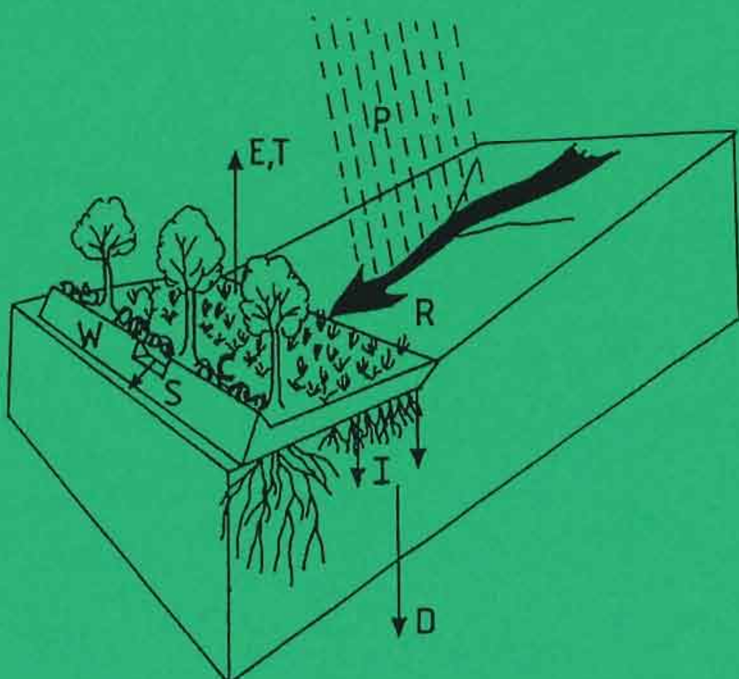
Agroforestry combined with water harvesting in the central zone of Chile

Soil properties and biomass production

Osvaldo Salazar G.



MSc Thesis (Examensarbete)
Supervisors (Handledare): Abraham Joel & Manuel Casanova

Institutionen för markvetenskap
Avdelningen för lantbrukets hydroteknik

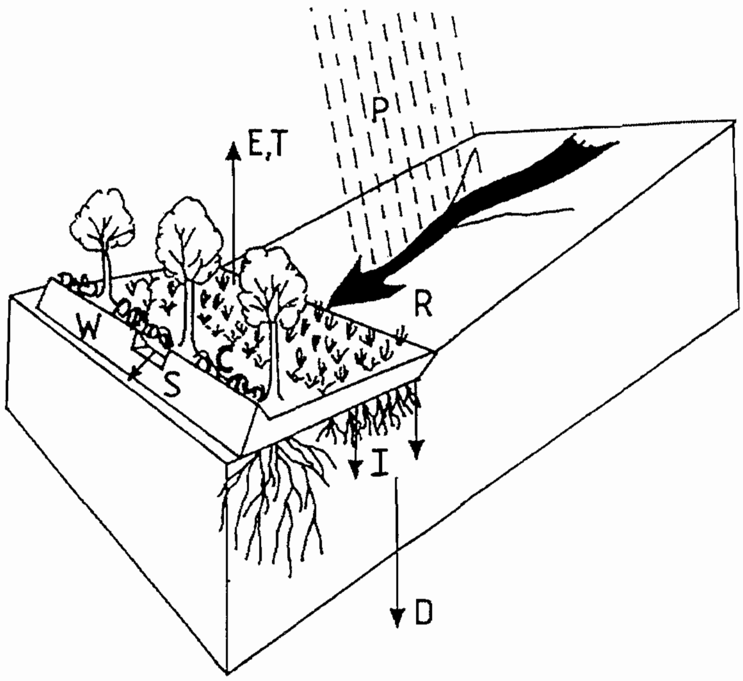
Avdelningsmeddelande 03:2
Communications

Swedish University of Agricultural Sciences
Department of Soil Sciences
Division of Agricultural Hydrotechnics

Uppsala 2003
ISSN 0282-6569
ISRN SLU-HY-AVDM--03/2--SE

Agroforestry combined with water harvesting in the central zone of Chile
Soil properties and biomass production

Osvaldo Salazar G.



MSc Thesis (Examensarbete)
Supervisors (Handledare): Abraham Joel & Manuel Casanova

Institutionen för markvetenskap
Avdelningen för lantbrukets hydroteknik

Avdelningsmeddelande 03:2
Communications

Swedish University of Agricultural Sciences
Department of Soil Sciences
Division of Agricultural Hydrotechnics

Uppsala 2003
ISSN 0282-6569
ISRN SLU-HY-AVDM--03/2--SE

TABLE OF CONTENTS

ABSTRACT

This paper analyses a study of agroforestry combined with water harvesting in the inner rainfed zone of central Chile during a four-year period. The aim of this study was to provide knowledge on agroforestry combined with water harvesting and to evaluate its performance in the semiarid zone of Chile. Both soil properties and plant growth in the agroforestry systems with water harvesting were analysed and the results compared with those of other crop management systems in the same zone. Soil analysis revealed a lack of differences between treatments, a fact that might be related mainly to the short study time. The use of runoff water for supplemental irrigation of agroforestry systems in the central zone of Chile proved to be beneficial for both soil properties and plant productivity. Agroforestry with water harvesting showed higher positive effects in soil properties such as soil organic matter content and total nitrogen content, mainly in the deeper layers, than the other crop management systems. *Acacia saligna* trees with water harvesting produced the highest growth. The annual prairie in agroforestry with water harvesting showed the lowest biomass production, which might have been related to the increased shading by the trees.

RESUMEN

Introducción

En zonas semiáridas el agua es un recurso natural escaso de gran valor para la agricultura. Bajo condiciones de secano solo los aportes de las precipitaciones determinarán el éxito o fracaso de la producción agrícola. De esta forma, para contrarrestar la degradación de suelos en ecosistemas frágiles de Chile es necesario una sostenible diversificación de la agricultura. Un posible camino es la implementación de sistemas agroforestales. Estos han sido concebidos para dar solución a problemas agrícolas presentes en suelos degradados al contribuir tanto con diversidad ecológica como estabilidad económica (Lundgren, 1982)

Sin embargo, en zonas de secano los componentes vegetales de los sistemas agroforestales presentan por el uso del agua competición mas que complementaridad (Le Roux *et al.*, 1995; Kho, 2000). Ovalle *et al.* (2002) también reportan que en sistemas agroforestales de la zona central de Chile se produce una fuerte competición por el agua en la capa arable entre los árboles y la estrata herbácea.

Lövenstein *et al.* (1991) basado en sus resultados sugiere que la agroforestería asociada a un sistema de cosecha de aguas puede ser una solución viable. La cosecha de escurrimientos superficiales ha sido usada como riego suplementario en áreas de secano ayudando tanto a incrementar como a sostener la producción de alimentos en estas regiones (Bhushan, *et al.* 1992; Tabor, 1995; Li, *et al.*, 2000).

Hay muchos estudios que reportan las numerosas interacciones entre los árboles, el suelo y cultivos que se producen en los sistemas agroforestales. Sin embargo, nuevas investigaciones con tecnologías de bajo costo como la cosecha de aguas son necesarias para mejorar la productividad de los sistemas agroforestales en zonas semiáridas (Tesfaye Abebe, 1994; Bunch, 1999). Esta tesis analiza un estudio de agroforestería bajo cosecha de aguas en el secano interior de la zona central de Chile realizado durante un período de cuatro años. El objetivo fue evaluar el funcionamiento de la agroforestería asociada a un sistema de cosecha

de aguas y comparar sus resultados, tanto de análisis de suelos como de mediciones en las especies vegetales presentes, con otros sistemas de manejo en la misma zona.

Materiales y Método

Este estudio fué realizado en el secano de la zona central de Chile a 20 km de Santiago (33° 28′ Sur -70° 50′ Oeste, altitud 470 m s.n.m.) entre 1996 y el 2000. La zona de estudio estaba dentro de la estación experimental Germán Greve Silva que pertenece a la Facultad de Ciencias Agronómicas de la Universidad de Chile.

Los suelos son franco arenosos, localizados en un plano ligeramente inclinado (pendiente 7-10 %), descansan sobre una subestrata de origen coluvial y tienen una matriz franco arcillo arenosa a menos de 100 cm. El suelo es un mollisol de origen coluvial con influencia aluvial, pertenece a la Serie de suelos *Piedmont Cuesta Barriga* y ha sido clasificado como Typic Haploxeroll (Luzio, 1996).

El clima de la zona se clasifica como templado cálido con una estación seca prolongada (6 a 8 meses) según la clasificación climática de Köeppen. La distribución de las precipitaciones se caracteriza por una fuerte estacionalidad, concentrandose el 75 % de las precipitaciones en los meses de invierno.

Quince parcelas fueron instaladas con un diseño de bloques al azar con tres repeticiones por tratamiento. Los tratamientos fueron agroforestería asociada a cosecha de aguas, árboles multipropósito asociados a cosecha de aguas, agroforestería, árboles multipróposito y un control. Las especies vegetales seleccionadas fueron *Acacia saligna* como árbol multipróposito y *Avena sativa* como cultivo anual. Cada parcela tenía una área total de 165 m^2 (15 m x 11 m). Las parcelas con el sistema de cosecha de aguas tenían un área de captación de escurrimientos de 110 m^2 (11 m x 10 m) y un área cultivada de 55 m^2 (11 m x 5 m).

El muestreo de suelos fue realizado en todos los tratamientos en un área de 11 m x 5 m, localizada en el tercio inferior de cada parcela. Las profundidades de muestreo fueron 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm. En total quince submuestras fueron tomadas por cada profundidad.

Las muestras de suelo se usaron para realizar análisis químicos y físicos. Los análisis se realizaron en los laboratorios de la Facultad de Ciencias Agronómicas de la Universidad de Chile durante el 2001. De esta forma se determinó mediante métodos estándar el contenido de materia orgánica, nitrógeno total, fósforo total, potasio total, capacidad de intercambio catiónico, reacción del suelo, distribución del tamaño de particulas y densidad aparente. Los resultados fueron sometidos a análisis de varianza (ANDEVA, $p<0.05$) y a la pueba t de Student $p<0.05$.

Resultados y Discusión

El estudio presentó serias dificultades los dos primeros años. Como consecuencia el segundo año fue necesario replantar muchos árboles. In 1998, los tratamientos con agroforestería se cambiaron a una asociación entre *Acacia saligna* y la pradera anual que crecía en condiciones naturales. Luego en 1999, la pradera anual se midió. En octubre del año 2000, se realizaron mediciones a los árboles de *Acacia saligna* y un muestreo de suelos en todos los tratamientos.

Agroforestería asociada a cosecha de aguas presentó una falta de diferencias significativas con los otros tratamintos en casi todos los análisis de suelo a un nivel de significancia de 0.05. Esto podría ser atribuido al hecho que el tiempo de estudio ha sido corto. Por lo tanto, su potencial contribución a mejorar las propiedades del suelo pueden no haber sido realizadas todavía. Similares resultados han sido reportadas en otros estudios, como los de Kaya y Nair (2001) en Mali, y Neupane y Thapa (2001) en Nepal, después de 4 y 2 años respectivamente. En este sentido, Nair *et al.* (1995) agrega que a menudo los potenciales beneficios de la agroforestería sobre el suelo no se manifiestan en el corto plazo. A pesar de esto, la agroforestería bajo cosecha de aguas mostró positivos efectos con las mayores acumulaciones de tanto la materia orgánica como de nitrógeno total en las capas más profundas.

Por otra parte cuando el sistema de cosecha de aguas fue usado como riego suplementario para los árboles multipróposito favoreció la depositación de materiales finos en estos. Entonces el desafío es determinar en futuras investigaciones tanto el tamaño óptimo de las áreas de captación como otras prácticas alternativas. Además, es importante determinar en nuevas investigaciones si las áreas de captación pueden cubrir los requerimientos hídricos de los árboles y los cultivos (Boers *et al.*, 1986).

Los tratamientos con agroforestería presentaron una mayor extracción del potasio del suelo, relacionado principalmente al cultivo de *Avena sativa.* En este sentido, Lehmann *et al.* (1999a) agrega que para un balance positivo de nitrógeno, fósforo y potasio, es necesario un retorno de nutrientes a través de la aplicación como mulch de una parte de la biomasa cosechada.

