk density and increased soil porosity found in buffered and undisturbed areas may enhance root penetration through the soil profile. In contrast, cultivated fields and grazed pastures have generally greater soil bulk density than those of undisturbed buffers (native grassland or forest soils; Meek et al. 1992; Taboada and Lavado 1993; Jaiyeoba 1995) which affect root growth. For an Alfisol and Entisol, Panayiotopoulos et al. (1994) found that compaction created by traffic and tillage increased the soil bulk density and penetration resistance and subsequently resulted in reduction of all root growth parameters such as number of roots, mean and total root length, rate of root elongation and fresh and dry root mass. Increased soil bulk density is one of the factors responsible for poor aeration in the soil and hence restricted root growth which affects the uptake of nutrients from the soil (Lipiec et al. 1991; Czyz and Tomaszewska 1993; Lipiec and Stêpniewski 1995; Lal 1996; Lipiec and Hatano 2003). Since grazed pasture areas are more compacted due to cattle grazing (Kumar et al. 2008), root growth parameters, aeration and uptake of nutrients in grazed areas could be lower as compared to ungrazed areas.

In rotational grazing, described by James Anderson near the end of the 18th century in Scotland (Voisin 1959), pastures are subdivided into smaller paddocks in which animals are allowed to graze in a sequence. It is an alternative grazing management practice to minimize soil compaction. In this management system, plants capture sufficient resources such as light, water and nutrients to enhance plant growth on which livestock graze more efficiently (Briske et al. 2008). Rotational grazing encourages uniform consumption of the grass (Fuhlendorf and Engle 2001), and decreases compaction and soil erosion (Warren et al. 1986; Turner et al. 1997). These grazing management systems are especially designed to redistribute grazing pressure (i.e., forage availability/forage demand) in time and space for any given stocking rate (i.e., animal number/land area/time; Heitschmidt and Taylor 1991). The root distribution under rotationally grazed areas may be different from areas which are continuously grazed.

It is hypothesized that root distributions are different between agroforestry and grass buffers as compared to grazed pasture areas. Very few researchers have studied the root distribution pattern throughout the soil profile as influenced by agroforestry and grass buffers in pasture management systems. The objective of this study was to evaluate differences in root length density and root and soil carbon content within agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) treatments.

Materials and Methods

Experimental Site and Management

The study site is located at the Horticulture and Agroforestry Research Center (HARC) in New Franklin, Missouri (39°02'N, 92°46'W, 195 m above mean sea level). The experimental site was established in 2000 to compare the influence of grass and agroforestry buffers on runoff water quality. Prior to establishment, most of the area was in tall fescue grass (*Festuca arundinacea* Schreb.). The pasture areas and buffers were seeded with tall fescue (*Festuca arundinacea* Schreb; Kentucky 31) in 2000. The pastures were seeded with red clover (*Trifolium pretense* L.) and lespedeza (*Kummerowia stipulacea* Maxim.) into the fescue in 2003. Eastern cottonwood trees (*Populus deltoids* Bortr. ex Marsh.) were planted into the fescue to create the agroforestry buffers in 2001. Trees were planted at 3-m spacing within and between rows in four rows. Cottonwood trees are fast growing and reach about 35 meters with a lifespan of about 70 years (Kumar et al. 2008).

Soils at the site are Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs). Additional details about the weather, watershed characteristics and management practices can be found in Kumar et al. (2008).

Fences were installed between pasture areas and the agroforestry and grass buffer areas to prevent cattle access to the buffers. Each year, cattle were introduced in the watershed area with weights between 450 to 590 kg. The number of cattle for the small watershed (0.8 ha) was three. Seventy-five percent of the grazing area was divided into six rotationally grazed paddocks and these were separated by a fence for cattle management. The other 25% of the grazing area was continuously grazed. The cows were moved between paddocks on each Monday and Thursday with each paddock being grazed for 3.5 days and rested for 17.5 days (Kumar et al. 2008).

Treatments and Sampling Procedures

Study treatments included agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG), and continuously grazed pasture (CG) with six replications per treatment. Agroforestry buffer (AgB) root samples were taken from three replicate trees each in two tree rows in the agroforestry buffer area. Three core samples were taken 20 cm from the base of the tree trunk. Six additional core samples, three each at 50 and 100 cm distances from the base of the tree trunk, were also taken from the agroforestry buffer treatment. Grass buffer (GB) samples were taken from six replicate locations in the grass buffer areas; three soil cores were sampled at six replicate sampling positions. Rotationally grazed pasture (RG) samples were taken from six replicate rotationally grazed areas and continuously grazed pasture (CG) samples were taken from six replicate continuously grazed areas; three cores at each replicate sampling position for both the treatments. A total of 108 soil core samples were taken (54 from AgB treatment, and 18 cores each from the remaining three treatments) from the four treatments.

One-meter deep soil cores were collected from each treatment in August 2007 and 2008 with a Gator mounted soil auger. A 5.1 cm diam. metal tube was mechanically driven into the ground to extract a soil core. Soil cores were collected in plastic sleeves inserted inside the metal soil probe. The tube had a crowfoot head which prevented the soil core from falling out of the tube when removed from the soil (Bohm, 1979). Soil cores were labeled and transported to the laboratory. These cores were stored at 4°C, until measurements were taken, because root respiration may result in 5-10% loss of weight in 24 hours after sampling (Van Noordwijk and Floris 1979).

Root Parameters

Soils were segregated by horizons, and roots were separated from each sample. Subsequently, roots were washed with water to remove soil particles, and separated into three diameter classes (<1, 1-2, 2-3 mm) by soil horizon (Fig. 6.1). Root length and surface area were determined for the three diameter classes as well as the total for the each soil horizon using a flatbed scanner assisted with computer software (WinRhizo 2003b, Regent Instruments, Inc., Montreal, Canada). Root length and surface area were expressed in root length cm/100 cm^3 and root surface area cm^2/100 cm^3 soil, respectively. After scanning, each root sample was dried at 70°C for 48 hours and then immediately weighed to determine root dry weight expressed in g/100 cm^3.

Root and Soil Carbon

After scanning the roots and determining the root dry weight, roots were prepared for determination of root carbon. Root samples weighing between 100-150 mg were used to determine the carbon content for AgB, GB, and RG treatment. For the CG treatment, root carbon was determined for the whole soil profile as the root sample was insufficient to determine carbon by each horizon.

After root separation, a soil sample (200-250 mg) from each horizon from each core was air dried and sieved (< 2 mm diameter) before determination of soil carbon. The soil and root carbon content were measured by dry combustion of the samples at 750°C in the presence of oxygen (induction furnace by apparatus C144) by LECO method.

Statistical Analysis

A test for homogeneity of variance was conducted to evaluate the variability within the different treatments due to the systematic arrangement of treatments. Analysis of variance (ANOVA) was further conducted with SAS using the GLM procedure when variances within treatments were homogeneous (SAS Institute 1999). The contrast *buffer vs. pastures* was also determined. An estimate for the least significant difference (Duncan's LSD) between treatments at the same depth or different depths was obtained using the Mixed procedure in SAS. Statistical differences were declared significant at the $\alpha = 0.05$ level.

Results and Discussion

Root Length Density

Root length density (RLD) is the most useful measure of root growth for application to environmental soil science (Merril et al. 2002). Root length density expressed in cm root length per 100 cm^3 soil, was significantly different ($P<0.01$) among treatments in 2008 (Table 6.1). Significant differences were found for the *'buffers vs. pastures'* contrast. Buffer treatments (167 cm/100 cm^3) had 4.5 times higher root length density as compared to pasture treatments (37.25 cm/100 cm^3). The AgB treatment had 8.1% higher (not significant) RLD compared to the GB treatment (Table 6.1). The AgB treatment had 2.7 and 16.1 times higher RLD compared to the RG and CG treatments, respectively (Table 6.1). The AgB treatment had the highest (173.5 cm/100 cm^3) and continuously grazed pasture had the lowest (10.8 cm/100 cm^3) RLD. Similar trends were observed in 2007.

Schenk and Jackson (2002) found that trees had the highest root length followed by grasses and annual plants. In their study, size of root systems was proportional to above ground plant biomass. In an another study, Udawatta and Henderson (2003) reported that in Menfro soils, mature oak trees had 9,272 m/m^2 root length within a 2.0 m soil depth. In the current study, for similar soils, eastern cottonwood trees (AgB treatment) had 4110.4 m/m^2 root length density within about a 1.0 m soil depth. The differences in roots between the two studies could be due to differences in age and species of trees, treatment and land management, and the sampling depth. Higher RLD can be used as an indication of the proportional share of the soil resource accessed by the plant (Bowen 1985). The buffers had higher RLD and hence roots of these buffers can extract more water and nutrients from the soil profile with their extensive deep root system as compared to grazed pasture systems.

The RLD determined by diameter classes (0-1, 1-2 and 2-3 mm) were also compared among the four treatments. The RLD for 0-1 and 1-2 mm diameter classes were significantly different among the treatments ($P<0.01$; $P<0.04$, respectively; Table 6.1). The *'buffers vs. pastures'* contrast was significant only for 0-1 mm diameter class. The RLD for the buffers was about 5 times higher for the 0-1 mm diameter class compared to pasture treatments. The RLD decreased with an increase in the root diameter class (Table 6.1).

Depth influenced RLD of all root diameter classes and the total RLD ($P<0.01$). The interaction between treatments and soil depth for RLD was also found to be significant for the total and all root diameter classes ($P<0.01$; Table 6.1). The RLD decreased exponentially with soil depth ($r^2 = 0.38$; Fig. 6.2). About 70% of the total RLD was present in the top 30 cm of soil (Fig. 6.3). Buffers (3878.1 m/m^2) had three times higher total root length compared with pastures (1270.8 m/m^2; Fig. 6.4). The AgB treatment (4110.4 m/m^2) had the highest and CG treatment (355.9 m/m^2) had the lowest total RLD (Fig. 6.4).

The root length density values from the current study were correlated with soil bulk density values reported in a previous study by Kumar et al. (2008) for the same experimental site. The root length density decreased with an increase in the soil bulk density as observed for all the treatments; RLD was negatively correlated with soil bulk density ($r = -0.69$). The buffer treatments had better root growth probably due to lower soil bulk density and higher soil porosity for these treatments compared to pasture treatments (Kumar et al. 2008). Mattos et al. (2003) found that root density decreased from 1.85 cm cm^{-3} at the 0- to 15-cm depth to 0.16 cm cm^{-3} at the 30- to 45-cm depth within 50 cm from the tree trunk. They also reported that at 150 cm from the tree trunk, root density was 48% less as compared to 50 cm from the tree trunk. Higher root length density in the buffers will probably assist in reducing surface runoff and soil erosion. It has been reported in previous studies that the soil erosion rate is inversely proportional to root length density (Kamyab 1991) and root volume (Dunaway et al. 1994).

At least 50% of the root length has been reported to be in the upper 0.3 m of soil and 95% within the upper 2 m of soil (Schenk and Jackson 2002). Root length and mass generally decrease exponentially with soil depth which was first proposed by Gerwitz and Page (1974). A similar exponential decrease pattern (r^2 = 0.39) of the root length and mass was found in the current study. Other researchers, Jama et al (1998), also reported that root length of trees declined with depth. A decrease in root length density of soybean and corn roots with soil depth was reported by Allmaras et al (1975). Surface soil horizons generally have a higher density of roots as these horizons have higher nutrient and oxygen concentrations and lower soil bulk density (McGinty 1976; Gray and Leiser 1982; Coppin and Richards 1990). Wynn et al (2004) found that root length density decreased with increasing soil depth and root diameter. Findings in the current study agree with results from other studies.

Root Dry Weight and Surface Area

Root surface area is an indicator of the potential for exploitation of water and nutrients from soil zones (van Noordwijk et al. 1994). Root dry weight and surface area of roots were significantly different ($P<0.01$) among treatments in 2008 ($P<0.01$; Table 6.1). Significant differences were also found for the *'buffers vs. pastures'* contrast for both parameters. On average, buffer treatments had 288% (0.101 g/100 cm^3) and 210% (42.75 cm^2/100 cm^3) higher root dry weight and surface area, respectively, compared to pasture treatments (0.026 g/100 $cm^3$and 13.8 cm^2/100 cm^3, respectively). Root dry weight and surface area for AgB and GB treatments were significantly higher relative to the CG treatment; the surface area was also significantly higher for the RG treatment compared to the CG treatment. These findings support the data mentioned in the root length section. The buffer treatments (AgB and GB) had larger diameter roots as compared to grazed pasture systems (RG and CG; Table 6.1).

The surface area was also determined for the three root diameter classes: 0-1, 1-2 and 2-3 mm diameter. The surface area was significantly different among the treatments for the 0-1 mm diameter class ($P<0.01$; Table 6.1). Surface area was highest for the buffers compared to pasture treatments for all the root diameter classes with significant differences occurring for the 0-1 and 2-3 mm diameter classes.

Depth significantly influenced the root dry weight and surface area ($P<0.01$). Significant interactions between treatments and soil depth for both parameters was also found ($P<0.01$; Table 6.1). Root dry weight decreased with soil depth; a similar decrease with soil depth was also found for surface area (Fig. 6.3). About 75% of the total surface area was present in the top 30 cm of soil (Fig. 6.3). Buffers (7.98 m^2/m^2) had 287% (3.87 times) higher total surface area compared with pastures (2.06 m^2/m; Fig. 6.4). Total surface area is an indicator of the potential for exploitation of water and nutrients from the soil profile (van Noordwijk et al. 1994). Higher root surface area in the buffers may enhance uptake of water and nutrients from the soil as compared to pasture treatments. The total surface area for the AgB treatment was highest (8.35 m^2/m^2) and for the CG treatment was the lowest (0.53 m^2/m^2).

Root and Soil Carbon Content

Root carbon for the AgB, GB, and RG treatments was determined for the 70-cm deep soil profiles in 10-cm depth intervals. The root samples were insufficient below the 70 cm soil depth for the determination of root carbon. For the CG treatment, root carbon was determined for the whole soil profile (0-70 cm) by combining the entire root sample from all the soil depths, as the sample size was insufficient to determine carbon for each horizon for each replicate.

Root carbon (C_{root}) was significantly different among the treatments ($P<0.001$). The C_{root} was higher for the buffers as compared to pasture treatments. The C_{root} was about 3% higher for the buffers (32.2%) compared to RG treatment (31.3%; Fig. 6.5). The AgB treatment had the highest C_{root} throughout the soil profile as compared to the other treatments.

Soil carbon was determined for the 75-cm soil profile in 5-cm depth intervals. The soil carbon (C_{soil}) was also significantly different among the treatments ($P<0.001$; Fig. 6.5). The C_{soil} was about 115% higher for the buffers (0.86%) compared to pasture treatments (0.40%). The AgB treatment had the highest (0.93%) and RG treatment had the lowest (0.20%) C_{soil} throughout the profile (Fig. 6.5). The C_{soil} was slightly higher for the CG treatment compared to the RG treatment. This was probably due to the fact that cattle were continuously grazed in the CG area and manure deposition in this area by cattle may have improved the soil carbon of the CG treatment. The C_{soil} decreased with soil depth (Fig. 6.5).

Tree roots help in building up soil carbon. It was reported in previous studies that when agricultural land changed to forest land, an average increase in soil carbon of about 33.8 g C m^{-2} y^{-1} (Post and Kwon 2000) and 30.0 g C m^{-2} y^{-1} (Schlesinger 1990) occurred after 40-50 years. Similarly, Paul et al. (2002) estimated an increase of 30.2 g C m^{-2} y^{-1} after reforestation of agricultural lands. The percentage change in soil carbon for reforestation of agricultural land (0- to 30-cm depth) was estimated at 0.56% $year^{-1}$ (Polglase et al. 2000; Paul et al. 2002). Results of the current study agree with these findings. The study site was established in 2000 and the observed differences occurred within 7 to 8 years. More soil carbon accumulation could be expected, as trees mature and roots occupy more soil volume.

Spatial Distribution of Roots in Agroforestry Buffer

Tree roots are often not uniformly spatially distributed with distance from the tree trunk. Tree and grass roots in the AgB treatment were found to be at the highest density at 20 cm among the distances sampled, and decreased from 20 to 100 cm distance; however, the differences were not statistically significant (Fig. 6.6). Root length density at 20 cm from the tree trunk was about 8.6 and 25% higher compared to root length density at 50 and 100 cm distance, respectively. Similarly, root dry weight at 20 cm distance was about 11 and 12.5% higher compared to those at 50 and 100 cm. However, significant differences were not found in roots at any distance for both parameters. Similar to our results, decreasing tree root length with increasing distance from a tree row was reported by Van Noordwijk et al. (1996). In another study, Moreno et al (2005) found that the root length density of Holm-oak trees decreased with distance (20 to 120 cm from tree trunk) and depth. These results suggest that trees established for the protection of water and soil quality should be established at a tighter initial spacing, so that surface roots can help improve soil and water quality. Trees may be harvested once canopy closure occurs.

Conclusions

This study was conducted to examine the influence of agroforestry and grass buffers on root length density and root and soil carbon compared to grazed pasture systems. The RLD, root dry weight and surface area of roots for the buffers were higher compared to pasture treatments. Root and soil carbon were also higher for the buffers compared to pasture treatments. Buffer treatments (167 $cm/100cm^3$) had 4.5 times higher root length density as compared to pasture treatments (37.25 cm/100 cm^3). The AgB treatment had the highest (173.5 cm/100 cm^3) RLD and CG had the lowest (10.8 $cm/100cm^3$) RLD. Buffer treatments had 288 and 210%, respectively, higher dry weight and surface area of roots compared to pasture treatments. The root carbon was about 3% higher for the buffers compared to the RG treatment. The soil carbon was about 115% higher for the buffers compared to pasture treatments. All the measured root parameters decreased with soil depth.

The current study illustrates that buffers had the highest root length density and root carbon compared to pastures which may help in extracting water and nutrients from deeper in the soil profile which shallow root systems are unable to extract. The roots of the buffers have improved soil carbon which will improve soil structure, and hence improve soil hydraulic properties which aid in reducing surface water runoff and sediment loss from watersheds.

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References

Allaire-Leung SE, Gupta SC, Moncrief JF (2000) Water and solute movement in soil as influenced by macropore characteristics: macropore continuity. J Contam Hydrol 41:283-301

Allmaras RR, Nelson WW, Voorhees WB (1975) Soybean and corn rooting in southwestern Minnesota: I water-uptake sink II. Root distributions and related water inflow. Soil Sci Soc Am Proc 39:764-777

Atkinson D (1973) Observations on the phosphorus nutrition of two sand dune communities at Ross links. J Ecol 61:117-133

Bohm W (1979) Methods of studying root systems. Springer-Verlag. New York. pp188

Bowen GD (1985) Roots as a component of tree productivity. In: Cannell MGR and Jackson JE (eds) Attributes of trees as crop plants. Institute of terrestial ecology natural environment research council, Abbots Ripton UK, pp303-315

Briske DD, Derner JD, Brown JR, Fuhlendorf SD, Teague WR, Havstad KM, Gillen RL, Ash AJ, WillmsWD (2008) Rotational grazing on rangelands: reconciliation of Perception and Experimental Evidence. Rangeland Ecol Manage 61:3-17

Cadisch GP, de Willigen Suprayogo D, Mobbs DC, van Noordwijk M, Rowe EC (2004) Catching and competing for mobile nutrients in soils. In: van Noordwijk M G Cadisch and C K Ong (eds) Belowground interactions in tropical agroecosystems. MA:CABI Publishing, pp171-191

Comerford M, Kidder BG, Mollitor AV (1984) Importance of subsoil fertility to forest and non-forest plant nutrition. In: E L Stone (ed) Forest soils and treatment impact. Proc North Am Forest Soils Conf Knoxville, TN University of Tennessee, pp394-404

Coppin NJ, Richards IG (1990) Use of vegetation in civil engineering Butterworths London

Czyz E, Tomaszewska J (1993) Changes of aeration conditions and the yield of sugar beet on sandy soil of different density. Polish J Soil Sci 36:1-9

Dunaway D, Swanson SR, Wendel J, Clary W (1994) The effect of herbaceous plant communities and soil textures on particle erosion of alluvial streambanks. Geomorphology 9:47-56

Esthman J, Rose CW, Cameron DM, Rance SJ, Talsa M, Edword DAC (1990) Tree/pasture interaction at a range tree densities in an agroforestry experiments II Water uptake in relation to rooting pattern. Aust J Agric Res 41:696-707

Fuhlendorf SD, Engle DM (2001) Restoring heterogeneity on rangelands: ecosystem management based on evolutionary grazing patterns. Bioscience 51:625-632

Gerwitz A, Page ER (1974) An empirical mathematical model to describe plant root systems. J Appl Ecol 11:773-781

Gold MA, Hanover JW (1987) Agroforestry systems for temperate zones. Agrofor Syst 5:109-121

Gray DH, Leiser A (1982) Biotechnical slope protection and erosion control. Van Nostrand Reinhold, New York

Heitschmidt RK, Taylor Jr CA (1991) Livestock production In: RK Heitschmidt and JW Stuth (eds) Grazing management: an ecological perspective. Portland OR USA: Timber Press, pp161–177

Jaiyeoba IA (1995) Changes in soil properties related to different land uses in part of the Nigerian semi-arid Savannah. Soil Use and Manage 11:84-89

Jama B, Buresh RJ, Ndufa JK, Shepherd KD (1998) Vertical distribution of roots and soil nitrate: tree species and phosphorus effects. Soil Sci Soc Am J 62:280-286

Jin CX, Romkens MJM, Griffioen F (2000) Estimating Manning's roughness coefficient for shallow flow in non-submerged vegetative filter strips. Trans ASAE 43:1459-1466

Jonsson K, Fidjeland L, Maghembe JA, Hogberg P (1988) The vertical distribution of fine roots of five tree species and maize in Morogoro Tanzania. Agrofor Syst 6:63-69

Kamyab I (1991) Streambank stability prediction for C6 stream type reconstruction. PhD dissertation, Univ of Nevada Reno

Kumar S, Anderson SH, Bricknell LG, Udawatta RP, Gantzer CJ (2008) Soil hydraulic properties influenced by agroforestry and grass buffers for grazed pasture systems. J Soil Water Conserv 63:224-232

Lal R (1996) Axe load and tillage effects on crop yields on a Mollic Ochraqualf in northwest Ohio. Soil Till Res 36:143-160

Lehmann J (2003) Subsoil root activity in tree-based cropping systems. Plant and Soil 255:319-331

Lipiec J, Håkansson I, Tarkiewicz S, Kossowski J (1991) Soil physical properties and growth of spring barley as related to the degree of compactness of two soils. Soil Till Res 19:307-317

Lipiec J, Hatano R (2003) Quantification of compaction effects on soil physical properties and crop growth. Geoderma 16:107-136

Lipiec J, Stêpniewski W (1995) Effects of soil compaction and tillage systems on uptake and losses of nutrients. Soil Till Res 35:37-52

Mattos D, Graetz DA, Alva AK (2003) Biomass Distribution and Nitrogen-15 Partitioning in Citrus Trees on a Sandy Entisol. Soil Sci Soc Am J 67:555–563

McGinty DT (1976) Comparative root and soil dynamics on a white pine watershed and in the hardwood forest in the Coweeta Basin. PhD dissertation, University of Georgia, Athens

Meek BD, Rechel ER, Carter LM, DeTar WR, Urie AL (1992) Infiltration rate of a sandy loam soil: effects of traffic tillage and plant roots. Soil Sci Soc Am J 56:908-913

Mekonnen K, Buresh RJ, Jama B (1997) Root and inorganic nitrogen distributions in sesbania fallow natural fallow and maize. Plant Soil 188:319-327

Merrill SD, Tanaka DL, Hanson JD (2002) Root length growth of eight crop species in Haplustoll soils. Soil Sci Soc Am J 66:913-923

Moreno G, Obrador JJ, Cubera E, Dupraz C (2005) Fine root distribution in Dehesas of Central-Western Spain. Plant and Soil 277:153-162

O'Neill GJ, Gordon AM (1994) The nitrogen filtering capability of Carolina poplar in an artificial riparian zone. J Environ Qual 23:1218-1223

Panayiotopoulos KP, Papadopoulou CP, Hatjjioannidou A (1994) Compaction and penetration resistance of an Alfisol and Entisol and their influence on root growth of maize seedlings. Soil Till Res 31:323–337

Paul KI, Polglase PO, Nyakuengama JG, Khanna PK (2002) Change in soil carbon following afforestation. Forest Ecology Manage 168:241-257

Polglase PJ, Paul KI, Khanna PK, Nyakuengama JG, O'Connell AM, Grove TS, Battaglia M (2000) Change in soil carbon following afforestation or reforestation Technical report no 20 Australian Greenhouse Office Canberra Australia

Post WM, Kwon KC (2000) Soil carbon sequestration and land-use change: processes and potential. Global Change Biology 6:317–327

Rasse DP, Smucker AJM, Santos D (2000) Alfalfa root and shoot mulching effects on soil hydraulic properties and aggregation. Soil Sci Soc Am J 64:725-731

Sanchez PA (1995) Science in agroforestry. Agrofor Syst 30:5-55

SAS Institute (1999) SAS user's guide Statistics SAS Inst Cary NC

Schenk HJ, Jackson RB (2002) The global biogeography of root systems. Ecological Monographs 72:311-328

Schlesinger WH (1990) Evidence from chronosequence studies for a low carbon-storage potential of soils. Nature 348: 232-234.

Stone EL, Kalisz PJ (1991) On the maximum extent of tree roots. For Ecol Man 46:59-102

Szabo AA, Osztoics Szilagyi F (2001) Natural wastewater treatment in Hungary. Water Sci Technol 44:331–338

Taboada MA, Lavado RS (1993) Influence of cattle trampling on soil porosity under alternate dry and ponded conditions. Soil Use and Manage 9:139-143

Traore O, Groleau-Renaud V, Plantureux S, Tubeileh A, Boeuf-Tremblay V (2000) Effect of root mucilage and modeled root exudates on soil structure. Eur J Soil Sci 51:575-581

Tufekcioglu A, Raich JW, Isenhart TM, Schultz RC (1999) Fine root dynamics, coarse root biomass, root distribution and soil respiration in a multispecies riparian buffer in Central Iowa USA. Agrofor Syst 44:163-174

Turner LW, Absher CW, Evans JK (1997) Planning fencing systems for intensive grazing management, University of Kentucky Cooperative Extension Service Pub ID-74 Lexington KY, pp 1-12

Udawatta RP, Henderson GS (2003) Root distribution relationships to soil properties in Missouri oak stands: a productivity index. Soil Sci Soc Am J 67:1869-1878

Udawatta RP, Krstansky JJ, Henderson GS, Garrett HE (2002) Agroforestry practices runoff and nutrient loss: a paired watershed comparison. J Environ Qual 31:1214-1225

van Noordwijk M, Brouwer G (1991) Review of quantitative root length data in agriculture. In: Persson H and B L McMichael (eds) Plant roots and their environment, Amsterdam The Netherlands: Elsevier, pp 515-525

van Noordwijk M, Floris J (1979) Loss of dry weight during washing and storage of root samples. Plant Soil 53:239-243

van Noordwijk M, Lawson G, Soumare A, Groot JJR, Hariah K (1996) Root distribution of trees and crops competition and/or complementarity. In: CK Ong and P Huxley (eds) Tree Crop Interactions- a physiological approach, CAB International Wallingford UK, pp 319-364

van Noordwijk M, Spek LY, de Willigen P (1994) Proximal root diameter as predictor of total root size for fractal branching models. Plant Soil 164:107-117

Vandenbeldt RJ (1991) Rooting systems of western and southern African *Faidherbia albida* (Del.) A. Chev. (syn. *Acacia albida* Del.): a comparative analysis with biogeographic implications. Agrof Sys 14:233-244

Voisin A (1959) Grass productivity New York NY USA: Philosophical Library p353

Warren SD, Blackburn WH, Taylor CA (1986) Soil hydrologic response to number of pastures and stocking density under intensive rotation grazing. J Range Manage 39:500-504

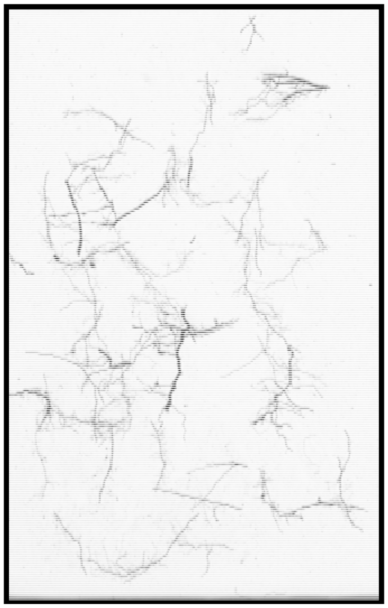
Wienhold BJ, Tanaka DL (2000) Haying tillage and nitrogen fertilization influences on infiltration rates at a conservation reserve program site. Soil Sci Soc Am J 64:379-381

Wynn TM, Mostaghimi S, Burger JA, Harpold AA, Henderson MB, Henry LA (2004) Variation in root density along stream banks. J Environ Qual 33:2030–2039

Table 6.1. Root parameters [(dry weight, root length density, and surface area for all size classes, Total) and (root length density and surface area for 0-1, 1-2 and 2-3 mm diameter classes)] for the different root diameter classes for the agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) treatments, and the analysis of variance (2008 year).

	Root parameters								
				Root diameter classes					
	Total			0-1 mm		1-2 mm		2-3 mm	
	Dry weight	Root length	Surface area	Root length	Surface area	Root length	Surface area	Root length	Surface area
	(g/ 100 cm^3)	(cm/ 100 cm^3)	(cm^2/ 100 cm^3)	(cm/ 100 cm^3)	(cm^2/ 100 cm^3)	(cm/ 100 cm^3)	(cm^2/ 100 cm^3)	(cm/ 100 cm^3)	(cm^2/ 100 cm^3)
Treatment									
AgB	0.096a	173.5a	41.7a	125.2a	23.3a	16.1a	6.9a	3.8a	3.8a
GB	0.106a	160.5a	43.8a	119.2a	16.5a	20.4a	7.0a	5.1a	4.8a
RG	0.048ab	63.7b	26.1a	38.0b	12.8a	20.1a	5.0ab	3.4a	0.2a
CG	0.004b	10.8b	1.5b	10.5b	1.4b	0.2b	0.1b	0.0a	0.0a
	Analysis of variance P > F								
Treatment	<0.001	<0.001	0.012	<0.001	<0.001	0.04	0.091	0.184	0.113
Buffers vs. Pastures	<0.001	<0.001	<0.001	<0.001	<0.001	0.145	0.062	0.063	0.006
Depth	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Treatment by depth	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.043

Means followed by the same letter are not significantly different at the 0.05 probability level.



