Tropical dryland agroforestry on clay soils:

Analysis of systems based on *Acacia senegal* in the Blue Nile region, Sudan

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Academic dissertation

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ABSTRACT

Acacia senegal, the gum arabic producing tree, is the most important component in traditional dryland agroforestry systems in the Blue Nile region, Sudan. The aim of the present study was to provide new knowledge on the potential use of *A. senegal* in dryland agroforestry systems on clay soils, as well as information on tree/crop interaction, and on silvicultural and management tools, with consideration on system productivity, nutrient cycling and sustainability. Moreover, the aim was also to clarify the intra-specific variation in the performance of *A. senegal* and, specifically, the adaptation of trees of different origin to the clay soils of the Blue Nile region.

In agroforestry systems established at the beginning of the study, tree and crop growth, water use, gum and crop yields, nutrient cycling and system performance were investigated for a period of four years (1999 to 2002). Trees were grown at 5 x 5 m and 10 x 10 m spacing alone or in mixture with sorghum or sesame; crops were also grown in sole culture.

The symbiotic biological N_2 fixation by *A. senegal* was estimated using the ^{15}N natural abundance (δ^{15}N) procedure in eight provenances collected from different environments and soil types of the gum arabic belt and grown in clay soil in the Blue Nile region. *Balanites aegyptiaca* (a non-legume) was used as a non-N-fixing reference tree species, so as to allow ^{15}N-based estimates of the proportion of the nitrogen in trees derived from the atmosphere.

In the planted acacia trees, measurements were made on shoot growth, water-use efficiency (as assessed by the δ^{13}C method) and (starting from the third year) gum production. Carbon isotope ratios were obtained from the leaves and branch wood samples.

The agroforestry system design caused no statistically significant variation in water use, but the variation was highly significant between years, and the highest water use occurred in the years with high rainfall. No statistically significant differences were found in sorghum or sesame yields when intercropping and sole crop systems were compared (yield averages were 1.54 and 1.54 ha^{-1} for sorghum and 0.36 and 0.42 t ha^{-1} for sesame in the intercropped and mono-crop plots, respectively). Thus, at an early stage of agroforestry system management, *A. senegal* had no detrimental effect on crop yield, but the pattern of resource capture by trees and crops may change as the system matures.

Intercropping resulted in taller trees and larger basal and crown diameters as compared to the development of sole trees. It also resulted in a higher land equivalent ratio. When gum yields were analysed it was found that a significant positive relationship existed between the second gum picking and the total gum yield. The second gum picking

seems to be a decisive factor in gum production and could be used as an indicator for the total gum yield in a particular year.

In trees, the concentrations of N and P were higher in leaves and roots, whereas the levels of K were higher in stems, branches and roots. Soil organic matter, N, P and K contents were highest in the upper soil stratum. There was some indication that the P content slightly increased in the topsoil as the agroforestry plantations aged. At a stocking of 400 trees ha^{-1} (5 x 5 m spacing), *A. senegal* accumulated in the biomass a total of 18, 1.21, 7.8 and 972 kg ha^{-1}of N, P, K and OC, respectively. Trees contributed ca. 217 and 1500 kg ha^{-1} of K and OC, respectively, to the top 25-cm of soil over the first four years of intercropping.

Acacia provenances of clay plain origin showed considerable variation in seed weight. They also had the lowest average seed weight as compared to the sandy soil (western) provenances.

At the experimental site in the clay soil region, the clay provenances were distinctly superior to the sand provenances in all traits studied but especially in basal diameter and crown width, thus reflecting their adaptation to the environment. Values of $\delta^{13}C$, indicating water use efficiency, were higher in the sand soil group as compared to the clay one, both in leaves and in branch wood. This suggests that the sand provenances (with an average value of -28.07‰) displayed conservative water use and high drought tolerance. Of the clay provenances, the local one (Bout) displayed a highly negative (-29.31‰) value, which indicates less conservative water use that resulted in high productivity at this particular clay-soil site. Water use thus appeared to correspond to the environmental conditions prevailing at the original locations for these provenances.