La *Acacia saligna* en los tratamientos con sistema de cosecha de aguas presentó los mayores perímetros basales de tronco, con un número menor de ramas primarias, pero estas últimas de perímetro mayor. Esto se relacionó a un mayor aporte de agua por el sistema de cosecha de escurrimientos que incrementaría el crecimiento de los árboles y la producción de biomasa. Sin embargo, las diferencias no fueron siempre siginificativas. En este sentido, Droppelmann y Berliner (2000) encontraron que en los sistemas agroforestales o sistemas de producccción de árboles multipropósito el funcionamiento de los árboles, como *Acacia saligna*, depende de un gran número de factores medioambientales que muchas veces son difíciles de determinar y manipular. En este sentido, Lövenstein y Berliner (1993) agregan que gran cantidad de errores son introducidos por árboles con muchas ramas primarias de pequeño diámetro, como *Acacia saligna*, a pesar que el perímetro del tronco aparece como el estimador de la biomasa más confiable. En agroforestería bajo cosecha de aguas la pradera anual presentó la menor producción de biomasa, que podría ser relacionada al efecto del sombreamiento de los árboles.

Conclusiones

El uso del sistema de cosecha de aguas para suplementar el aporte de agua al sistema agroforestal probó ser beneficioso tanto para las propiedades del suelo como para la producción vegetal. La agroforestería bajo cosecha de aguas mostró mayores efectos positivos que los otros sistemas de manejo. Este sistema presentó efectos positivos en las propiedades del suelo, como la materia orgánica y el contenido de nitrógeno total, principalmente en las capas más profundas. Los árboles de *Acacia saligna* bajo el sistema de cosecha de aguas presentaron los mayores crecimientos. En agroforestería bajo cosecha de aguas la pradera anual presentó la menor producción de biomasa, que podría ser relacionada al efecto del sombreamiento de los árboles. Los análisis de suelos revelaron una falta de diferencias significativas entre los tratamientos, que podría estar relacionado a que el período de estudio fue breve.

1. INTRODUCTION

The water in semiarid zones is a scarce natural resource, with a high value for agricultural activities. Under rainfed conditions, only the amount of rainfall determines the success or failure of agricultural production. In the inner rainfed zone of central Chile, the rainfall regime has an irregular distribution, and few rains of high intensity increase the soil erosion rate (Ellies, 2000).

In order to counteract the soil degradation in the fragile ecosystems of Chile, a sustainable diversification of the agriculture is needed. One possible way is the implementation of agroforestry systems, which have been suggested as a solution to the farming problems experienced on degraded soils and which contribute to both ecological diversity and economic stability (Lundgren, 1982). In particular, agroforestry has proved to be a land use system of high productivity, improving the economy of the impoverished farmers who live in the inner rainfed zone of central Chile (Ovalle *et al.*, 2000).

However, in rainfed zones the components of agroforestry systems present competition rather than complementation as regards water use (Le Roux *et al.*, 1995; Kho, 2000). In agroforestry in mediterranean central Chile, Ovalle *et al.* (2002) also reported a strong competition for water in the upper soil profile between the trees and the associated herbaceous strata. Under such conditions, the expected yield advantage for annual crops will not occur, because it only succeeds when the water status of the soil profile remains high throughout the entire growing season (McIntyre *et al.*, 1997). Furthermore, in such conditions nutrient contribution through fine root turnover is small, particularly in relation to that of aboveground biomass (Govindarajan *et al.*, 1996).

Based on their results, Lövenstein *et al.* (1991) suggest that agroforestry combined with runoff water harvesting in arid land can be a viable solution. Runoff water harvesting has been used for supplemental irrigation of agroforestry systems in rainfed areas, helping both to increase and sustain food production in these regions (Bhushan *et al.* 1992; Tabor, 1995; Li *et al.*, 2000).

There are many published studies of agroforestry systems, which report numerous tree-soil-crop interactions occurring in rainfed zones. However, further research is needed on low-input technologies such as water harvesting to improve the productivity of agroforestry systems (Tesfaye Abebe, 1994; Bunch, 1999). Properly developed, such crop management systems can be a real alternative in semiarid regions. This MSc thesis analyses a study of agroforestry combined with water harvesting in the inner rainfed zone of central Chile and presents results of both analysis of soil properties and tree-crop production carried out over a four-year period.

2. AIMS AND OBJECTIVES

The aim of this study was to provide further knowledge on agroforestry combined with water harvesting and to evaluate the performance of such a system in the semiarid zone of Chile. The objectives were to record and evaluate both soil properties and plant growth parameters in the agroforestry systems with water harvesting and to compare the findings with results from other crop management systems.

3. THE HYPOTHESIS

The basic hypothesis was that the agroforestry system with water harvesting would be the crop management system that produced the best positive effects both as regards soil properties and the highest plant productivity. The greater availability of water through runoff water harvesting was expected to increase plant growth and therefore increase both the soil organic matter and the rate of nitrogen fixation.

4. CROP MANAGEMENT SYSTEMS

4.1 Agroforestry

An appropriate agroforestry system has the potential to control erosion, maintain soil organic matter and soil physical properties, increase nitrogen fixation and promote efficient nutrient cycling (Young, 1991). Furthermore agroforestry has the potential to increase food production through improvement of the soil fertility (Young, 1989). Breman and Kessler (1997) add that benefits of agroforestry are mainly in terms of improving efficiency of nutrient inputs as an alternative for fertilisers.

In agroforestry, the perennial trees contribute to the major changes in soil fertility (Nair, 1984). Agroforestry has a potential soil improvement capacity that indirectly enhances crop production, based first on increasing the supply of nutrients within the rooting zone and on the retrieval of nutrients from below; and second on improving soil physical conditions and biological activity (Buresh and Tian, 1998). However, Kho (2000) suggests that the net effect of trees on the availability of nutrients other than nitrogen is generally negative and that subtraction outweighs addition of these nutrients in the crop rootzone. On the other hand, Haggar *et al.* (1993) reports that in agroforestry systems, there is higher nitrogen availability than in sole cropping systems, due mainly to high organic matter inputs from the trees in the agroforestry.

In agroforestry with water harvesting, differences in the rooting systems mean that soil water uptake by the trees and the annual crop has different spatial and temporal patterns (Morris *et al.*, 1990; Lehmann *et al.*, 1998a). In such cases, tree roots do not explore the upper soil layers efficiently but take up water from deeper layers, so the water from surface layers can be used by annual crops without affecting production of the perennial crop (Lövenstein *et al.*, 1991). Furthermore, tree root systems can react to the change from dry to wet seasons and compensate by growing deeper during drought periods (Lehmann *et al.*, 1998b). So, the integration of deep-rooting trees with a cultivated crop allows a higher efficiency of nutrient use (Hartemink *et al.*, 1996; Lehmann *et al.*, 1999a).

4.2 Water Harvesting

Water harvesting is defined as a method for inducing, collecting, storing and conserving local surface runoff. It is used for agriculture in arid and semiarid regions, where the scarce and erratic rainfall produces runoff with an intermittent character (Boers and Ben-Asher, 1982; Laryea, 1992). Runoff is collected in catchment areas adjacent to infiltration basin areas with crops, fodder, trees or natural vegetation (Boers, 1994). The aim of catchment areas is to induce runoff and collect this water in the basin areas located at the lower end of the slope, where it can be stored and conserved in the rootzone for future use (Arnon, 1992; Finkel and Finkel, 1986). The collected runoff also can be stored in some type of tank to supply drinking water for animals and humans or for supplemental irrigation of crops (Frasier and Myers, 1983). Furthermore, agroforestry with water harvesting improves water use efficiency due to the reduction in unproductive water loss from bare soil (Droppelmann *et al.*, 2000).

4.3 Acacia saligna

Acacia saligna has been used and studied as the basis for agroforestry systems on several farms where pasture or crops can be grown between the rows (Lefroy *et al.*, 1992). It is a native Australian species that can be used as a windbreak to protect crops grown between the rows and to reduce wind erosion and desertification of marginal cropland (Tiedeman and Johnson, 1992). In arid and semiarid zones, this leguminous tree has proved to have an adaptation to drought, having a high productivity both as wood and fodder (Dumancic and Le Houérou, 1981; Gutteridge, 1990; Stewart *et al.* 1993; Navit *et al.*, 1999). *Acacia saligna* has been introduced with success in the inner rainfed zone of Chile, exhibiting good adaptation and growth potential (Alcaíno *et al.*, 1995).

In Kenya, *Acacia saligna* has been used as a multipurpose tree in agroforestry with water harvesting trials, causing an increase in available soil nitrogen which benefits other crops (Lehmann *et al.*, 1999b). It also brought about a decrease in nutrient leaching under runoff irrigation compared to a monocropped grass crop in the same zone (Lehmann *et al.*, 1999a). In addition, Witkowski (1991) in Australian coastal zones determined that total nitrogen concentrations were significantly higher under canopies and adjacent open areas of *Acacia saligna* after its establishment.

5. MATERIALS AND METHODS

5.1 Study site

This study was carried out in a rainfed area of central Chile, 20 km from Santiago (33° 28′ South -70° 50′ West, altitude 470 m a.s.l) between 1996 and 2000. The field experiment is located at the Germán Greve Silva Experimental Station, which belongs to the Faculty of Agronomy at the University of Chile (Figure 1).

The soil is a sandy loam of up to 100 cm depth, located on a slightly inclined plain (slope 7-10%), resting on a colluvial substratum (gravel and stones) and have a sandy clay loam matrix a less of 100 cm. The soil is a mollisol of colluvial origin with alluvial influence, belonging to the soil series *Piedmont Cuesta Barriga* and has been classified as a Typic Haploxeroll (Luzio, 1996). It has a thermic soil temperature regime (average annual temperature: 14.2°C) and a xeric soil moisture regime. The soil is well drained, with a moderately slow internal drainage and rapid external drainage.

The climate in the study area is classified according to Köeppen climatic classes as Warm Temperate with an extended dry season (6 to 8 months), corresponding to Csb1: temperate climate zone, with dry and warm summers, winter rainfall, annual thermal amplitude higher than 10 °C and annual mean precipitation of approximately 270 mm, and characterized by a strong seasonal rainfall distribution, with 75 % falling in the winter months. Between 1996 and 2000, the rainfall distribution was irregular between years, ranging from 80 to 671 mm year^{-1} (Table 1), with the highest monthly amount falling during June (Figure 2).

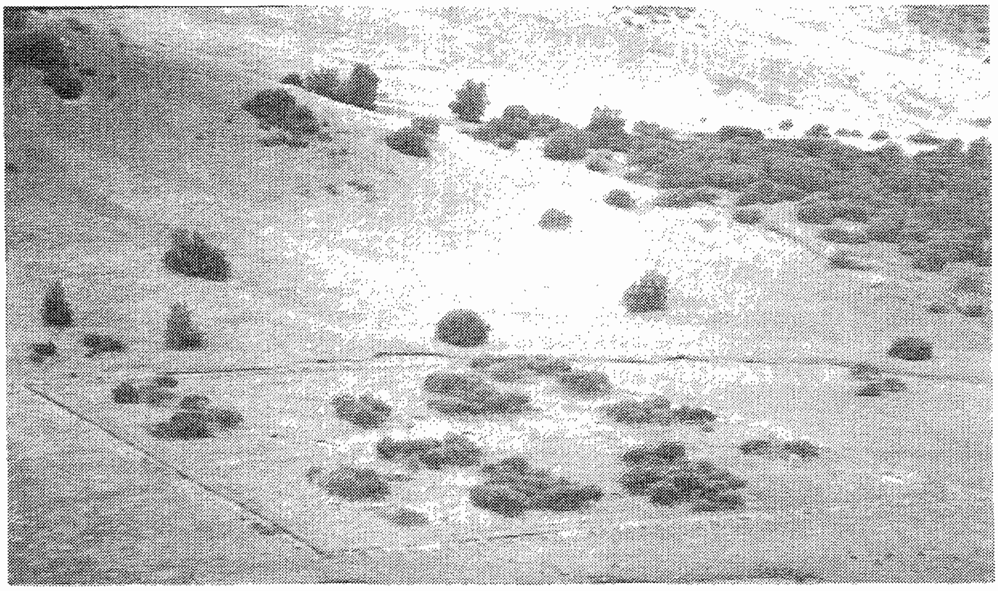


Figure 1. Photo of the field experiment at the Germán Greve Silva Experimental Station.