Agroforestry Buffer (AgB)

Grass Buffer (GB)

Rotationally Grazed (RG)

Continuously Grazed (CG)

Fig. 6.1. Typical scanned root samples from the surface 0-10 cm soil horizon for the agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) treatments.

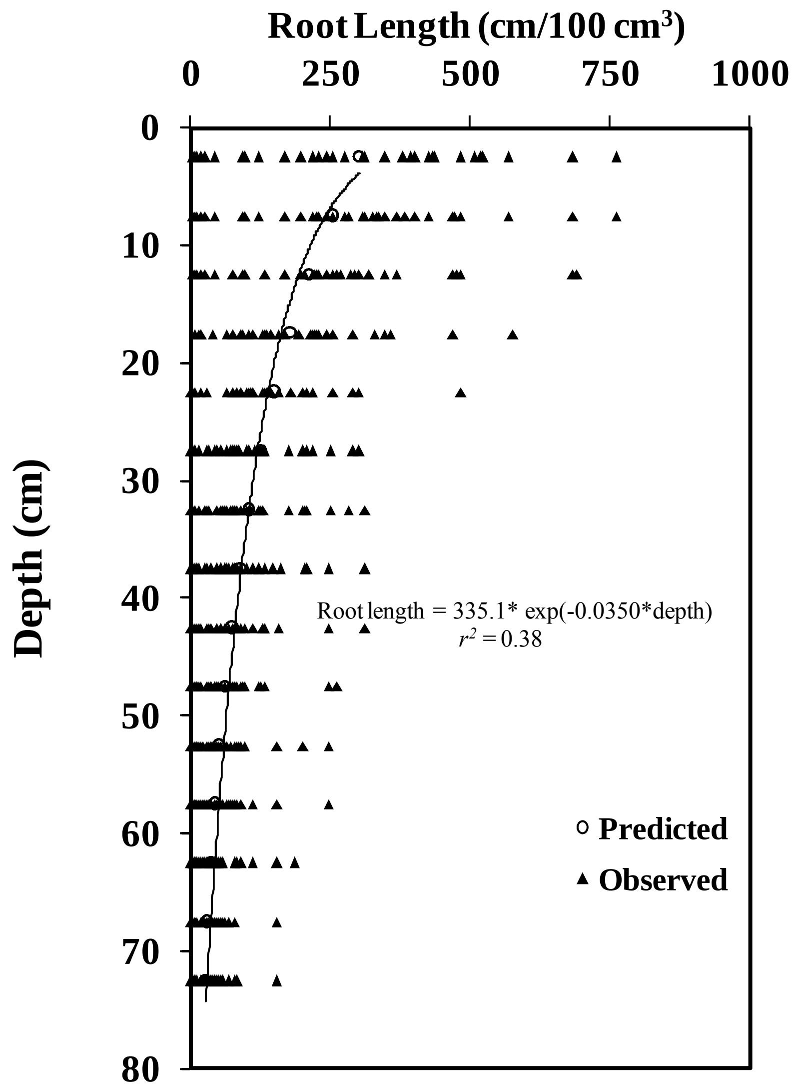


Fig. 6.2. Vertical distribution of root length density in a Hapludalf soil profile, averaged across all four treatments.

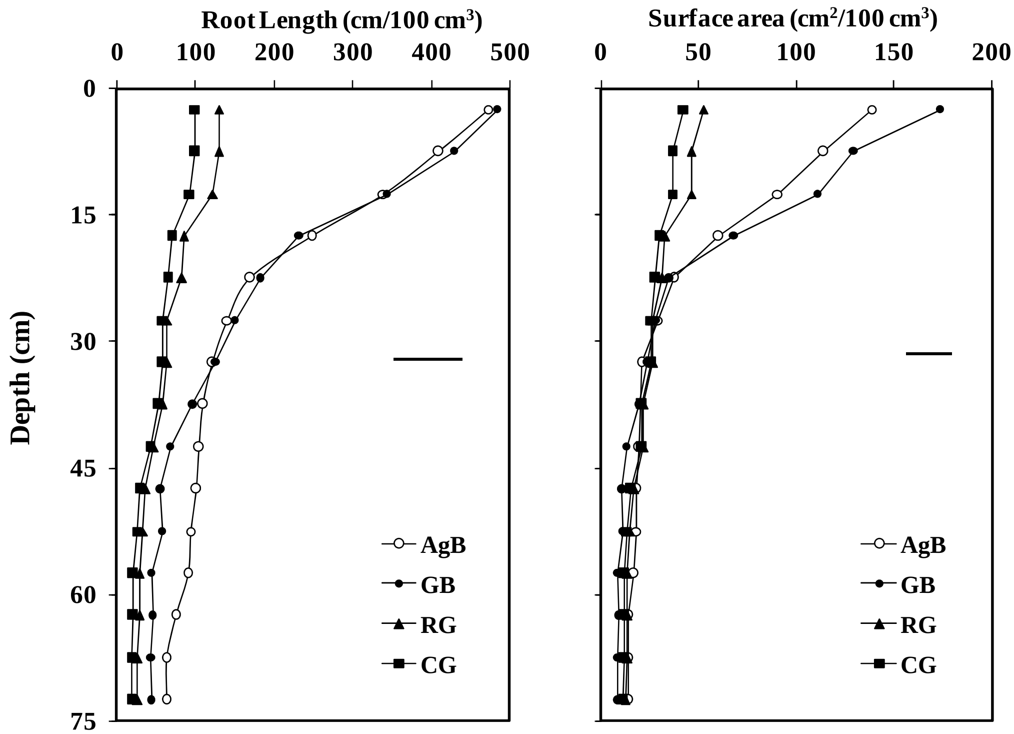


Fig. 6.3. Average root length density and surface area for the agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) treatments. The bar indicates LSD (0.05) values with significant differences among treatments.

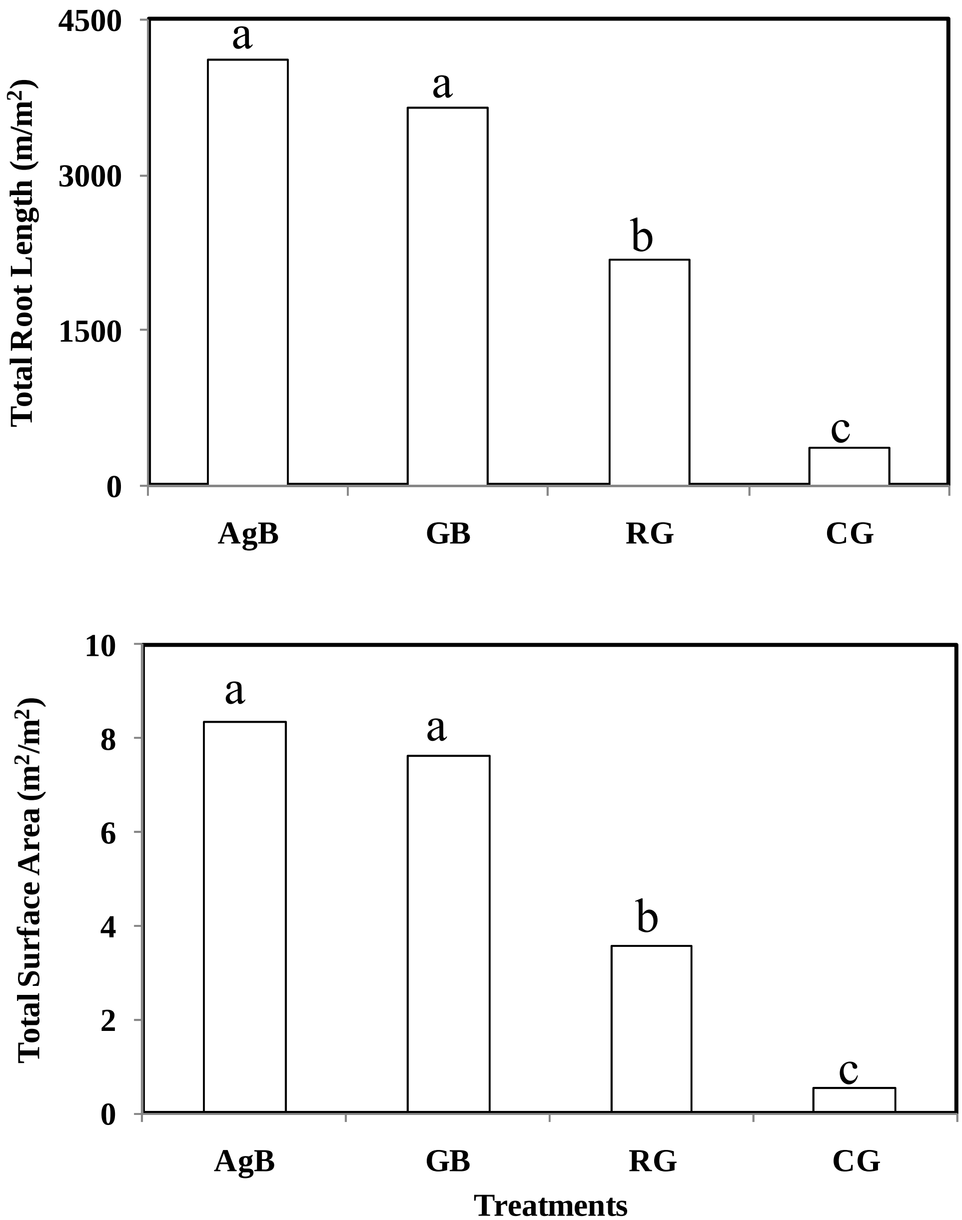


Fig. 6.4. Total root length and total surface area for the agroforestry buffer (AgB), grass buffer (GB), rotationally grazed pasture (RG) and continuously grazed pasture (CG) treatments for 0-75 cm soil depth. Mean values with the same letter are not significantly different at the 0.05 level.

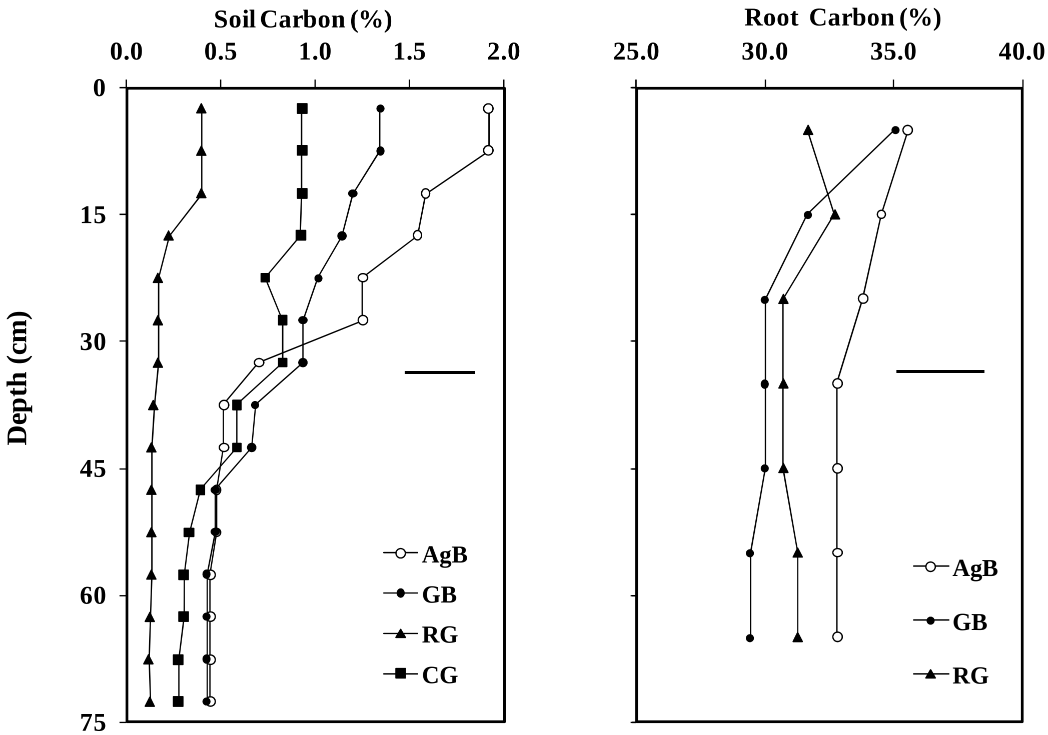


Fig. 6.5. Average soil and root carbon for the agroforestry buffer (AgB), grass buffer (GB), and rotationally grazed pasture (RG) treatments. For the continuously grazed (CG) treatment the soil carbon was 28.7% for the whole profile; insufficient root sample was available for the carbon analysis in CG treatment by soil depth. Bars indicate LSD (0.05) values with significant differences among treatments.

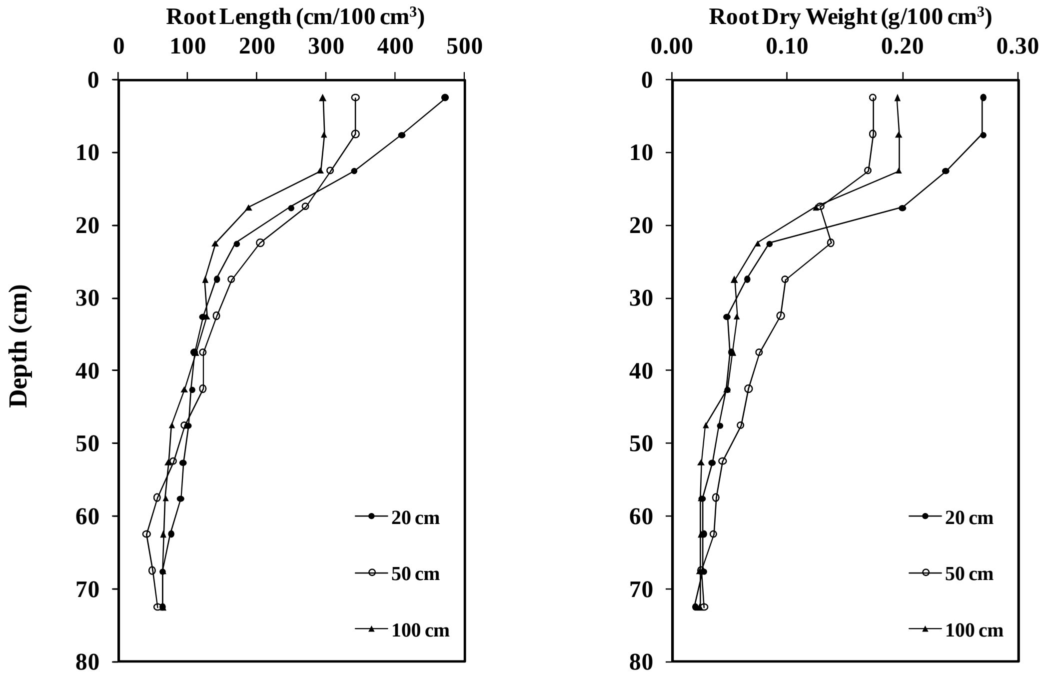


Fig. 6.6. Spatial distribution of root length density and root dry weight measured at 20, 50 and 100 cm distance from the tree trunk in the agroforestry buffer treatment

CHAPTER 7

APEX MODEL SIMULATION OF RUNOFF AND SEDIMENT LOSSES FROM AGROFORESTRY BUFFERS FOR WATERSHEDS UNDER PASTURE MANAGEMENT

ABSTRACT

Buffers have been found to reduce non-point source pollution (NPSP) from watersheds. Hydrologic simulation models may assist in predicting the effects of buffers on runoff and sediment losses from small watersheds. The objective of this study was to calibrate, validate and simulate runoff and sediment losses and compare with values under agroforestry buffer watersheds and control watersheds (no buffer) for seven years. The experimental design consists of four watersheds under pastures management which were monitored from 2002 through 2008; two with agroforestry buffers (AgB 100 and AgB 300) and two control watersheds (CW 400 and CW 600). Pasture areas included red clover (*Trifolium pretense* L.) and lespedeza (*Kummerowia stipulacea* Maxim.) planted into fescue (*Festuca arundinacea* Schreb.) while AgB included Eastern cottonwood trees (*Populus deltoids* Bortr. ex Marsh.) planted into fescue. The model was calibrated from 2002 to 2005 and was validated from 2005 to 2008. The r^2 and NSE values for the calibration and validation period of the runoff varied from 0.52 to 0.78 and 0.50 to 0.74, respectively. The model did not predict sediment loss very well probably due to insufficient number of measured events and low measured sediment loss. The measured runoff was 57% higher for CW watersheds compared to AgB watersheds. The measured sediment loss was 95% higher for CW watersheds compared to AgB watersheds. After calibrating and validating the model, it was run for long-term scenario analyses for 10 years from 1999 to 2008. Buffer width had an influence on the runoff. Simulated runoff decreased 24% when the buffer width was doubled compared to losses associated with the measured buffer width. Simulated runoff from the CW watersheds was 11% higher with double stocking density (relative to measured density) compared to AgB watersheds with double stocking density. With half stocking density (relative to measured density), the AgB watershed had 18% lower runoff compared to CW. Results from this study imply that establishment of agroforestry buffers on grazed pasture watersheds reduce runoff and sediment losses compared to control watersheds without buffers.

Keywords**:** agroforestry buffer, AgB; agricultural policy extender (APEX) model; CW, control watershed; NSE, Nash and Sutcliffe.

Introduction

To assess the long-term benefits of soil conservation practices, simulation models are often used. Models can provide long-term simulations of different combinations of cropping systems and conservation practices, effects of best management practices, and agricultural management practices, and assist in selection of appropriate conservation approaches (Wang et al., 2008). Models calibrated and validated with measured runoff, sediment and nutrient losses from watersheds have been used to assist policy makers in selecting conservation practices and allocating resources (Singh and Frevert, 2006). Watershed studies typically take long time periods to detect differences due to changes in annual weather patterns and time for plant establishment, especially where trees are involved. Due to monitoring costs and variable weather patterns, it is often difficult to assess management effects on environmental quality. This difficulty can be overcome by using simulation models which have been calibrated with measured data. There are several models that are currently being used to simulate management effects with alternative land uses: SWAT (Soil and Water Assessment Tool) model (Gassman et al. 2005; Gassman et al. 2007), WEPP (Water Erosion Prediction Project), EPIC (originally the Erosion Productivity Impact Calculator; now the Environmental Policy Integrated Climate) model (Gassman et al. 2005; Gassman et al. 2007), and APEX (Agricultural Policy Extender) (Williams et al., 2006; Williams et al., 2008). All these models require different types of inputs such as climate data, soil properties, land management, and landscape data to run the model effectively.

Wang et al. (2006) reported that different watershed models like CREAMS (a field-scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems; Knisel, 1980), ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria; Kiniry et al., 1992), APEX (Williams and Izaurralde, 2005), and SWAT (Soil and Water Assessment Tool; Arnold et al., 1998) have been developed to assess the effects of changes in land use, land cover, different management practices and weather conditions on soil and water erosion on small and large watershed scales. Wang et al. (2006) also reported that these models generally use a daily time step.

The Agricultural Policy Extender (APEX) model is suitable for small watersheds or field-scale simulations and is an extension of the EPIC model (Williams, 1990; Williams and Sharpley, 1989). This model was developed in the 1990's to address environmental problems associated with livestock and other agricultural production systems on a field-scale, on the whole farm-scale, or on a small watershed-scale (Gassman et al., 2005).

The APEX model is developed from several earlier mature and well tested models (Wang et al., 2008). A few examples from where the APEX model components are derived, as reported by Wang et al (2008), include: (i) the soil carbon cycling submodel taken from the Century model (Parton et al., 1993; Parton et al., 1994) as developed by Izaurralde et al. (2006), (ii) the pesticide component submodel was derived from the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987), and (iii) the plant competition component was derived from the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) model (Kiniry et al., 1992).

Harman et al. (2004) reported that the APEX model simulates different cropping and management practices and their environmental effects on a whole farm basis, which is a larger scale of simulation compared to the EPIC model. The APEX model has been used to evaluate government policy effects on soil erosion in the USA and simulate soil erosion (sheet and rill) caused by wind and water (Wang et al., 2006).

The APEX model is used to see the effects of different conservation practices such as buffers on runoff and sediment losses from watersheds (Harman et al., 2004). In Central Texas, Harman et al. (2004) evaluated atrazine use in corn (*Zea mays*) and sorghum (*Sorghum bicolor*) production on 66,000 ha for the Aquilla watershed using the APEX model to compare effects of conservation practices on runoff. In Missouri, Farrand et al. (2002) used the APEX model to calibrate the paired watershed study at the Greenley Research Center to predict environmental benefits of tree and grass buffer practices. Because of its strength in simulating agricultural management systems, the APEX model is used for cultivated cropland (Wang et al., 2006).

Installation of undisturbed buffers such as agroforestry buffers, grass buffers, and vegetative filter strips on the down slope edge of grazed pasture areas in watersheds has been shown to improve soil hydraulic properties (Kumar et al., 2008; Kumar et al., 2010) and has helped in reducing surface runoff and nutrient transport. These buffers or vegetative filters can help reduce the movement of sediments and nutrients from grazed pasture areas to streams (Daniels and Gilliam, 1996). The APEX model could be used to simulate runoff, sediment, and nutrient losses from these grazed pasture areas. This model can be used to simulate the effects of buffers, filter strips, grassed waterways, intensive grazing management, and also land application of manure removed from feedlots (Wang et al., 2008).

Few studies have evaluated and simulated the effects of buffers on runoff and sediment losses from grazed pasture systems. The objective of this study was to simulate runoff and sediment losses from grazed pasture watersheds with agroforestry buffers compared to watersheds with no buffers (control).

Materials and Methods

Location, Description and Land Management of Watersheds

The four small watersheds evaluated in this study are located at the Horticulture and Agroforestry Research Center (HARC) in New Franklin, Missouri (39°02’N, 92°46’W, 195 m above mean sea level; Fig. 7.1). The watersheds were established in 2000 to compare the influence of agroforestry buffers on runoff water quality.

Prior to establishment, most of the area was in tall fescue grass (*Festuca arundinacea* Schreb.). Two watersheds are divided into rotationally grazed (RG), continuously grazed (CG) and agroforestry buffer (AgB) areas; while the remaining two (control) watersheds are divided into RG and CG areas with no buffer. The dimensions and land management of all the watersheds are given in Tables 7.1 and 7.2. The pasture areas and buffers were seeded with tall fescue (*Festuca arundinacea* Schreb; Kentucky 31) in 2000. The pastures were seeded with red clover (*Trifolium pretense* L.) and lespedeza (*Kummerowia stipulacea* Maxim.) into the fescue in 2003. Eastern cottonwood trees (*Populus deltoids* Bortr. ex Marsh.) were planted into the fescue to create the agroforestry buffers in 2001. Trees were planted in four rows at 3-m spacing both within and between rows. Cottonwood trees are fast growing and reach about 35 meters with a lifespan of about 70 years.

Soils at the site are Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs). Additional details about the weather, watershed characteristics and management practices can be found in Kumar et al. (2008).

Grazing Schedule

Grazing was initiated at the site in late March or early April and discontinued in late October or early November each year. During late July or early August, the cattle were removed for about one month due to poor grass growth (Kumar et al., 2008).

Fences were installed between pasture areas and the agroforestry buffer areas to prevent cattle access to the buffers. Each year, cattle were introduced in the watershed area with weights between 450 to 590 kg. The number of cattle for each small watershed (0.8 ha) was three. Seventy-five percent of the grazing area was divided into six rotationally grazed paddocks and these were separated by a fence for cattle management.

The other 25% of the grazing area was continuously grazed. The cows were moved between paddocks on each Monday and Thursday with each paddock being grazed for 3.5 days and rested for 17.5 days.

Data Collection Methods

The runoff and sediment losses from the agroforestry buffer watersheds (AgB 100 and AgB 300) and control watersheds (CW 400 and CW 600) were collected from February/March to late-December. The data used for the current study were from March through November each year from 2002 to 2008. The runoff was measured in m^3 ha^{-1}, which then was converted to mm; whereas, sediments were measured in kg ha^{-1} and converted to tons ha^{-1}. The APEX runoff output and sediment output are in mm and tons ha^{-1} units.

Each watershed is instrumented with a 2-foot H flume, an ISCO water sampler (Lincoln, NE, USA), and an ISCO bubbler flow measuring device to record flow rate, water level, sampling time as well as collect water samples. During December, these units were removed from the watersheds because of low temperatures.

The sampler is controlled by the flow measuring devices to collect water samples. After each 5 m^3 flow, a 125-mL sample was collected and samples were composited and analyzed for sediment. Unprocessed samples were refrigerated at 4°C until analysis. After a runoff event, flow, level, and sample intake time data were downloaded to a laptop computer.

For the estimation of sediment weight, known volumes of a well mixed sample were filtered through a pre-weighed glass microfiber filter (934-AH) using a vacuum pump [maximum vacuum 7 lbs in^{-2} (48263.3 Pa) above ambient)]. The filters were then dried at 105°C and sediment weight was calculated.

Description of the APEX Model

The APEX model simulates cropping systems, cultural practices and their environmental effects on a whole-farm scale (Williams et al., 2008). The model is based on a daily time-step (Harman et al., 2004). The APEX model has been used to simulate agroforestry practices such as riparian buffers (buffers placed near the stream), shelterbelts, and farm analysis throughout Missouri and nearby states (FAPRI, 2002). This model simulates runoff and sediment loss from small farms (up to 2500 km^2 area), feeding areas, crop fields, or buffer strips or parts of larger watersheds with a variety of soil, climate, landscape, crop rotation and management combinations (Gassman et al., 2005).

The APEX model uses crop and land management data, cropping systems, soil and climate data (Wang et al., 2006). These researchers also reported that the APEX model also contains a database of more than 60 crops including vegetables, a few grass and tree species for simulation of runoff, sediment and nutrient losses.

The APEX model has components for routing water, sediments, nutrients, and pesticides across landscapes and channel systems to a watershed outlet (Wang et al., 2008). For estimating potential evaporation, the Hargreaves method was used (Hargreaves and Samani, 1985).

APEX Model Inputs

The APEX model inputs include: weather (precipitation, maximum and minimum temperature), soil properties, watershed management, grazing schedule, and site information (Table 7.1; Table 7.2; Table 7.3; Fig. 7.2). The input dataset was used for simulations from 2002-2008. The basic soil property (texture, pH, CEC, organic carbon) values up to 40 cm soil depth were used from previous publications for the current site (Kumar et al., 2008). The soil bulk density, saturated hydraulic conductivity, and soil water content at field capacity and wilting point were measured in 2006. The soil properties values from 30-40 cm soil depth were used for the 40-100 cm soil profile. The annual precipitation of the experimental site for the last 50 years (1956-2006 year) is 967 mm; mean temperature in July is 25.6°C and mean temperature in January is -2.1°C (Fig. 7.2; Kumar et al., 2008).

Grazing Component

Each AgB watershed had one continuously grazed area (CG), a rotationally grazed area (RG) and a buffer area; whereas, each control watershed had continuously grazed and rotationally grazed areas but no buffer area. The AgB100 and AgB300 watersheds were divided into 18 subareas (6 each for CG, RG, and buffer areas). For the CG and RG areas, one herd of three cows was assigned, and the buffers did not have any cows. For RG, cows were rotationally grazed whereas, for CG the cows were continuously grazed with no rest. For CW400 and CW600, a total of 12 subareas were formed (6 each for CG and RG areas).

Sensitivity Analysis of the APEX Model

Simulation Methodology

The APEX model operates on daily time step with simulations from 2002 through 2008. A sensitive analysis for all the watersheds were performed for the model and detailed information on parameters and their ranges are given in Table 7.4.

Model Calibration and Validation

The APEX model was calibrated using data from 2002 through 2005. The runoff and sediment yield data were collected from all four watersheds and these measured data were compared with the model simulated output data. The sensitive parameters were adjusted (given in Table 7.2) to improve the model output. These parameters were adjusted to allow for calibration using measured values for the 2002-2005 (Table 7.5).

After calibrating the model from 2002 to 2005, the validation for the model was performed from 2006 to 2008 by keeping the same parameters as used for the calibration period.

Evaluation of Model Performance

Simulated and measured values of runoff and sediment losses were compared using r^2, and Nash-Sutcliffe efficiency (EF) (Nash and Sutcliffe, 1970) coefficients. The Nash and Sutcliffe (1970) efficiency equation is as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Q_m - Q_s)^2}{\sum_{i=1}^{n}(Q_m - Q_a)^2} \quad (1)$$

where, NSE is the efficiency of the model, Q_m are measured values, Q_s are simulated values, Q_a is the average measured value, and n is the number of events. The APEX performance was also evaluated by conducting statistical tests with SAS (SAS Institute 1999).

Scenario Analysis

The model was calibrated for the 2002-2005 period and the same parameter values were used for the validation period from 2006 through2008. The r^2 and Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970) coefficients were calculated between the simulated and measured values for the evaluation period of the model. The calibrated and validated models for each watershed were run to assess several scenarios. Three scenario analyses were performed: (i) watersheds with and without buffers using half the buffer width of the experimental watersheds and double the buffer width of the experimental watersheds; (ii) watersheds containing only CG areas for the entire pasture and watersheds with only RG areas for the entire pasture area, and (iii) watersheds having grazed pasture areas with normal, half and double stocking densities.

Results and Discussion

APEX Model Calibration

The sensitive analysis of the APEX model showed that the model output was sensitive to the following parameters for the runoff: curve number (CN) retention parameter, Soil Conservation Service CN, runoff curve number initial abstraction, and Hargreaves potential evapotranspiration (PET) equation coefficient (Table 7.4). The parameters which were sensitive for sediment yield were sediment routing exponent, sediment routing coefficient, and sediment routing travel time coefficient (Table 7.4). The calibration of runoff and sediment yield was performed from 2002 to 2005. The calibration period included one year of grazing (2005).

The model was calibrated by adjusting these parameters for the 2002-2005 period (Table 7.5). The model was felt to be well calibrated based on NSE values greater than 0.51 and r^2 values greater than 0.52. The r^2 and NSE values for the AgB 100 watershed were 0.70 and 0.68, and for the AgB 300 were 0.52, and 0.51, respectively (Fig. 7.4). For the CW 400 watershed, r^2 and NSE values were 0.78 and 0.69, and for the CW 600 watershed the values were 0.65 and 0.63, respectively (Fig. 7.3).