Results suggest that *A. senegal* provenances from the clay part of the gum belt are adapted for a faster growth rate and higher biomass and gum productivity as compared to provenances from sand regions. A strong negative relationship was found between the per-tree gum yield and water use efficiency, as indicated by $\delta^{13}C$. The differences in water use and gum production were greater among provenance groups than within them, suggesting that selection among rather than within provenances would result in distinct genetic gain in gum yield.

The relative $\delta^{15}N$ values (‰) were higher in *B. aegyptiaca* than in the N_2-fixing acacia provenances. The amount of N_{dfa} increased significantly with age in all provenances, indicating that *A. senegal* is a potentially efficient nitrogen fixer and has an important role in agroforestry development. The total above-ground contribution of fixed N to foliage growth in 4-year-old *A. senegal* trees was highest in the Rahad sand-soil provenance (46.7 kg N ha^{-1}) and lowest in the Mazmoom clay-soil provenance (28.7 kg N ha^{-1}). This study represents the first use of the $\delta^{15}N$ method for estimating the N input by *A. senegal* in the gum belt of Sudan.

Key words: *Acacia senegal*, agroforestry, clay plain, $\delta^{13}C$, $\delta^{15}N$, gum arabic, nutrient cycling, N_{dfa}, *Sorghum bicolor*, *Sesamum indicum*

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PREFACE

The work reported here was carried out at the Viikki Tropical Resources Institute (VITRI), Department of Forest Ecology, University of Helsinki, as a part of the research project “Integrated Forest Resources Management for Combating Desertification in Sudano-Sahelian Africa”, and later, the project “Trees, agroforestry and land use in dryland Africa” (TALDA), both financed by the Academy of Finland. The study also received funding during the field period in Sudan from the Agricultural Research Corporation of the Sudan. Moreover, the study received funding from the University of Helsinki at its later stages.

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I wish to express my appreciation to my colleagues and friends at VITRI, with whom I had useful discussions and suggestions. I again list them promptly with no title; I thank Vesa Kaarakka, Jörn Laxén, Teija Reyes, Mark Appiah, Riikka Otsamo, Abdalla Gaafar, Eddie Glover, Eshetu Yirdaw, Anu Eskonheimo, Minna Hares, Sakina Elshibli, Ping Zhou, Kurt Walter, Omar Abdi, Maarit Kallio, Talvikki Aittoniemi, Olli Taskinen, Jukka Lippu, Sirkka Bergström, Varpu Heliara, Wending Huang, Syed Alam and Fobissie Kalame.

Many thanks go to the members of the Finnish society who have cordially welcomed me and my family through the whole study period for their gracious hospitality, and from whom we have gained knowledge of many things, for example, how to survive in Finland during a cold winter.

Last but not least, very special thanks are due to my wife Wissal Abdel Rahman and my daughter Isrra, who have been my companions throughout my study. Their support and enthusiasm have provided the incentive for the successful completion of this study.

Helsinki, April 2006
El Amin Yousif A. Raddad

LIST OF ORIGINAL PAPERS

This thesis is based on the following original articles, which are referred to in the text by their respective Roman numerals (I-V).

I. Raddad, E.Y., Luukkanen, O., Salih, A.A., Kaarakka, V. and Elfadl, M.A. 2006. Productivity and nutrient cycling in young *Acacia senegal* farming systems on Vertisol in the Blue Nile region, Sudan. Agroforestry Systems. http://www.springerlink.com/agfo. DOI: 10.1007/s10457-006-9009-6

II. Raddad, E.Y. and Luukkanen, O. 2005. The influence of different *Acacia senegal* agroforestry systems on soil water and crop yields in clay soils of the Blue Nile region, Sudan. Agricultural Water Management. (Accepted). http://www.elsevier.com/agwat/

III. Raddad, E.Y. 2006. Ecophysiological and genetic variation in seedling traits and in first-year field performance of eight *Acacia senegal* provenances in the Blue Nile, Sudan. New Forests (NEFO23R1). http://www.springerlink.com/nefo.