Table 1. Rainfall (mm) between 1996 and 2000

Year	Rainfall (mm month^{-1})												Total (mm year^{-1})
	Jan	Feb	Mar	Apr	May	Jun	Jul	Agu	Sep	Oct	Nov	Dec	
1996	0.0	0.0	0.0	36.3	6.8	37.5	26.3	26.3	0.0	3.8	0.0	0.0	137.0
1997	0.0	0.0	0.0	0.0	132.0	252.0	44.0	99.0	57.0	70.0	8.0	9.0	671.0
1998	0.0	3.0	0.0	28.0	14.0	21.0	0.0	0.0	14.0	0.0	0.0	0.0	80.0
1999	0.0	0.0	17.0	10.0	0.0	46.0	26.0	93.0	80.0	21.0	0.0	0.0	293.0
2000	0.0	10.0	0.0	12.0	14.0	258.0	0.0	0.0	65.0	0.0	0.0	0.0	359.0

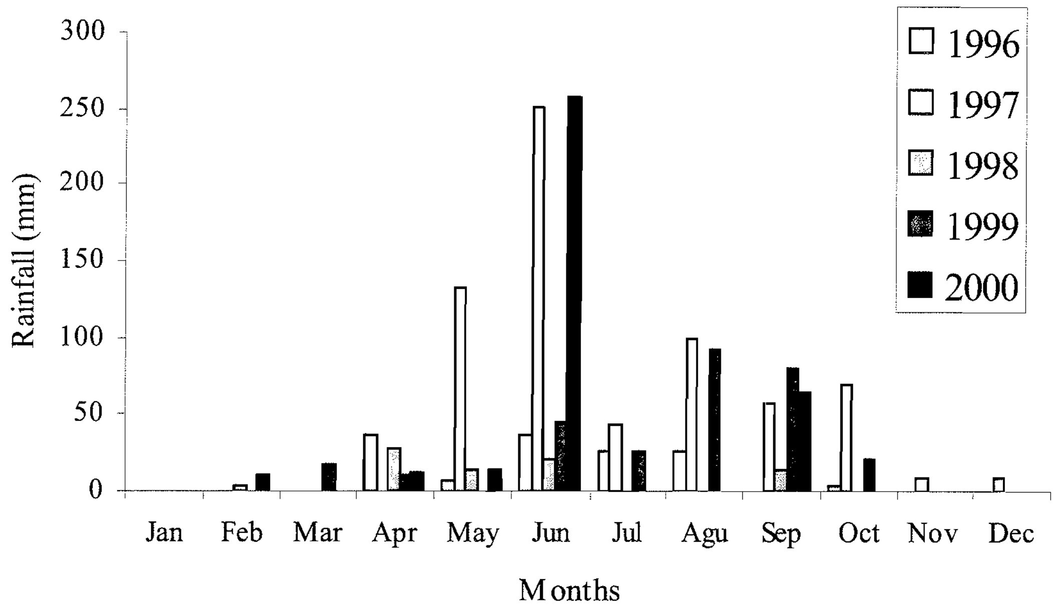


Figure 2. Rainfall distribution between 1996 and 2000 (mm month^{-1}) at The Germán Greve Silva Experimental Station.

The inner rainfed zone of central Chile has a common natural ecosystem generally observed as thorny trees and shrubs with a spring-time grass cover rich in annual plants (Silva and Lozano, 1986). The dominant vegetation is *Acacia cavens* steppe, a woody formation named "espinal" (Ovalle and Squella, 1988). The herbaceous vegetation is called mediterranean annual prairie and is mainly composed of species like *Erodium botrys*, *Erodium cicutarium*, *Trisetobromus hirtus* and *Vulpia dertonensis* (Ovalle *et al.*, 1981; Acuña *et al.*, 1983).

5.2 Experimental design and treatments

Fifteen plots were installed in a randomised block design. The treatments were two crop management systems, two water management systems and a control, with three replications per treatment. The experimental layout is presented in Figure 3.

The crop management systems were agroforestry and woody perennial (Table 2). After discussion with a local scientist, *Acacia Saligna* was chosen as the woody perennial component. The annual crop was *Avena sativa.*

The experimental plots were surrounded by walls, of which the lowest wall had a device to control surplus water. Each plot had a total area of 165 m^2 (15 m x 11 m). The water harvesting plots consisted of a runoff catchment area of 110 m^2 (11 m x 10 m) and a crop growing area of 55 m^2 (11 m x 5 m) (Figure 4). The ratio between catchment and crop areas was calculated as a first approximation, taking into account the historic rainfall in the zone.

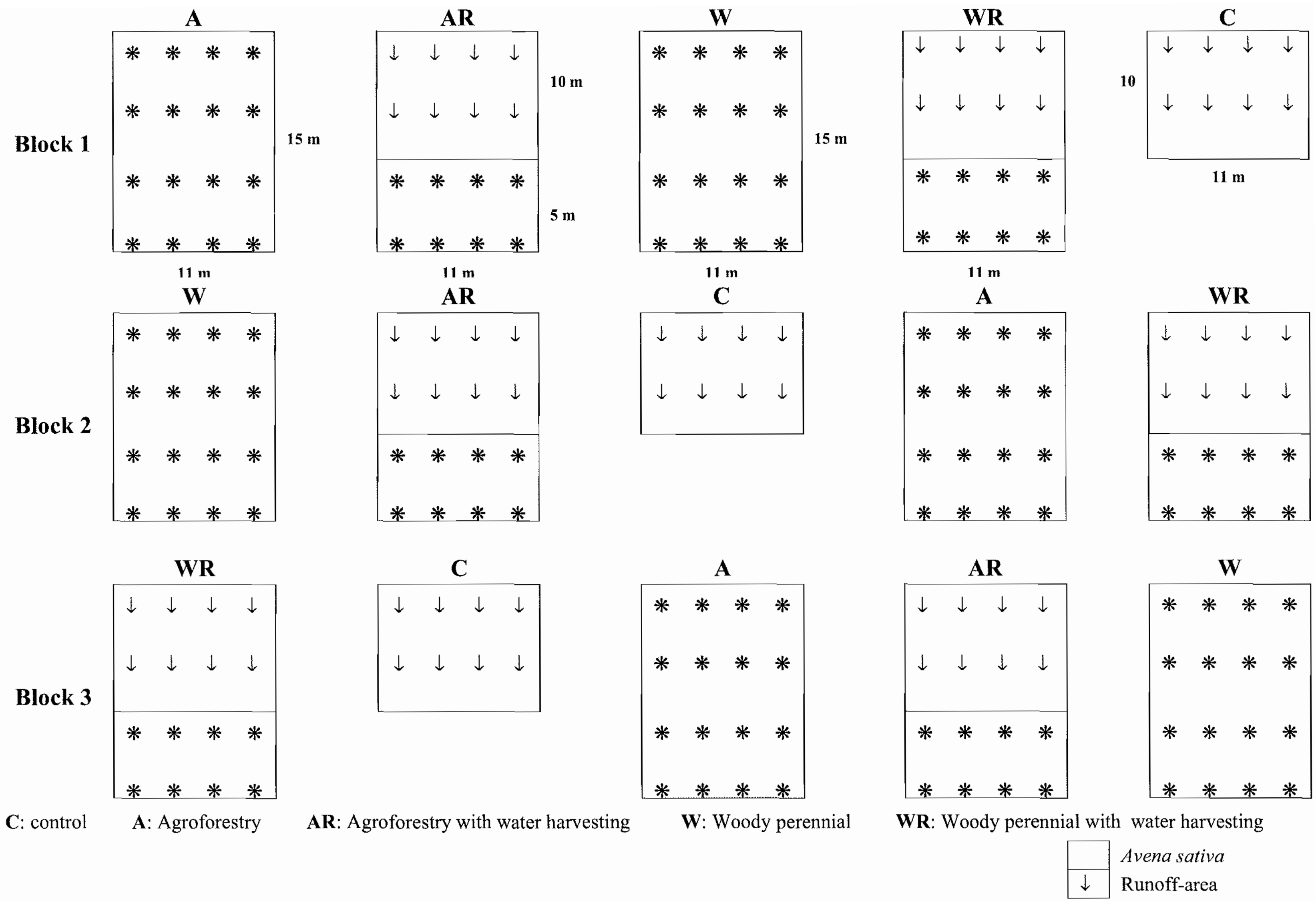


Figure 3. Crop and water management experimental layout.

Table 2. Description of the treatments

	Treatment	Species	Cultivated area (m^2)	Runoff area (m^2)	Total area (m^2)
C	Control	Annual prairie	0	110	110
A	Agroforestry	*Acacia saligna* *Avena sativa* Annual prairie	165	0	165
AR	Agroforestry with water harvesting	*Acacia saligna* *Avena sativa* Annual prairie	55	110	165
W	Woody perennial	*Acacia saligna* Annual prairie	165	0	165
WR	Woody perennial with water harvesting	*Acacia saligna* Annual prairie	55	110	165

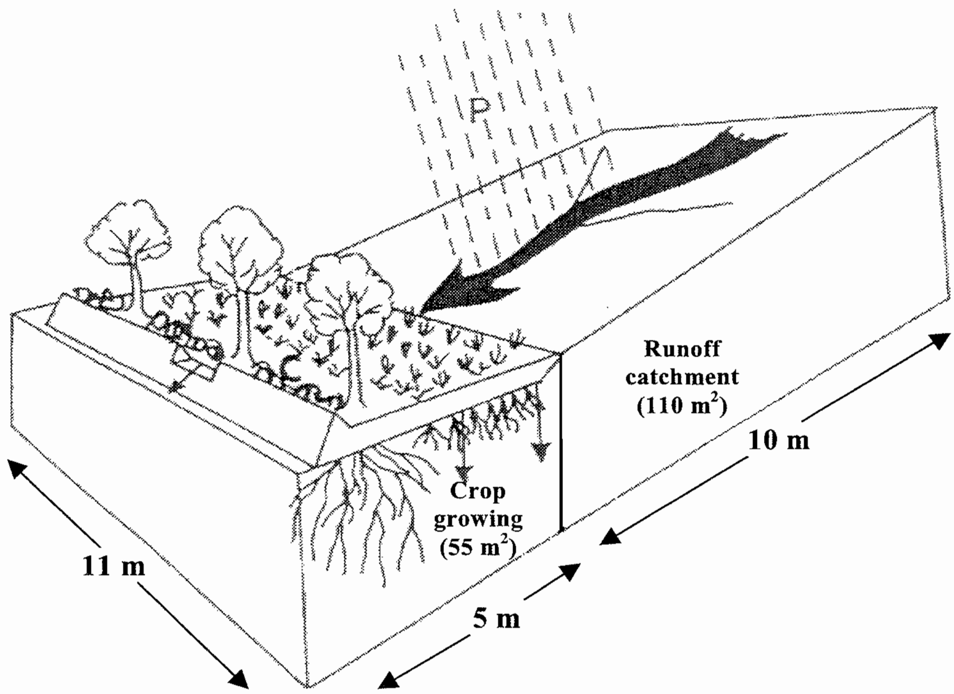


Figure 4. Water harvesting plot layout.

In 1996, the study began with a soil sampling of the experimental site for a chemical characterisation (Table 3).

Table 3. Chemical characterisation of the experimental site

Depth (cm)	pH H_2O	SOM [1] ($g\ kg^{-1}$)	EC [2] ($dS\ m^{-1}$)	N [3] ($g\ kg^{-1}$)	P [4] ($g\ kg^{-1}$)	K [5] ($g\ kg^{-1}$)
0-15	6.2	53.5	0.47	0.012	0.047	0.627

[1] Soil organic matter
[2] Electric conductivity
[3] Available nitrogen
[4] Available phosphorus
[5] Available potassium

Subsequently, the treatments were laid out in the same year and comprised the following activities:

Control (C). This treatment represents the natural conditions. The soil was not disturbed by tillage.

Agroforestry (A). In this treatment, 16 trees of *Acacia saligna* were planted. The trees were planted in a 4 m wide alley with 3 m spacing between trees within rows. Four rows were planted with four trees per row. The soil was ploughed to a depth of 10 cm and *Avena sativa* sown on the whole plot.

Agroforestry with water harvesting (AR). In this treatment, 8 trees of *Acacia saligna* were planted. The trees were planted in a 4 m wide band with 3 m spacing between trees within rows. Two rows were planted with four trees per row (Figure 5). The soil was ploughed to a depth of 10 cm and *Avena sativa* sown only on the cultivated area.