The model was also calibrated for sediment loss. The same parameter settings which were used for calibration of runoff were used for sediment yield. The APEX model did not calibrate well for the sediment yield. The r^2 for the CW 400 watershed was 0.78 and NSE was 0.69 and these were the best among all the four watersheds (Fig. 7.5). The AgB watersheds had very little sediment loss which reduced the number of measured events and amount lost. Due to insufficient number of measured events from these watersheds, the model did not calibrate well.

APEX Model Validation

After calibration, the model was validated using the same parameter values. The model validation of runoff and sediment yield was performed for the 2006 to 2008 measurement years. The r^2 and NSE values for the runoff during the validation period for the AgB 100 watershed were 0.77 and 0.74, and for the AgB 300 watershed were 0.63, and 0.59, respectively (Fig. 7.4). For the CW 400 watershed, r^2 and NSE values were 0.62 and 0.60, and for the CW 600 watershed, the values were 0.53 and 0.50, respectively (Fig. 7.3).

The validation for sediment yield was also done with the same parameters set for runoff and sediment calibration. The current site did not have sufficient measured events for sediment loss, and because of this the model did not validate well. The r^2 and NSE for the CW 400 watershed was 0.19 and 0.17, respectively, and was the best amongst all four watersheds (Fig. 7.5).

Measured Runoff and Sediment Yield

The measured runoff from the agroforestry watersheds was lower compared to control watersheds. The total measured runoff from the AgB watersheds was about 348 mm, whereas runoff from the CW watersheds was about 548 mm (Fig. 7.6) from 2002 to 2008 (cumulative total of runoff from March through November for the seven years). The runoff for AgB watersheds (total of AgB 100 and AgB 300 watersheds) was about 36.4% lower compared to control watersheds (total of CW 400 and CW 600 watersheds). Udawatta et al. (2002) reported that agroforestry buffer strips reduced water runoff by about 9% compared to a control watershed with no buffer strips for a claypan soil. The buffers in the AgB100 and AgB 300 watersheds reduced the runoff compared to control watersheds. Similar findings were reported by De la Cruz and Vergara (1987) and Muschler and Bonnemann (1997). Agroforestry buffers help in reducing runoff from agricultural areas by improving soil hydraulic properties (Gilliam, 1994; Udawatta et al., 2002; Abu-Zreig et al., 2003; Lovell and Sullivan, 2006).

The AgB watersheds also had lower sediment loss compared to CW watersheds (cumulative total of sediment loss from March through November for the seven years). On average, AgB (46.9 kg ha^{-1}) watersheds had about 48.6% lower sediment loss compared to control (91.4 kg ha^{-1}) watersheds. These agroforestry buffers have been widely studied in agricultural settings and have reduced nutrient losses from agricultural lands (Baker et al., 2000; Udawatta et al., 2002). Buffers can remove up to 97% of sediments in runoff before entering into a stream if these buffers are well maintained (Lee et al., 2003; Lowrance et al., 2002). In a recent study of a riparian buffer strip in central Iowa, Lee et al. (2003) reported that switch grass (*Panicum virgatum* L.) buffers removed 95% of sediments compared to no buffers.

Scenario Analysis

After calibration, the model was used to predict runoff for certain selected scenarios. Long-term scenario analyses were evaluated from 1999 to 2008, keeping all the parameters unchanged after calibration (Table 7.6). Simulated runoff values are cumulative from March through November for the ten years.

Scenario 1: Buffer Width Influence on Runoff

The width of the agroforestry watersheds was reduced by half and doubled. The simulated runoff decreased with an increase in buffer width and increased with a decrease in buffer width compared to measured buffer width (Table 7.6).The runoff was significantly affected by the buffer width treatment ($P<0.01$). The CW watershed (no buffer) had the highest (877 mm) value of runoff as compared to AgB with half buffer width (866 mm), AgB with full buffer width (783 mm), and AgB with double buffer width (593 mm). The reduction in runoff was highly correlated with buffer width (*r* = -0.97). Doubling the measured buffer width appeared to reduce the runoff by 24% (Table 7.6). The vegetative filters or buffers can help reduce the movement of runoff, sediments and nutrients from source areas on uplands to the streams (Daniels and Gilliam, 1996); the bigger the buffer, the lower the runoff.

Scenario 2: Continuously Grazed (CG) and Rotationally Grazed (RG) Pasture Influence on Runoff

The AgB watersheds having either full CG or full RG pasture areas compared with CW watersheds having full CG areas or full RG areas were compared. The CW watershed with either RG or CG areas had higher runoff compared to AgB watersheds with either RG or CG areas; however the differences were not significant ($P<0.40$). The AgB watershed with RG (783 mm) had 10% lower runoff (not significant) compared to the AgB watershed with CG (873 mm; Table 7.6). This implies that the pasture area when rotationally grazed had better soil properties, less compaction from cattle and a trend in reduced runoff compared to continuously grazed pasture.

Scenario 3: Influence of Stocking Density on Runoff

Runoff from the AgB and CW watersheds was simulated with stocking density of the grazed pasture reduced by half and doubled. All four watersheds gave similar trends with runoff significantly affected by the six different treatments in this scenario ($P<0.02$). Reducing stocking density by half, decreased runoff; while increasing stocking density by two times increased runoff compared to the measured stocking density (Table 6). The

AgB watershed with half of the measured stocking density had 9% lower runoff and the AgB watershed with double the measured stocking density had 2.7% higher runoff compared to AgB watersheds with measured stocking density (Table 7.6). A similar trend was observed for the CW watersheds. The runoff from CW watersheds with half the measured stocking density had 0.7% lower and from watersheds with double the measured stocking density had 1.6% higher runoff compared to CW watersheds with measured stocking density.

Line et al (2000) reported that livestock exclusion fencing reduces the amount of sediment and nutrient losses from a grazing area. The reduction in the grazing area relative to the buffer and or reduction in the stocking density per unit area may reduce the amount of runoff and sediment losses from an area as observed in the current study.

The current findings showed that agroforestry buffers are important in reducing the runoff and sediment losses from grazed pasture watersheds. The results from this study showed when ungrazed agroforestry buffers were installed at the downslope edge of grazed pasture areas, they improved soil hydraulic properties and improved water infiltration. Additionally, pollutants from grazed pasture areas will probably be reduced when runoff from grazed pasture areas moves through the buffers prior to movement to streams or lakes. These pollutants can be immobilized by the roots and or infiltrate with the water in the buffer areas and reduce effects on water quality of streams.

Summary/Conclusions

Runoff and sediment losses from agroforestry (AgB) watersheds were compared with control watersheds (CW, without buffer). Runoff and sediment measured data from

AgB watersheds were 36.4 and 48.6%, respectively, lower compared with control watersheds. The runoff and sediment data were used to calibrate and validate the APEX model to simulate runoff and sediment loss during the years from 2002 through 2008. The r^2 and NSE values for the runoff calibration (2002 to 2005) and validation (2005 to 2008) periods for all four watersheds varied from 0.52 to 0.78 and 0.51 to 0.74, respectively. The APEX model did not simulate sediment loss very well (NSE values were less than 0.19) probably due to insufficient measured events and low sediment loss.

Measured runoff was 36.4% lower for AgB (348 mm) watersheds compared to CW (548 mm) watersheds. Measured sediment losses for AgB (46.9 kg ha^{-1}) watersheds were 49% lower compared to CW (91.4 kg ha^{-1}) watersheds (values are cumulative from March through November for seven measurement years). After calibrating and validating the model, the models were run for long-term scenario analyses for ten years. Buffer width had a significant influence on runoff. Runoff was 24% lower when the buffer width was doubled. Runoff from the AgB (804 mm) watersheds was 9.8% lower with double the stocking density compared to CW (891 mm) watersheds with double the stocking density. With half stocking density, the AgB (714 mm) watershed had 18% lower runoff compared to CW (871 mm).

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References

Abu-Zreig, M., R.P. Rudra, H.R. Whitely, M.N. Lalonde, and N.K. Kaushik. 2003. Phosphorus removal in vegetated filter strips. J. Environ. Qual. 32:613-619.

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. “Large Area Hydrologic Modeling and Assessment,” pt.1, “Model Development.” J. Amer. Water Res. Assoc. 34:73-89.

Baker, J.L., S.K. Mickelson, K. Arora, and A.K. Misra. 2000. The potential of vegetated filter strips to reduce pesticide transport. p. 272–287. *In* T.R. Steinheimer et al. (ed.) Agrochemical movement: Perspective and scale. American Chemical Society, Washington, DC.

Daniels, R.B., and J.W. Gilliam. 1996. Sediment and chemical load reduction by grass and riparian filters. Soil Sci. Soc. Am. J. 60:246–251

De la Cruz, R.E., and N.T. Vergara. 1987. Protective and ameliorative roles of agroforestry: an overview. p. 3-30. *In* N.T. Vergara and N.D. Briones (ed.) Agroforestry in the Humid Tropics. Environment and Policy Institute, Southeast Asian Regional Center for Graduate Study, Honolulu, Hawaii.

FAPRI, 2002. Food and Agricultural Policy Research Institute, College of Agriculture, Food and natural Resources, University of Missouri, Columbia, MO 65211.

Farrand, D.T., R.P. Udawatta, and H.E. Garrett. 2002. Predicting environmental benefits of Agroforestry preactices in northern Missouri using APEX. Agronomy abstracts 2002. Annual meetings. Indianapolis, Indiana, Nov. 10-14, 2002. American Society of agronomy, 677, South Segoe Road, Madison, Wisconsin 53711.

Gassman, P.W., M. Reyes, C.H. Green, and J.G. Arnold. 2007. The Soil and Water Assessment Tool: Historical development, applications, and future directions. Trans. ASABE 50(4): 1211- 1250.

Gassman, P.W., M. Reyes, C.H. Green, and J.G. Arnold. 2007. The Soil and Water Assessment Tool: Historical development, applications, and future directions. Trans. ASABE 50(4):1211-1250.

Gassman, P.W., J.R. Williams, V.W. Benson, R.C. Izaurralde, L.M. Hauck, C.A. Jones, J.D. Atwood, J.R. Kiniry, and J.D. Flowers. 2005. Historical development and applications of the EPIC and APEX Models. Working paper 05-WP 397. Centre for agricultural and riral development, Iowa state university, Ames, Iowa, 50011-1070.

Gilliam, J.W. 1994. Riparian wetlands and water quality. J. Environ.Qual. 23:896-900.

Hargreaves, G.H., and Z.A. Samani. 1985. Reference crop evapotranspiration from temperature. Applied Engr. Agric. 1:96-99.

Harman, W.L., E. Wang, and J.R. Williams. 2004. Reducing Atrazine Losses: Water Quality Implications of Alternative Runoff Control Practices. J. Environ. Qual. 33:7-12.

Izaurralde, R.C., J.R. Williams, W.B. McGill, and N.J. Rosenberg. 2006. Simulating soil C dynamics with EPIC: model description and testing against long-term data. Ecol. Model. 192 (3–4):362–384.

Kiniry, J.R., R. Blanchet, J.R. Williams, V. Texier, C.A. Jones, and M. Cabelguenne. 1992. “Sunflower Simulation using EPIC and ALMANAC Models.” Field Crops Res. 30:403–423.

Knisel, W.G. (ed.) 1980. CREAMS: A field scale model for chemical, runoff, and erosion from agricultural management systems: Conservation Research Report, no. 26, US Department of Agriculture, Washington, D.C. p. 640.

Kumar, S., S.H. Anderson, and R.P. Udawatta. 2010. Agroforestry and grass buffer influences on CT-measured macropores under grazed pasture systems. Soil Sci. Soc. Am. J. 74:1-10.

Kumar, S., S.H. Anderson, L.G. Bricknell, R.P. Udawatta, and C.J. Gantzer. 2008. Soil hydraulic properties influenced by agroforestry and grass buffers for grazed pasture systems. J. Soil Water Conserv.63:224-232.

Lee, K.H., Isenhart, T.M., Schultz, R.C. 2003. Sediment and nutrient removal in an established multi-species riparian buffer. J. Soil Water Conserv. 58(1), 1-8.

Leonard, R.A., W.G. Knisel, and D.A. Still. 1987. GLEAMS: groundwater loading effects of agricultural management system. Trans. ASAE 30 (5), 1403–1418.

Line, D.E., W.A. Harman, G.D. Jennings, E.J. Thompson, and D.L. Osmond. 2000. Nonpoint-source pollutant load reductions associated with livestock exclusion. J. Environ. Qual. 29:1882-1890.

Lovell, S.T. and W.C. Sullivan. 2006. Environmental benefits of conservation buffers in the United States: Evidence, promise, and open questions. Agriculture, Ecosystems and Environment 112:249-260.

Lowrance, R., and S.R. Crow. 2002. Implementation of riparian buffer systems for landscape management. p. 145-158. *In* L. Ryszkowski (ed.), Landscape ecology in Agroecosystems Management. CRC Press, Washington, DC.

Muschler R.G., and A. Bonnemann. 1997. Potentials and limitations of agroforestry for changing land-use in the tropics: experiences from Central America. Forest Ecol. Manage. 91:61–73

Nash, J. E., and J. E. Sutcliffe. 1970. River flow forecasting through conceptual models: Part 1. A discussion of principles. J. Hydrology 10(3):282-290.

Parton, W.J., D.S. Ojima, C.V. Cole, and D.S. Schimel. 1994. A general model for soil organic matter dynamics: sensitivity to litter chemistry, texture and management. In: Quantitative Modeling of Soil Forming Processes, SSSA Spec. Public. No. 39, Madison, WI, pp. 147–167.

Parton, W.J., J.M.O. Scurlock, D.S. Ojima, T.G. Gilmanov, R.J. Scholes, D.S. Schimel, T. Kirchner, J.C. Menaut, T. Seastedt, E. Garcia Moya, A. Kamnalrut, and J.I. Kinyamario. 1993. Observations and modelling of biomass and soil organic matter dynamics for the grassland biome worldwide. Global Biogeochem. Cycles 7:785–809.

SAS Institute. 1999. SAS user's guide. Statistics. SAS Inst., Cary, NC.

Singh, V.P., and D.K. Frevert. 2006. Watershed Models.CRC press. Taylor and Francis. Boca Raton, FL.

Udawatta, R.P., J.J. Krstansky, G.S. Henderson, and H.E. Garrett. 2002. Agroforestry practices, runoff, and nutrient loss: a paired watershed comparison. J. Environ. Qual. 31:1214-1225.

Wang, E., C. Xin, J.R. Williams, and C. Xu. 2006. Predicting Soil Erosion for Alternative Land Uses. J. Environ. Qual. 35:459-467.

Wang, X., P.W. Gassman, J.R. Williams, S. Potter, and A.R. Kemanian. 2008. Modeling the impacts of soil management practices on runoff, sediment yield, maize productivity, and soil organic carbon using APEX. Soil & Tillage Research 101:78–88.

Williams, J. R., and A. N. Sharpley. 1989. EPIC-Erosion/productivity impact calculator: 1. Model documentation. Technical Bulletin No. 1768. Washington, D.C.: USDA Agricultural Research Service.

Williams, J.R. 1990. The erosion productivity impact calculator (EPIC) model: A case history. Phil. Trans. R. Soc. Lond. 329:421-428.

Williams, J.R., and R.C. Izaurralde. 2005. The APEX model. BRC Rep. 2005-02. Blackland Res. Center, Texas A&M Univ., Temple, TX.

Williams, J.R., E. Wang, A. Meinardus, W.L. Harman, M. Siemers, and J.D. Atwood. 2006. APEX users guide v.2110. Temple, TX: Texas A&M University, Texas Agricultural Extension Service, Texas Agricultural Experiment Station, Blacklands Research Center.

Williams, J.R., R.C. Izaurralde, and E.M. Steglich. 2008. Agricultural Policy/Environmental eXtender Model: Theoretical documentation version 0604 (Draft). BREC Report # 2008-17. Temple, TX: Texas AgriLIFE Research, Texas A&M University, Blackland Research and Extension Center.

Table 7.1. The watershed dimensions including rotationally grazed, continuously grazed, and buffer areas for the AgB (100 and 300), and CW (400 and 600) watersheds.

Watershed					Buffer				Continuous Grazing				Rotational Grazing			
	Length	Width	Total area	Slope	Length	Width	Total area	Slope	Length	Width	Total area	Slope	Length	Width	Total area	Slope
	(m)	(m)	(ha)	(%)	(m)	(m)	(ha)	(%)	(m)	(m)	(ha)	(%)	(m)	(m)	(ha)	(%)
AgB 100	106.5	61.35	0.65	10.5	106.5	15.0	0.16	2.30	106.5	15.3	0.16	0.53	106.5	31	0.33	10.5
AgB 300	115.6	75.80	0.88	13.5	115.6	15.4	0.18	2.20	115.6	9.09	0.11	0.68	115.6	51.3	0.59	13.5
CW 400	71.0	68.10	0.48	12.5	-	-	-	-	71.00	9.50	0.067	0.71	71.00	58.6	0.42	12.5
CW 600	106.0	75.00	0.80	9.93	-	-	-	-	106.0	8.50	0.090	0.72	106.0	66.5	0.70	9.93

Table 7.2. The initial soil properties for the experimental site for agroforestry buffer (AgB100 and 300) and control (CW400 and CW600) watersheds at HARC, New Franklin. Data obtained from Kumar et al. (2008).

Soil depth	Soil	Sand	Silt	Clay	Texture	CEC‡	OC‡	-----pH-----	
cm	horizon	-------- $g\ kg^{-1}$---------				$cmol\ kg^{-1}$	$g\ kg^{-1}$	$CaCl_2$	H_2O
0-10	A	37	638	325	SCL‡	22.7	12	6.4	5.1
10-20	AB	38	639	322	SCL	21.9	9	6.4	5.1
20-30	Bt_1	40	641	319	SCL	21.2	6.1	6.4	5.1
30-40	Bt_2	40	641	319	SCL	21.2	6.1	6.4	5.1

‡SCL, Silty Clay Loam
‡CEC Cation Exchange Capacity
‡OC Organic Carbon

Table 7.3. The soil bulk density (BD), saturated hydraulic conductivity (K_{sat}), water content at field capacity, and water content at permanent wilting point (PWP) for the agroforestry buffer and control watersheds. Data obtained from Kumar et al. (2008).

Agroforestry Buffer					
				Soil water content	
Soil depth	Soil	BD	K_{sat}	Field capacity	PWP
cm	horizon	g cm^{-3}	mm hr^{-1}	%	%
0-10	A	1.04	182.16	0.38	0.15
10-20	AB	1.35	38.99	0.35	0.12
20-30	Bt_1	1.32	14.94	0.36	0.13
30-40	Bt_2	1.42	9.23	0.37	0.12
Rotationally Grazed Area (RG)					
0-10	A	1.35	8.41	0.43	0.12
10-20	AB	1.48	1.40	0.37	0.13
20-30	Bt_1	1.47	2.67	0.36	0.16
30-40	Bt_2	1.36	3.43	0.37	0.13
Continuously Grazed Area (CG)					
0-10	A	1.45	0.10	0.41	0.14
10-20	AB	1.46	7.75	0.36	0.12
20-30	Bt_1	1.43	2.35	0.40	0.16
30-40	Bt_2	1.43	2.26	0.39	0.16

Table 7.4. Input parameters and their ranges used in sensitive analysis for runoff and sediments in APEX model for AgB (100 and 300) and Control watersheds (400 and 600).

Input File	Parameter	Remarks	Range
		Runoff	
PARM	parm16	CN retention parameter	1.0-1.5
	parm17	Soil evaporation plant cover factor	0-0.05
	parm20	Runoff curve number initial abstraction	0.05-0.4
	parm23	Hargreaves PET equation coefficient	0.0023-0.0032
	Parm34	Hargreaves PET equation exp	0.5-0.6
APEXCOUNT	NVCNO		0-4.0
		Sediments	
PARM	parm18	Sediment routing exponent	1-1.5
	parm19	Sediment routing coefficient	0.01-0.05
	parm45	Sediment routing travel time coefficient	0.5-10

Table 7.5. The parameters and their values used for calibration analysis in APEX model for AgB (100 and 300) and Control watersheds (400 and 600).

Input File	Parameter	Remarks	Value
Watershed			
AgB 100 and AgB 300			
PARM	parm16	CN retention parameter	1.0
	parm17	Soil evaporation plant cover factor	0.5
	parm20	Runoff curve number initial abstraction	0.05
	parm23	Hargreaves PET equation coefficient	0.0023
	parm34	Hargreaves PET equation exp	0.6
	parm42	SCS curve number index coefficient	2.5
APEXCOUNT	NVCNO		0
CW 400 and CW 600			
PARM	parm16	CN retention parameter	1.0
	parm17	Soil evaporation plant cover factor	0.1
	parm20	Runoff curve number initial abstraction	0.05
	parm23	Hargreaves PET equation coefficient	0.0023
	parm34	Hargreaves PET equation exp	0.5
	parm42	SCS curve number index coefficient	0.5
APEXCOUNT	NVCNO		0

Table 7.6. Simulation results (means and analysis of variance) for three scenarios from 1999 through 2008 (cumulative total of runoff from March through November for the ten years): buffer width, rotational vs. continuous grazing, and stocking density.

Scenario 1 – Buffer Width	
Treatment Means	Runoff (mm)
Control watershed (no buffer)	877a
AgB watershed (half buffer width)	866a
AgB watershed (full buffer width)	783a
AgB watershed (double buffer width)	593b
Analysis of variance *p>F*	
Treatment	0.01
Scenario 2 – Rotational vs. Continuous Grazing	
Treatment Means	
AgB watershed with CG pasture area	873a
AgB watershed with RG pasture area	783a
Control watershed with CG pasture area	867a
Control watershed with RG pasture area	857a
Analysis of variance *p>F*	
Treatment	0.40
Scenario 3 – Stocking Density	
Treatment Means	
AgB watershed with full stocking density	783bc
AgB watershed with half stocking density	714c
AgB watershed with double stocking density	804abc
Control watershed (no buffer)	877ab
Control watershed with half stocking density	871ab
Control watershed with double stocking density	891a
Analysis of variance *p>F*	
Treatment	0.02

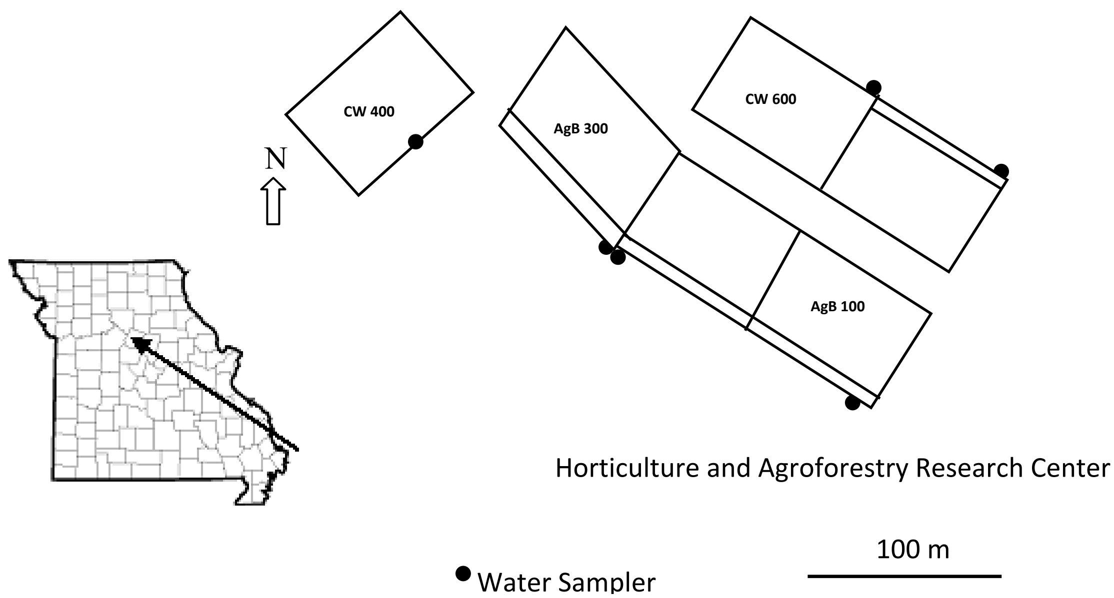


Fig. 7.1. The agroforestry (AgB) and control (CW) watersheds at the Horticulture and Agroforestry Research Center (HARC), New Franklin, Missouri. Narrow strips on AgB 100 and AgB 300 watersheds represent agroforestry buffers. The inset map shows approximate location of the HARC Center in Missouri, USA.

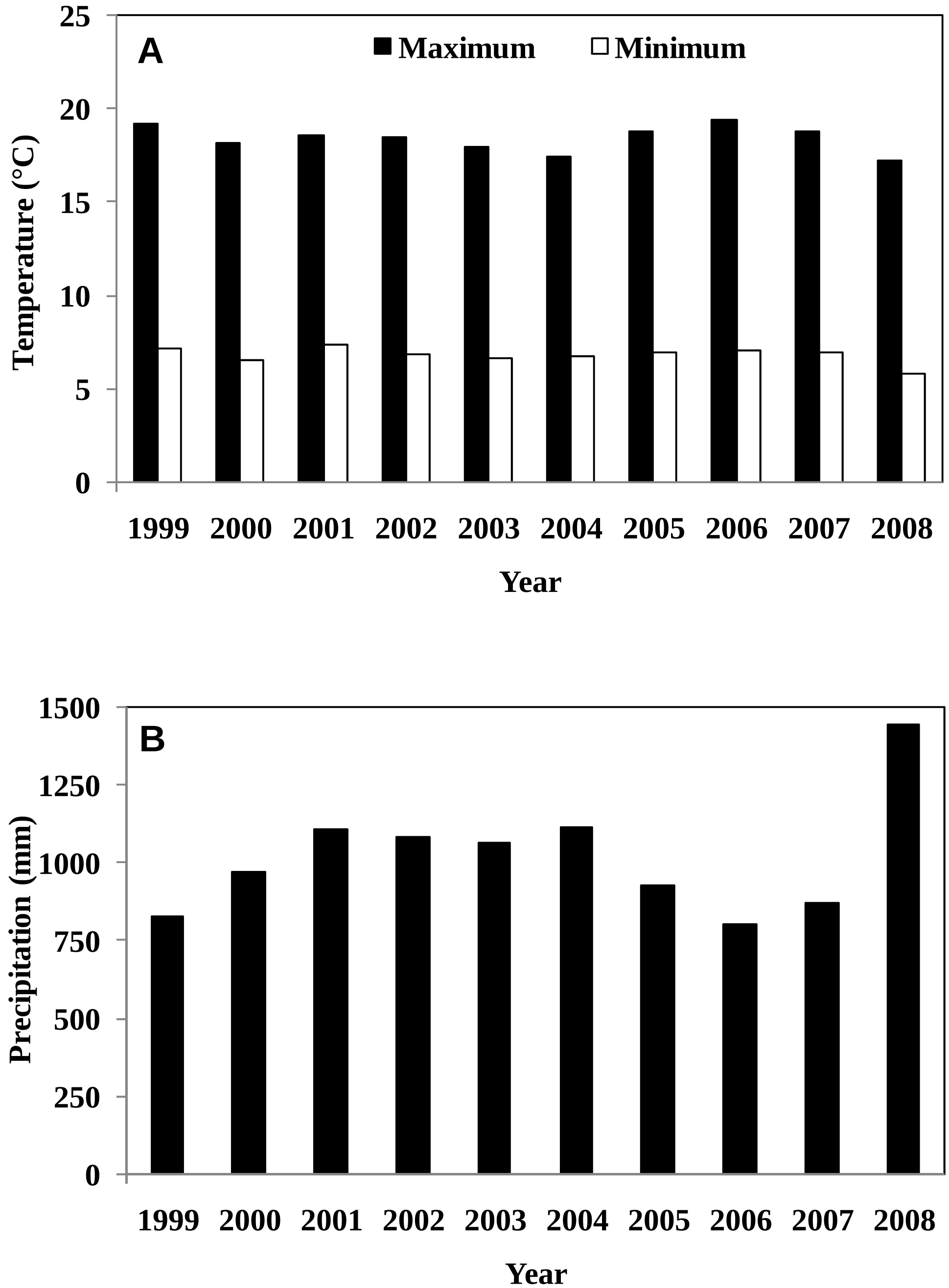


Fig. 7.2. Average annual temperature (maximum and minimum; A) and total annual precipitation (B) of the study site from 1999 to 2008.

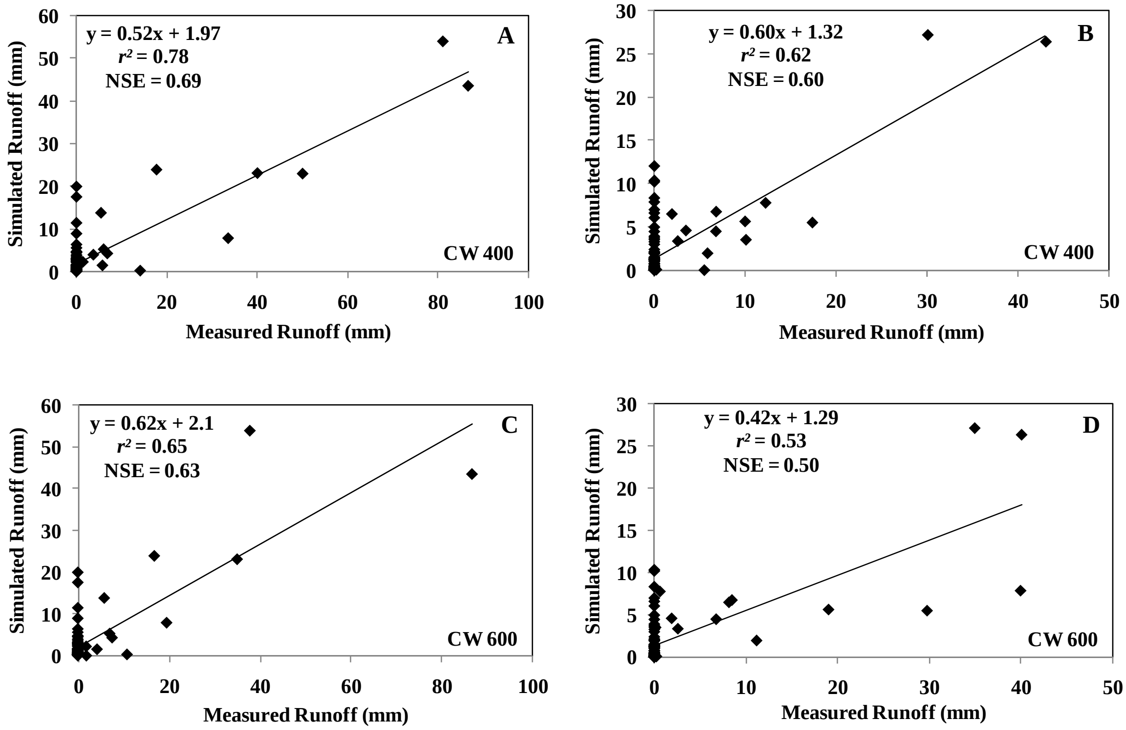


Fig. 7.3 Measured versus simulated runoff for calibration (A, CW 400; C, CW 600) from 2002 to 2005 and validation (B, CW 400; D, CW 600) from 2005 to 2008 (cumulative total of runoff from March through November each year).