IV. Raddad, E.Y. and Luukkanen, O. 2006. Adaptive genetic variation in water use efficiency and gum yield in *Acacia senegal* provenances grown on clay soil in the Blue Nile region, Sudan. Forest Ecology and Management 226: 219-229. http://www.elsevier.com/locate/foreco. doi:10.1016/j.foreco.2006.01.036

V. Raddad, E.Y., Salih, A.A., Elfadl, M.A., Kaarakka, V. and Luukkanen O. 2005. Symbiotic nitrogen fixation in eight *Acacia senegal* provenances in dryland clays of the Blue Nile Sudan estimated by the ^{15}N natural abundance method. Plant and Soil 275: 261-269. http://www.springerlink.com/plso. DOI: 10.1007/s11104-005-2152-4

NB: These publications should be referred to according to the bibliographic information given above. No reference to the reprints in this thesis should be made.

In studies I and V, E.Y. Raddad introduced the research idea, organized experimental arrangements, collected and analyzed the data and prepared the manuscripts which were revised jointly with the rest of the authors. During the study period in Sudan, A.A. Salih and M.A. Elfadl provided support in methodological phases.
In studies II and IV, E.Y. Raddad introduced the research idea, organized the experimental arrangements, collected and analyzed the data in Sudan and prepared the manuscripts which were revised by O. Luukkanen.

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LIST OF ACRONYMS AND ABBREVIATIONS

$^{13}C/^{12}C$	Carbon isotope ratios
$^{15}N/^{14}N$	Nitrogen isotope ratios
AF	Agroforestry
AI	Aridity index
ANOV	Analysis of variance
ARC	Agricultural Research Corporation (Sudan)
C/N	Carbon to nitrogen ratio
Ca	Atmospheric carbon dioxide concentration
Ci	Intercellular carbon dioxide concentration
DRS	Damazin Research Station
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FNC	Forests National Corporation
FRC	Forestry Research Centre
ha	Hectare
HSD	Honestly significant difference
IAEA	International Atomic Energy Agency
ICRAF	International Centre for Research in Agroforestry (World Agroforestry Centre)
IES	Institute of Environmental Studies (Sudan)
IIED	International Institute for Environment and Development (UK)
ISRIC	International Soil Reference and Information Centre
ISSS	International Society of Soil Science
LER	Land equivalent ratio
$Mg\ m^{-3}$	Megagram per cubic meter
NAR	Net assimilation rate
N_{dfa}	Nitrogen derived from the atmosphere
NPK	Nitrogen, phosphorus, potassium
NWFP	Non-wood forest product
OC	Organic carbon
P	Phosphorus (also precipitation)
PDB	Pee Dee Belemnite
PET	Potential evapotranspiration
PUE	Precipitation use efficiency
R^2	Coefficient of determination
RCBD	Randomized complete block design
RGR	Relative growth rate
SOM	Soil organic matter
SWC	Soil water content
SWS	Soil water storage
TE	Transpiration efficiency

VAM	Vesicular-arbuscular mycorrhizal fungi
WC	Water content
WU	Water use
WUE	Water use efficiency
$\delta^{13}C$	Difference in the relative abundance of the heavy carbon isotope (^{13}C)
$\delta^{15}N$	Difference in the relative abundance of the heavy nitrogen isotope(^{15}N)

1. INTRODUCTION

1.1 Background

In recent years, the land use in Sudan has been characterized by large-scale land degradation and loss of tree cover. These two processes are interrelated and caused by human activities, such as wood harvesting, overgrazing and land clearing for farmland expansion. Deprived farmers have responded to declining land productivity by abandoning their existing degraded cropland and moving to new lands for cultivation of their rainfed agricultural crops.

Over the last few decades there has been a clear evident southwardly recede of isohyets coupled with more frequent droughts. This may be a constant trend or just a stage of a long cycle (cf. Eskonheimo 2006). This phenomenon combined with overgrazing and removal of the tree cover for various purposes may be causing desert encroachment and perhaps a similar recede of the boundaries of all ecological zones. There have also been changes in the quality of their vegetation composition. Some species that were once dominant or very conspicuous have greatly decreased, some almost to the edge of extinction (Mahmoud et al. 1996).