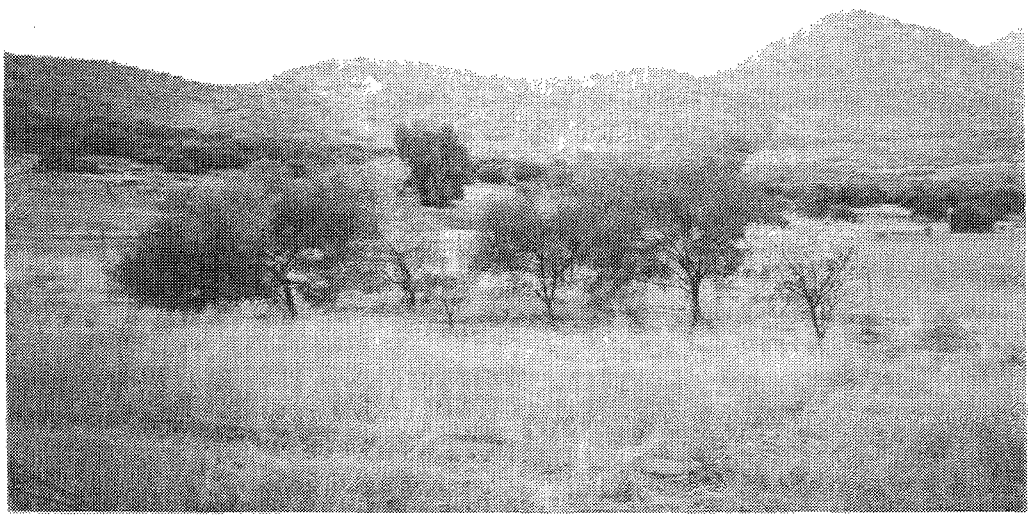


Figure 5. Photo of agroforestry with water harvesting plot.

Woody perennial (W). In this treatment, 16 trees of *Acacia saligna* were planted. The trees were planted in a 4 m wide alley with 3 m spacing between trees within rows. Four rows were planted with four trees per row. The soil was not disturbed by tillage.

Woody perennial with water harvesting (WR). In this treatment, 8 trees of *Acacia saligna* were planted. The trees were planted in a 4 m wide alley with 3 m spacing between trees within rows. Two rows were planted with four trees per row. The soil was not disturbed by tillage.

5.3 Soil sampling

Soil sampling were carried out in all treatments in an area of 11 m x 5 m located in the lower third of each plot. Therefore, soil samples were not taken in the runoff area. Soil sampling depths were 0-10 cm, 10-20 cm, 20-30 cm and 30-40 cm. Fifteen subsamples per soil layer were pooled into one sample. These soil samples were used in the soil analyses.

5.4 Soil chemical analyses

In order to measure the effects of the treatments in the soil chemical properties, some soil chemical analyses were carried out. Standard determinations of soil organic matter content, total nitrogen content, total phosphorus content, total potassium contents, cation exchange capacity and soil reaction were carried out at the Soil Chemical Laboratory of the Faculty of Agronomy, University of Chile, during 2001. The following methods of analysis were used.

5.4.1 Soil organic matter content

Soil organic matter content was determined according to the Walkley and Black method (Black, 1965). Soils from each plot were bulked, air-dried, crushed and sieved (0.5 mm). A weighed sample of 10 to 25 mg of soil was transferred to an Erlenmeyer flask. Oxidizable matter in this sample was oxidised by $Cr_2O_7^{2-}$. This reaction was facilitated by the heat generated when two volumes of H_2SO_4 were mixed with one volume of 1N $K_2Cr_2O_7$ solution. The excess $Cr_2O_7^{2-}$ was determined by titration with standard $FeSO_4$ solution, and the quantity of substances oxidised was calculated from the amount of $Cr_2O_7^{2-}$ reduced.

5.4.2 Total nitrogen content, total phosphorus content and total potassium content

These analyses were determined according to Lachica *et al.* (1965). This method was developed for plant analysis and adapted for soil. In this method, the same soil sample was prepared for three analyses. Soils from each plot were bulked, air-dried, crushed and sieved (0.5 mm). A weighed sample of 0.5 mg of soil was transferred to an Erlenmeyer flask. The oxidizable matter in this sample was oxidised by a humid mineralization obtaining a mineralized solution. Subsequently:

Total nitrogen was determined by the Kjeldahl method. The nitrogen in the mineralized solution was converted to ammonium by digestion with concentrated H_2SO_4 containing substances that promote this conversion. Ammonium was determined from the amount of NH_3 liberated by distillation.

Total phosphorus was determined by the molybdenum blue method. This method is based on the principle that when a mineralized solution containing orthophosphate ions is mixed with acid molybdate, the solution forms a phosphomolybdate complex that can be reduced by reducing agent to molybdenum blue colour. The intensity of the blue colour varies with the phosphorus concentration and is determined by a colorimetric method.

Total potassium was determined directly in the mineralized solution by flame photometry.

5.4.3 Cation exchange capacity

Cation exchange capacity was determined by the sodium acetate method (pH 8.2) according to Black (1965). Soils from each plot were bulked, air-dried, crushed and sieved (2 mm). A weighed sample of 10 g of soil was treated with 1 N sodium acetate at pH 8.2 and excess sodium removed with 95 % ethanol. Then sodium ions were displaced by washing with a neutral ammonium acetate solution (pH 7), which saturates the exchange material with ammonium. Finally, the sodium displaced was determined in a flame photometer.

5.4.4 Soil pH

Soil pH was measured in water in a 1:2.5 soil:solution ratio, according Dewis and Freitas (1970). Soils from each plot were bulked, air-dried, crushed and sieved (2 mm). The pH of the solution was determined electronically on a direct-reading pH meter calibrated with buffer solutions.

5.5 Soil physical analyses

Some soil physical analyses were carried out with the aim of monitoring the effects of the treatments on the soil physical properties. Standard determinations of particle size distribution and bulk density were carried out at the Irrigation Laboratory of the Faculty of Agronomy, University of Chile, during 2001. The following methods of analysis were used.

5.5.1 Particle size distribution

Particle size distribution was determined according to Bouyoucos's hydrometer method described by Dewis and Freitas (1970). The method is based in Stoke's Law. The density is measured with a special hydrometer of streamlined design. Soils from each plot were bulked, air-dried, crushed and sieved (2 mm). A 50 g soil sample was used.

The soil samples did not have high organic matter content or calcium carbonate contents. Therefore, no pre-treatment of the soil samples was carried out to remove these components. Soil samples were simply dispersed with sodium oxalate.

5.5.2 Bulk density

Bulk density of soil was determined according to the method described by Dewis and Freitas (1970). This method was chosen because the soil samples had a high gravel and stone content. Clods of soil of irregular shape were weighed, coated with paraffin wax to prevent absorption of water and their volume determined through of the displacement of a weight of water according to Archimedes' principle.

5.6 Vegetation measurements

In order to determine the plant development of *Acacia saligna* trees and biomass production of annual prairie, the following standard determinations were used in each case.

5.6.1 *Acacia saligna*

The method of measuring *Acacia saligna* growth was similar to that used by Olivares and Alvarado (1991) in Chile for measuring the plant development of *Acacia caven*. This method consists of the following measurements:

Trunk basal perimeter at 10 cm (BP). The perimeter was measured on the trunk at 10 cm above the ground line (Figure 6).

Figure 6. Measurement of the trunk basal perimeter at 10 cm in the *Acacia saligna*.

Stem attachment height (SAH). This is the point where the trunk is clearly divided into two or more stems (Figure 7).

Figure 7. Measurement of the stem attachment height in the *Acacia saligna.*

Stem number/tree (SN). The stem must originate directly from the trunk and be at least one-half the perimeter of the trunk. Any axis separating from the trunk and less than half the diameter of the trunk was considered to be a branch.

Stem perimeter (SP). The perimeter was measured on the entire number of stems per tree at the point of attachment with the trunk (Figure 8).

Figure 8. Measurement of the stem perimeter in the *Acacia saligna.*

5.6.2 Annual prairie

The biomass production of the annual prairie was determined according to the point quadrat method (Su-cherng Hu, 1995). Six randomised samples (square of 0.25 m^2) per plot were taken in the lower third of each plot (11 x 5 m) (Figure 9). In total, an area of 1.5 m^2 was harvested per plot. Annual prairie was harvested, weighed, dried at 70 °C for 48 hours and weighed again. The yield of the annual prairie was expressed in kg per hectare.

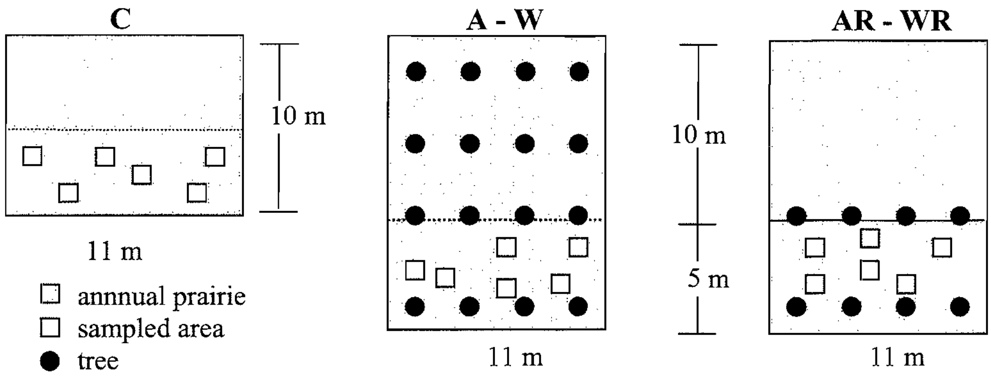


Figure 9. Measurement of annual prairie in the Control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR).

5.7 Statistical analyses

The control was compared with each treatment using the Student's *t*-test at $p<0.05$. Subsequently the other treatments were compared by analysis of variance (ANOVA) at $p<0.05$ using a randomised complete block design.

All data both from soil analyses and vegetation measurements were statistically explored using STATGRAPHICS Version 7.0 Software.

6. RESULTS AND DISCUSSION

The results of soil analyses and vegetation measurements are presented and discussed in this section. In order to compare the crop management systems evaluated in the study, a general discussion is presented at the end.

Several difficulties were experienced during the first two years. Rodents (*Octodon degu*) attacked the stand of *Acacia saligna* trees and sheep accidentally entered the study area and grazed the vegetation. As a consequence, in the second year it was necessary to replant many trees. *Avena sativa* was harvested, but its biomass production not determined. In 1998, the agroforestry treatments were changed to an association between *Acacia saligna* and annual prairie that was grown in natural conditions (Table 4). Therefore in 1999, the annual prairie was measured. In October 2000, measurements on *Acacia saligna* trees and soil sampling of every treatment were carried out.

Table 4. Description of the treatments during the years

Treatment	Species	
	1996-1998	1998-2000
Control	Annual prairie	Annual prairie
Agroforestry	*Acacia saligna* *Avena sativa* Annual prairie	*Acacia saligna* Annual prairie
Agroforestry with water harvesting	*Acacia saligna* *Avena sativa* Annual prairie	*Acacia saligna* Annual prairie
Woody perennial	*Acacia saligna* Annual prairie	*Acacia saligna* Annual prairie
Woody perennial with water harvesting	*Acacia saligna* Annual prairie	*Acacia saligna* Annual prairie

6.1 Soil chemical analyses

6.1.1 Soil organic matter content

The soil organic matter content varied between the different layers and treatments. The highest amounts were found in the 0-10 cm layer. In this layer, the control and woody perennial showed the highest contents, both with 60 g kg^{-1}. On the other hand, agroforestry with water harvesting showed the lowest content in this layer, 40 g kg^{-1}. This low content in agroforestry with water harvesting could be associated with a redistribution of the soil organic matter in the plough layer (0-20 cm) caused by tillage. Therefore, the tillage associated with increased supply of runoff would favour the transport of soil organic matter towards the 10-20 cm layer. As confirmation of this, in the 10-20 layer, agroforestry with water harvesting showed the highest organic matter content, 33 g kg^{-1}. In the same layer, the control had the lowest content, 16 g kg^{-1}. However, both in the 0-10 and 10-20 layers, differences were not found to be statistically significant, due to the high standard deviations recorded in the treatments.

In the 20-30 layer, agroforestry with water harvesting again had the highest organic matter content, 22 g kg^{-1}, and was significantly different from the control, which had the lowest content, 17 g kg^{-1} ($p<0.05$). Finally in the 30-40 layer, agroforestry with water harvesting once more had the highest content, 19 g kg^{-1}, and woody perennial with water harvesting the lowest, 13 g kg^{-1}, but these differences were not statistically significant.

In this study, agroforestry with water harvesting had the highest soil organic matter content in deeper layers (20 to 40 cm). This is because the tillage improves the infiltrability of the cultivated areas, augmenting the soil moisture availability in the deeper layers. Moreover, the use of the deeper stored water is a marked advantage in runoff agroforestry (Lövenstein *et al.*, 1991). Therefore, these practices had positive effects in improving the water content in the deeper layers, which is needed in the processes of root turnover (Kaarakka, 1996; Peugeot *et* *al.*, 1997; Rockström and Valentin, 1997). Soil organic matter contents are shown in Table 5, and the results are expressed in g kg^{-1}.