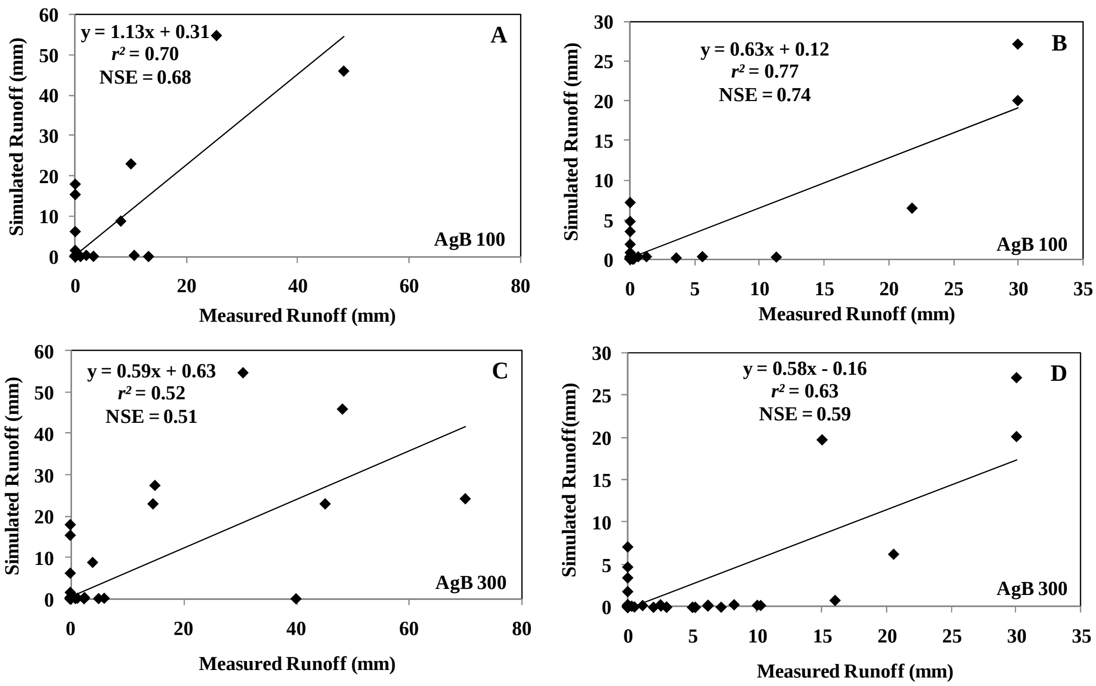


Fig. 7.4 Measured versus simulated runoff for calibration (A, AgB 100; C, AgB 300) from 2002 to 2005 and validation (B, AgB 100; D, AgB 300) from 2005 to 2008 (cumulative total of runoff from March through November each year).

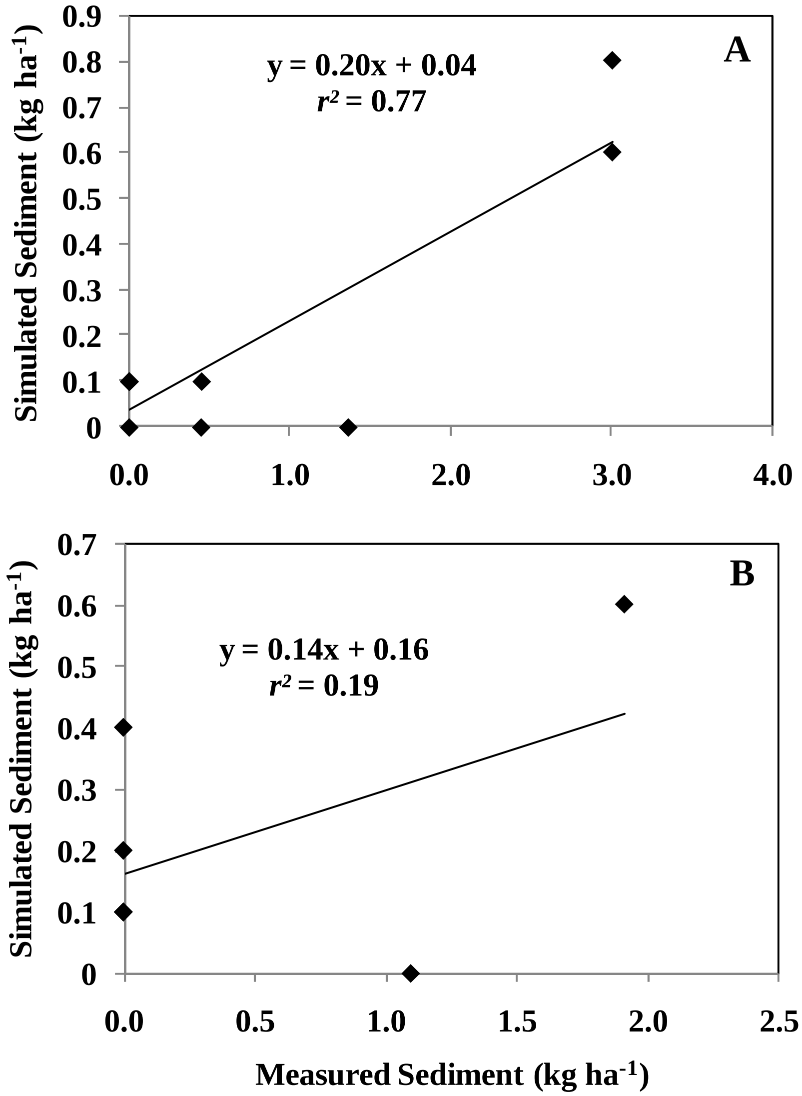


Fig. 7.5 Measured versus simulated sediment loss for calibration (A, CW 400) from 2002 to 2005 and validation (B, CW 400) from 2005 to 2008 (cumulative total of sediment yield from March through November each year).

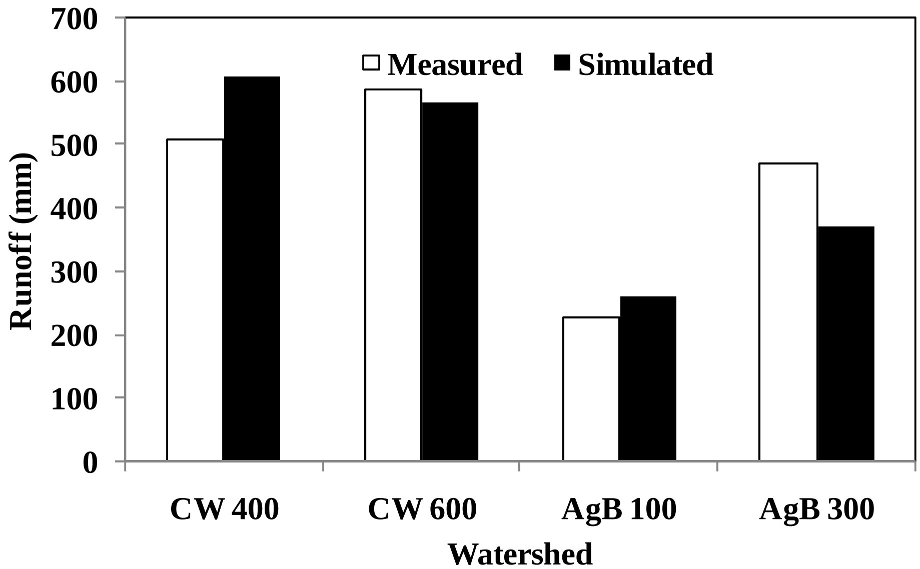


Fig. 7.6 Measured and simulated total runoff for control (CW 400 and CW 600) and agroforestry (AgB 100 and AgB 300) watersheds from 2002 to 2008 (cumulative total of runoff from March through November for the seven years).

CHAPTER 8

CONCLUSIONS

Soil hydraulic properties, root growth, runoff loss, and sediment loss from soils managed under rotationally-grazed pasture (RG), continuously grazed pasture (CG), grass buffer (GB), and agroforestry buffer (AgB) areas were studied from 2006-2009. The experimental site is located at the Horticulture and Agroforestry Research Center in New Franklin, MO. Grazed pasture areas (RG and CG) and GB areas included red clover (*Trifolium pretense* L.) and lespedeza (*Kummerowia stipulacea* Maxim.) planted into fescue (*Festuca arundinacea* Schreb.) while AgB included Eastern cottonwood trees (*Populus deltoids* Bortr. ex Marsh.) planted into fescue. Soils at the site were Menfro silt loam (fine-silty, mixed, superactive, mesic Typic Hapludalfs).

The following conclusions were determined from the five experimental studies:

Study 1 – Soil Hydraulic Properties

1. Bulk density (BD) was significantly lower for buffer treatments as compared to pasture treatments. Buffers had significantly higher water retained for the 0.0, -0.4, and -1.0 kPa pressures compared to pasture treatments, but lower water retained at -10.0, -20.0, and -30.0 kPa pressures.

2. Soil macroporosity (>1000 μm diam.) was 2.1 times higher for the buffer treatments compared to the pasture treatments for the 0-10 cm soil depth. Buffer treatments had greater total porosity, macroporosity, coarse mesoporosity (60 to 1000 μm diam.) and fine mesoporosity (10 to 60 μm diam.) but lower microporosity (< 10 μm diam.) compared to the pasture treatments.

3. The saturated hydraulic conductivity (K_{sat}) values were higher for buffers compared with grazed pasture areas which were related to the significantly higher total porosity and soil macroporosity found for the buffer treatments.

Study 2 – CT-Measured Pore Parameters

1. The buffer treatments had greater CT-measured total number of pores, number of macropores, number of coarse mesopores, porosity, macroporosity, coarse mesoporosity, area of largest pore, and fractal dimension of macropores compared with grazed pasture treatments.

2. The circularity of macropores was found to be lower in the buffer treatments than pasture treatments.

3. All CT-measured pore parameters except circularity were positively correlated with K_{sat}.

Study 3 – Ponded and Tension Infiltration

1. Buffers had 30 and 14 times higher quasi-steady state infiltration (q_s) in 2007 and 2008, respectively, as compared to pasture treatments.

2. The Green-Ampt and Parlange models appeared to adequately fit the measured infiltration data for the treatments as shown with coefficients of determination. Fitted sorptivity (S) and saturated hydraulic conductivity (K_s) parameters were highest for the GB treatment and lowest for the CG treatment.

3. Tension infiltration measurements were used to illustrate the influence of macropores on water infiltration in the soil. The infiltration rate decreased more between 0 and 150 mm tension for the buffer treatments compared to the pasture treatments. This was attributed to more macropores present in the buffer treatments which increased the water infiltration in the buffer areas compared to grazed pasture areas. Findings from the study were similar for both years.

Study 4 – Root Parameters

1. The root length density (RLD), root dry weight and surface area of roots for the buffers were higher compared to pasture treatments.

2. Buffer treatments (167 cm/100cm^3) had 4.5 times higher root length density as compared to pasture treatments (37.25 cm/100 cm^3). The AgB treatment had the highest (173.5 cm/100 cm^3) RLD and CG had the lowest (10.8 cm/100cm^3) RLD.

3. Buffer treatments had 288 and 210%, respectively, higher dry weight and surface area of roots compared to pasture treatments.

4. The root carbon was about 3% higher for the buffers compared to the RG treatment. The soil carbon was about 115% higher for the buffers compared to pasture treatments. All the measured root parameters decreased with soil depth.

Study 5 – Watershed Runoff and Sediment Losses

1. Runoff and sediment losses from the agroforestry (AgB) and control watersheds (CW) were measured. The APEX model was used to simulate runoff and sediment losses by using measured soil property data. The model was calibrated using data from 2002-2005 and then validated with data from 2006-2008.

2. The r^2 and NSE values for the runoff calibration (2002 to 2005) and validation (2005 to 2008) periods for all four watersheds varied from 0.52 to 0.78 and 0.51 to 0.74, respectively. The APEX model did not simulate sediment loss very well probably due to insufficient measured events and low sediment loss.

3. Runoff was 36% lower for AgB (348 mm) watersheds compared to CW (548 mm) watersheds. Sediment losses for AgB (46.9 kg ha^{-1}) watersheds were 49% lower compared to CW (91.4 kg ha^{-1}) watersheds.

4. Buffer width had a significant influence on runoff. Runoff was 24% lower when the buffer width was doubled. Runoff from the AgB (804 mm) watersheds was 9.8% lower with double the stocking density compared to CW (891 mm) watersheds with double the stocking density. With half stocking density, the AgB (714 mm) watershed had 18% lower runoff compared to CW (871 mm).

SUMMARY

The agroforestry and grass buffers improved the soil hydraulic properties compared to grazed pasture systems. Whearas, hydraulic properties deteriorated in grazed pastures. This study shows that soil hydraulic properties which are related to infiltration were higher within buffer treatments and lower within grazed pasture areas. Grazing reduced infiltration rates for pasture areas compared to buffer areas with no cattle access. The current findings show that the buffer areas had lower BD, and higher porosity, macroporosity, K_{sat} and infiltration rates which imply lower runoff compared to pasture areas. Buffer areas were fenced which prevented cattle grazing in these areas which probably benefited the soil hydraulic properties.

Grass and agroforestry buffers add organic matter to the soil from their roots and improve soil porosity and macroporosity and hence improve water infiltration into the soil. These undisturbed buffers (GB and AgB) had the highest RLD and C_{root} compared to pastures which may help in extracting water and nutrients from deeper in the soil profile which shallow root systems are unable to extract. The roots of the buffers have improved C_{soil} which will improve soil structure, and hence improve soil hydraulic properties which aid in reducing surface water runoff and sediment loss from watersheds. Runoff from the AgB watersheds was 36% lower compared to CW watersheds (without buffers). Sediment losses for AgB (46.9 kg ha^{-1}) watersheds were 49% lower compared to CW (91.4 kg ha^{-1}) watersheds. Buffer width had a significant influence on runoff which reduced the runoff from the AgB watersheds. Runoff was 24% lower when the buffer width was doubled.

APPENDICES

APPENDIX 1

A 1.1. Laboratory measurements for saturated hydraulic conductivity (Ksat) with bentonite around core edges and bulk density (BD) for soil core samples measured in 2006 and used in Chapter 3. CG= continuously grazed pasture, RG= rotationally grazed pasture, GB= grass buffer, and AgB=agroforestry buffer.

Treatment	Replication	Depth	K_{sat}	Bulk Density
		cm	mm hr^{-1}	g cm^{-3}
CG	1	0-10	0.004	1.49
CG	2	0-10	0.006	1.42
CG	3	0-10	0.025	1.46
CG	4	0-10	0.405	1.45
CG	5	0-10	0.137	1.52
CG	6	0-10	0.009	1.36
RG	1	0-10	0.30	1.37
RG	2	0-10	18.50	1.34
RG	3	0-10	4.90	1.31
RG	4	0-10	8.40	1.35
RG	5	0-10	2.39	1.40
RG	6	0-10	15.94	1.31
GB	1	0-10	126.30	1.16
GB	2	0-10	126.30	1.16
GB	3	0-10	126.30	1.16
GB	4	0-10	161.36	1.14
GB	5	0-10	104.55	1.15
GB	6	0-10	112.82	1.18
AgB	1	0-10	34.70	1.08
AgB	2	0-10	24.29	1.07
AgB	3	0-10	304.13	1.08
AgB	4	0-10	57.44	1.14
AgB	5	0-10	157.05	0.97
AgB	6	0-10	515.34	0.90
CG	1	0-20	7.80	1.43
CG	2	0-20	7.80	1.40
CG	3	0-20	9.46	1.46
CG	4	0-20	2.26	1.49
CG	5	0-20	11.30	1.49
CG	6	0-20	7.87	1.50
RG	1	0-20	0.339	1.51
RG	2	0-20	1.43	1.57

A1.1 Cont'd

Treatment	Replication	Depth cm	Ksat mm hr^{-1}	Bulk Density g cm^{-3}
RG	3	0-20	3.02	1.41
RG	4	0-20	1.23	1.44
RG	5	0-20	1.73	1.54
RG	6	0-20	0.66	1.44
GB	1	0-20	30.08	1.30
GB	2	0-20	22.07	1.29
GB	3	0-20	36.50	1.15
GB	4	0-20	36.50	1.28
GB	5	0-20	22.04	1.29
GB	6	0-20	71.60	1.33
AgB	1	0-20	194.63	1.33
AgB	2	0-20	21.90	1.32
AgB	3	0-20	3.51	1.41
AgB	4	0-20	2.05	1.42
AgB	5	0-20	7.81	1.34
AgB	6	0-20	4.01	1.30
CG	1	0-30	6.70	1.43
CG	2	0-30	3.07	1.45
CG	3	0-30	2.04	1.40
CG	4	0-30	0.105	1.45
CG	5	0-30	0.551	1.43
CG	6	0-30	1.66	1.45
RG	1	0-30	2.48	1.52
RG	2	0-30	1.26	1.48
RG	3	0-30	0.49	1.42
RG	4	0-30	1.48	1.46
RG	5	0-30	7.58	1.47
RG	6	0-30	2.70	1.46
GB	1	0-30	62.88	1.25
GB	2	0-30	27.46	1.30
GB	3	0-30	14.05	1.31
GB	4	0-30	5.33	1.22
GB	5	0-30	8.01	1.28
GB	6	0-30	23.60	1.24
AgB	1	0-30	15.85	1.23
AgB	2	0-30	2.72	1.39
AgB	3	0-30	11.24	1.34
AgB	4	0-30	16.89	1.34
AgB	5	0-30	16.18	1.33

A1.1 Cont'd

Treatment	Replication	Depth	Ksat	Bulk Density
CG	1	0-40	1.97	1.48
CG	2	0-40	2.68	1.47
CG	3	0-40	1.04	1.35
CG	4	0-40	0.76	1.45
CG	5	0-40	2.34	1.44
CG	6	0-40	4.74	1.42
RG	1	0-40	1.22	1.37
RG	2	0-40	2.03	1.36
RG	3	0-40	1.88	1.36
RG	4	0-40	1.10	1.39
RG	5	0-40	3.40	1.33
RG	6	0-40	10.95	1.34
GB	1	0-40	25.21	1.31
GB	2	0-40	89.42	1.31
GB	3	0-40	40.03	1.38
GB	4	0-40	11.31	1.33
GB	5	0-40	41.50	1.23
GB	6	0-40	41.50	1.31
AgB	1	0-40	7.06	1.42
AgB	2	0-40	5.74	1.44
AgB	3	0-40	8.20	1.40
AgB	4	0-40	4.81	1.45
AgB	5	0-40	9.99	1.42
AgB	6	0-40	19.57	1.40

A 1.2. Volumetric water content (m^3 m^{-3}) values for soil core samples at 0, -0.4, -1, -2.5, -5, and -10 kPa soil water pressure measured in 2006 and used in Chapter 3. CG= continuously grazed pasture, RG= rotationally grazed pasture, GB= grass buffer, and AgB=agroforestry buffer.

Treatment	Replication	Depth	Soil Water Pressure, -kPa							
			0.0	0.4	1.0	2.5	5.0	10.0	20.0	30.0
CG	1	0-10	0.45	0.44	0.43	0.43	0.42	0.42	0.41	0.40
CG	2	0-10	0.44	0.44	0.43	0.42	0.42	0.42	0.41	0.41
CG	3	0-10	0.47	0.45	0.43	0.42	0.41	0.40	0.40	0.39
CG	4	0-10	0.55	0.53	0.51	0.50	0.50	0.50	0.49	0.49
CG	5	0-10	0.45	0.42	0.40	0.39	0.38	0.38	0.37	0.37
CG	6	0-10	0.46	0.46	0.45	0.44	0.43	0.43	0.42	0.42
RG	1	0-10	0.52	0.49	0.47	0.46	0.44	0.44	0.43	0.43
RG	2	0-10	0.53	0.47	0.46	0.44	0.43	0.42	0.42	0.41
RG	3	0-10	0.53	0.48	0.47	0.45	0.44	0.44	0.43	0.43
RG	4	0-10	0.57	0.52	0.49	0.47	0.47	0.46	0.45	0.45
RG	5	0-10	0.55	0.48	0.47	0.46	0.45	0.44	0.43	0.43
RG	6	0-10	0.55	0.50	0.48	0.45	0.44	0.43	0.42	0.42
GB	1	0-10	0.62	0.55	0.48	0.44	0.42	0.41	0.40	0.39
GB	2	0-10	0.62	0.55	0.52	0.46	0.45	0.43	0.42	0.41
GB	3	0-10	0.62	0.55	0.52	0.46	0.45	0.43	0.41	0.40
GB	4	0-10	0.60	0.52	0.48	0.44	0.42	0.41	0.40	0.40
GB	5	0-10	0.57	0.54	0.49	0.45	0.43	0.42	0.41	0.40
GB	6	0-10	0.58	0.55	0.49	0.44	0.44	0.41	0.40	0.40
AgB	1	0-10	0.62	0.52	0.49	0.47	0.45	0.43	0.42	0.41
AgB	2	0-10	0.56	0.52	0.49	0.46	0.44	0.42	0.41	0.40
AgB	3	0-10	0.56	0.48	0.43	0.41	0.40	0.39	0.38	0.38
AgB	4	0-10	0.60	0.52	0.48	0.45	0.42	0.41	0.40	0.39
AgB	5	0-10	0.61	0.54	0.48	0.43	0.41	0.39	0.38	0.37
AgB	6	0-10	0.57	0.50	0.41	0.37	0.35	0.34	0.33	0.32
CG	1	0-20	0.46	0.44	0.41	0.38	0.37	0.36	0.35	0.35
CG	2	0-20	0.49	0.44	0.41	0.39	0.38	0.37	0.37	0.36
CG	3	0-20	0.48	0.44	0.42	0.39	0.38	0.38	0.37	0.37
CG	4	0-20	0.48	0.44	0.43	0.40	0.39	0.39	0.38	0.38
CG	5	0-20	0.51	0.43	0.41	0.39	0.38	0.37	0.37	0.36
CG	6	0-20	0.43	0.42	0.41	0.38	0.37	0.37	0.36	0.35
RG	1	0-20	0.45	0.43	0.42	0.41	0.40	0.39	0.38	0.37
RG	2	0-20	0.49	0.44	0.43	0.42	0.41	0.41	0.40	0.39
RG	3	0-20	0.53	0.45	0.44	0.42	0.40	0.38	0.37	0.36
RG	4	0-20	0.46	0.45	0.43	0.41	0.40	0.39	0.38	0.37
RG	5	0-20	0.51	0.42	0.41	0.40	0.39	0.38	0.37	0.36

A 1.2 Cont'd

Treatment	Replication	Depth	Soil Water Pressure, -kPa							
			0.0	0.4	1.0	2.5	5.0	10.0	20.0	30.0
GB	1	0-20	0.54	0.51	0.47	0.42	0.41	0.39	0.38	0.37
GB	2	0-20	0.53	0.50	0.49	0.46	0.43	0.40	0.40	0.37
GB	3	0-20	0.52	0.51	0.48	0.45	0.42	0.42	0.38	0.37
GB	4	0-20	0.61	0.49	0.46	0.42	0.39	0.38	0.37	0.36
GB	5	0-20	0.59	0.50	0.49	0.45	0.43	0.41	0.40	0.39
GB	6	0-20	0.52	0.49	0.46	0.42	0.40	0.39	0.37	0.37
AgB	1	0-20	0.50	0.46	0.44	0.42	0.39	0.38	0.37	0.36
AgB	2	0-20	0.51	0.47	0.45	0.42	0.39	0.38	0.36	0.35
AgB	3	0-20	0.51	0.44	0.42	0.41	0.38	0.36	0.35	0.34
AgB	4	0-20	0.48	0.43	0.43	0.41	0.39	0.38	0.37	0.36
AgB	5	0-20	0.50	0.46	0.43	0.41	0.39	0.37	0.35	0.34
AgB	6	0-20	0.52	0.47	0.43	0.40	0.38	0.36	0.35	0.34
CG	1	0-30	0.45	0.45	0.43	0.40	0.39	0.39	0.38	0.38
CG	2	0-30	0.50	0.46	0.44	0.43	0.42	0.42	0.41	0.40
CG	3	0-30	0.49	0.46	0.44	0.43	0.42	0.41	0.40	0.40
CG	4	0-30	0.50	0.46	0.44	0.43	0.43	0.42	0.41	0.41
CG	5	0-30	0.50	0.45	0.44	0.43	0.42	0.42	0.41	0.40
CG	6	0-30	0.46	0.46	0.44	0.43	0.42	0.42	0.41	0.41
RG	1	0-30	0.43	0.43	0.41	0.40	0.39	0.37	0.36	0.36
RG	2	0-30	0.51	0.44	0.43	0.41	0.39	0.38	0.37	0.36
RG	3	0-30	0.51	0.46	0.44	0.42	0.40	0.39	0.38	0.37
RG	4	0-30	0.48	0.45	0.43	0.42	0.41	0.40	0.39	0.38
RG	5	0-30	0.56	0.46	0.43	0.40	0.37	0.35	0.34	0.33
RG	6	0-30	0.49	0.48	0.46	0.44	0.42	0.40	0.39	0.38
GB	1	0-30	0.57	0.48	0.46	0.42	0.39	0.37	0.36	0.35
GB	2	0-30	0.54	0.50	0.48	0.43	0.40	0.38	0.37	0.36
GB	3	0-30	0.52	0.48	0.46	0.42	0.40	0.38	0.36	0.35
GB	4	0-30	0.57	0.51	0.48	0.42	0.39	0.36	0.34	0.34
GB	5	0-30	0.55	0.51	0.48	0.45	0.42	0.39	0.37	0.36
GB	6	0-30	0.52	0.52	0.46	0.41	0.39	0.37	0.36	0.35
AgB	1	0-30	0.53	0.50	0.47	0.44	0.41	0.39	0.38	0.37
AgB	2	0-30	0.53	0.46	0.45	0.43	0.41	0.39	0.38	0.37
AgB	3	0-30	0.51	0.45	0.44	0.41	0.38	0.36	0.35	0.34
AgB	4	0-30	0.55	0.47	0.46	0.42	0.40	0.38	0.37	0.36
AgB	5	0-30	0.50	0.47	0.45	0.41	0.37	0.35	0.34	0.32
AgB	6	0-30	0.50	0.47	0.45	0.43	0.40	0.39	0.38	0.37
CG	1	0-40	0.45	0.45	0.43	0.42	0.41	0.41	0.40	0.40

A 1.2 Cont'd

Treatment	Replication	Depth	Soil Water Pressure, -kPa							
			0.0	0.4	1.0	2.5	5.0	10.0	20.0	30.0
CG	2	0-40	0.48	0.45	0.44	0.43	0.42	0.42	0.41	0.41
CG	3	0-40	0.52	0.48	0.44	0.42	0.41	0.40	0.39	0.39
CG	4	0-40	0.49	0.46	0.45	0.43	0.43	0.42	0.41	0.41
CG	5	0-40	0.50	0.46	0.44	0.43	0.42	0.42	0.41	0.40
CG	6	0-40	0.45	0.44	0.41	0.40	0.39	0.38	0.37	0.37
RG	1	0-40	0.48	0.47	0.44	0.42	0.40	0.38	0.37	0.36
RG	2	0-40	0.48	0.46	0.44	0.42	0.40	0.38	0.37	0.36
RG	3	0-40	0.50	0.46	0.44	0.42	0.40	0.39	0.38	0.37
RG	4	0-40	0.46	0.46	0.44	0.42	0.41	0.40	0.39	0.38
RG	5	0-40	0.53	0.50	0.48	0.43	0.40	0.38	0.36	0.36
RG	6	0-40	0.52	0.49	0.47	0.44	0.41	0.39	0.38	0.37
GB	1	0-40	0.55	0.49	0.47	0.43	0.39	0.37	0.35	0.34
GB	2	0-40	0.56	0.47	0.43	0.39	0.37	0.36	0.35	0.34
GB	3	0-40	0.52	0.48	0.44	0.41	0.39	0.38	0.37	0.36
GB	4	0-40	0.51	0.50	0.48	0.43	0.41	0.40	0.40	0.39
GB	5	0-40	0.54	0.50	0.46	0.42	0.38	0.37	0.36	0.35
GB	6	0-40	0.61	0.53	0.49	0.43	0.39	0.38	0.37	0.36
AgB	1	0-40	0.49	0.48	0.46	0.43	0.40	0.39	0.37	0.37
AgB	2	0-40	0.48	0.46	0.45	0.42	0.40	0.38	0.37	0.36
AgB	3	0-40	0.53	0.46	0.44	0.42	0.39	0.38	0.37	0.36
AgB	4	0-40	0.54	0.48	0.46	0.44	0.42	0.40	0.39	0.38
AgB	5	0-40	0.51	0.48	0.46	0.43	0.40	0.38	0.37	0.36
AgB	6	0-40	0.52	0.48	0.46	0.43	0.42	0.39	0.38	0.37

A 1.3. Pore size distribution (m^3 m^{-3}) values for soil core samples measured in 2006 and used in Chapter 3. AgB=agroforestry buffer, GB= grass buffer, RG= rotationally grazed pasture, CG= continuously grazed pasture.

Treatment	Replication	Depth	Macropores (>1000 µm)	Coarse Mesopores (60- to 1000- µm)	Fine Mesopores (10- to 60- µm)	Micro-pores (<10 µm)	Total Pores
CG	1	0-10	0.01	0.02	0.02	0.40	0.45
CG	2	0-10	0.00	0.03	0.01	0.41	0.44
CG	3	0-10	0.01	0.04	0.02	0.39	0.47
CG	4	0-10	0.02	0.03	0.01	0.49	0.55
CG	5	0-10	0.03	0.03	0.02	0.37	0.45
CG	6	0-10	0.00	0.02	0.01	0.42	0.46
RG	1	0-10	0.04	0.04	0.02	0.43	0.52
RG	2	0-10	0.06	0.04	0.02	0.41	0.53
RG	3	0-10	0.05	0.04	0.02	0.43	0.53
RG	4	0-10	0.05	0.05	0.02	0.45	0.57
RG	5	0-10	0.07	0.03	0.02	0.43	0.55
RG	6	0-10	0.05	0.07	0.02	0.42	0.55
GB	1	0-10	0.07	0.13	0.03	0.39	0.62
GB	2	0-10	0.07	0.11	0.03	0.41	0.62
GB	3	0-10	0.07	0.11	0.05	0.40	0.62
GB	4	0-10	0.08	0.09	0.03	0.40	0.60
GB	5	0-10	0.03	0.11	0.03	0.40	0.57
GB	6	0-10	0.03	0.11	0.04	0.40	0.58
AgB	1	0-10	0.10	0.07	0.04	0.41	0.62
AgB	2	0-10	0.04	0.08	0.04	0.40	0.56
AgB	3	0-10	0.08	0.08	0.02	0.38	0.56
AgB	4	0-10	0.08	0.10	0.03	0.39	0.60
AgB	5	0-10	0.08	0.13	0.04	0.37	0.61
AgB	6	0-10	0.08	0.14	0.03	0.32	0.57
CG	1	0-20	0.03	0.07	0.02	0.35	0.46
CG	2	0-20	0.04	0.06	0.02	0.36	0.49
CG	3	0-20	0.04	0.05	0.02	0.37	0.48
CG	4	0-20	0.04	0.04	0.02	0.38	0.48
CG	5	0-20	0.08	0.05	0.02	0.36	0.51
CG	6	0-20	0.00	0.05	0.02	0.35	0.43
RG	1	0-20	0.01	0.03	0.03	0.37	0.45
RG	2	0-20	0.05	0.03	0.02	0.39	0.49
RG	3	0-20	0.07	0.06	0.04	0.36	0.53

A1.3 Cont'd

Treatment	Replication	Depth	Macropores (>1000 μm)	Coarse Mesopores (60- to 1000- μm)	Fine Mesopores (10- to 60- μm)	Micro-pores (<10 μm)	Total Pores
RG	5	0-20	0.09	0.03	0.03	0.36	0.51
RG	6	0-20	0.05	0.04	0.03	0.36	0.48
GB	1	0-20	0.04	0.10	0.03	0.37	0.54
GB	2	0-20	0.02	0.08	0.06	0.37	0.53
GB	3	0-20	0.01	0.09	0.05	0.37	0.52
GB	4	0-20	0.12	0.10	0.03	0.36	0.61
GB	5	0-20	0.09	0.08	0.04	0.39	0.59
GB	6	0-20	0.03	0.09	0.03	0.37	0.52
AgB	1	0-20	0.03	0.07	0.03	0.36	0.50
AgB	2	0-20	0.03	0.08	0.04	0.35	0.51
AgB	3	0-20	0.07	0.06	0.04	0.34	0.51
AgB	4	0-20	0.04	0.04	0.03	0.36	0.48
AgB	5	0-20	0.05	0.07	0.04	0.34	0.50
AgB	6	0-20	0.05	0.09	0.04	0.34	0.52
CG	1	0-30	0.00	0.06	0.02	0.38	0.45
CG	2	0-30	0.04	0.04	0.02	0.40	0.50
CG	3	0-30	0.04	0.04	0.02	0.40	0.49
CG	4	0-30	0.04	0.03	0.02	0.41	0.50
CG	5	0-30	0.05	0.03	0.02	0.40	0.50
CG	6	0-30	0.00	0.03	0.02	0.41	0.46
RG	1	0-30	0.00	0.04	0.03	0.36	0.43
RG	2	0-30	0.06	0.05	0.03	0.36	0.51
RG	3	0-30	0.05	0.06	0.03	0.37	0.51
RG	4	0-30	0.04	0.04	0.02	0.38	0.48
RG	5	0-30	0.11	0.09	0.04	0.33	0.56
RG	6	0-30	0.01	0.06	0.03	0.38	0.49
GB	1	0-30	0.09	0.09	0.04	0.35	0.57
GB	2	0-30	0.04	0.09	0.05	0.36	0.54
GB	3	0-30	0.04	0.08	0.04	0.35	0.52
GB	4	0-30	0.07	0.12	0.05	0.34	0.57
GB	5	0-30	0.04	0.09	0.06	0.36	0.55
GB	6	0-30	0.00	0.13	0.03	0.35	0.52
AgB	1	0-30	0.03	0.09	0.04	0.37	0.53

A 1.3 Cont'd

Treatment	Replication	Depth	Macropores (>1000 µm)	Coarse Mesopores (60- to 1000- µm)	Fine Mesopores (10- to 60- µm)	Micro-pores (<10 µm)	Total Pores
AgB	3	0-30	0.06	0.07	0.04	0.34	0.51
AgB	4	0-30	0.07	0.08	0.04	0.36	0.55
AgB	5	0-30	0.03	0.09	0.05	0.32	0.50
AgB	6	0-30	0.04	0.06	0.03	0.37	0.50
CG	1	0-40	0.00	0.04	0.02	0.40	0.45
CG	2	0-40	0.03	0.03	0.02	0.41	0.48
CG	3	0-40	0.04	0.07	0.02	0.39	0.52
CG	4	0-40	0.03	0.04	0.02	0.41	0.49
CG	5	0-40	0.04	0.04	0.02	0.40	0.50
CG	6	0-40	0.01	0.05	0.02	0.37	0.45
RG	1	0-40	0.01	0.06	0.04	0.36	0.48
RG	2	0-40	0.03	0.06	0.04	0.36	0.48
RG	3	0-40	0.05	0.05	0.03	0.37	0.50
RG	4	0-40	0.01	0.05	0.03	0.38	0.46
RG	5	0-40	0.02	0.10	0.05	0.36	0.53
RG	6	0-40	0.04	0.08	0.04	0.37	0.52
GB	1	0-40	0.06	0.10	0.05	0.34	0.55
GB	2	0-40	0.09	0.10	0.02	0.34	0.56
GB	3	0-40	0.04	0.08	0.03	0.36	0.52
GB	4	0-40	0.02	0.09	0.02	0.39	0.51
GB	5	0-40	0.04	0.11	0.03	0.35	0.54
GB	6	0-40	0.07	0.14	0.04	0.36	0.61
AgB	1	0-40	0.01	0.08	0.03	0.37	0.49
AgB	2	0-40	0.02	0.06	0.03	0.36	0.48
AgB	3	0-40	0.07	0.07	0.03	0.36	0.53
AgB	4	0-40	0.06	0.06	0.04	0.38	0.54
AgB	5	0-40	0.03	0.07	0.04	0.36	0.51
AgB	6	0-40	0.04	0.06	0.05	0.37	0.52

APPENDIX 2

A 2.1. Laboratory measurements for saturated hydraulic conductivity (Ksat) with bentonite around the edges and bulk density (BD) for soil core samples measured in 2007 and used for Chapter 4. AgB=agroforestry buffer, GB= grass buffer, RG= rotationally grazed pasture, CG= continuously grazed pasture.

Treatment	Replication	Depth	Bulk Density g cm^{-3}	Ksat mm hr^{-1}
AgB	1	0-10	1.17	464.18
AgB	1	10-20	1.40	17.63
AgB	1	20-30	1.44	12.74
AgB	1	30-40	1.48	12.54
AgB	1	40-50	1.49	12.09
AgB	2	0-10	1.12	206.81
AgB	2	10-20	1.41	33.83
AgB	2	20-30	1.38	16.93
AgB	2	30-40	1.39	27.63
AgB	2	40-50	1.39	2.33
AgB	3	0-10	1.24	127.96
AgB	3	10-20	1.36	77.36
AgB	3	20-30	1.40	67.65
AgB	3	30-40	1.44	17.65
AgB	3	40-50	1.50	17.36
AgB	4	0-10	1.30	305.13
AgB	4	10-20	1.44	24.97
AgB	4	20-30	1.45	18.27
AgB	4	30-40	1.45	3.43
AgB	4	40-50	1.48	9.34
AgB	5	0-10	1.27	134.96
AgB	5	10-20	1.30	10.65
AgB	5	20-30	1.44	7.10
AgB	5	30-40	1.41	11.59
AgB	5	40-50	1.47	4.51
AgB	6	0-10	1.23	112.09
AgB	6	10-20	1.46	29.12
AgB	6	20-30	1.52	4.77
AgB	6	30-40	1.48	7.10
AgB	6	40-50	1.42	6.81

A 2.1. Cont'd

Treatment	Replication	Depth	Bulk Density g cm^{-3}	Ksat mm hr^{-1}
GB	1	0-10	1.12	409.79
GB	1	10-20	1.33	100.11
GB	1	20-30	1.37	27.43
GB	1	30-40	1.32	25.21
GB	1	40-50	1.32	29.72
GB	2	0-10	1.11	428.19
GB	2	10-20	1.42	120.19
GB	2	20-30	1.35	89.42
GB	2	30-40	1.46	89.42
GB	2	40-50	1.40	19.98
GB	3	0-10	1.16	326.30
GB	3	10-20	1.36	86.50
GB	3	20-30	1.42	64.47
GB	3	30-40	1.38	40.03
GB	3	40-50	1.38	40.03
GB	4	0-10	1.24	336.13
GB	4	10-20	1.25	36.50
GB	4	20-30	1.41	34.29
GB	4	30-40	1.28	11.31
GB	4	40-50	1.28	11.31
GB	5	0-10	1.24	104.55
GB	5	10-20	1.46	41.50
GB	5	20-30	1.42	41.50
GB	5	30-40	1.25	7.10
GB	5	40-50	1.25	6.86
GB	6	0-10	1.18	86.37
GB	6	10-20	1.27	71.60
GB	6	20-30	1.43	18.40
GB	6	30-40	1.29	25.47
GB	6	40-50	1.43	14.00
RG	1	0-10	1.29	28.87
RG	1	10-20	1.29	58.24
RG	1	20-30	1.42	35.76
RG	1	30-40	1.50	29.38

A 2.1. Cont'd

Treatment	Replication	Depth	Bulk Density g cm^{-3}	Ksat mm hr^{-1}
RG	1	40-50	1.47	19.50
RG	2	0-10	1.29	11.28
RG	2	10-20	1.40	44.21
RG	2	20-30	1.43	80.01
RG	2	30-40	1.45	3.32
RG	2	40-50	1.53	4.02
RG	3	0-10	1.40	3.78
RG	3	10-20	1.54	4.48
RG	3	20-30	1.45	6.86
RG	3	30-40	1.53	23.34
RG	3	40-50	1.47	9.27
RG	4	0-10	1.33	20.86
RG	4	10-20	1.40	3.48
RG	4	20-30	1.48	5.96
RG	4	30-40	1.42	21.57
RG	4	40-50	1.61	2.32
RG	5	0-10	1.39	7.36
RG	5	10-20	1.36	34.20
RG	5	20-30	1.46	21.90
RG	5	30-40	1.48	27.81
RG	5	40-50	1.43	11.13
RG	6	0-10	1.41	2.38
RG	6	10-20	1.22	36.20
RG	6	20-30	1.37	20.30
RG	6	30-40	1.35	10.95
RG	6	40-50	1.44	17.26
CG	1	0-10	1.24	2.27
CG	1	10-20	1.56	7.80
CG	1	20-30	1.45	24.54
CG	1	30-40	1.53	5.68
CG	1	40-50	1.57	3.38
CG	2	0-10	1.42	2.47
CG	2	10-20	1.46	17.03
CG	2	20-30	1.50	12.57
CG	2	30-40	1.47	2.68

A 2.1 Cont'd

Treatment	Replication	Depth	Bulk Density g cm^{-3}	Ksat mm hr^{-1}
CG	2	40-50	1.43	4.91
CG	3	0-10	1.31	7.00
CG	3	10-20	1.44	23.30
CG	3	20-30	1.45	16.50
CG	3	30-40	1.47	6.70
CG	3	40-50	1.51	7.00
CG	4	0-10	1.39	3.55
CG	4	10-20	1.49	2.26
CG	4	20-30	1.40	1.00
CG	4	30-40	1.44	7.05
CG	4	40-50	1.47	5.79
CG	5	0-10	1.40	6.91
CG	5	10-20	1.44	11.30
CG	5	20-30	1.33	13.81
CG	5	30-40	1.45	35.25
CG	5	40-50	1.55	4.73
CG	6	0-10	1.40	2.26
CG	6	10-20	1.39	35.01
CG	6	20-30	1.43	3.89
CG	6	30-40	1.41	10.11
CG	6	40-50	1.35	11.89

A 2.2. CT-measured total number of (pores, macropores, and coarse mesopores), largest pore size (mm^2), circularity, fractal dimension of macropores, total macroporosity, and coarse mesoporosity measured in 2007. AgB=agroforestry buffer, GB= grass buffer, RG= rotationally grazed pasture, CG= continuously grazed pasture. Soil depths are 10 cm increments beginning at 0 cm.

			Number						Porosity		
Treatment	Replication	Depth	Total Pores	Macro-pores	Coarse-meso-pores	Largest Pore	Circularity	Fractal dimension	Total porosity	Macro-porosity	Coarse-Meso-porosity
AgB	1	1	98	36	62	14	0.85	1.64	0.050	0.044	0.007
AgB	1	2	62	21	41	7	0.85	1.33	0.028	0.023	0.005
AgB	1	3	28	7	23	4	0.94	1.11	0.007	0.004	0.003
AgB	1	4	27	6	18	3	0.92	1.08	0.007	0.005	0.002
AgB	1	5	34	6	28	3	0.91	1.15	0.007	0.004	0.003
AgB	2	1	86	30	56	10	0.83	1.52	0.044	0.038	0.007
AgB	2	2	16	4	10	10	0.90	1.05	0.005	0.004	0.001
AgB	2	3	30	8	22	10	0.89	1.28	0.008	0.006	0.002
AgB	2	4	28	5	23	10	0.91	1.18	0.006	0.004	0.002
AgB	2	5	33	23	50	10	0.85	1.30	0.036	0.027	0.009
AgB	3	1	108	38	70	10	0.84	1.56	0.056	0.047	0.008
AgB	3	2	14	1	9	10	0.92	0.84	0.002	0.001	0.001
AgB	3	3	32	6	26	10	0.93	1.18	0.009	0.006	0.003
AgB	3	4	30	3	27	10	0.95	1.03	0.005	0.002	0.003
AgB	3	5	31	4	27	10	0.96	1.04	0.005	0.002	0.003
AgB	4	1	135	55	80	24	0.83	1.64	0.086	0.058	0.028
AgB	4	2	47	14	32	6	0.89	1.25	0.018	0.014	0.004

A 2.2. Cont'd

Treatment	Replication	Depth	Total Pores	Macro-pores	Coarse-meso-pores	Largest Pore	Circularity	Fractal dimension	Total porosity	Macro-porosity	Coarse-Meso-porosity
AgB	4	3	42	8	34	2	0.91	1.12	0.009	0.005	0.004
AgB	4	4	33	4	29	3	0.95	1.32	0.007	0.004	0.003
AgB	4	5	28	7	21	4	0.92	1.06	0.007	0.005	0.002
AgB	5	1	148	49	100	24	0.85	1.59	0.070	0.059	0.012
AgB	5	2	26	8	19	5	0.85	1.18	0.010	0.008	0.002
AgB	5	3	21	5	16	3	0.93	1.06	0.006	0.004	0.002
AgB	5	4	24	4	20	4	0.95	1.08	0.005	0.003	0.002
AgB	5	5	36	3	33	2	0.94	1.09	0.005	0.002	0.003
AgB	6	1	37	6	21	2	0.92	1.26	0.006	0.004	0.002
AgB	6	2	28	8	19	3	0.89	0.97	0.008	0.007	0.001
AgB	6	3	33	4	29	3	0.95	1.08	0.006	0.006	0.002
AgB	6	4	19	3	16	2	0.97	0.98	0.003	0.001	0.002
AgB	6	5	30	4	26	2	0.96	1.05	0.005	0.001	0.004
GB	1	1	133	34	99	10	0.89	1.61	0.070	0.058	0.011
GB	1	2	59	11	48	10	0.83	1.33	0.018	0.008	0.010
GB	1	3	52	10	42	10	0.88	1.21	0.013	0.009	0.004
GB	1	4	55	19	56	10	0.92	1.16	0.022	0.017	0.006
GB	1	5	67	13	54	10	0.89	1.38	0.014	0.008	0.006
GB	2	1	212	47	112	10	0.85	1.62	0.083	0.071	0.013
GB	2	2	98	25	74	10	0.89	1.49	0.032	0.023	0.009

A 2.2. Cont'd

Treatment	Replication	Depth	Total Pores	Macro-pores	Coarse-meso-pores	Largest Pore	Circularity	Fractal dimension	Total porosity	Macro-porosity	Coarse-Meso-porosity
GB	2	3	60	13	48	10	0.90	1.35	0.018	0.013	0.005
GB	2	4	56	15	41	10	0.88	1.32	0.014	0.009	0.005
GB	2	5	69	10	59	10	0.93	1.34	0.012	0.006	0.006
GB	3	1	163	47	116	10	0.84	1.71	0.106	0.094	0.012
GB	3	2	108	36	71	10	0.86	1.44	0.042	0.033	0.009
GB	3	3	61	20	40	10	0.86	1.28	0.027	0.023	0.004
GB	3	4	75	17	58	10	0.91	1.27	0.016	0.011	0.006
GB	3	5	75	28	79	10	0.87	1.39	0.030	0.021	0.009
GB	4	1	137	37	100	21	0.86	1.62	0.058	0.046	0.011
GB	4	2	114	30	84	12	0.87	1.52	0.044	0.035	0.009
GB	4	3	80	23	57	10	0.88	1.42	0.032	0.025	0.006
GB	4	4	90	24	66	5	0.86	1.39	0.026	0.019	0.007
GB	4	5	130	47	103	6	0.83	1.58	0.058	0.047	0.011
GB	5	1	140	41	99	15	0.85	1.57	0.061	0.050	0.011
GB	5	2	92	29	63	9	0.90	1.33	0.036	0.029	0.007
GB	5	3	37	5	32	4	0.92	1.15	0.008	0.004	0.003
GB	5	4	42	6	32	2	0.94	1.19	0.008	0.004	0.003
GB	5	5	72	17	75	2	0.91	1.44	0.023	0.015	0.008
GB	6	1	166	60	106	17	0.82	1.61	0.080	0.067	0.013

A 2.2. Cont’d

Treatment	Replication	Depth	Total Pores	Macro-pores	Coarse-meso-pores	Largest Pore	Circularity	Fractal dimension	Total porosity	Macro-porosity	Coarse-Meso-porosity
GB	6	2	105	23	82	4	0.90	1.45	0.025	0.017	0.008
GB	6	3	74	19	55	5	0.89	1.35	0.019	0.013	0.006
GB	6	4	66	14	53	5	0.91	1.45	0.015	0.009	0.006
GB	6	5	55	12	43	5	0.91	1.34	0.012	0.008	0.004
RG	1	1	17	3	14	10	0.89	1.09	0.004	0.002	0.001
RG	1	2	71	25	46	10	0.78	1.44	0.039	0.034	0.005
RG	1	3	41	11	30	10	0.89	1.33	0.014	0.011	0.003
RG	1	4	50	8	42	10	0.93	1.32	0.009	0.005	0.004
RG	1	5	40	7	33	10	0.92	1.10	0.008	0.004	0.003
RG	2	1	39	8	31	10	0.86	1.29	0.011	0.008	0.003
RG	2	2	41	11	29	10	0.86	1.28	0.017	0.014	0.003
RG	2	3	40	11	28	10	0.91	1.29	0.012	0.009	0.003
RG	2	4	27	5	22	10	0.95	0.97	0.005	0.003	0.002
RG	2	5	26	6	20	10	0.94	0.99	0.006	0.004	0.002
RG	3	1	23	4	19	10	0.84	1.09	0.006	0.004	0.002
RG	3	2	23	5	18	10	0.86	1.13	0.006	0.004	0.002
RG	3	3	15	3	12	10	0.89	1.06	0.004	0.003	0.001
RG	3	4	28	6	22	10	0.94	1.11	0.006	0.003	0.002
RG	3	5	30	6	24	10	0.93	1.12	0.006	0.003	0.003

A 2.2. Cont'd

Treatment	Replication	Depth	Total Pores	Macro-pores	Coarse-meso-pores	Largest Pore	Circularity	Fractal dimension	Total porosity	Macro-porosity	Coarse-Meso-porosity
RG	4	1	22	11	58	2	0.94	1.08	0.015	0.009	0.006
RG	4	2	11	2	9	1	0.89	1.06	0.002	0.001	0.001
RG	4	3	11	1	10	1	0.97	0.95	0.002	0.001	0.001
RG	4	4	20	2	18	1	0.97	1.01	0.003	0.002	0.001
RG	4	5	11	2	29	1	0.94	0.88	0.004	0.001	0.002
RG	5	1	11	1	10	1	0.95	0.98	0.002	0.001	0.001
RG	5	2	28	0	27	1	0.95	1.05	0.003	0.000	0.003
RG	5	3	35	7	29	1	0.96	1.09	0.006	0.003	0.003
RG	5	4	29	1	29	1	0.97	1.09	0.003	0.000	0.002
RG	5	5	24	4	20	2	0.94	1.05	0.005	0.002	0.002
RG	6	1	17	3	14	2	0.91	0.96	0.004	0.002	0.002
RG	6	2	65	13	63	2	0.91	1.33	0.014	0.007	0.007
RG	6	3	58	9	49	2	0.89	1.16	0.010	0.005	0.005
RG	6	4	47	8	38	1	0.93	1.18	0.008	0.004	0.004
RG	6	5	16	2	13	1	0.97	0.93	0.002	0.001	0.001
CG	1	1	29	10	31	10	0.84	1.30	0.012	0.009	0.003
CG	1	2	48	13	35	10	0.83	1.19	0.016	0.012	0.004
CG	1	3	33	8	25	10	0.89	1.12	0.011	0.008	0.003
CG	1	4	31	6	25	10	0.92	1.06	0.006	0.004	0.002
CG	1	5	22	3	18	10	0.91	0.91	0.003	0.002	0.001

A 2.2. Cont'd

Treatment	Replication	Depth	Total Pores	Macro-pores	Coarse-meso-pores	Largest Pore	Circularity	Fractal dimension	Total porosity	Macro-porosity	Coarse-Meso-porosity
CG	2	1	12	3	8	10	0.90	0.99	0.005	0.004	0.001
CG	2	2	37	11	26	10	0.88	1.17	0.021	0.018	0.003
CG	2	3	20	4	16	9	0.97	0.93	0.004	0.003	0.002
CG	2	4	24	3	21	3	0.95	0.99	0.005	0.003	0.003
CG	2	5	29	6	24	2	0.92	1.06	0.006	0.004	0.002
CG	3	1	32	9	23	2	0.84	1.24	0.012	0.010	0.002
CG	3	2	25	10	15	2	0.88	1.13	0.011	0.009	0.001
CG	3	3	24	5	19	2	0.90	1.11	0.007	0.005	0.002
CG	3	4	29	6	22	2	0.90	1.16	0.008	0.005	0.003
CG	3	5	20	1	19	2	0.97	1.04	0.003	0.001	0.002
CG	4	1	4	0	4	0	0.93	0.99	0.001	0.000	0.000
CG	4	2	19	0	19	1	0.93	1.01	0.002	0.000	0.002
CG	4	3	31	4	27	1	0.92	1.03	0.004	0.002	0.002
CG	4	4	26	4	22	1	0.95	1.02	0.004	0.002	0.002
CG	4	5	19	2	17	1	0.95	0.88	0.002	0.001	0.002
CG	5	1	18	2	16	1	0.94	0.99	0.003	0.001	0.001
CG	5	2	32	5	28	1	0.94	1.00	0.005	0.003	0.003
CG	5	3	27	1	26	1	0.98	1.02	0.003	0.000	0.003
CG	5	4	34	4	31	1	0.96	1.00	0.005	0.002	0.003
CG	5	5	26	2	24	1	0.97	1.01	0.004	0.001	0.003

A 2.2. Cont'd

Treatment	Replication	Depth	Total Pores	Macro-pores	Coarse-meso-pores	Largest Pore	Circularity	Fractal dimension	Total porosity	Macro-porosity	Coarse-Meso-porosity
CG	6	1	5	0	5	0	0.96	0.85	0.001	0.000	0.001
CG	6	2	31	2	29	1	0.96	1.01	0.003	0.001	0.003
CG	6	3	28	2	26	1	0.96	1.01	0.004	0.004	0.000
CG	6	4	28	14	63	1	0.95	1.01	0.010	0.010	0.000
CG	6	5	32	2	30	1	0.97	1.01	0.004	0.004	0.000

APPENDIX 3

A 3.1. Cumulative infiltration in the agroforestry buffer (AgB) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0.0	0.0	0.0	0.0	0.0	0.0
2	2.48	3.30	3.63	5.29	8.42	4.62
4	4.95	6.61	6.77	12.88	17.67	9.78
6	8.75	11.56	10.74	19.49	25.93	15.29
8	12.39	15.69	14.53	25.10	34.85	20.51
10	16.52	18.17	18.17	32.87	45.58	26.26
12	22.46	21.47	21.31	40.13	53.35	31.74
14	30.39	24.77	25.60	46.57	62.43	37.95
16	32.54	28.08	28.90	53.18	73.49	43.24
18	33.22	29.73	32.21	59.79	82.25	47.44
20	40.63	32.21	35.51	67.22	96.62	54.44
25	52.52	37.99	45.83	76.80	117.76	66.18
30	62.76	45.42	53.68	87.86	146.16	79.18
35	77.62	51.20	54.22	89.67	162.33	87.01
40	85.88	57.47	65.24	104.38	179.03	98.40
50	102.40	64.41	78.45	122.55	214.37	116.44
60	117.26	74.32	90.01	141.13	244.76	133.50
70	131.30	84.64	102.40	160.53	295.80	154.93
80		94.55	116.93	176.22	325.28	178.25
90		104.05	132.95	190.26	344.27	192.88

A 3.2. Cumulative infiltration in the grass buffer (GB) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0.0	0.0	0.0	0.0	0.0	0.0
2	12.88	13.38	11.40	11.07	4.95	5.62
4	25.27	26.92	23.78	23.29	6.61	11.07
6	37.66	40.20	35.34	35.51	6.61	17.34
8	51.36	52.35	46.90	50.37	6.61	23.45
10	65.73	65.40	60.12	68.54	8.26	27.42
12	80.10	73.66	74.98	86.71	8.26	34.68
14	94.14	82.74	88.19	94.96	8.67	39.14
16	109.17	89.68	99.75	114.78	8.67	42.28
18	126.01	100.08	112.97	131.30	10.74	47.57
20	142.70	107.85	122.05	151.12	11.56	51.36
25	177.87	129.32	136.91	182.50	23.12	63.75
30	214.21	152.44	149.30	211.11	34.68	72.01
32		164.33				
35	249.55	177.21	161.69	240.30		89.35
40	284.48	196.37	170.77	263.42	37.16	105.87
45	321.72	227.92		283.24		
46	328.99					
49	349.47					
50	359.38	262.43	196.54	306.37	39.64	124.86
55	397.53			321.23		
60	435.52	308.84	227.42	337.75	39.64	149.63
65	474.82			345.18		
70	514.46	358.89	251.70	379.03	41.70	163.67
75	552.94	380.03		400.50		
80	593.41	443.61	268.21	420.32	42.11	182.66
85		464.25				
90	670.37	484.73	286.38	454.18	44.59	185.97
100	749.31	530.65	302.07	499.60	49.55	207.11

A 3.3. Cumulative infiltration in the rotationally grazed pasture (RG) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	3.91	0.50	0.66	2.56	2.48	2.48
4	5.47	1.32	1.32	5.86	4.79	5.78
6	6.41	2.15	2.15	8.01	6.28	7.93
8	8.82	2.81	3.14	9.50	6.77	9.31
10	10.97	3.63	3.96	13.38	9.41	11.73
12	11.53	3.96	5.12	17.59	9.93	14.20
14	13.15	4.46	5.95	20.56	12.06	17.51
16	14.65	5.45	6.77	23.87	13.21	20.81
18	16.85	6.19	7.27	27.52	13.86	23.96
20	18.32	6.94	7.76	30.60	16.15	26.90
25	21.06	7.76	8.09	32.78	18.00	27.91
30	22.89	8.26	8.92	37.08	19.08	30.97
35	24.00					
40	27.30	9.91	9.74	40.38	20.91	32.37
60		11.23	10.07	42.54	24.11	34.85
80		12.72	11.73	46.90	26.26	36.66
90		14.04	13.21			
100			14.86	50.59	28.90	
120		15.03		53.91		

A 3.3. Cumulative infiltration in the continuously grazed pasture (CG) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	0.41	0.33	0.50	0.66	3.14	0.66
4	0.53	0.83	1.32	1.32	6.38	1.16
6	0.56	1.16	1.82	1.82	9.81	1.49
8	0.63	1.32	2.31	2.31	13.31	2.31
10	0.76	1.49	2.97	2.97	16.98	2.81
12	0.79	1.65	3.30	3.80	20.12	3.14
14	1.04	1.82	3.96	4.62	22.87	3.80
16	1.14	1.98	4.95	5.45	26.72	4.46
18	1.21	2.15	5.29	6.61	30.36	4.79
20	1.30	2.31	5.62	7.27	33.30	5.45
25	1.37	2.48	6.11	8.09	35.13	6.28
30	1.47	2.73	6.19	8.59	38.48	6.54
40	1.57	3.14	6.44	9.41	38.81	7.09
60	2.89	3.63	6.61	10.57	38.98	7.60
80	3.30	3.96	6.94	12.22	39.14	9.25
90	3.63	4.29	7.10	14.04		9.91
100			7.27			