Table 5. Soil organic matter content (g kg^{-1}) in different soil layers in control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatment	Soil organic matter content (g kg^{-1}) in different soil layers (cm)			
	0-10	10-20	20-30	30-40
C	60.3 ± 9.6	16.9 ± 2.1	17.3 ± 2.4	15.3 ± 3.8
A	55.2 ± 10.2 a	24.4 ± 8.3 a	21.0 ± 4.3 a	16.9 ± 1.3 a
AR	40.3 ± 23.2 a	33.9 ± 16.0 a	22.1 ± 1.8 a *	19.1 ± 7.1 a
W	60.1 ± 12.9 a	18.5 ± 6.8 a	18.2 ± 5.5 a	14.7 ± 6.1 a
WR	52.1 ± 11.3 a	25.8 ± 8.0 a	20.7 ± 1.1 a	13.0 ± 4.8 a

Different letters down a column indicate significant differences at $p<0.05$ (from ANOVA, n = 3; means and standard deviations)
* down a column indicates significant difference from the control at $p<0.05$ (from Student's *t*-test; n = 3)

6.1.2 Soil pH

Soil pH measured in water showed only slight variations between the different layers and treatments. At the 0-10 cm layer, levels between 6.0-6.3 were found. In the other layers, the soil pH levels were increased slightly to 6.2-6.4. However, differences between the treatments were not statistically significant. Soil pH levels are shown in Table 6.

Table 6. pH in different soil layers in control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatment	pH in different soil layers (cm)			
	0-10	10-20	20-30	30-40
C	6.3 ± 0.3	6.4 ± 0.1	6.4 ± 0.0	6.4 ± 0.3
A	6.0 ± 0.1 a	6.3 ± 0.2 a	6.3 ± 0.2 a	6.3 ± 0.2 a
AR	6.1 ± 0.2 a	6.3 ± 0.1 a	6.4 ± 0.2 a	6.4 ± 0.1 a
W	6.2 ± 0.1 a	6.2 ± 0.2 a	6.4 ± 0.2 a	6.4 ± 0.3 a
WR	6.2 ± 0.1 a	6.4 ± 0.1 a	6.4 ± 0.1 a	6.4 ± 0.1 a

Different letters down a column indicate significant differences at $p<0.05$ (from ANOVA, n = 3; means and standard deviations)
* down a column indicates a significant difference from the control at $p<0.05$ (from Student's *t*-test; n = 3)

6.1.3 Total nitrogen content

Total nitrogen content varied between the different layers and treatments. The highest amounts were found in the 0-10 cm layer, where woody perennial showed the highest content of 2.5 g kg^{-1}. Agroforestry with water harvesting had the lowest content in this layer, 1.6 g kg^{-1}, which was related to the mixture of organic matter between 0-20 cm depth caused by tillage. As a consequence, in the 10-20 layer agroforestry with water harvesting had the highest content, 1.1 g kg^{-1}, and the control the lowest content, 0.7 g kg^{-1}. However, differences in both the 0-10 cm and 10-20 cm layers were not statistically significant. In the 20-30 layer, agroforestry with water harvesting had the highest total N content, 0.9 g kg^{-1}, and the control the lowest content, 0.6 g kg^{-1}, although again differences were not statistically significant. Finally in the 30-40 layer, agroforestry with water harvesting had the highest content, 0.8 g kg^{-1}, and was significantly different from the control, which had the lowest content, 0.5 g kg^{-1} (p<0.05). Total nitrogen contents are shown in Table 7, and the results expressed in g kg^{-1}.

Table 7. Total nitrogen content (g kg^{-1}) in different soil layers in control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatment	Total nitrogen content (g kg^{-1}) in different soil layers (cm)			
	0-10	10-20	20-30	30-40
C	2.3 ± 0.5	0.7 ± 0.3	0.6 ± 0.2	0.5 ± 0.1
A	2.2 ± 0.2 a	0.8 ± 0.5 a	0.7 ± 0.3 a	0.6 ± 0.2 a
AR	1.6 ± 0.9 a	1.1 ± 0.4 a	0.9 ± 0.3 a	0.8 ± 0.0 a *
W	2.5 ± 0.2 a	0.8 ± 0.1 a	0.7 ± 0.1 a	0.6 ± 0.1 a
WR	2.2 ± 0.6 a	0.9 ± 0.2 a	0.8 ± 0.1 a	0.7 ± 0.1 a

Different letters down a column indicate significant differences at p<0.05 (from ANOVA, n = 3; means and standard deviations)
* down a column indicates a significant difference from the control at p<0.05 (from Student's t-test; n=3)

In this study, agroforestry with water harvesting had the highest total nitrogen content in the deeper layers (20 to 40 cm). This augmentation of total nitrogen content also might be related to higher root turnover. Lehmann and Zech (1998) note that root turnover seems to be only one process of nitrogen recycling through below-ground biomass in an agroforestry system with water harvesting. In their study, root nitrogen input was higher in a tree + crop combination than in sole cropped trees and crops.

6.1.4 Total phosphorus content

Total phosphorus content did not vary greatly between the different treatments and layers. Furthermore, no significant differences in P content were found in this study. The highest amounts of P were recorded in the 0-10 cm soil layer, where both control and agroforestry showed the highest content, 1.9 g kg^{-1}, and woody perennial with water harvesting the lowest content, 1.6 g kg^{-1}. In the 10-20 cm layer, agroforestry showed the highest content, 1.7 g kg^{-1}, and agroforestry with water harvesting the lowest, 1.3 g kg^{-1}. In the 20-30 cm layer, the control showed the highest content, 1.8 g kg^{-1}, and woody perennial the lowest content, 1.5 g kg^{-1}. Finally in the 30-40 cm layer, the control had the highest content, 1.7 g kg^{-1}, while in this layer agroforestry with water harvesting, woody perennial and woody perennial with water harvesting had the lowest P contents, all 1.4 g kg^{-1}. Total phosphorus contents are shown in Table 8, and the results expressed in g kg^{-1}.

Table 8. Total phosphorus content (g kg^{-1}) in different soil layers in control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatment	Total phosphorus content (g kg^{-1}) in different soil layers (cm)			
	0-10	10-20	20-30	30-40
C	1.9 ± 0.2	1.7 ± 0.1	1.8 ± 0.2	1.7 ± 0.2
A	1.9 ± 0.3 a	1.8 ± 0.3 a	1.7 ± 0.3 a	1.6 ± 0.0 a
AR	1.7 ± 0.1 a	1.3 ± 0.7 a	1.6 ± 0.4 a	1.4 ± 0.4 a
W	1.7 ± 0.4 a	1.5 ± 0.3 a	1.5 ± 0.3 a	1.4 ± 0.3 a
WR	1.6 ± 0.1 a	1.6 ± 0.1 a	1.6 ± 0.1 a	1.4 ± 0.1 a

Different letters down a column indicate significant differences at $p<0.05$ (from ANOVA, n = 3; means and standard deviations)
* down a column indicates a significant difference from the control at $p<0.05$ (from Student's *t*-test; n = 3)

6.1.5 Total potassium content

Total potassium content varied between the different layers and treatments. The highest amounts were found in the 0-10 cm soil layer, where the control had the highest content, 5.4 g kg^{-1}, and agroforestry with water harvesting the lowest content, 4.6 g kg^{-1}. However, the differences found in the 0-10 layer were not statistically significant. In the 10-20 layer, the control showed the highest total K content, 5.0 g kg^{-1}, and this was significantly different ($p<0.05$) from the agroforestry with water harvesting treatment, which had the lowest content, 4.2 g kg^{-1}. In the 20-30 layer, the control had the highest content, 5.1 g kg^{-1}, and was significantly different ($p<0.05$) from the agroforestry with water harvesting treatment, which had the lowest content, 3.8 g kg^{-1} ($p<0.05$). Furthermore in the same layer, woody perennial with water harvesting had a significantly higher content than agroforestry with water harvesting ($p<0.05$). Finally in the 30-40 layer, the control had the highest content, 5.0 g kg^{-1}, and showed a significant difference ($p<0.05$) from agroforestry, which had the lowest content, 4.1 g kg^{-1}. Moreover in the same layer, woody perennial with water harvesting had a significantly higher content than agroforestry ($p<0.05$). Total potassium contents are shown in Table 9, and the results expressed in g kg^{-1}.

Table 9. Total potassium content (g kg^{-1}) in different soil layers in control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatment	Total potassium content (g kg^{-1}) in different soil layers (cm)			
	0-10	10-20	20-30	30-40
C	5.4 ± 0.7	5.0 ± 0.4	5.1 ± 0.2	5.0 ± 0.3
A	4.7 ± 0.4 a	4.6 ± 0.3 a	4.3 ± 0.6 ab	4.1 ± 0.3 b *
AR	4.6 ± 0.3 a	4.2 ± 0.1 a *	3.8 ± 0.2 b *	4.2 ± 0.4 ab
W	4.7 ± 0.2 a	4.6 ± 0.4 a	4.5 ± 0.7 ab	4.6 ± 0.6 ab
WR	4.8 ± 0.2 a	4.7 ± 0.1 a	4.9 ± 0.3 a	4.8 ± 0.3 a

Different letters down a column indicate significant differences at $p<0.05$ (from ANOVA, n = 3; means and standard deviations)
* down a column indicates a significant difference from the control at $p<0.05$ (from Student's *t*-test; n = 3)

Therefore, the control had the highest total potassium content in all layers. This means that the potassium has been exported to the *Acacia saligna* and the *Avena sativa* and there has not been a recycling of this nutrient.

The agroforestry and agroforestry with water harvesting treatments had a lower total potassium content than both woody perennial and woody perennial with water harvesting treatments. This might be attributable to a greater extraction of potassium by the *Avena sativa* crop. This macronutrient is exported from the soil with *Avena sativa* harvest, both in the grain and in straw. A similar situation was reported by Lehmann *et al.* (1999a) in an agroforestry system in Kenya cropped with *Sorghum bicolor*, where the potassium nutrient balance was negative when sorghum straw was removed from the plot.

Furthermore, this progressive reduction in total potassium content might be attributable to the root systems, since grass species such as *Avena sativa* have a higher root density than tree legumes (Bowen, 1985; Schroth and Zech, 1995). Therefore, grasses have a competitive advantage in taking up poorly mobile soil nutrients like potassium (Ong, 1991; Shelton, 1994). Lehmann *et al.* (1998a) in a study of agroforestry with water harvesting report similar results, where total root length density of sorghum was found to be twice that of *Acacia saligna.*

6.1.6 Cation exchange capacity

Cation exchange capacity (CEC) varied between the different layers and treatments. However, in this study, no significant differences were found due to the high standard deviations recorded in the treatments. The highest CEC levels were found in the 0-10 cm layer, where agroforestry had the highest level, 26 me/100 g soil, and woody perennial the lowest, 18 me/100 g soil. In the 10-20 cm layer, both the control and agroforestry with water harvesting showed the highest levels, 22 me/100 g soil, and woody perennial the lowest, 17 me/100 g soil. In the 20-30 cm layer, agroforestry with water harvesting had the highest level, 21 me/100 g soil, and woody perennial the lowest content, 15 me/100 g soil. Finally in the 30-40 cm layer, agroforestry with water harvesting showed the highest level, 23 me/100 g soil, and woody perennial the lowest content, 15 me/100 g soil. Cation exchange capacity levels are shown in Table 10, and the results expressed in me/100 g soil.

Table 10. Cation exchange capacity (me/100 g soil) in different soil layers in control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatment	Cation exchange capacity (me/100 g soil) in different soil layers (cm)			
	0-10	10-20	20-30	30-40
C	25.8 ± 11.4	22.7 ± 13.8	20.8 ± 12.8	21.2 ± 11.5
A	26.0 ± 6.5 a	21.7 ± 5.3 a	18.8 ± 6.2 a	18.2 ± 5.8 a
AR	20.8 ± 6.1 a	22.0 ± 7.9 a	21.3 ± 3.4 a	23.0 ± 6.1 a
W	18.6 ± 1.8 a	17.6 ± 0.7 a	15.1 ± 8.4 a	15.0 ± 8.3 a
WR	20.4 ± 1.2 a	19.1 ± 3.3 a	17.9 ± 3.8 a	18.7 ± 1.3 a

Different letters down a column indicate significant differences at $p<0.05$ (from ANOVA, n = 3; means and standard deviations)

* down a column indicates a significant difference from the control at $p<0.05$ (from Student's *t*-test; n = 3)

6.2 Soil physical analyses

6.2.1 Particle size distribution

Particle size distribution varied between the different treatments. However in this study, only clay and sand content showed significant differences in the 0-10 soil layer. The results are reported below by particle size.