A 3.4. Cumulative infiltration in the agroforestry buffer (AgB) treatment measured in 2008.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
3	33.03					13.21
5	44.59	4.95	3.30	8.26	9.91	14.86
7	54.50					14.86
8	57.80					16.93
9	61.11					
10	62.76	6.61	4.95	13.21	19.82	17.75
12	67.71					17.84
15	71.84	11.56	8.26	21.47		18.17
20	84.23	14.86	11.56	28.08	52.85	18.17
24	85.88	18.17	14.86	34.68	95.79	
30	89.18	21.47	16.52	42.94	138.73	18.17
32	90.84				186.63	18.99
38	97.44					18.99
40	99.09	26.43	18.17	52.85	252.69	18.99
44	100.75					19.82
48	102.40					
50	104.05	31.38	19.82	56.15	302.24	21.14
56	107.35					21.47
60	109.00	41.29	23.12	59.46	341.87	22.46
64	111.48					
70		47.90	26.43	62.76	478.95	23.12
72	113.96					
75						24.61
76	115.61					
80		54.50	46.24	67.71	495.47	
85	120.56					24.77
90	122.22	59.46	67.71	69.37	518.59	26.43
100		79.28		82.58		
110	127.17	109.00		95.79		28.08
120	128.66					29.73
130	142.03					51.20
140	158.55					67.71

A 3.5. Cumulative infiltration in the grass buffer (GB) treatment measured in 2008.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	**0**	0	0
1.5	49.55	49.55	13.21			57.80
2	66.06	64.41	19.82		0.83	
2.5	80.93	84.23		11.56	8.26	85.88
3	97.44				28.08	97.44
3.5	110.65				31.38	109.00
4	125.52		35.51		33.03	
4.5	137.08			23.12		132.13
5	151.94				37.99	
5.5	163.50			28.90		
7.5			59.46			132.13
8			61.11	97.44	49.55	135.43
9	164.33				52.85	140.38
9.5			71.02			
10	165.16	85.88		109.00	57.80	
11	173.41	89.18	82.58	118.91		
12	193.23	120.56	90.84	130.47		
12.5	201.49	132.13		140.38		
13	209.75	140.38	92.49		67.71	162.68
13.5	219.66					
14	224.61	148.64	95.79	148.64		
14.5	234.52					
15	242.78	156.90		156.90	75.97	178.37
16	260.12	171.76			77.62	183.32
17	274.16	178.37				
18	289.02	184.98	120.56	156.90		204.79
19	303.89	194.88		165.16		
20	322.06	209.75	127.17	175.07	89.18	
21	335.27	219.66	133.78	188.28		
22	346.83	229.57				
24			146.99	215.53	104.05	239.48
26			163.50	234.52		
26.5	350.13					
27.5	358.39					267.55
28	368.30		170.11	250.21	117.26	
29	378.21		180.02			
30	396.38			267.55		
31	409.59					289.02
32	422.80	231.22	194.88		127.17	

A 3.5. Cont'd

Minutes	Cumulative Infiltration (mm)					
	I	II	III	IV	V	VI
33	436.01			297.28		300.58
34	449.23	237.83		318.75	132.13	
35	464.09	246.08				
36	478.95	252.69				314.62
37	479.78				141.21	323.71
38	480.61		195.71			
40	493.82	283.24	196.54			
41	495.47	289.02	198.19		156.90	323.71
42	497.12					
43	510.33					
44	521.89	310.49		320.40		340.22
45	536.76	317.93		331.14	158.55	
49	538.41		203.14	333.62	160.20	
50	540.06	346.83	214.70	341.87		377.38
51	549.97	361.69	218.01	352.61		
52			220.07			
53	573.09	361.69	227.92	361.69	167.63	389.77
55	597.87			374.91		401.33
58			239.48	404.63	179.19	415.37
60	609.43	366.65				
61	612.73	368.30	251.04		187.45	
62		373.25		419.50		427.76
66		396.38		442.62	199.01	440.97
67	622.64	402.98	269.21			
68	629.25		275.81	459.14		453.35
70	642.46	421.15	279.94		207.27	
71		426.10				462.44
74		444.27	289.02	460.79	216.35	462.44
75	660.63					
76	663.93	451.70	295.63			
77		459.14		472.35	226.26	477.30
79		469.04	305.54		232.04	
80	693.66		310.49	487.21		492.99
82	716.78					
83		475.65	322.06	503.73		508.68
86		485.56		518.59	241.95	521.89
87		503.73				
89		518.59			251.04	534.28
91			343.53			

A 3.5. Cont'd

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
92	725.04	518.59	345.18	546.67	258.47	549.15
95	743.20	519.42	353.43	559.88		559.05
97	747.33	530.98		571.44	268.38	
98						570.62
100	779.54	542.54				
101				602.82	276.64	580.53
102	799.36					
105	829.09				289.85	
106						598.69
107	852.21					
109	872.03					
111	873.68	592.91		645.76	299.76	
112		597.04				
113		605.30				
114	900.10					
115		613.56				
116		616.86			311.32	
118	921.57	625.12	355.09			
120	949.65	638.33	363.34			
121		639.98				
123	959.56					
124	970.29					
125	979.38	643.28				
126	999.20					
128	1028.92					
131	1040.49					
134	1053.70					

A 3.6. Cumulative infiltration in the rotationally grazed pasture (RG) treatment measured in 2008.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
5	3.47	2.48	21.47	3.30	9.91	1.65
10	3.80	4.95	37.16	7.43	13.21	3.30
15	3.96	4.95	56.15	14.86	14.04	4.54
20	4.13	4.95	72.67		14.04	4.95
25	4.23	4.95	89.18		14.86	5.12
30	4.29	4.95	107.35	21.47	14.86	
35			115.61			
40	4.95	6.61	127.17	28.08		
45						8.42
50	6.61	6.77	148.64	34.68	15.69	
55			161.85			
60	9.91	8.26	171.76	41.29	18.58	
68			175.89			
70		9.58	204.79	47.07	19.82	11.56
80			231.22	52.85		
90			239.48	59.46	21.47	
100			244.43	63.59		
110				68.54		
120				74.32		

A 3.7. Cumulative infiltration in the continuously grazed pasture (CG) treatment measured in 2008.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
5	19.82	11.56	0.83	1.65	9.91	4.95
10	37.99	19.82	3.30	2.89	21.47	8.26
15	54.50	24.77	4.95	4.95	31.38	11.56
20	77.62	29.73		5.78	41.29	
25	94.14				49.55	18.17
30	109.00			6.61	57.80	
35	122.22	37.99			69.37	24.77
40	133.78			6.77	75.97	
45	145.34	42.94	8.26		85.88	29.73
50	155.25					
55	165.16					34.68
60	180.02		18.17	8.26	100.75	
65		44.59			118.09	38.81
70	191.58	46.24			146.16	
75			29.73			43.77
80	204.79	47.90	33.03	9.41	171.76	
90	272.51	49.55	39.64	9.91	181.67	49.55
95			42.94			
100	363.34	51.20	47.90		186.63	
110	480.61		51.20			59.46

A 3.8. Cumulative infiltration at 50-mm tension in the agroforestry buffer (AgB) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	0.000	0.007	0.007	0.262	0.059	0.425
4	0.029	0.020	0.013	0.151	0.098	0.216
6	0.032	0.052	0.026	0.079	0.438	0.255
8	0.035	0.281	0.052	0.131	0.563	0.281
10	0.035	0.445	0.033	0.203	0.700	0.327
12	0.042	0.582	0.020	0.216	0.766	0.393
14	0.068	0.615	0.026	0.242	0.811	0.412
16		0.654	0.072	0.262	0.825	0.432
18			0.105			0.478

A 3.9. Cumulative infiltration at 50 mm tension in the grass buffer (GB) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	0.065	0.013	0.524	0.419	0.020	0.831
4	0.118	0.183	0.635	0.550	0.033	0.883
6	0.177	0.406	0.818	0.589	0.033	0.916
8	0.196	0.602	1.034	0.622	0.033	0.942
10	0.229	0.746	1.224	0.648	0.000	0.962
12	0.262	0.942	1.407	0.668	0.000	0.988
14	0.294	1.099	1.610	0.687	0.007	1.008
16	0.393		1.793	0.785	0.013	1.027
18	0.596				0.020	
20					0.065	

A 3.10. Cumulative infiltration at 50 mm tension in the rotationally grazed pasture (RG) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	0.0065	0.0000	0.0458	0.0065	0.0065	0.0131
4	0.0196	0.0065	0.1898	0.0393	0.0065	0.0131
6	0.0393	0.0131	0.2225	0.0589	0.0065	0.0262
8	0.0589	0.0196	0.2225	0.0589	0.0131	0.0458
10	0.0785	0.0327	0.2225	0.0720	0.0458	0.0458
12	0.0851	0.0360	0.2290	0.0785	0.0654	0.0524
14	0.1047	0.0458	0.2356	0.0851	0.1178	0.0524
16	0.1178	0.0654	0.2683	0.0851	0.1178	0.0524
18					0.1309	

A 3.11.Cumulative infiltration at 50-mm tension in the continuously grazed pasture (CG) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	0.020	0.020	0.007	0.007	0.013	0.046
4	0.052	0.216	0.007	0.013	0.016	0.059
6	0.079	0.229	0.013	0.013	0.046	0.098
8	0.118	0.236	0.026	0.013	0.072	0.118
10	0.137	0.236	0.033	0.013	0.079	0.118
12	0.157	0.236	0.039	0.026	0.092	0.118
14	0.177	0.236	0.041	0.033	0.131	0.131
16	0.196	0.262	0.042	0.039	0.144	0.137
18	0.203		0.046		0.145	
20					0.147	

A 3.12.Cumulative infiltration at 100-mm tension in the agroforestry buffer (AgB) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.007	0.013	0.007	0.046	0.026	0.007
4	0.013	0.026	0.013	0.065	0.033	0.013
6	0.020	0.065	0.014	0.072	0.039	0.020
8	0.026	0.144	0.014	0.079	0.059	0.033
10	0.036	0.151	0.020	0.085	0.085	0.020
12	0.046	0.157	0.026	0.098	0.085	0.020
15	0.059	0.164	0.033	0.105	0.105	0.026
16		0.170	0.065	0.108	0.111	0.033
20			0.079			0.033

A 3.13.Cumulative infiltration at 100 mm tension in the grass buffer (GB) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	0.059	0.020	0.033	0.007	0.000	0.000
4	0.118	0.020	0.072	0.020	0.007	0.000
6	0.124	0.020	0.118	0.020	0.013	0.000
8	0.164	0.046	0.465	0.033	0.020	0.000
10	0.203	0.059	0.851	0.059	0.033	0.000
12	0.314	0.079	1.263	0.144	0.033	0.007
14	0.419	0.098	1.669	0.145	0.046	0.059
16	0.550	0.144	1.695	0.151	0.059	
18	0.615	0.144				
20						

A 3.14.Cumulative infiltration at 100 mm tension in the rotationally grazed pasture (RG) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	0.000	0.007	0.020	0.013	0.026	0.013
4	0.007	0.023	0.039	0.013	0.020	0.013
6	0.016	0.033	0.007	0.013	0.013	0.026
8	0.020	0.049	0.000	0.026	0.013	0.046
10	0.026	0.056	0.007	0.039	0.013	0.046
12	0.033	0.069	0.020	0.052	0.013	0.052
14	0.036	0.079	0.023	0.052	0.026	0.052
16	0.039	0.085	0.033	0.065	0.046	0.052
18					0.046	

A 3.15.Cumulative infiltration at 100-mm tension in the continuously grazed pasture (CG) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	0.013	0.013	0.033	0.020	0.000	0.007
4	0.052	0.033	0.033	0.039	0.000	0.007
6	0.065	0.039	0.039	0.046	0.007	0.033
8	0.075	0.046	0.039	0.072	0.007	0.052
10	0.098	0.046	0.039	0.085	0.000	0.079
12	0.118	0.047	0.046	0.085	0.007	0.085
14	0.124	0.049	0.049	0.086	0.007	0.092
16	0.131	0.065	0.049	0.105	0.007	0.092
18	0.131		0.049		0.007	
20					0.020	

A 3.16.Cumulative infiltration at 150-mm tension in the agroforestry buffer (AgB) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0.00	0.00	0.00	0.00	0.00	0.00
2	0.000	0.033	0.000	0.007	0.026	0.046
4	0.000	0.079	0.046	0.013	0.033	0.065
6	0.013	0.079	0.085	0.020	0.052	0.039
8	0.013	0.079	0.105	0.026	0.092	0.026
10	0.020	0.079	0.137	0.033	0.131	0.052
12	0.026	0.079	0.144	0.039	0.151	0.072
15	0.026	0.079	0.151	0.046	0.154	0.085
16		0.085	0.157	0.052	0.158	0.092
20			0.164	0.065		0.105
22				0.072		
24				0.079		

A 3.17.Cumulative infiltration at 150 mm tension in the grass buffer (GB) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	0.006	0.033	0.007	0.013	0.020	0.007
4	0.032	0.039	0.013	0.026	0.020	0.013
6	0.065	0.046	0.020	0.046	0.020	0.020
8	0.078	0.048	0.013	0.085	0.020	0.026
10	0.084	0.049	0.013	0.052	0.020	0.033
12	0.084	0.052	0.007	0.065	0.020	0.039
14	0.071	0.056	0.105	0.065	0.026	0.059
16	0.071		0.124	0.105	0.026	
18	0.084		0.124	0.124		
20						

A 3.18.Cumulative infiltration at 150 mm tension in the rotationally grazed pasture (RG) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	0.039	0.033	0.013	0.072	0.013	0.000
4	0.046	0.049	0.033	0.072	0.020	0.000
6	0.072	0.056	0.059	0.072	0.020	0.000
8	0.085	0.059	0.085	0.072	0.020	0.000
10	0.088	0.062	0.085	0.072	0.020	0.000
12	0.088	0.065	0.157	0.072	0.020	0.000
14	0.088	0.062	0.164	0.072	0.021	0.000
16	0.092	0.072	0.170	0.077	0.026	0.013
					0.039	

A 3.19.Cumulative infiltration at 150-mm tension in the continuously grazed pasture (CG) treatment measured in 2007.

	Cumulative Infiltration (mm)					
Minutes	I	II	III	IV	V	VI
0	0	0	0	0	0	0
2	0.007	0.011	0.007	0.039	0.000	0.005
4	0.010	0.013	0.026	0.059	0.013	0.007
6	0.020	0.052	0.039	0.085	0.013	0.007
8	0.046	0.079	0.052	0.098	0.026	0.013
10	0.062	0.098	0.056	0.131	0.033	0.013
12	0.082	0.105	0.062	0.131	0.046	0.013
14	0.085	0.111	0.065	0.137	0.046	0.013
16	0.085	0.112	0.065	0.144	0.046	0.014
18	0.085		0.065		0.052	
20					0.054	

APPENDIX 4

A 4.1. Root parameters [(dry weight, root length density, and surface area for all size classes, Total) and (root length density and surface area for 0-1, 1-2 and 2-3 mm diameter classes)] for the different root diameter classes measured in 2008. AgB=agroforestry buffer, GB= grass buffer, RG= rotationally grazed pasture, CG= continuously grazed pasture.

	Root parameters								
				Root diameter classes					
	Total			0-1 mm		1-2 mm		2-3 mm	
	Dry weight	Root length	Surface area	Root length	Surface area	Root length	Surface area	Root length	Surface area
	(g/ 100 cm^3)	(cm/ 100 cm^3)	(cm^2/ 100 cm^3)	(cm/ 100 cm^3)	(cm^2/ 100 cm^3)	(cm/ 100 cm^3)	(cm^2/ 100 cm^3)	(cm/ 100 cm^3)	(cm^2/ 100 cm^3)
Treatment									
AgB	0.381a	138.3a	36.46a	115.20a	17.53a	38.82a	5.76a	1.67a	1.48a
GB	0.475a	160.8a	40.24a	125.44a	16.58a	45.72a	4.31ab	0.51b	0.46b
RG	0.140b	68.3b	23.76b	39.36b	7.40b	14.19b	2.75bc	0.42b	0.37b
CG	0.074b	46.8b	10.28c	37.57b	6.47b	4.71b	1.73c	0.28b	0.34b
	Analysis of variance P > F								
Treatment	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.0491	0.0725
Depth	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Treatment by depth	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.0511	0.1129
Buffers vs Pastures	0.174	0.025	0.023	0.530	0.990	0.075	0.751	0.170	0.152

A 4.2. Root parameters [(dry weight, OD (g); root length density, RLD (cm/100 cm^3); and surface area, SA (cm^2/100 cm^3) for all size classes, Total) and (root length density and surface area for 0-1, 1-2 and 2-3 mm diameter classes)] for the different root diameter classes measured in 2008. TRT, treatments, REP, replication, AgB=agroforestry buffer, GB= grass buffer, RG= rotationally grazed pasture, CG= continuously grazed pasture.

				Total		Root Diameter Classes					
						0-1 mm	1-2 mm	2-3 mm	0-1 mm	1-2 mm	2-3 mm
TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
AgB	1	5	0.079	434.63	144.20	219.30	16.47	1.03	82.25	6.54	0.75
AgB	1	10	0.079	335.95	114.60	219.30	16.47	1.03	62.51	6.54	0.75
AgB	1	15	0.047	267.94	62.19	157.21	11.59	0.20	25.01	4.44	0.14
AgB	1	20	0.047	169.26	32.59	157.21	11.59	0.20	25.01	4.44	0.14
AgB	1	25	0.021	109.22	22.81	96.29	12.62	0.26	15.19	5.53	0.17
AgB	1	30	0.040	78.77	18.92	66.53	10.72	1.48	10.98	5.20	1.09
AgB	1	35	0.040	78.77	18.92	66.53	10.72	1.48	10.98	5.20	1.09
AgB	1	40	0.016	55.46	12.63	40.01	10.79	0.37	9.38	5.29	0.24
AgB	1	45	0.016	55.46	12.63	40.01	10.79	0.37	5.84	5.29	0.24
AgB	1	50	0.013	55.46	12.63	40.01	10.79	0.00	5.84	0.85	0.00
AgB	1	55	0.013	55.46	12.63	40.01	10.79	0.00	5.84	0.85	0.00
AgB	1	60	0.009	51.20	10.66	34.24	1.43	0.00	5.84	0.52	0.00
AgB	1	65	0.009	51.20	10.66	34.24	1.43	0.00	5.84	0.52	0.00
AgB	1	70	0.009	51.20	10.66	34.24	1.43	0.00	5.84	0.52	0.00
AgB	1	75	0.009	51.20	10.66	34.24	1.43	0.00	5.84	0.52	0.00
AgB	2	5	0.244	482.55	73.84	234.89	38.05	11.92	36.45	16.20	10.16
AgB	2	10	0.244	383.87	73.84	234.89	38.05	11.92	36.45	16.20	10.16
AgB	2	15	0.244	285.19	73.84	234.89	38.05	11.92	36.45	16.20	10.16
AgB	2	20	0.134	127.81	26.65	111.79	13.34	2.39	16.79	5.60	1.90
AgB	2	25	0.134	127.81	26.65	111.79	13.34	2.39	16.79	5.60	1.90
AgB	2	30	0.134	127.81	26.65	111.79	13.34	2.39	16.79	5.60	1.90
AgB	2	35	0.030	59.68	4.69	25.96	1.31	0.10	3.68	0.66	0.07
AgB	2	40	0.030	59.68	4.69	25.96	1.31	0.10	3.68	0.66	0.07
AgB	2	45	0.017	59.68	6.52	36.28	2.05	0.15	4.97	0.93	0.10
AgB	2	50	0.017	59.68	6.52	36.28	2.05	0.15	4.97	0.93	0.10
AgB	2	55	0.017	59.68	6.52	36.28	2.05	0.15	4.97	0.93	0.10
AgB	2	60	0.021	55.46	6.52	36.28	2.73	0.30	7.52	1.34	0.21
AgB	2	65	0.038	55.46	6.52	36.28	4.94	0.96	0.79	2.77	0.62
AgB	2	70	0.038	55.46	6.52	36.28	4.94	0.96	0.79	2.77	0.62

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
AgB	2	75	0.009	55.46	6.52	36.28	1.43	0.00	9.38	0.52	0.00
AgB	3	5	0.166	392.22	141.92	166.29	26.18	2.94	94.93	10.15	1.82
AgB	3	10	0.166	333.01	92.58	156.42	26.18	1.91	85.07	10.15	1.82
AgB	3	15	0.166	293.54	82.71	77.68	26.18	1.91	65.33	10.15	1.82
AgB	3	20	0.166	194.86	53.11	77.68	26.18	1.91	36.71	10.15	1.82
AgB	3	25	0.030	91.25	39.95	47.65	5.29	1.47	21.74	2.39	1.01
AgB	3	30	0.030	55.46	31.49	47.65	5.29	1.47	7.49	2.39	1.01
AgB	3	35	0.030	55.46	11.76	47.65	5.29	1.47	7.49	2.39	1.01
AgB	3	40	0.030	54.45	11.76	47.65	5.29	1.47	7.49	2.39	1.01
AgB	3	45	0.038	54.45	11.76	47.65	5.29	1.47	7.49	4.77	2.02
AgB	3	50	0.038	30.53	4.28	4.89	4.94	0.96	0.79	2.77	0.62
AgB	3	55	0.038	30.53	4.28	4.89	4.94	0.96	0.79	2.77	0.62
AgB	3	60	0.038	30.53	4.28	4.89	4.94	0.96	0.79	2.77	0.62
AgB	3	65	0.038	30.53	4.28	4.89	4.94	0.96	0.79	2.77	0.62
AgB	3	70	0.038	30.53	4.28	4.89	4.94	0.96	0.79	2.77	0.62
AgB	3	75	0.009	30.53	4.28	4.89	1.43	0.00	0.79	0.52	0.00
AgB	4	5	0.641	567.52	181.35	432.39	91.02	43.44	67.71	39.07	48.35
AgB	4	10	0.641	567.52	181.35	432.39	91.02	43.44	67.71	39.07	48.35
AgB	4	15	0.586	477.23	149.93	367.55	80.07	29.02	59.04	34.02	35.63
AgB	4	20	0.507	356.34	109.43	284.86	50.66	20.41	46.41	20.89	27.41
AgB	4	25	0.075	180.89	34.77	165.35	14.58	0.84	25.34	5.74	0.65
AgB	4	30	0.072	176.17	33.53	161.84	13.26	0.53	25.05	5.35	0.36
AgB	4	35	0.072	176.17	33.53	161.84	13.26	0.53	25.05	5.35	0.36
AgB	4	40	0.077	160.10	31.90	144.53	14.50	0.53	22.96	5.83	0.36
AgB	4	45	0.063	131.75	27.50	113.69	17.16	0.40	18.03	6.85	0.27
AgB	4	50	0.063	131.75	27.50	113.69	17.16	0.40	18.03	6.85	0.27
AgB	4	55	0.028	82.54	27.50	73.81	4.84	0.00	6.75	1.83	0.00
AgB	4	60	0.028	82.54	27.50	73.81	4.84	0.00	6.75	1.83	0.00
AgB	4	65	0.022	82.54	16.70	73.81	4.84	0.08	6.75	3.22	0.06
AgB	4	70	0.022	44.25	16.70	39.05	4.84	0.08	6.75	3.22	0.06
AgB	4	75	0.022	44.25	16.70	39.05	4.84	0.08	6.75	3.22	0.06
AgB	5	5	0.414	520.12	117.77	334.33	64.07	22.18	53.33	26.64	21.27
AgB	5	10	0.414	470.78	117.77	334.33	64.07	22.18	53.33	26.64	21.27
AgB	5	15	0.303	346.31	94.98	273.80	54.97	17.06	43.36	22.93	15.30
AgB	5	20	0.303	346.31	94.98	273.80	54.97	17.06	43.36	22.93	15.30
AgB	5	25	0.205	218.88	60.45	171.41	36.45	10.87	27.75	15.13	9.87
AgB	5	30	0.070	114.63	24.93	98.00	14.99	2.35	15.97	5.82	1.15

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
AgB	5	35	0.070	80.63	16.33	70.17	5.35	2.35	11.82	2.24	0.97
AgB	5	40	0.102	80.63	19.32	71.83	6.42	2.35	12.94	2.71	2.11
AgB	5	45	0.102	80.63	19.32	71.83	6.42	1.41	12.94	2.71	2.11
AgB	5	50	0.067	80.63	18.70	71.83	6.11	1.41	12.41	2.57	2.14
AgB	5	55	0.067	85.62	18.70	71.83	6.11	1.41	12.41	2.57	2.14
AgB	5	60	0.014	74.78	13.34	71.83	1.84	0.08	11.89	0.67	0.05
AgB	5	65	0.011	42.36	8.37	41.15	1.21	0.00	7.65	0.46	0.00
AgB	5	70	0.011	42.36	8.37	41.15	1.21	0.00	7.65	0.46	0.00
AgB	5	75	0.022	42.36	8.37	41.15	1.21	0.08	7.65	0.46	0.06
AgB	6	5	0.090	436.33	171.93	304.57	25.93	6.74	47.17	10.61	4.73
AgB	6	10	0.090	369.23	102.86	304.57	25.93	6.74	47.17	10.61	4.73
AgB	6	15	0.097	368.78	78.68	334.18	27.70	6.47	51.75	11.30	4.54
AgB	6	20	0.060	291.75	45.81	232.29	20.14	4.27	35.04	5.53	0.47
AgB	6	25	0.046	291.75	39.08	198.95	14.14	0.54	30.48	4.26	0.41
AgB	6	30	0.046	291.75	39.08	198.95	11.18	0.54	30.48	4.26	0.41
AgB	6	35	0.051	282.60	39.08	198.95	11.18	0.81	40.82	5.12	0.61
AgB	6	40	0.051	247.33	39.08	198.95	11.18	0.81	34.91	4.91	0.61
AgB	6	45	0.051	247.33	39.08	198.95	11.18	0.81	34.91	4.91	0.61
AgB	6	50	0.051	247.33	39.08	198.95	11.18	0.81	34.91	4.91	0.61
AgB	6	55	0.051	247.33	39.08	198.95	11.18	0.81	34.91	4.91	0.61
AgB	6	60	0.051	247.33	39.08	198.95	11.18	0.81	34.91	4.91	0.61
AgB	6	65	0.046	186.91	39.08	161.80	11.18	0.81	25.72	9.49	3.38
AgB	6	70	0.046	154.10	39.08	127.76	11.18	0.81	21.97	10.32	3.77
AgB	6	75	0.046	154.10	39.08	127.76	11.18	0.81	21.97	10.32	3.77
AgB50	1	5	0.152	218.11	43.63	140.54	62.82	14.44	17.26	14.33	6.90
AgB50	1	10	0.152	218.11	43.63	140.54	62.82	14.44	17.26	14.33	6.90
AgB50	1	15	0.152	218.11	43.63	140.54	62.82	14.44	17.26	14.33	6.90
AgB50	1	20	0.106	158.29	30.74	118.48	32.06	7.51	15.33	7.99	4.04
AgB50	1	25	0.074	112.37	19.69	80.17	26.17	5.83	9.35	5.58	2.80
AgB50	1	30	0.072	105.36	19.05	69.94	30.30	4.91	8.54	6.38	2.36
AgB50	1	35	0.072	105.36	19.05	69.94	30.30	4.91	8.54	6.38	2.36
AgB50	1	40	0.025	67.47	15.35	56.58	10.66	0.23	9.88	4.21	0.15
AgB50	1	45	0.025	67.47	15.35	56.58	10.66	0.23	9.88	4.21	0.15
AgB50	1	50	0.025	10.47	2.85	0.56	7.20	2.70	0.06	1.76	0.91
AgB50	1	55	0.025	10.47	2.85	0.56	7.20	2.70	0.06	1.76	0.91
AgB50	1	60	0.007	9.29	1.38	7.46	1.50	0.33	0.78	0.34	0.11
AgB50	1	65	0.007	9.29	1.38	7.46	1.50	0.33	0.78	0.34	0.11
AgB50	1	70	0.007	9.24	2.27	3.76	5.15	0.33	0.35	1.72	0.11

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
AgB50	1	75	0.014	6.55	1.55	1.58	3.62	1.35	0.14	0.88	0.45
AgB50	2	5	0.123	273.95	58.52	245.33	24.93	3.35	37.16	10.33	2.89
AgB50	2	10	0.123	273.95	58.52	245.33	24.93	3.35	37.16	10.33	2.89
AgB50	2	15	0.157	223.80	50.22	191.68	26.99	4.81	29.55	11.25	3.95
AgB50	2	20	0.157	223.80	50.22	191.68	26.99	4.81	29.55	11.25	3.95
AgB50	2	25	0.138	157.56	36.03	132.89	19.94	4.48	20.22	8.42	3.72
AgB50	2	30	0.112	99.92	24.81	81.78	13.50	4.41	12.92	5.71	3.67
AgB50	2	35	0.077	73.93	14.21	69.52	4.18	0.02	11.87	1.50	0.01
AgB50	2	40	0.077	73.93	14.21	69.52	4.18	0.02	11.87	1.50	0.01
AgB50	2	45	0.023	76.34	14.23	72.70	3.43	0.00	12.36	1.21	0.00
AgB50	2	50	0.023	76.34	14.23	72.70	3.43	0.00	12.36	1.21	0.00
AgB50	2	55	0.025	61.62	11.76	59.15	2.47	0.00	10.67	0.87	0.00
AgB50	2	60	0.025	67.47	15.35	56.58	10.66	0.23	9.88	4.21	0.15
AgB50	2	65	0.030	31.33	8.90	21.97	6.58	2.79	3.10	2.95	2.21
AgB50	2	70	0.030	31.33	8.90	21.97	6.58	2.79	3.10	2.95	2.21
AgB50	2	75	0.030	31.33	8.90	21.97	6.58	2.79	3.10	2.95	2.21
AgB50	3	5	0.171	402.39	88.03	353.56	43.88	4.16	55.32	18.39	3.18
AgB50	3	10	0.171	402.39	88.03	353.56	43.88	4.16	55.32	18.39	3.18
AgB50	3	15	0.161	317.78	72.36	278.24	35.39	3.45	46.61	14.22	2.66
AgB50	3	20	0.095	216.73	43.56	198.70	16.31	1.29	31.20	6.42	0.95
AgB50	3	25	0.084	128.54	23.52	120.79	7.40	0.07	18.31	2.69	0.05
AgB50	3	30	0.080	125.24	23.15	118.71	6.19	0.01	18.57	2.27	0.01
AgB50	3	35	0.080	125.24	23.15	118.71	6.19	0.01	18.57	2.27	0.01
AgB50	3	40	0.067	89.52	16.06	85.77	3.69	0.01	13.27	1.36	0.01
AgB50	3	45	0.067	89.52	16.06	85.77	3.69	0.01	13.27	1.36	0.01
AgB50	3	50	0.068	71.77	13.56	67.32	4.02	0.43	10.38	1.53	0.30
AgB50	3	55	0.035	97.40	18.42	91.90	4.85	0.64	14.21	1.88	0.45
AgB50	3	60	0.045	65.06	15.53	57.05	6.73	1.29	10.31	2.64	0.90
AgB50	3	65	0.025	10.47	2.85	0.56	7.20	2.70	0.06	1.76	0.91
AgB50	3	70	0.025	67.47	15.35	56.58	10.66	0.23	9.88	4.21	0.15
AgB50	3	75	0.025	67.47	15.35	56.58	10.66	0.23	9.88	4.21	0.15
AgB50	4	5	0.387	684.23	185.74	529.91	136.32	16.96	91.60	56.77	13.52
AgB50	4	10	0.387	684.23	185.74	529.91	136.32	16.96	91.60	56.77	13.52
AgB50	4	15	0.387	684.23	185.74	529.91	136.32	16.96	91.60	56.77	13.52
AgB50	4	20	0.283	576.98	160.27	434.04	129.57	12.55	77.67	53.58	9.92
AgB50	4	25	0.385	484.23	138.00	356.78	114.92	12.15	64.98	46.71	10.54
AgB50	4	30	0.175	301.96	72.34	255.55	41.28	4.86	44.28	16.45	4.68
AgB50	4	35	0.197	312.81	73.26	271.48	36.32	4.61	46.10	14.68	4.64

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
AgB50	4	40	0.197	312.81	73.26	271.48	36.32	4.61	46.10	14.68	4.64
AgB50	4	45	0.197	312.81	73.26	271.48	36.32	4.61	46.10	14.68	4.64
AgB50	4	50	0.182	262.23	55.47	235.36	24.78	1.74	38.17	10.28	1.38
AgB50	4	55	0.135	201.52	41.98	180.68	19.62	1.08	29.15	8.04	0.79
AgB50	4	60	0.101	111.76	24.32	97.56	13.73	0.45	16.10	5.50	0.31
AgB50	4	65	0.101	111.76	24.32	97.56	13.73	0.45	16.10	5.50	0.31
AgB50	4	70	0.025	67.47	15.35	56.58	10.66	0.23	9.88	4.21	0.15
AgB50	4	75	0.025	67.47	15.35	56.58	10.66	0.23	9.88	4.21	0.15
AgB50	5	5	0.137	308.25	72.86	223.25	70.11	14.14	31.69	22.04	9.49
AgB50	5	10	0.137	308.25	72.86	223.25	70.11	14.14	31.69	22.04	9.49
AgB50	5	15	0.087	226.24	48.40	164.16	51.71	9.85	22.98	14.05	5.83
AgB50	5	20	0.087	226.24	48.40	164.16	51.71	9.85	22.98	14.05	5.83
AgB50	5	25	0.102	131.76	38.81	93.06	21.29	17.09	14.16	7.40	13.76
AgB50	5	30	0.102	131.76	38.81	93.06	21.29	17.09	14.16	7.40	13.76
AgB50	5	35	0.102	129.84	36.87	94.26	18.29	16.91	13.89	6.23	13.61
AgB50	5	40	0.066	132.93	35.09	92.16	27.69	12.34	13.67	8.24	10.39
AgB50	5	45	0.066	132.93	35.09	92.16	27.69	12.34	13.67	8.24	10.39
AgB50	5	50	0.035	95.14	16.96	73.96	19.48	1.19	10.23	4.67	0.65
AgB50	5	55	0.035	65.63	12.81	53.87	10.39	1.30	8.05	2.78	0.82
AgB50	5	60	0.045	78.70	15.76	71.92	5.16	1.51	11.14	2.14	1.08
AgB50	5	65	0.045	78.70	15.76	71.92	5.16	1.51	11.14	2.14	1.08
AgB50	5	70	0.033	61.38	12.15	55.07	4.49	1.60	7.97	1.88	1.25
AgB50	5	75	0.037	84.50	17.78	70.90	13.41	0.16	10.70	5.29	0.11
AgB50	6	5	0.088	169.94	35.22	139.06	27.93	2.83	21.67	8.32	1.72
AgB50	6	10	0.088	169.94	35.22	139.06	27.93	2.83	21.67	8.32	1.72
AgB50	6	15	0.088	169.94	35.22	139.06	27.93	2.83	21.67	8.32	1.72
AgB50	6	20	0.054	218.44	43.48	138.32	60.40	18.72	16.63	13.94	8.01
AgB50	6	25	0.054	218.44	43.48	138.32	60.40	18.72	16.63	13.94	8.01
AgB50	6	30	0.054	218.44	43.48	138.32	60.40	18.72	16.63	13.94	8.01
AgB50	6	35	0.045	106.09	20.19	91.87	9.81	3.69	12.83	3.00	2.32
AgB50	6	40	0.028	54.55	11.64	45.08	5.81	3.63	7.14	1.39	2.29
AgB50	6	45	0.028	54.55	11.64	45.08	5.81	3.63	7.14	1.39	2.29
AgB50	6	50	0.028	54.55	11.64	45.08	5.81	3.63	7.14	1.39	2.29
AgB50	6	55	0.014	39.85	7.59	37.06	2.73	0.02	6.31	0.81	0.01
AgB50	6	60	0.009	5.43	0.92	2.83	2.56	0.04	0.29	0.57	0.01
AgB50	6	65	0.009	5.43	0.92	2.83	2.56	0.04	0.29	0.57	0.01
AgB50	6	70	0.033	61.38	12.15	55.07	4.49	1.60	7.97	1.88	1.25
AgB50	6	75	0.037	84.50	17.78	70.90	13.41	0.16	10.70	5.29	0.11

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
AgB100	1	5	0.175	217.33	55.23	184.10	27.23	5.87	31.26	11.49	4.98
AgB100	1	10	0.185	226.44	52.08	199.61	24.00	2.72	33.70	9.91	2.01
AgB100	1	15	0.185	226.44	52.08	199.61	24.00	2.72	33.70	9.91	2.01
AgB100	1	20	0.090	90.84	23.08	78.24	8.26	4.25	12.71	3.25	4.97
AgB100	1	25	0.090	90.84	23.08	78.24	8.26	4.25	12.71	3.25	4.97
AgB100	1	30	0.012	44.01	6.97	43.17	0.83	0.00	6.04	0.30	0.00
AgB100	1	35	0.022	58.96	11.38	54.92	3.36	0.67	8.74	1.29	0.49
AgB100	1	40	0.031	55.25	11.99	48.73	5.42	1.10	8.44	2.09	0.80
AgB100	1	45	0.020	32.62	6.92	29.49	2.95	0.18	5.26	1.10	0.13
AgB100	1	50	0.020	32.62	6.92	29.49	2.95	0.18	5.26	1.10	0.13
AgB100	1	55	0.020	32.62	6.92	29.49	2.95	0.18	5.26	1.10	0.13
AgB100	1	60	0.020	32.62	6.92	29.49	2.95	0.18	5.26	1.10	0.13
AgB100	1	65	0.020	32.62	6.92	29.49	2.95	0.18	5.26	1.10	0.13
AgB100	1	70	0.020	32.62	6.92	29.49	2.95	0.18	5.26	1.10	0.13
AgB100	1	75	0.020	32.62	6.92	29.49	2.95	0.18	5.26	1.10	0.13
AgB100	2	5	0.156	253.06	57.16	224.00	23.59	5.21	35.99	9.97	4.22
AgB100	2	10	0.156	253.06	57.16	224.00	23.59	5.21	35.99	9.97	4.22
AgB100	2	15	0.156	253.06	57.16	224.00	23.59	5.21	35.99	9.97	4.22
AgB100	2	20	0.058	103.07	22.33	88.00	12.75	2.32	11.89	5.73	1.68
AgB100	2	25	0.058	103.07	22.33	88.00	12.75	2.32	11.89	5.73	1.68
AgB100	2	30	0.031	72.84	11.33	69.52	3.32	0.00	9.34	1.14	0.00
AgB100	2	35	0.031	72.84	11.33	69.52	3.32	0.00	9.34	1.14	0.00
AgB100	2	40	0.014	37.42	7.87	33.11	4.31	0.00	5.74	1.79	0.00
AgB100	2	45	0.014	37.42	7.87	33.11	4.31	0.00	5.74	1.79	0.00
AgB100	2	50	0.014	37.42	7.87	33.11	4.31	0.00	5.74	1.79	0.00
AgB100	2	55	0.014	37.42	7.87	33.11	4.31	0.00	5.74	1.79	0.00
AgB100	2	60	0.014	37.42	7.87	33.11	4.31	0.00	5.74	1.79	0.00
AgB100	2	65	0.014	37.42	7.87	33.11	4.31	0.00	5.74	1.79	0.00
AgB100	2	70	0.014	37.42	7.87	33.11	4.31	0.00	5.74	1.79	0.00
AgB100	2	75	0.014	37.42	7.87	33.11	4.31	0.00	5.74	1.79	0.00
AgB100	3	5	0.126	348.64	74.07	262.19	70.06	15.57	35.87	20.56	8.06
AgB100	3	10	0.126	348.64	74.07	262.19	70.06	15.57	35.87	20.56	8.06
AgB100	3	15	0.123	319.74	69.02	234.79	67.12	17.24	31.79	19.42	9.41
AgB100	3	20	0.068	136.69	28.96	113.78	18.88	3.81	18.03	6.39	2.93
AgB100	3	25	0.068	136.69	28.96	113.78	18.88	3.81	18.03	6.39	2.93
AgB100	3	30	0.051	123.72	26.31	103.34	18.09	2.06	16.84	6.01	1.48
AgB100	3	35	0.051	123.72	26.31	103.34	18.09	2.06	16.84	6.01	1.48
AgB100	3	40	0.051	123.72	26.31	103.34	18.09	2.06	16.84	6.01	1.48

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
AgB100	3	45	0.060	127.84	27.52	102.01	22.60	3.12	16.54	6.93	1.95
AgB100	3	50	0.056	122.56	27.72	92.89	26.46	3.10	15.89	8.36	1.94
AgB100	3	55	0.035	70.82	14.46	43.89	25.10	1.83	6.66	5.86	0.84
AgB100	3	60	0.035	70.82	14.46	43.89	25.10	1.83	6.66	5.86	0.84
AgB100	3	65	0.023	78.93	17.12	36.66	40.37	1.63	5.96	9.35	0.61
AgB100	3	70	0.023	78.93	17.12	36.66	40.37	1.63	5.96	9.35	0.61
AgB100	3	75	0.023	78.93	17.12	36.66	40.37	1.63	5.96	9.35	0.61
AgB100	4	5	0.312	481.24	139.11	383.85	77.15	19.15	62.93	32.50	24.33
AgB100	4	10	0.312	481.24	139.11	383.85	77.15	19.15	62.93	32.50	24.33
AgB100	4	15	0.312	481.24	139.11	383.85	77.15	19.15	62.93	32.50	24.33
AgB100	4	20	0.122	328.11	77.33	281.16	40.03	6.26	44.81	16.45	6.76
AgB100	4	25	0.070	207.14	42.81	184.55	18.56	3.89	28.90	7.25	2.84
AgB100	4	30	0.070	207.14	42.81	184.55	18.56	3.89	28.90	7.25	2.84
AgB100	4	35	0.070	207.14	42.81	184.55	18.56	3.89	28.90	7.25	2.84
AgB100	4	40	0.055	148.30	33.00	130.31	14.25	3.61	20.61	5.46	2.62
AgB100	4	45	0.045	130.21	28.22	116.63	10.00	3.45	18.02	3.85	2.51
AgB100	4	50	0.032	126.21	25.88	119.59	6.19	0.12	19.52	2.41	0.08
AgB100	4	55	0.032	155.93	29.86	148.96	6.42	0.09	24.28	2.52	0.06
AgB100	4	60	0.032	155.93	29.86	148.96	6.42	0.09	24.28	2.52	0.06
AgB100	4	65	0.032	155.93	29.86	148.96	6.42	0.09	24.28	2.52	0.06
AgB100	4	70	0.029	152.46	30.16	144.27	7.64	0.09	24.51	2.99	0.06
AgB100	4	75	0.029	152.46	30.16	144.27	7.64	0.09	24.51	2.99	0.06
AgB100	5	5	0.245	244.44	57.88	209.36	29.63	5.12	5.12	35.61	12.03
AgB100	5	10	0.245	244.44	57.88	209.36	29.63	5.12	5.12	35.61	12.03
AgB100	5	15	0.245	244.44	57.88	209.36	29.63	5.12	5.12	35.61	12.03
AgB100	5	20	0.245	244.44	57.88	209.36	29.63	5.12	5.12	35.61	12.03
AgB100	5	25	0.062	100.82	21.50	90.53	10.12	0.17	0.17	15.42	4.35
AgB100	5	30	0.062	100.82	21.50	90.53	10.12	0.17	0.17	15.42	4.35
AgB100	5	35	0.062	100.82	21.50	90.53	10.12	0.17	0.17	15.42	4.35
AgB100	5	40	0.062	100.82	21.50	90.53	10.12	0.17	0.17	15.42	4.35
AgB100	5	45	0.032	88.40	19.65	73.23	14.89	0.27	0.27	11.43	6.32
AgB100	5	50	0.032	88.40	19.65	73.23	14.89	0.27	0.27	11.43	6.32
AgB100	5	55	0.032	88.40	19.65	73.23	14.89	0.27	0.27	11.43	6.32
AgB100	5	60	0.027	56.85	11.00	52.59	4.17	0.07	0.07	7.76	1.68
AgB100	5	65	0.026	42.43	6.75	41.01	0.87	0.01	0.01	5.86	0.31
AgB100	5	70	0.026	42.43	6.75	41.01	0.87	0.01	0.01	5.86	0.31
AgB100	5	75	0.026	42.43	6.75	41.01	0.87	0.01	0.01	5.86	0.31
AgB100	6	5	0.172	228.88	52.35	194.04	27.06	7.10	28.65	11.61	5.66

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
AgB100	6	10	0.172	228.88	52.35	194.04	27.06	7.10	28.65	11.61	5.66
AgB100	6	15	0.172	228.88	52.35	194.04	27.06	7.10	28.65	11.61	5.66
AgB100	6	20	0.172	228.88	52.35	194.04	27.06	7.10	28.65	11.61	5.66
AgB100	6	25	0.103	202.03	47.13	175.80	21.11	4.90	27.74	9.30	3.87
AgB100	6	30	0.103	202.03	47.13	175.80	21.11	4.90	27.74	9.30	3.87
AgB100	6	35	0.105	202.69	46.48	171.54	25.81	5.18	26.04	11.28	4.02
AgB100	6	40	0.105	202.69	46.48	171.54	25.81	5.18	26.04	11.28	4.02
AgB100	6	45	0.120	156.74	41.82	125.51	24.24	6.76	19.70	11.04	5.36
AgB100	6	50	0.021	50.23	10.90	45.68	4.46	0.07	7.36	1.79	0.06
AgB100	6	55	0.021	50.23	10.90	45.68	4.46	0.07	7.36	1.79	0.06
AgB100	6	60	0.021	50.23	10.90	45.68	4.46	0.07	7.36	1.79	0.06
AgB100	6	65	0.034	40.86	7.74	38.03	1.75	0.03	6.69	0.62	0.02
AgB100	6	70	0.034	40.86	7.74	38.03	1.75	0.03	6.69	0.62	0.02
AgB100	6	75	0.034	40.86	7.74	38.03	1.75	0.03	6.69	0.62	0.02
GB	1	5	0.573	761.91	277.35	463.47	207.85	88.80	73.13	77.69	85.45
GB	1	10	0.573	761.91	277.35	463.47	207.85	88.80	73.13	77.69	85.45
GB	1	15	0.664	690.83	257.63	407.07	194.79	87.19	61.78	72.35	84.27
GB	1	20	0.188	255.36	54.36	200.28	52.24	2.75	31.11	14.36	1.45
GB	1	25	0.188	255.36	54.36	200.28	52.24	2.75	31.11	14.36	1.45
GB	1	30	0.065	249.66	51.84	197.29	49.68	2.57	30.31	13.29	1.30
GB	1	35	0.065	249.66	51.84	197.29	49.68	2.57	30.31	13.29	1.30
GB	1	40	0.048	209.09	45.10	173.71	33.92	1.33	27.56	10.47	0.73
GB	1	45	0.027	81.50	15.50	58.96	21.77	0.73	7.71	6.35	0.31
GB	1	50	0.027	81.50	15.50	58.96	21.77	0.73	7.71	6.35	0.31
GB	1	55	0.015	88.71	16.77	66.47	21.46	0.73	9.11	6.24	0.31
GB	1	60	0.014	91.03	16.56	76.30	13.59	1.06	10.36	4.47	0.58
GB	1	65	0.014	91.03	16.56	76.30	13.59	1.06	10.36	4.47	0.58
GB	1	70	0.013	68.89	11.65	56.72	11.09	0.99	7.55	2.75	0.53
GB	1	75	0.013	68.89	11.65	56.72	11.09	0.99	7.55	2.75	0.53
GB	2	5	0.803	523.57	120.88	316.25	49.04	3.69	16.96	2.60	0.18
GB	2	10	0.703	424.89	101.15	217.57	39.18	3.69	16.96	2.60	0.18
GB	2	15	0.661	301.63	87.57	191.22	27.77	3.69	12.59	1.98	2.51
GB	2	20	0.072	243.79	78.67	60.23	12.04	3.48	6.15	0.54	2.40
GB	2	25	0.072	145.11	9.60	60.23	2.17	3.48	6.15	0.54	2.40
GB	2	30	0.032	116.73	10.13	53.39	2.68	1.16	8.13	0.71	0.74
GB	2	35	0.030	91.48	10.82	53.08	7.50	1.00	8.04	1.59	0.69
GB	2	40	0.030	61.88	10.82	53.08	7.50	1.00	8.04	1.59	0.69
GB	2	45	0.013	53.85	9.04	49.04	3.89	0.49	7.52	0.80	0.17

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
GB	2	50	0.006	37.40	5.42	33.35	3.56	0.49	4.09	0.69	0.17
GB	2	55	0.006	37.40	5.42	33.35	3.56	0.49	4.09	0.69	0.17
GB	2	60	0.005	37.40	7.29	33.35	0.51	0.00	6.50	0.18	0.00
GB	2	65	0.005	37.40	7.29	33.35	0.51	0.00	6.50	0.18	0.00
GB	2	70	0.018	37.40	6.54	33.35	0.00	0.00	6.38	0.00	0.00
GB	2	75	0.018	37.40	6.54	33.35	0.00	0.00	6.38	0.00	0.00
GB	3	5	0.030	424.89	219.56	316.25	9.57	0.39	16.96	2.60	0.18
GB	3	10	0.030	326.21	120.88	217.57	9.57	0.39	16.96	2.60	0.18
GB	3	15	0.083	202.95	117.18	191.22	8.04	3.69	12.59	1.98	2.51
GB	3	20	0.072	145.11	68.80	139.18	2.17	3.48	6.15	0.54	2.40
GB	3	25	0.072	145.11	49.07	139.18	2.17	3.48	6.15	0.54	2.40
GB	3	30	0.032	87.13	10.13	53.39	2.68	1.16	8.13	0.71	0.74
GB	3	35	0.030	61.88	10.82	53.08	7.50	1.00	8.04	1.59	0.69
GB	3	40	0.030	61.88	10.82	53.08	7.50	1.00	8.04	1.59	0.69
GB	3	45	0.013	53.85	9.04	49.04	3.89	0.49	7.52	0.80	0.17
GB	3	50	0.006	37.40	5.42	33.35	3.56	0.49	4.09	0.69	0.17
GB	3	55	0.006	37.40	5.42	33.35	3.56	0.49	4.09	0.69	0.17
GB	3	60	0.005	37.40	7.29	50.35	0.51	0.00	6.50	0.18	0.00
GB	3	65	0.005	37.40	7.29	50.35	0.51	0.00	6.50	0.18	0.00
GB	3	70	0.018	34.45	6.54	34.45	0.00	0.00	6.38	0.00	0.00
GB	3	75	0.018	34.45	6.54	34.45	0.00	0.00	6.38	0.00	0.00
GB	4	5	0.040	380.05	136.53	257.99	20.57	2.58	22.72	8.18	2.66
GB	4	10	0.040	281.37	87.19	257.99	20.57	2.58	22.72	8.18	2.66
GB	4	15	0.030	133.46	26.26	116.20	16.32	0.80	16.69	6.48	0.60
GB	4	20	0.030	133.46	26.26	116.20	16.32	0.80	16.69	6.48	0.60
GB	4	25	0.019	109.45	21.18	99.88	8.17	1.20	15.35	3.22	0.90
GB	4	30	0.023	121.97	23.21	112.51	8.06	1.22	17.16	3.22	0.91
GB	4	35	0.023	121.97	23.21	112.51	8.06	1.22	17.16	3.22	0.91
GB	4	40	0.023	121.97	23.21	112.51	8.06	1.22	17.16	3.22	0.91
GB	4	45	0.019	97.50	18.57	88.91	7.20	1.20	13.16	2.89	0.90
GB	4	50	0.019	97.50	18.57	88.91	7.20	1.20	13.16	2.89	0.90
GB	4	55	0.019	97.50	18.57	88.91	7.20	1.20	13.16	2.89	0.90
GB	4	60	0.005	37.32	7.57	37.00	0.22	0.10	5.18	0.10	0.07
GB	4	65	0.003	44.86	9.77	44.39	0.33	0.14	6.31	0.15	0.11
GB	4	70	0.003	54.20	11.97	53.08	0.98	0.14	8.26	0.39	0.11
GB	4	75	0.006	58.29	14.54	56.13	1.88	0.28	10.54	0.74	0.20
GB	5	5	0.179	311.58	148.38	230.60	23.21	4.19	29.89	9.52	4.20
GB	5	10	0.179	311.58	49.70	185.21	23.21	4.19	29.89	9.52	4.20

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
GB	5	15	0.169	262.34	38.11	142.11	18.96	2.41	23.86	7.82	2.14
GB	5	20	0.179	144.39	34.29	124.04	17.89	2.33	20.96	7.30	2.09
GB	5	25	0.179	144.39	34.29	124.04	17.89	2.33	20.96	7.30	2.09
GB	5	30	0.168	129.25	32.32	109.02	17.76	2.33	19.30	7.25	2.09
GB	5	35	0.015	26.52	2.43	12.03	0.38	0.30	1.77	0.14	0.25
GB	5	40	0.015	12.71	2.43	12.03	0.38	0.30	1.77	0.14	0.25
GB	5	45	0.004	11.33	1.57	11.33	0.00	0.00	1.44	0.00	0.00
GB	5	50	0.004	7.83	0.98	11.33	0.00	0.00	0.87	0.00	0.00
GB	5	55	0.004	7.83	0.98	11.33	0.00	0.00	0.87	0.00	0.00
GB	5	60	0.004	7.83	0.98	11.33	0.00	0.00	0.87	0.00	0.00
GB	5	65	0.004	7.83	0.98	11.33	0.00	0.00	0.87	0.00	0.00
GB	5	70	0.004	7.83	0.98	11.33	0.00	0.00	4.79	0.48	0.00
GB	5	75	0.004	7.83	0.98	11.33	0.00	0.00	4.79	0.48	0.00
GB	6	5	0.574	508.08	139.08	405.08	76.33	22.46	63.29	31.44	24.34
GB	6	10	0.574	470.33	139.08	370.93	76.33	22.46	63.29	31.44	24.34
GB	6	15	0.574	470.33	139.08	370.93	76.33	22.46	63.29	31.44	24.34
GB	6	20	0.569	470.33	145.18	370.93	80.25	22.13	67.09	34.01	23.70
GB	6	25	0.110	299.58	40.85	182.16	15.80	2.83	27.46	6.97	2.43
GB	6	30	0.110	200.90	40.85	182.16	15.80	2.83	27.46	6.97	2.43
GB	6	35	0.110	200.90	40.85	182.16	15.80	2.83	27.46	6.97	2.43
GB	6	40	0.081	112.70	25.65	100.39	10.18	2.12	17.12	4.77	1.93
GB	6	45	0.081	112.70	25.65	100.39	10.18	2.12	17.12	4.77	1.93
GB	6	50	0.008	70.15	18.85	57.36	10.18	2.12	10.71	3.72	3.85
GB	6	55	0.009	78.29	18.75	67.18	10.18	0.61	12.32	5.36	0.41
GB	6	60	0.012	57.87	11.62	56.42	1.45	0.00	10.49	0.55	0.00
GB	6	65	0.012	57.87	11.62	56.42	1.45	0.00	10.49	0.55	0.00
GB	6	70	0.012	57.87	11.62	56.42	1.45	0.00	10.49	0.55	0.00
GB	6	75	0.012	57.87	11.62	56.42	1.45	0.00	10.49	0.55	0.00
RG	1	5	0.169	197.99	60.87	124.77	29.92	6.54	33.64	12.96	0.00
RG	1	10	0.169	197.99	60.87	124.77	29.92	6.54	33.64	12.96	0.00
RG	1	15	0.169	197.99	60.87	124.77	29.92	6.54	33.64	12.96	0.00
RG	1	20	0.035	112.20	21.61	82.49	4.06	5.92	13.27	1.74	0.00
RG	1	25	0.035	112.20	21.61	82.49	4.06	5.92	13.27	1.74	0.00
RG	1	30	0.013	32.18	5.67	31.60	0.57	0.01	4.33	0.22	0.00
RG	1	35	0.013	32.18	5.67	31.60	0.57	0.01	4.33	0.22	0.00
RG	1	40	0.004	28.14	4.56	27.98	0.15	0.00	4.27	0.06	0.00
RG	1	45	0.004	28.14	4.56	27.98	0.15	0.00	4.27	0.06	0.00
RG	1	50	0.005	48.21	8.11	47.90	0.31	0.00	4.27	0.12	0.00

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
RG	1	55	0.005	48.21	8.11	47.90	0.31	0.00	4.27	0.12	0.00
RG	1	60	0.005	48.21	8.11	47.90	0.31	0.00	4.27	0.12	0.00
RG	1	65	0.005	48.21	8.11	47.90	0.31	0.00	4.27	0.12	0.00
RG	1	70	0.005	48.21	8.11	47.90	0.31	0.00	4.27	0.12	0.00
RG	1	75	0.005	48.21	8.11	47.90	0.31	0.00	4.27	0.12	0.00
RG	2	5	0.218	98.11	15.52	50.88	38.21	8.61	2.09	0.83	0.64
RG	2	10	0.218	98.11	7.63	50.88	38.21	8.61	2.09	0.83	0.64
RG	2	15	0.218	98.11	7.63	50.88	38.21	8.61	2.09	0.83	0.64
RG	2	20	0.101	64.28	7.63	36.16	25.50	2.28	2.09	0.83	0.64
RG	2	25	0.069	64.28	7.63	36.16	20.79	7.09	2.09	0.26	0.64
RG	2	30	0.069	64.28	7.63	36.16	20.79	7.09	1.39	0.26	0.64
RG	2	35	0.069	64.28	7.63	36.16	20.79	7.09	1.39	0.26	0.64
RG	2	40	0.069	64.28	5.99	36.16	20.79	7.09	1.39	0.26	0.64
RG	2	45	0.050	54.47	3.57	36.16	5.15	5.93	1.39	0.26	0.00
RG	2	50	0.030	45.24	3.57	38.68	6.52	0.00	0.40	0.26	0.00
RG	2	55	0.030	45.24	3.57	38.68	6.52	0.00	0.40	0.26	0.00
RG	2	60	0.030	45.24	3.57	38.68	6.52	0.00	0.40	0.26	0.00
RG	2	65	0.030	45.24	3.57	38.68	6.52	0.00	0.40	0.26	0.00
RG	2	70	0.003	28.39	3.57	19.50	8.89	0.00	0.40	0.26	0.00
RG	2	75	0.003	28.39	3.57	19.50	8.89	0.00	0.40	0.26	0.00
RG	3	5	0.033	97.01	40.91	84.41	61.66	9.41	24.94	8.61	1.18
RG	3	10	0.033	97.01	32.54	84.41	61.66	9.41	15.08	8.61	1.18
RG	3	15	0.033	97.01	32.54	84.41	61.66	9.41	15.08	8.61	1.18
RG	3	20	0.033	75.18	32.54	42.02	30.57	2.56	15.08	1.32	1.18
RG	3	25	0.033	75.18	32.54	42.02	30.57	2.56	15.08	1.32	0.00
RG	3	30	0.033	75.18	32.54	42.02	30.57	2.56	15.08	1.32	0.00
RG	3	35	0.033	75.18	32.54	42.02	30.57	2.56	15.08	1.32	0.00
RG	3	40	0.024	45.30	18.14	6.30	24.84	4.29	7.85	1.32	0.00
RG	3	45	0.024	18.63	18.14	6.30	24.84	4.29	7.85	1.32	0.00
RG	3	50	0.019	18.63	11.10	3.75	10.19	3.63	4.61	1.32	0.00
RG	3	55	0.019	18.63	11.10	3.75	10.19	3.63	4.61	1.32	0.00
RG	3	60	0.019	18.63	11.10	3.75	10.19	3.63	4.61	1.32	0.00
RG	3	65	0.019	18.63	11.10	3.75	10.19	3.63	4.61	1.32	0.00
RG	3	70	0.018	18.63	11.10	1.67	10.19	3.40	4.47	1.32	0.00
RG	3	75	0.009	18.63	3.76	1.67	10.19	0.00	1.28	1.32	0.00
RG	4	5	0.045	94.57	30.84	39.20	24.77	9.97	7.43	3.35	0.87
RG	4	10	0.045	94.57	30.84	39.20	24.77	9.97	7.43	3.35	0.87
RG	4	15	0.045	94.57	30.84	39.20	24.77	9.97	7.43	3.35	0.87