Clay. The highest amounts were found in the 0-10 cm layer, where woody perennial with water harvesting showed the highest content of 16 % and was significantly different from both agroforestry with water harvesting and agroforestry (p<0.05). This large clay content in woody perennial with water harvesting might have been caused by the runoff catchment system, which favoured the transport of fine particles from catchment areas and their deposition in cultivated areas. Similarly, Evett and Dutt (1985) in a study of erosion in water harvesting systems also determined higher losses of clay in catchment areas than in the original soil. In addition, Pratap Narain *et al.* (1998) determined that *Leucaena leucocephala* hedges reduced runoff and soil loss, due mainly to the barrier effect of trees and micro-terraces formed through sediment deposition. Moreover in the rainfed zone in Chile, the input of clay by runoff water from catchment area to cultivated area was increased for the concentrated rainfall falling in the winter months, when the annual prairie that protected soil was less widespread (Silva and Lozano, 1986). In addition, Li and Gong (2002) report that catchment areas present serious soil erosion problems with high intensity rainfall.

In the 10-20 soil layer, both woody perennial and woody perennial with water harvesting had the highest clay content, 16 %, and agroforestry with water harvesting the lowest content, 14 %. In the 20-30 layer, the control treatment had the highest content, 17%, and agroforestry with water harvesting the lowest, 13 %. Finally in the 30-40 layer, the control again had the highest content, 18 %, and agroforestry with water harvesting the lowest content, 15 %. Clay contents are shown in Table 11, and the results expressed as percentages by weight.

Table 11. Clay content (% w/w) in different soil layers in control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatment	Clay content (% w/w) in different soil layers (cm)			
	0-10	10-20	20-30	30-40
C	13.8 ± 1.7	15.9 ± 2.4	17.6 ± 2.1	18.2 ± 1.0
A	14.0 ± 2.8 b	15.7 ± 3.3 a	16.2 ± 3.9 a	17.2 ± 3.9 a
AR	13.3 ± 1.9 b	14.1 ± 1.5 a	13.8 ± 2.6 a	15.4 ± 2.3 a
W	15.1 ± 1.8 ab	16.1 ± 2.8 a	16.5 ± 2.6 a	17.1 ± 2.6 a
WR	16.4 ± 1.9 a	16.0 ± 0.6 a	15.6 ± 1.0 a	17.7 ± 1.5 a

Different letters down a column indicate significant differences at p<0.05 (from ANOVA, n = 3; means and standard deviations)
* down a column indicates a significant difference from the control at p<0.05 (from Student's t-test; n = 3)

Silt. In the 0-10 cm soil layer, woody perennial with water harvesting showed the highest content of 27 %, which may have been caused by the runoff favouring the transport of fine particles from catchment areas. On the other hand, woody perennial showed the lowest silt content, 19 %. In the 10-20 layer, agroforestry with water harvesting showed the highest content, 24 %, and the control the lowest content, 20 %. In the 20-30 layer, the control, agroforestry with water harvesting and woody perennial treatments all had a higher content of 22 % and woody perennial with water harvesting a lower content of 20 %. Finally in the 30-40 layer, the control had the highest content, 24 %, and agroforestry with water harvesting the lowest content, 19 %. Silt contents are shown in Table 12, and the results expressed as percentages by weight.

Table 12. Silt content (% w/w) in different soil layers in control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatment	Silt content (% w/w) in different soil layers (cm)			
	0-10	10-20	20-30	30-40
C	20.5 ± 7.8	20.0 ± 0.8	22.2 ± 5.0	24.5 ± 1.7
A	20.5 ± 6.8 a	22.8 ± 1.6 a	21.6 ± 6.0 a	21.9 ± 3.3 a
AR	25.2 ± 0.6 a	24.8 ± 1.7 a	22.6 ± 2.1 a	19.5 ± 4.4 a
W	19.7 ± 8.2 a	21.7 ± 3.6 a	22.4 ± 1.8 a	21.5 ± 1.4 a
WR	27.1 ± 2.6 a	23.3 ± 3.7 a	20.2 ± 6.6 a	21.6 ± 1.5 a

Different letters down a column indicate significant differences at $p<0.05$ (from ANOVA, n = 3; means and standard deviations)
* down a column indicates a significant difference from the control at $p<0.05$ (from Student's *t*-test; n = 3)

Sand. In the 0-10 cm layer, both control and woody perennial showed the highest sand content of 65 %. In the same layer, woody perennial was significantly different ($p<0.05$) from woody perennial with water harvesting, which showed the lowest content, 56 %. In the 10-20 layer, the control had the highest content, 64%, and woody perennial with water harvesting the lowest content, 60 %. In the 20-30 layer, woody perennial with water harvesting had the highest content, 64 %, and the control the lowest content, 60 %. Finally in the 30-40 layer, agroforestry with water harvesting had the highest content, 65 %, and the control the lowest content, 15 %. Sand contents are shown in Table 13, and the results expressed as percentages by weight.

Table 13. Sand content (% w/w) in different soil layers in control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatment	Sand content (% w/w) in different soil layers (cm)			
	0-10	10-20	20-30	30-40
C	65.7 ± 7.6	64.1 ± 2.8	60.2 ± 6.7	57.3 ± 1.1
A	64.1 ± 5.7 ab	61.5 ± 4.1 a	62.2 ± 8.8 a	60.9 ± 4.8 a
AR	61.5 ± 2.2 ab	61.1 ± 2.7 a	63.7 ± 3.1 a	65.1 ± 5.7 a
W	65.2 ± 6.6 a	62.1 ± 6.2 a	61.1 ± 4.2 a	61.4 ± 2.4 a
WR	56.4 ± 0.7 b	60.7 ± 3.7 a	64.1 ± 7.6 a	60.7 ± 2.8 a

Different letters down a column indicate significant differences at $p<0.05$ (from ANOVA, n = 3; means and standard deviations)
* down a column indicates a significant difference from the control at $p<0.05$ (from Student's *t*-test; n = 3)

6.2.2 Bulk density

In the 0-10 cm layer, all the treatments had a bulk density of 1.2 Mg m^{-3} except agroforestry, which had a lower value, 1.1 Mg m^{-3}. This lower bulk density in agroforestry can be attributed firstly to increased soil organic matter and root activity of perennial trees, and secondly to increased soil biological activity by soil macrofauna (Yamoah *et al.*, 1986; Alegre and Rao, 1996; Rao *et al.*, 1998). Bulk density values are shown in Table 14, and the results expressed in Mg m^{-3}.

Table 14. Bulk density (Mg m^{-3}) in different soil layers in control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatment	Bulk density (Mg m^{-3}) in different soil layers (cm)			
	0-10	10-20	20-30	30-40
C	1.2 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	1.3 ± 0.1
A	1.1 ± 0.1 b	1.3 ± 0.1 a	1.3 ± 0.0 a	1.4 ± 0.1 b
AR	1.2 ± 0.1 ab	1.3 ± 0.0 a	1.3 ± 0.0 a	1.5 ± 0.1 a
W	1.2 ± 0.1 ab	1.4 ± 0.1 a	1.3 ± 0.1 a	1.3 ± 0.0 b
WR	1.2 ± 0.1 a	1.2 ± 0.2 a	1.4 ± 0.0 a	1.3 ± 0.0 b

Different letters down a column indicate significant differences at $p<0.05$ (from ANOVA, n = 3; means and standard deviations)
* down a column indicates a significant difference from the control at $p<0.05$ (from Student's *t*-test; n = 3)

In the 10-20 layer, both control and woody perennial had the highest value, 1.4 Mg m^{-3}, and woody perennial with water harvesting the lowest value, 1.2 Mg m^{-3}. In the 20-30 layer, both control and woody perennial with water harvesting showed the highest value, 1.4 Mg m^{-3}, and the other treatments the lower value of 1.3 Mg m^{-3}. Finally in the 30-40 soil layer, agroforestry with water harvesting had the highest value, 1.5 Mg m^{-3}, and this was significantly different from the other treatments ($p<0.05$) which had values between 1.3 Mg m^{-3} and 1.4 Mg m^{-3}.

6.3 Vegetation measurements

6.3.1 *Acacia saligna*

Tree survival by the end of the trial was high (Table 15). Tree mortality was mainly related to attacks by rodents. All trees were measured in terms of trunk basal perimeter at 10 cm (BP), stem number/tree (SN), stem attachment height (SAH) and stem perimeter (SP) (Table 16).

For trunk basal perimeter, both agroforestry with water harvesting and woody perennial with water harvesting showed the highest value of 28 cm and agroforestry a lower value of 26 cm, although this difference was not statistically significant. Thus, the greater water supply from runoff had a positive effect in increasing the trunk basal perimeter, a parameter related directly to high biomass production of *Acacia saligna* (Stewart and Salazar, 1992; Lövenstein and Berliner, 1993; Droppelmann and Berliner, 2000).

Table 15. Number of trees in the treatments during the study, in agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatment	No of trees per treatment		Survival
	1996	2000	(%)
A	48	47	97.9
AR	24	23	95.8
W	48	46	95.8
WR	24	21	87.5

In the main stem attachment height, woody perennial with water harvesting showed the highest value of 52 cm and agroforestry with water harvesting the lowest value, 46 cm, although this difference was not statistically significant.

In the stem number/tree, woody perennial had the highest value with 2.6 stems/tree and showed significant differences with the water harvesting treatments ($p<0.05$). Agroforestry with water harvesting and woody perennial with water harvesting showed the lowest values with 2.1 and 2.3 main stems/tree respectively. Furthermore, agroforestry showed significant differences to agroforestry with water harvesting ($p<0.05$).

In the stem perimeter, both agroforestry with water harvesting and woody perennial with water harvesting had the highest value, 18 cm. On the other hand, both agroforestry and woody perennial had the lowest value, 17 cm, although this difference was not statistically significant. The difference between the treatments might be attributable to a better water supply in trees with water harvesting, which would induce the trees to produce fewer stems but of a greater perimeter.

Table 16. *Acacia saligna* measurements: trunk basal perimeter at 10 cm (BP), stem number/tree (SN), stem attachment height (SAH) and stem perimeter (SP), in agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Number of trees (n) and measurements	Treatments			
	A	AR	W	WR
n	47	23	46	21
BP (cm)	26.2 ± 1.9 a	28.2 ± 1.7 a	27.4 ± 3.1 a	28.9 ± 4.1 a
SN (No stem $tree^{-1}$)	2.4 ± 0.2 ab	2.1 ± 0.1 c	2.6 ± 0.1 a	2.3 ± 0.1 bc
SAH (cm)	50.2 ± 10.7 a	43.0 ± 5.0 a	50.7 ± 4.8 a	52.7 ± 9.8 a
SP (cm)	17.0 ± 1.7 a	18.6 ± 1.0 a	17.0 ± 1.7 a	18.5 ± 3.0 a

Different letters within a column indicate significant differences at $p<0.05$ (from ANOVA, n = 3; means and standard deviations)

6.3.2 Annual prairie

In the annual prairie biomass production, agroforestry had the highest biomass production of 2038 kg $ha^{-1}$and was significantly different (p<0.05) from agroforestry with water harvesting, which had the lowest value of 1356 kg ha^{-1}. This lower value in agroforestry with water harvesting might be related to the higher growth of *Acacia saligna*, which would increase the shading over the prairie. The results of annual prairie are shown in Table 17, and the results expressed in kg ha^{-1}.

Table 17. Annual prairie biomass production (kg ha^{-1}) in control (C), agroforestry (A), agroforestry with water harvesting (AR), woody perennial (W) and woody perennial with water harvesting (WR)

Treatments	Biomass production (kg ha^{-1})
C	1483 ± 487
A	2038 ± 479 a
AR	1356 ± 304 b
W	1915 ± 451 a
WR	1685 ± 404 ab

Different letters down a column indicate significant differences at p<0.05 (from ANOVA, n = 3; means and standard deviations)
* down a column indicates a significant difference from the control at p<0.05 (from Student's t-test; n = 3)

6.4 General discussion

Agroforestry with water harvesting showed a lack of significant differences at the 0.05 level compared to the other treatments in almost all the soil analyses. This might be due to the fact that this study was of short duration and therefore its potential contributions towards improving soil properties may not have been fully realised. Similar situations in other agroforestry trials were reported by both Kaya and Nair (2001) in Mali and Neupane and Thapa (2001) in Nepal, after 4 and 2 years respectively. In addition, Nair *et al.* (1995) also noted that in agroforestry, the potential long-term benefits of soil improvement are often not manifested in the short-term. Other possible causes of the lack of difference might be both the small numbers of replicates and the shallow soil samples. Despite this, agroforestry with water harvesting showed some positive effects, with the highest accumulation of both soil organic matter and total nitrogen content in the deeper layers as a result of increased root turnover.