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
RG	4	20	0.036	88.55	12.99	25.34	24.77	10.67	6.53	3.35	0.87
RG	4	25	0.036	83.81	12.99	25.34	17.05	1.48	0.56	0.96	0.00
RG	4	30	0.036	83.81	12.99	25.34	17.05	1.48	0.56	0.96	0.00
RG	4	35	0.036	83.81	12.99	25.34	17.05	1.48	0.56	0.96	0.00
RG	4	40	0.036	83.81	12.99	25.34	17.05	1.48	0.56	0.96	0.00
RG	4	45	0.036	83.81	8.41	25.34	17.05	1.48	0.56	0.96	0.00
RG	4	50	0.025	12.60	8.41	5.58	9.11	0.35	0.56	0.96	0.00
RG	4	55	0.025	12.60	8.41	5.58	8.30	0.52	0.56	0.96	0.00
RG	4	60	0.025	10.66	8.41	5.58	8.30	0.52	0.56	0.96	0.00
RG	4	65	0.025	10.66	8.41	5.58	8.30	0.52	0.56	0.96	0.00
RG	4	70	0.025	10.66	8.41	5.58	8.30	0.52	0.56	0.96	0.00
RG	4	75	0.025	10.66	8.41	5.58	8.30	0.52	0.56	0.96	0.00
RG	5	5	0.060	121.74	82.44	116.59	45.36	7.57	40.15	19.10	0.20
RG	5	10	0.060	121.74	62.71	116.59	45.36	7.57	30.28	19.10	0.20
RG	5	15	0.060	77.30	62.71	47.52	45.36	7.57	30.28	19.10	0.20
RG	5	20	0.038	77.30	62.71	47.52	27.27	4.94	28.12	11.05	0.20
RG	5	25	0.076	77.30	55.48	47.52	27.64	0.94	28.12	11.21	0.69
RG	5	30	0.076	77.30	55.48	47.52	27.64	0.94	28.12	11.21	0.69
RG	5	35	0.076	77.30	55.48	47.52	27.64	0.94	28.12	11.21	0.69
RG	5	40	0.028	77.30	44.59	47.52	22.78	0.66	19.96	9.15	0.48
RG	5	45	0.023	46.49	51.59	36.92	28.21	0.97	19.96	11.32	0.70
RG	5	50	0.023	42.84	26.72	34.07	8.68	0.03	19.96	3.28	0.02
RG	5	55	0.025	23.06	26.72	20.76	8.68	0.06	19.96	4.17	0.04
RG	5	60	0.025	23.06	26.72	20.76	8.68	0.06	19.96	4.17	0.04
RG	5	65	0.025	23.06	26.72	20.76	8.68	0.06	19.96	4.17	0.04
RG	5	70	0.025	23.06	26.72	20.76	8.68	0.06	19.96	4.17	0.04
RG	5	75	0.025	23.06	26.72	20.76	8.68	0.06	19.96	4.17	0.04
RG	6	5	0.136	167.29	82.93	79.90	36.73	10.59	43.56	23.58	0.04
RG	6	10	0.136	167.29	82.93	79.90	36.73	10.59	43.56	23.58	0.04
RG	6	15	0.136	167.29	82.93	79.90	36.73	10.59	43.56	23.58	0.04
RG	6	20	0.120	93.48	60.14	24.85	36.73	7.91	33.03	16.38	0.04
RG	6	25	0.089	82.86	57.12	18.17	36.73	7.91	32.85	12.92	0.04
RG	6	30	0.050	47.98	46.11	18.17	29.99	7.91	27.10	7.41	0.04
RG	6	35	0.050	47.98	46.11	18.17	29.99	7.91	27.10	7.41	0.04
RG	6	40	0.039	47.98	43.79	18.17	23.93	0.00	23.04	9.73	0.04
RG	6	45	0.039	47.98	43.79	18.17	23.93	0.00	23.04	9.73	0.04
RG	6	50	0.039	47.98	43.79	18.17	23.93	0.00	23.04	9.73	0.04
RG	6	55	0.026	47.98	30.79	18.17	23.93	0.00	16.50	10.70	0.04

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
RG	6	60	0.022	25.06	23.35	18.17	23.93	0.00	13.26	7.35	0.04
RG	6	65	0.022	25.06	23.35	18.17	23.93	0.00	13.26	7.35	0.04
RG	6	70	0.031	25.06	23.35	18.17	23.93	0.00	17.17	7.35	0.04
RG	6	75	0.046	25.06	23.35	18.17	23.93	0.00	19.29	7.35	0.04
CG	1	5	0.003	19.26	2.02	19.23	0.03	0.00	1.65	0.01	0.00
CG	1	10	0.003	19.26	2.02	19.23	0.03	0.00	1.65	0.01	0.00
CG	1	15	0.003	19.37	2.02	19.35	0.03	0.00	1.65	0.01	0.00
CG	1	20	0.003	19.37	2.02	19.35	0.03	0.00	1.65	0.01	0.00
CG	1	25	0.003	3.41	0.45	3.41	0.00	0.00	0.41	0.00	0.00
CG	1	30	0.003	3.41	0.45	3.41	0.00	0.00	0.41	0.00	0.00
CG	1	35	0.003	3.41	0.45	3.41	0.00	0.00	0.41	0.00	0.00
CG	1	40	0.003	3.41	0.45	3.41	0.00	0.00	0.41	0.00	0.00
CG	1	45	0.003	3.41	0.45	3.41	0.00	0.00	0.41	0.00	0.00
CG	1	50	0.003	3.41	0.45	3.41	0.00	0.00	0.41	0.00	0.00
CG	1	55	0.003	3.41	0.45	3.41	0.00	0.00	0.41	0.00	0.00
CG	1	60	0.003	3.41	0.45	3.41	0.00	0.00	0.41	0.00	0.00
CG	1	65	0.003	3.41	0.45	3.41	0.00	0.00	0.41	0.00	0.00
CG	1	70	0.003	3.41	0.45	3.41	0.00	0.00	0.41	0.00	0.00
CG	1	75	0.003	3.41	0.45	3.41	0.00	0.00	0.41	0.00	0.00
CG	2	5	0.003	26.34	3.56	25.62	0.72	0.00	2.93	0.27	0.00
CG	2	10	0.003	26.34	3.56	25.62	0.72	0.00	2.93	0.27	0.00
CG	2	15	0.003	26.34	3.56	25.62	0.72	0.00	2.93	0.27	0.00
CG	2	20	0.003	18.13	2.77	17.06	0.26	0.00	1.73	0.09	0.00
CG	2	25	0.003	17.21	1.40	14.50	0.36	0.00	1.15	0.13	0.00
CG	2	30	0.003	14.94	1.40	14.50	0.44	0.00	2.29	0.16	0.00
CG	2	35	0.003	14.94	1.40	14.50	0.44	0.00	2.29	0.16	0.00
CG	2	40	0.003	14.94	1.40	11.73	0.44	0.00	2.86	0.43	0.00
CG	2	45	0.003	14.94	1.40	11.73	0.44	0.00	2.86	0.43	0.00
CG	2	50	0.003	12.44	1.16	11.73	0.44	0.00	1.65	0.32	0.00
CG	2	55	0.003	12.44	1.16	11.73	0.21	0.00	1.65	0.32	0.00
CG	2	60	0.003	6.58	0.74	6.58	0.00	0.00	0.66	0.00	0.00
CG	2	65	0.003	6.58	0.74	6.58	0.00	0.00	0.66	0.00	0.00
CG	2	70	0.003	6.31	0.63	6.31	0.00	0.00	0.54	0.00	0.00
CG	2	75	0.003	4.50	0.63	6.31	0.00	0.00	0.91	0.00	0.00
CG	3	5	0.003	5.74	0.93	5.38	0.35	0.00	0.70	0.15	0.00
CG	3	10	0.003	5.74	0.93	5.38	0.35	0.00	0.70	0.15	0.00
CG	3	15	0.003	5.74	0.93	5.38	0.35	0.00	0.70	0.15	0.00
CG	3	20	0.008	6.92	1.28	6.54	0.39	0.00	1.02	0.15	0.00

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
CG	3	25	0.008	6.92	1.28	6.54	0.39	0.00	1.02	0.15	0.00
CG	3	30	0.008	6.92	1.28	6.54	0.39	0.00	1.02	0.15	0.00
CG	3	35	0.008	6.92	1.28	6.54	0.39	0.00	1.02	0.15	0.00
CG	3	40	0.004	3.49	0.75	3.39	0.10	0.00	0.69	0.04	0.00
CG	3	45	0.004	3.49	0.75	3.39	0.10	0.00	0.69	0.04	0.00
CG	3	50	0.004	3.49	0.75	3.39	0.10	0.00	0.69	0.04	0.00
CG	3	55	0.004	3.49	0.75	3.39	0.10	0.00	0.69	0.04	0.00
CG	3	60	0.004	3.49	0.75	3.39	0.10	0.00	0.69	0.04	0.00
CG	3	65	0.004	3.49	0.75	3.39	0.10	0.00	0.69	0.04	0.00
CG	3	70	0.004	3.49	0.75	3.39	0.10	0.00	0.69	0.04	0.00
CG	3	75	0.004	3.49	0.75	3.39	0.10	0.00	0.69	0.04	0.00
CG	4	5	0.009	43.94	7.44	40.97	2.97	0.00	6.07	1.03	0.00
CG	4	10	0.009	43.94	7.44	40.97	2.97	0.00	6.07	1.03	0.00
CG	4	15	0.009	43.94	7.44	40.97	2.97	0.00	6.07	1.03	0.00
CG	4	20	0.005	39.85	7.54	37.53	2.31	0.00	6.45	0.79	0.00
CG	4	25	0.005	29.47	4.76	29.27	0.20	0.00	4.41	0.07	0.00
CG	4	30	0.005	29.47	4.76	29.27	0.20	0.00	4.41	0.07	0.00
CG	4	35	0.005	29.47	4.76	29.27	0.20	0.00	4.41	0.07	0.00
CG	4	40	0.004	24.09	3.17	24.09	0.00	0.00	2.98	0.00	0.00
CG	4	45	0.004	15.28	1.73	15.28	0.00	0.00	1.64	0.00	0.00
CG	4	50	0.004	15.28	1.73	15.28	0.00	0.00	1.64	0.00	0.00
CG	4	55	0.004	15.28	1.73	15.28	0.00	0.00	1.64	0.00	0.00
CG	4	60	0.003	14.49	1.66	15.28	0.00	0.00	1.75	0.00	0.00
CG	4	65	0.003	14.49	1.66	15.28	0.00	0.00	1.75	0.00	0.00
CG	4	70	0.004	8.01	0.93	8.01	0.00	0.00	0.85	0.00	0.00
CG	4	75	0.004	8.01	0.93	8.01	0.00	0.00	0.85	0.00	0.00
CG	5	5	0.003	6.52	0.89	6.50	0.02	0.00	0.78	0.01	0.00
CG	5	10	0.003	6.52	0.89	6.50	0.02	0.00	0.78	0.01	0.00
CG	5	15	0.003	6.52	0.89	6.50	0.02	0.00	0.78	0.01	0.00
CG	5	20	0.003	6.52	0.89	6.50	0.02	0.00	0.78	0.01	0.00
CG	5	25	0.004	6.87	0.98	6.83	0.04	0.00	0.85	0.01	0.00
CG	5	30	0.004	6.87	0.98	6.83	0.04	0.00	0.85	0.01	0.00
CG	5	35	0.004	6.87	0.98	6.83	0.04	0.00	0.85	0.01	0.00
CG	5	40	0.004	6.87	0.98	6.83	0.04	0.00	0.85	0.01	0.00
CG	5	45	0.004	6.87	0.98	6.83	0.04	0.00	0.85	0.01	0.00
CG	5	50	0.005	8.64	1.27	8.57	0.07	0.00	1.05	0.03	0.00
CG	5	55	0.005	8.64	1.27	8.57	0.07	0.00	1.05	0.03	0.00
CG	5	60	0.005	8.64	1.27	8.57	0.07	0.00	1.05	0.03	0.00

A 4.2. Cont'd

TRT	REP	Depth (cm)	OD wt (g)	RLD	SA	RLD			SA		
CG	5	65	0.005	8.64	1.27	8.57	0.07	0.00	1.05	0.03	0.00
CG	5	70	0.005	8.64	1.27	8.57	0.07	0.00	1.05	0.03	0.00
CG	5	75	0.005	8.64	1.27	8.57	0.07	0.00	1.05	0.03	0.00
CG	6	5	0.003	11.20	1.01	11.20	0.00	0.00	0.92	0.00	0.00
CG	6	10	0.003	11.20	1.01	11.20	0.00	0.00	0.92	0.00	0.00
CG	6	15	0.003	11.27	1.01	11.27	0.00	0.00	0.92	0.00	0.00
CG	6	20	0.003	13.24	1.00	13.24	0.00	0.00	0.90	0.00	0.00
CG	6	25	0.003	1.99	0.25	1.99	0.00	0.00	0.22	0.00	0.00
CG	6	30	0.003	1.99	0.25	1.99	0.00	0.00	0.22	0.00	0.00
CG	6	35	0.003	1.99	0.25	1.99	0.00	0.00	0.22	0.00	0.00
CG	6	40	0.003	1.99	0.25	1.99	0.00	0.00	0.22	0.00	0.00
CG	6	45	0.003	1.99	0.25	1.99	0.00	0.00	0.22	0.00	0.00
CG	6	50	0.003	1.99	0.25	1.99	0.00	0.00	0.22	0.00	0.00
CG	6	55	0.003	1.99	0.25	1.99	0.00	0.00	0.22	0.00	0.00
CG	6	60	0.003	1.99	0.25	1.99	0.00	0.00	0.22	0.00	0.00
CG	6	65	0.003	1.99	0.25	1.99	0.00	0.00	0.22	0.00	0.00
CG	6	70	0.003	1.99	0.25	1.99	0.00	0.00	0.22	0.00	0.00
CG	6	75	0.003	1.99	0.25	1.99	0.00	0.00	0.22	0.00	0.00

*AgB50 = root sampling in agroforestry buffer treatment at 50 cm away from tree trunk, and AgB 100 = root sampling in agroforestry buffer treatment at 100 cm away from tree trunk.

A 4.3. Soil carbon measured in 2008 and used in Chapter 5. AgB=agroforestry buffer, GB= grass buffer, RG= rotationally grazed pasture, and CG= continuously grazed pasture.

Treatment	Replication	Soil depth (cm)	Soil carbon (%)
AgB	1	5	1.51
AgB	1	10	1.51
AgB	1	15	1.51
AgB	1	20	1.34
AgB	1	25	1.34
AgB	1	30	1.34
AgB	1	35	0.72
AgB	1	40	0.72
AgB	1	45	0.72
AgB	1	50	0.58
AgB	1	55	0.58
AgB	1	60	0.58
AgB	1	65	0.58
AgB	1	70	0.58
AgB	1	75	0.58
AgB	2	5	1.62
AgB	2	10	1.62
AgB	2	15	1.62
AgB	2	20	1.62
AgB	2	25	1.24
AgB	2	30	1.24
AgB	2	35	1.24
AgB	2	40	0.49
AgB	2	45	0.49
AgB	2	50	0.49
AgB	2	55	0.49
AgB	2	60	0.36
AgB	2	65	0.36
AgB	2	70	0.36
AgB	2	75	0.36
AgB	3	5	2.01
AgB	3	10	2.01
AgB	3	15	2.01
AgB	3	20	2.01
AgB	3	25	0.93

A 4.3. Cont'd

Treatment	Replication	Soil depth	Soil carbon
AgB	3	30	0.93
AgB	3	35	0.67
AgB	3	40	0.67
AgB	3	45	0.67
AgB	3	50	0.65
AgB	3	55	0.65
AgB	3	60	0.65
AgB	3	65	0.65
AgB	3	70	0.65
AgB	3	75	0.65
AgB	4	5	2.53
AgB	4	10	2.53
AgB	4	15	1.19
AgB	4	20	1.19
AgB	4	25	1.49
AgB	4	30	1.49
AgB	4	35	0.17
AgB	4	40	0.17
AgB	4	45	0.17
AgB	4	50	0.17
AgB	4	55	0.17
AgB	4	60	0.17
AgB	4	65	0.17
AgB	4	70	0.17
AgB	4	75	0.17
GB	1	5	1.20
GB	1	10	1.20
GB	1	15	0.76
GB	1	20	0.76
GB	1	25	0.76
GB	1	30	0.74
GB	1	35	0.74
GB	1	40	0.74
GB	1	45	0.63
GB	1	50	0.63
GB	1	55	0.63
GB	1	60	0.63
GB	1	65	0.63
GB	1	70	0.63

A 4.3. Cont'd

Treatment	Replication	Soil depth	Soil carbon
GB	1	75	0.63
GB	2	5	1.20
GB	2	10	1.20
GB	2	15	1.20
GB	2	20	1.03
GB	2	25	1.03
GB	2	30	0.84
GB	2	35	0.84
GB	2	40	0.84
GB	2	45	0.84
GB	2	50	0.26
GB	2	55	0.26
GB	2	60	0.26
GB	2	65	0.26
GB	2	70	0.26
GB	2	75	0.26
GB	3	5	1.62
GB	3	10	1.62
GB	3	15	1.62
GB	3	20	1.62
GB	3	25	1.24
GB	3	30	1.24
GB	3	35	1.24
GB	3	40	0.49
GB	3	45	0.49
GB	3	50	0.49
GB	3	55	0.49
GB	3	60	0.36
GB	3	65	0.36
GB	3	70	0.36
GB	3	75	0.36
GB	4	5	1.34
GB	4	10	1.34
GB	4	15	1.19
GB	4	20	1.14
GB	4	25	1.01
GB	4	30	0.90
GB	4	35	0.90
GB	4	40	0.65

A 4.3. Cont'd

Treatment	Replication	Soil depth	Soil carbon
GB	4	45	0.69
GB	4	50	0.50
GB	4	55	0.50
GB	4	60	0.45
GB	4	65	0.45
GB	4	70	0.45
GB	4	75	0.45
RG	1	5	0.40
RG	1	10	0.40
RG	1	15	0.40
RG	1	20	0.40
RG	1	25	0.18
RG	1	30	0.18
RG	1	35	0.18
RG	1	40	0.18
RG	1	45	0.15
RG	1	50	0.15
RG	1	55	0.15
RG	1	60	0.15
RG	1	65	0.15
RG	1	70	0.13
RG	1	75	0.13
RG	2	5	0.64
RG	2	10	0.64
RG	2	15	0.64
RG	2	20	0.14
RG	2	25	0.14
RG	2	30	0.14
RG	2	35	0.14
RG	2	40	0.11
RG	2	45	0.11
RG	2	50	0.11
RG	2	55	0.11
RG	2	60	0.11
RG	2	65	0.11
RG	2	70	0.11
RG	2	75	0.14
RG	3	5	0.30
RG	3	10	0.30

A 4.3. Cont'd

Treatment	Replication	Soil depth	Soil carbon
RG	3	15	0.30
RG	3	20	0.13
RG	3	25	0.13
RG	3	30	0.13
RG	3	35	0.13
RG	3	40	0.13
RG	3	45	0.12
RG	3	50	0.12
RG	3	55	0.12
RG	3	60	0.12
RG	3	65	0.12
RG	3	70	0.11
RG	3	75	0.11
RG	4	5	0.23
RG	4	10	0.23
RG	4	15	0.23
RG	4	20	0.22
RG	4	25	0.22
RG	4	30	0.22
RG	4	35	0.22
RG	4	40	0.15
RG	4	45	0.15
RG	4	50	0.15
RG	4	55	0.15
RG	4	60	0.15
RG	4	65	0.12
RG	4	70	0.12
RG	4	75	0.12
CG	1	5	0.82
CG	1	10	0.82
CG	1	15	0.82
CG	1	20	0.82
CG	1	25	0.82
CG	1	30	1.19
CG	1	35	1.19
CG	1	40	1.19
CG	1	45	1.19
CG	1	50	0.42
CG	1	55	0.42

A 4.3. Cont'd

Treatment	Replication	Soil depth	Soil carbon
CG	1	60	0.42
CG	1	65	0.42
CG	1	70	0.23
CG	1	75	0.23
CG	2	5	0.86
CG	2	10	0.86
CG	2	15	0.86
CG	2	20	0.90
CG	2	25	0.90
CG	2	30	0.90
CG	2	35	0.90
CG	2	40	0.24
CG	2	45	0.24
CG	2	50	0.24
CG	2	55	0.24
CG	2	60	0.24
CG	2	65	0.24
CG	2	70	0.32
CG	2	75	0.32
CG	3	5	0.82
CG	3	10	0.82
CG	3	15	0.82
CG	3	20	0.74
CG	3	25	0.74
CG	3	30	0.74
CG	3	35	0.74
CG	3	40	0.43
CG	3	45	0.43
CG	3	50	0.43
CG	3	55	0.43
CG	3	60	0.31
CG	3	65	0.31
CG	3	70	0.31
CG	3	75	0.31
CG	4	5	1.23
CG	4	10	1.23
CG	4	15	1.23
CG	4	20	1.23
CG	4	25	0.48

A 4.3. Cont'd

Treatment	Replication	Soil depth	Soil carbon
CG	4	30	0.48
CG	4	35	0.48
CG	4	40	0.48
CG	4	45	0.48
CG	4	50	0.48
CG	4	55	0.23
CG	4	60	0.23
CG	4	65	0.23
CG	4	70	0.23
CG	4	75	0.23

A 4.4. Root carbon measured in 2008 and used in Chapter 5. AgB=agroforestry buffer, GB= grass buffer, RG= rotationally grazed pasture, and CG= continuously grazed pasture.

Treatment	Replication	Soil depth (cm)	Root carbon (%)
AgB	1	10	32.33
AgB	1	20	32.33
AgB	1	30	31.98
AgB	1	40	31.98
AgB	1	50	31.98
AgB	1	60	31.98
AgB	1	70	31.98
AgB	2	10	35.50
AgB	2	20	34.35
AgB	2	30	34.35
AgB	2	40	34.35
AgB	2	50	34.35
AgB	2	60	34.35
AgB	2	70	34.35
AgB	3	10	32.22
AgB	3	20	32.22
AgB	3	30	28.39
AgB	3	40	28.39
AgB	3	50	28.39
AgB	3	60	28.39
AgB	3	70	28.39
AgB	4	10	38.17
AgB	4	20	35.11
AgB	4	30	35.00
AgB	4	40	35.00
AgB	4	50	35.00
AgB	4	60	35.00
AgB	4	70	35.00
AgB	5	10	40.00
AgB	5	20	37.98
AgB	5	30	37.98
AgB	5	40	37.98
AgB	5	50	37.98
AgB	5	60	37.98
AgB	5	70	37.98
AgB	6	10	35.13

A 4.4. Cont'd

Treatment	Replication	Soil depth	Root carbon
AgB	6	20	35.13
AgB	6	30	35.16
AgB	6	40	29.11
AgB	6	50	29.11
AgB	6	60	29.11
AgB	6	70	29.11
GB	1	10	36.07
GB	1	20	32.95
GB	1	30	22.99
GB	1	40	22.99
GB	1	50	22.99
GB	1	60	22.99
GB	1	70	22.99
GB	2	10	37.93
GB	2	20	34.01
GB	2	30	33.31
GB	2	40	33.31
GB	2	50	33.31
GB	2	60	33.31
GB	2	70	33.31
GB	3	10	34.48
GB	3	20	33.85
GB	3	30	33.85
GB	3	40	33.85
GB	3	50	33.85
GB	3	60	33.85
GB	3	70	33.85
GB	4	10	34.11
GB	4	20	33.49
GB	4	30	33.49
GB	4	40	33.49
GB	4	50	33.49
GB	4	60	30.01
GB	4	70	30.01
GB	5	10	35.72
GB	5	20	23.19
GB	5	30	23.19
GB	5	40	23.19

A 4.4. Cont'd

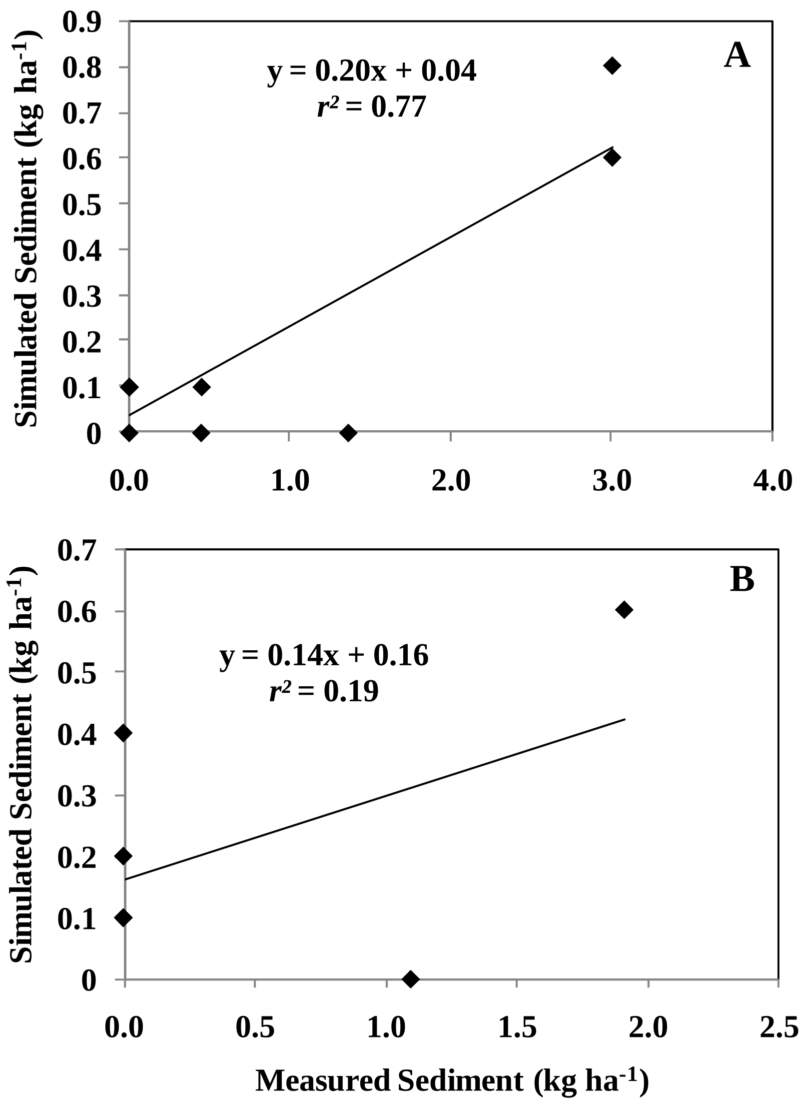
Treatment	Replication	Soil depth	Root carbon
GB	5	50	23.19
GB	5	60	23.19
GB	5	70	23.19
GB	6	10	36.01
GB	6	20	33.11
GB	6	30	33.11
GB	6	40	33.11
GB	6	50	33.11
GB	6	60	33.11
GB	6	70	33.11
RG	1	10	29.64
RG	1	20	32.63
RG	1	30	32.63
RG	1	40	32.63
RG	1	50	32.63
RG	1	60	32.63
RG	1	70	32.63
RG	2	10	34.11
RG	2	20	34.11
RG	2	30	33.28
RG	2	40	33.28
RG	2	50	33.28
RG	2	60	33.28
RG	2	70	33.28
RG	3	10	32.27
RG	3	20	32.27
RG	3	30	32.27
RG	3	40	32.27
RG	3	50	32.27
RG	3	60	32.27
RG	3	70	32.27
RG	4	10	30.98
RG	4	20	34.24
RG	4	30	26.11
RG	4	40	26.11
RG	4	50	26.11
RG	4	60	26.11
RG	4	70	26.11

A 4.4. Cont'd

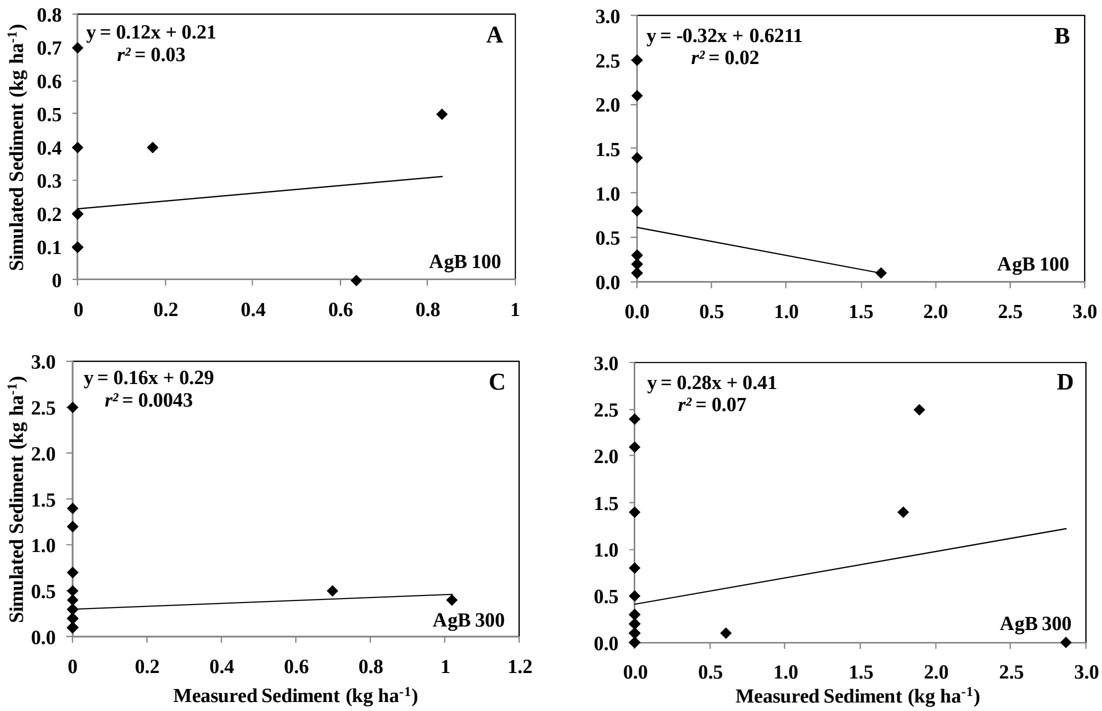
Treatment	Replication	Soil depth	Root carbon
RG	5	10	28.56
RG	5	20	28.56
RG	5	30	28.56
RG	5	40	28.56
RG	5	50	28.56
RG	5	60	28.56
RG	5	70	28.56
RG	6	10	34.39
RG	6	20	34.39
RG	6	30	31.40
RG	6	40	31.40
RG	6	50	31.40
RG	6	60	34.70
RG	6	70	34.70

APPENDIX 5

A 5.1. Measured versus simulated sediment loss for calibration (A, CW 400) from 2002 to 2005 and validation (B, CW 400) from 2005 to 2008. CW=control watershed.



A 5.2. Measured versus simulated sediment loss for calibration (A, AgB100; C, AgB 300) from 2002 to 2005 and validation (B, AgB 100; D, AgB 300) from 2005 to 2008. AgB=agroforestry buffer.



VITA

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