On other hand, water harvesting used as a water supply in a woody perennial system favoured siltation in the cultivated areas. The challenge for future research will be to determine both the optimum size of catchment area and the other alternative practices. Furthermore, the most important information to be found for a new experimental field is whether the catchment areas can cover the water requirements of the trees or crops for which they are designed (Boers *et al.*, 1986).

Agroforestry treatments showed a depletion of potassium content, related mainly to the exportation caused by the *Avena sativa* crop. Lehmann *et al.* (1999a) note that for a positive balance of nitrogen, phosphorus and potassium, a nutrient return through mulching of at least part of the harvested biomass is necessary. Moreover, Gupta (1989) in a study in India determined that continuous crop production using water harvesting along with manuring and mulching significantly increased both soil organic matter content and moisture retention in soil, reduced both bulk density and soil strength, and as a result of these changes caused an increase in soil moisture storage.

On the vegetation measurements, the *Acacia saligna* trees with water harvesting had higher truck basal perimeter, with fewer stems of greater perimeter. This is associated with a higher supply of water by runoff harvesting, which increased the tree growth and biomass production. However, the differences were not always statistically significant. In this regard, Droppelmann and Berliner (2000) found that in agroforestry systems or sole woodlots, the performance of multipurpose tree species such as *Acacia saligna* depended on a large number of environmental factors, which are sometimes difficult to determine and manipulate. Furthermore, Lövenstein and Berliner (1993) add that large errors are introduced for trees with many stems of small diameter, such as *Acacia saligna*, despite the fact that truck basal perimeter appears to be a more reliable biomass estimator. The annual prairie in agroforestry with water harvesting had the lowest biomass production, which might have been related to the increased shading by the trees.

7. CONCLUSIONS

- The use of runoff water for supplemental irrigation of agroforestry systems in the central zone of Chile proved to be beneficial for both soil properties and plant productivity.

- Agroforestry with water harvesting showed higher positive effects than the other crop management systems.

- Agroforestry with water harvesting produced positive effects on soil properties such as soil organic matter content and total nitrogen content, mainly in the deeper layers.

- *Acacia saligna* trees with water harvesting produced the highest growth.

- The annual prairie in agroforestry with water harvesting had the lowest biomass production. This may have been due to shading by the trees.

- Soil chemical analyses revealed a statically lack of differences between treatments, which might have been due mainly to the short duration of the present study.

ACKNOWLEDGEMENTS

This study would not have been possible without the Swedish University of Agricultural Science (SLU) and the Exchange Programme Linnaeus-Palme, which granted a scholarship for undertaking an International MSc thesis. In addition, this study was carried out thanks to the support of the Faculty of Agronomy at the University of Chile, in particular the Soil Science Department. Likewise, my supervisors Abraham Joel and Manuel Casanova deserve a grateful thought for helping me to develop this study and their useful discussions and guidance. Thanks to all the people who have contributed in one way or another to the accomplishment of this MSc paper, particularly to the following:

- All the staff at the Soil Science Department of the University of Chile, especially the teachers Carlos Benavides, Claudio Fernández, Oscar Seguel, Wilfredo Vera, Adriana Carrasco, Victor Garcia de Cortazar, Maria T. Varnero, Roberto Villa and Walter Luzio.

- The Department of Soil Sciences at the Swedish University of Agricultural Sciences.

- My family, my parents Carmen and Juan Carlos, my brothers Dayanna and Juan Carlos and my niece Jenifer

- My beloved Ariela.

- Finally, I want to thank to Luis, Olga and Monika for receiving me in their family here in Sweden.

REFERENCES

Acuña, H., Avendaño, J. & Ovalle. C. 1983. Caracterización y variabilidad de la pradera natural del secano de la zona Mediterránea subhúmeda. *Agricultura Técnica* (Chile). Vol 43. No 1. 27-38. (In Spanish)

Alcaíno, E., Benedetti, S., Perret, S. & Valdevenito, G. 1995. *Acacia saligna* una especie multipropósito: su potencial forrajero en la Provincia de Choapa, IV región. *Ciencias Forestales*. Vol 10. No 1-2. 73-84. (In Spanish)

Alegre, J.C. & Rao, M.R. 1996. Soil and water conservation by contour hedging in the humid tropics of Peru. *Agriculture, Ecosystems & Environment*. Vol 57. No 1. 17-25.

Arnon, I. 1992. Agriculture in dry land: principles and practice. Developments in Agricultural and Managed-Forest Ecology 26. Amsterdam.

Bhushan, L.S., Yadav, R.C., Singh, B.L., Tiwari, A.K., Singh, M., Gaur, M.L. & Babu Ram. 1992. Prospects for rainfed agriculture in gullied and ravine catchments through soil and water conservation practices. *Journal of Arid Environment*. Vol 23. No 4. 433- 441.

Black, C.A. 1965. *Methods of soil analysis*. ASA. Agronomy Monograph No 9. Madison Wisconsin.

Boers, Th.M. & Ben-Asher J. 1982. A review of rain water harvesting. *Agricultural Water Management*. Vol 5. No 2. 145-158.

Boers, Th.M., Zondervan, K. & Ben-Asher J. 1986. Micro-catchments-water harvesting (MCWH) for arid zone development. *Agricultural Water Management*. Vol 12. No 1-2. 21-39.

Boers, Th.M. 1994. Rainwater harvesting in arid and semiarid zones. Landbouwuniversiteit. Wageningen.

Bowen, G.D. 1985. Roots as a component of tree productivity. In: Cannel, M.G.R., & Jackson, J.E. (eds). *Attributes of Tree as Crop Plants*. Institute of Terrestrial Ecology, Abbots Ripton, UK. 303-315.

Breman, H. & Kessler, J.J. 1997. The potential of agroforestry in the Sahel and other semi-arid regions. *European Journal of Agronomy*. Vol 7. No 1-3. 25-33.

Buresh, R.J. & Tian, G. 1998. Soil improvement by trees in sub-Saharan Africa. *Agroforestry Systems*. Vol 38. No 1-3. 51-76.

Bunch, R. 1999. More productivity with fewer external inputs: Central American case studies of agroecological development and their broader implications. *Environment, Development and Sustainability*. Vol 1. No 3-4. 219-233.

Dewis, J. & Freitas, F. 1970. *Physical and Chemical Methods of Soil and Water Analysis*. FAO. Soils Bulletin No 10. Rome.

Droppelmann, K.J. & Berliner P.R. 2000. Biometric relationships and growth of pruned and non-pruned *Acacia saligna* under runoff irrigation in northern Kenya. *Forest Ecology and Management*. Vol 126. No 3. 349-359.

Droppelmann, K.J., Lehmann, J., Ephrath, J.E. & Berliner P.R. 2000. Water use efficiency and uptake patterns in a runoff agroforestry system in an arid environment. *Agroforestry Systems*. Vol 49. No 3. 223-243.

Dumancic, D. & Le Houérou, H.N. 1981. *Acacia cyanophylla* as supplementary feed for small stock in Libya. *Journal of Arid Environments*. Vol 4. No 2. 161-167.

Ellies, A. 2000. Soil erosion and its control in Chile – An o verview. *Acta geológica hispánica*. Vol 35. No 3-4. 279-284.

Evett, S.T. & Dutt, G.R. 1985. Effects of slope and rainfall intensity on erosion from sodium dispersed, compacted earth microcatchments. *Soil Sci. Soc. Am. J.* Vol 49. No 1. 202-206.

Finkel, H. J. & Finkel, M. 1986. Engineering Measures: Water Harvesting. In: Finkel, H. (ed). Semiarid Soil and Water Conservation. CRC Press, Inc, Israel. 93-101.

Frasier, G.W. & Myers, L.E. 1983. *Handbook of Water Harvesting*. USDA, Agricultural Research Service. Agriculture Handbook No 600. Washington, D.C.

Govindarajan, M., Rao, M.R, Mathuva, M.N. & Nair, P.K.R. 1996. Soil-Water and root dynamics under hedgerow intercropping in semiarid Kenya. *Agronomy Journal*. Vol 88. No 4. 513-520.

Gupta, J.P. 1989. Integrated effect of water harvesting, manuring and mulching on soil properties, growth and yield of crops in pearl millet-mungbean rotation. *Tropical Agriculture*. Vol 66. No 3. 233-239.

Gutteridge, R.C. 1990. Agronomic evaluation of tree and shrub species in Southeast Queensland. *Tropical Grasslands*. Vol 24. No 1. 29-36.

Haggar, J.P, Tanner, E.V.T, Beer, J.W & Kass, D.C.L. 1993. Nitrogen dynamics of tropical agroforestry and annual cropping systems. *Soil Biology & Biochemistry*. Vol 25. No 10. 1363-1378.

Hartemink, A.E., Buresh, R.J., Bashir Jama & Janssen, B.H. 1996. Soil nitrate and water dynamics in sesbania fallow, weed fallows, and maize. *Soil Sci. Soc. Am. J.* Vol 60. No 2. 568-574.

Kaarakka, V. 1996. Management of bushland vegetation using rainwater harvesting in eastern Kenya. Finnish Society of Forest Science and Finnish Forest Research Institute. Acta Forestalia Fennica 253. Helsinki.

Kaya, B. & Nair, P.K.R. 2001. Soil fertility and crop yields under improved-fallow systems in southern Mali. *Agroforestry Systems*. Vol 52. No 1. 1-11.

Kho, R.M. 2000. A general tree-environment-crop interaction equation for predictive understanding of agroforestry systems. *Agriculture, Ecosystems & Environment*. Vol 80. No 1-2. 87-100.

Lachica, M., Recalde, L. & Esteban, E. 1965. Análisis foliar. Métodos analíticos utilizados en la Estación Experimental Zaidín. *Anales de Edafología y Agrobiología*. Vol 24. No 9-10. 589 – 610. (In Spanish)

Laryea, K.B. 1992. Rainfed agriculture: water harvesting and soil water conservation. *Outlook on Agriculture*. Vol 21. No 4. 271-277.

Le Roux, X., Bariac, T. & Mariotti, A. 1995. Spatial partitioning of the soil water resource between grass and shrubs components in a West African humid savanna. *Oecologia*. Vol 104. No 2. 147-155.

Lefroy, E.C., Dann, P.R., Wildin, J.H, Wesley-Smith, R.N. & McGowan, A.A. 1992. Trees and shrubs as sources of fodder in Australia. *Agroforestry Systems*. Vol 20. 117-139.

Lehmann, J. & Zech, W. 1998. Fine root turnover of irrigated hedgerow intercropping in Northern Kenya. *Plant and Soil*. Vol 198. No 1. 19-31.

Lehmann, J., Droppelmann, K. & Zech, W. 1998a. Runoff irrigation of crops with contrasting root and shoot development in northern Kenya: water depletion and above- and below-ground biomass production. *Journal of Arid Environments*. Vol 38. No 3. 479-492.

Lehmann, J., Peter, I., Steglich, C., Gebauer, G., Huwe, B. & Zech, W. 1998b. Below-ground interactions in dryland agroforestry. *Forest Ecology and Management*. Vol 111. No 2-3. 157-169.

Lehmann, J., Weigl, D., Droppelmann, K., Huwe, B. & Zech, W. 1999a. Nutrient cycling in agroforestry system with runoff irrigation in Northern Kenya. *Agroforestry Systems*. Vol 43. No 1-3. 49-70.

Lehmann, J., Weigl, D., Peter, I., Droppelman, Gebauer, G., Goldbach, H. & Zech, W. 1999b. Nutrient interactions of alley cropped Sorghum bicolor and Acacia saligna in a runoff irrigation system in Northern Kenya. *Plant and Soil*, Vol 210. No 2. 249-262.

Li, F.R., Cook, S., Geballe, G.T. & Burch, W.R. 2000. Rainwater harvesting agriculture: an integrated system for water management on rainfed land in China's semiarid areas. *Ambio*. Vol 29. No 8. 477-483.

Li, X.Y. & Gong, J.D. 2002. Compacted microcatchments with local earth materials for rainwater harvesting in the semiarid region of China. *Journal of Hydrology*. Vol 257. No 1-4. 134-144.

Lundgren, B. 1982. Introduction. *Agroforestry Systems*. Vol 1. No 1. 3-6.

Luzio, W. 1996. Clasificación taxonómica de los suelos de la Región Metropolitana y VI Región (Keys to soil Taxonomy, SCS, USDA, 1994). Universidad de Chile, Facultad de Ciencias Agrarias y Forestales, Departamento de Ingeniería y Suelos. Santiago de Chile. (In Spanish)

Lövenstein, H.M. & Berliner, P.R. 1993. Biometric relationships for non-destructive above ground biomass estimations in young plantations of *Acacia salicina* Lindl. and *Eucalyptus occidentalis* Endl. *New Forests*. Vol 7. No 3. 255-273.

Lövenstein, H.M., Berliner, P.R. & Van Keulen, H. 1991. Runoff agroforestry in arid lands. Forest Ecology and Management. Vol 45. No 1-4. 59-70.

McIntyre, B.D., Riha, S.J. & Ong, C.K. 1997. Competition for water in a hedge-intercrop systems. *Field Crop Research*. Vol 52. No 1-2. 151-160.

Morris, R.A., Villegas, A.N., Polthanee, A. & Centeno, H.S. 1990. Water use by monocropped and intercropped cowpea and sorghum grown after rice. *Agronomy Journal*. Vol 82. No 4. 664-668.

Nair, P. K. R. 1984. Soil productivity aspects of agroforestry. ICRAF. Science and Practice of Agroforestry No 1. Nairobi.

Nair, P.K.R., Kang, B.T. & Kass, D.C.L. 1995. Nutrient cycling and soil-erosion control in agroforestry systems. pp. 117-138. In Juo, A.S.R. & Freed, R.D. (ed.) Agriculture and environment: bridging food production and environmental protection in developing countries. ASA Spec. Publ. 60. ASA, Madison, WI.

Navit, R., Ephrath, J.E., Berliner, P.R., & Saranga, Y. 1999. Drought resistance and water use efficiency in *Acacia saligna*. *Australian Journal of Botany*. Vol 47. No 4. 577-586.

Neupane, R.P. & Thapa, G.B. 2001. Impact of agroforestry on soil fertility and farm income under the subsistence farming system of the middle hills, Nepal. *Agriculture, Ecosystems & Environment*. Vol 84. No 2. 157-167.

Olivares, A & Alvarado, W. 1991. Relación entre el hábito de crecimiento del espino (*Acacia caven Mol.*) y la producción de leña y carbón. *Avances en Producción Animal*. Vol 16. No 1-2. 95-107. (In Spanish)

Ong, C.K. 1991. Interactions of light, water, and nutrients in agroforestry systems. In: Avery M.E., Cannell, M.G.R. and Ong, C.K. (eds). *Biophysical research for Asian agroforestry*. Winrock Int. and Oxford & IBH, New Delhi. 107-124.

Ovalle, C., Avendaño, J. Etienne. M., Muñoz, M. & Serra M. 1981. Determinación del valor pastoral en praderas naturales de la zona Mediterránea Subhúmeda y su relación con la carga animal. *Agricultura Técnica* (Chile). Vol 41. No 4. 221-231. (In Spanish)

Ovalle, C. & Squella, F. 1988. Terrenos de pastoreo con praderas anuales en el área de influencia climática mediterránea. In: Ruiz, I. (ed). Praderas para Chile. Instituto de Investigaciones Agropecuarias (INIA), Santiago, Chile. 369-410. (In Spanish)

Ovalle, C., Aronson, J., Avendaño, J. & del Pozo, A. 2000. Alternativas de praderas y sistemas agroforestales en relación con el manejo sostenible de los suelos en el secano interior de la zona central de Chile. INIA. Boletin INIA N° 42. Santiago de Chile (In Spanish)

Ovalle, C., Zagal, E., Fraga, A., Avendaño, J., Aronson, J. & Manzanares, P. 2002. Nutrient cycling and water balance in agroforestry systems with legume trees in Mediterranean central Chile. In: Gamini Keerthisingue (ed). Report of the Second Research Co-ordination Meeting of the FAO/IAEA Co-ordinated Research Project held in Kuala Lumpur, Malaysia on 7-11 May, 2001. IAEA, Vienna. 13-14.

Peugeot, C., Esteves, M., Galle, S. & Rajot, J.L. 1997. Runoff generation processes: results and analysis of field data collected at the East Central Supersite of the HAPEX-Sahel experiment. *Journal of Hydrology*. Vol 188-189. No 1-4. 179-202.

Pratap Narain, Singh, R.K., Sindhwal, N.S. & Joshie, P. 1998. Agroforestry for soil and water conservation in the western Himalayan valley region of India 1. Runoff, soil and nutrient losses. *Agroforestry Systems*. Vol 39. No 2. 175-189.

Rao, M.R., Nair, P.K.R. & Ong, C.K. 1998. Biophysical interactions in tropical agroforestry systems. *Agroforestry Systems*. Vol 38. No 1-3. 3-50.

Rockström J. & Valentin, C. 1997. Hillslope dynamics of on-farm generation of surface water flows: The case of rain-fed cultivation of pearl millet on sandy soil in the Sahel. *Agricultural Water Management*. Vol 33. No 2-3. 183-210.

Shelton, H.M. 1994. Establishment of Forage Tree Legumes. In: Gutteridge, R.C. and Shelton, H.M. (eds). *Forage Tree Legumes in Tropical Agriculture*. CAB International, Wallingford, UK. 132-142.

Schroth, G. & Zech, W. 1995. Root length dynamics in agroforestry with *Gliricidia sepium* as compared to sole cropping in the semi-deciduous rainforest zone of West Africa. *Plant and Soil*. Vol 170. 297-306.

Silva, M. & Lozano, U. 1986. Descripción de las principales especies forrajeras entre la zona mediterránea árida y la zona de las lluvias., Universidad de Chile, Facultad de Ciencias Agrarias y Forestales, Departamento de Producción Animal. Publicación docente No 9. Santiago de Chile. (In Spanish)

Stewart, J.L. and Salazar, R. 1992. A review of measurement options for multipurpose trees. *Agroforestry Systems*. Vol 19. 173-183.

Stewart, J. L., Dunsdon, A. J., Kishk, M. A. & Aly, M. K. 1993. Screening of non-industrial tree species on reclaimed desert land in Middle Egypt. *Journal of Arid Environments*. Vol 25. No 4. 375-385.

Su-cherng Hu .1995. Vegetative measures. In: Feng, J (ed.). *Soil Conservation Handbook*. Food and Fertilizer Technology Center for the Asian and Pacific Region, FFTC. Book Series No 11. Taiwan/Republic of China. III 1 – III 38.

Tabor, J.A. 1995. Improving crop yields in the Sahel by means of water-harvesting. *Journal of Arid Environments*. Vol 30. No 1. 83-106.

Tesfaye Abebe. 1994. Growth performance of some multipurpose trees and shrubs in the semi-arid areas of Southern Ethiopia. *Agroforestry Systems*. Vol 26. 237-248.

Tiedeman, J.A & Johnson, D.E. 1992. *Acacia cyanophylla* for forage and fuelwood in North Africa. *Agroforestry Systems*. Vol 17. 169-180.

Witkowski, E.T.F. 1991. Effects of invasive alien acacias on nutrient cycling in the coastal lowlands of the cape finbos. *Journal of Applied Ecology*. Vol 28. No 1. 1-15.

Yamoah, C.F, Agboola, A.A, Wilson, G.F & Mulongoy, K. 1986. Soil properties as affected by the use of leguminous shrubs for alley cropping with maize. *Agriculture, Ecosystems & Environments*. Vol 18. 167-177.

Young, A. 1989. *Agroforestry for Soil Conservation*. ICRAF. Science and Practice of Agroforestry No 4. Nairobi.

Young, A. 1991. Soil fertility. In: Avery M.E., Cannell, M.G.R. and Ong, C.K. (eds). *Biophysical research for Asian agroforestry*. Winrock Int. and Oxford & IBH, New Delhi. 187-208.

APPENDIX 1: LIST OF ABBREVIATIONS

A	Agroforestry
AR	Agroforestry with water harvesting
ASA	American Society of Agronomy
BP	Trunk basal perimeter at 10 cm
CEC	Cation exchange capacity
FAO	Food and Agriculture Organization of the United Nations
FFTC	Food and Fertilizer Technology Center
IAEA	International Atomic Energy Agency
ICRAF	International Council for Research in Agroforestry
INIA	Institute of Agricultural Research of Chile
SAH	Stem attachment height
SN	Stem number
SP	Stem perimeter
W	Woody perennial
WR	Woody perennial with water harvesting
USDA	United States Department of Agriculture

Förteckning över utgivna häften i publikationsserien

SVERIGES LANTBRUKSUNIVERSITET, UPPSALA. INSTITUTIONEN FÖR MARKVETENSKAP. AVDELNINGEN FÖR LANTBRUKETS HYDROTEKNIK. AVDELNINGSMEDDELANDE. Fr o m 1999

99:1 Kindvall, T. Strukturkalkning på lerjordar - effekter på markstruktur och sockerbetsskörd. 55 s.

99:2 Börjesson, E. Naturliga system för rening av lakvatten i Ranstad - vilka är möjligheterna? 67 s.

99:3 Gärdenäs, A. (ed). Scale and variability issuses in the soil-hydrological system. Workshop proceedings. The 25-27th of August 1999 at Wiks Castle, Sweden. 57 s.

99:4 Bengtson, L. Retention of colloids in lysimeter experiments on undisturbed macroporous clay soil. 43 s.

99:5 Wennman, P. Vegetationsfilter för rening av lakvatten - kväveaspekter. 45 s.

00:1 Stjernman, L. Gruvavfall som växtsubstrat - effekter av organiskt material. 58 s.

00:2 Björkman, N. Biologisk alvluckring - effekter av rödklöver och lusern på markstruktur och sockerbetsskörd. 58 s.

01:1 Gustafsson, H. The use of plants for soil remediation at Milford Haven Refinery in South Wales. 37 s.

02:1 Lundberg, M. Skador av is och ytvatten i vall i norra Sverige. 80 s.

02:2 Gustafsson Bjuréus, A. & Karlsson, J. Markstrukturindex – utvärdering av en metod att bedöma odlingssystemets uthållighet och jordarnas fysikaliska status. 167 S.

02:3 Andersson, J. Possible Strategies for Sustainable Land Use in the Hilly Area of Northern Vietnam. 88 s.

02:4 Berglund, K., Berglund, Ö. & Gustafson Bjuréus, A. Markstrukturindex – ett sätt att bedöma jordarnas fysikaliska status och odlingssystemets inverkan på markstrukturen. 132 s.

02:5 Eckersten, H., Jansson, P-E., Karlsson, S., Lindroth, A., Persson, B., Perttu, K., Blombäck, K., Karlberg, L., Persson, G., Cienciala, E., Kätterer, T., Gärdenäs, A. & Lewan, L. Biogeofysik - en introduktion. 146 s.

02:6 Lindström, J., Linnér, J. & Arvidsson, J. Tubulering – en kostnadseffektiv markvårdsåtgärd. 38 s.

03:1 Joel, A., Wesström, I. & Linnér, H. Reglerad dränering. Topografiska och hydrologiska förutsättningar i södra Sveriges kustnära jordbruksområden. 26 s.

03:2 Salazar G., O. Agroforestry combined with water harvesting in the central zone of Chile. Soil properties and biomass production. 37 s.

Denna serie meddelanden utges av Avdelningen för lantbrukets hydroteknik, Sveriges Lantbruksuniversitet, Uppsala. Serien innehåller sådana forsknings- och försöksredogörelser samt andra uppsatser som bedöms vara av i första hand internt intresse. Uppsatser lämpade för en mer allmän spridning publiceras bl a i avdelningens rapportserie. Tidigare nummer i meddelandeserien kan i mån av tillgång levereras från avdelningen.

This series of Communications is produced by the Division of Agricultural Hydrotechnics, Swedish University of Agricultural Sciences, Uppsala. The series consists of reports on research and field trials and of other articles considered to be of interest mainly within the department. Articles of more general interest are published in, for example, the department's Report series. Earlier issues in the Communications series can be obtained from the Division of Agricultural Hydrotechnics (subject to availability).

Distribution:

Sveriges Lantbruksuniversitet
Institutionen för markvetenskap
Avdelningen för lantbrukets hydroteknik
Box 7014
750 07 UPPSALA

Tel. 018-67 11 85, 67 11 86

Swedish University of Agricultural Sciences
Department of Soil Sciences
Division of Agricultural Hydrotechnics
P.O. Box 7014
S-750 07 UPPSALA, SWEDEN

Tel. +46-(18) 67 11 85, +46-(18) 67 11 86