The national strategy of Sudan for agriculture and natural resources aims at conservation and development of these resources. It aims at increasing of the forest area by 25% of the present area up to a total of ca. 70 million ha. It also aims at integration of agriculture and forestry by introduction of trees into the farming systems, so as to cover 20% of the land area in irrigation schemes and 10 to 20% of that in the rain-fed sector, whether mechanized or traditional. The strategy also aims at increasing the gum arabic production to 60, 000 tons annually, as well as paying attention to other non-wood forest products (NWFPs).

Acacia senegal (L.) Willd. (“hashab” in Arabic), a leguminous tree species belonging to the Mimosoideae subfamily, is the main agroforestry tree species in Sudan with a wide natural distribution in the Sudano-Sahelian zone of Africa (Raddad 1987, Ballal 2002). The tree is highly variable, with four distinct varieties recognized (Wickens et al. 1995). The variety *senegal* with which we are concerned here is the main source of gum arabic and a well-established traditional agroforestry tree component.

In the clay plains of the Blue Nile region in Sudan, extensive mechanized rainfed cultivation of sorghum, sesame, sunflower and other annual crops is practiced. Large areas have been completely cleared of tree cover. The productivity of these field crops has declined because of loss of soil fertility. As there is little deposition, accumulation or decomposition of soil organic material in this dryland environment, the natural soil fertility is threatened (Ardö and Olsson 2003). As a result, much of the abandoned farmland has been given to the national forest service (Forests National Corporation, FNC) for reforestation.

Many authors have already shown that traditional agroforestry with *A. senegal* is an ideal example for sustainable natural forest management. The dramatic increase in the animal and human population has led to increased pressure on the available natural resources, particularly land and the woody vegetation. Furthermore, intensive cultivation, overgrazing and tree cutting has led to land degradation and, consequently, decreased the land productivity. These factors have resulted in food shortage, poverty, and lack of fodder and fuelwood.

The traditional production of gum arabic from the acacia trees of this agroforestry system is an off-season income-generating activity for most of the farmers in this region. Gum yields have decreased, however, because of biotic, physical, socioeconomic and institutional reasons. There is a need to look at this traditional dryland management from a more holistic perspective. Proper integration of the gum-yielding tree into the production system needs to be evaluated and studied from a crop and tree physiology viewpoint, since, in contrast to western Sudan where agroforestry is practiced on sandy soil, in the Blue Nile clay plains *A. senegal* has only recently been introduced into the farming systems. Understanding the water balance of the system and the nutrient cycling is of paramount importance for the future management sustainability.

1.2 Vertisols (clay soils)

Vertisols are dark montmorillonite-rich clays with characteristics shrinking/swelling properties. This group of soils with a high clay content (>30% to at least 50 cm from the surface) and in dry condition with typical cracks which are at least 1 cm wide and reach a depth of 50 cm or even more is often also called heavy cracking clay soil. When this clay soil rewets it clasps and the result is a soil that mixes up preventing the formation of the distinct horizons found in most other soil orders. Vertisols are fertile, rich in organic matter, high in clay and low in permeability. Vertisols form distinct cracks in the dry season that can tear plant roots. The dry period can seriously limit the types of crops that can grow on these soil types. They have a very high water holding capacity and are normally very high in fertility. They are difficult to till when either wet or dry without destruction of the soil structure (Bunting and Lea 1962, FAO 1998).

The typical clay soil of the Blue Nile region is dark-coloured, alkaline (pH ≤ 8) and dries during the dry season forming very deep cracks; these cracks are 2-15 cm wide at the surface, and they turn narrower downwards and elongate as far as to 150 cm depth. With the advent of the rains, the clay absorbs moisture mainly through these cracks and swells, which closes the cracks. After this, the water penetration is extremely slow and temporary flooding or water-logging is frequently experienced, especially after heavy showers (El Houri 1986).

1.3 Drylands

Drylands are defined as areas where the ratio of the mean annual precipitation (P) to potential evapotranspiration (PET) is less than 0.65. They are classified into four climatic zones on the basis of aridity index (AI) values, defined as hyper-arid (<0.03), arid (0.03 to <0.20), semi-arid (0.20 to <0.50) and dry sub-humid (0.50 to 0.65; Middleton and Thomas 1997).

Globally, drylands cover 40% of the Earth’s total land surface, excluding the hyper-arid lands that cover about 8% (UNDP/UNSO 1997). Out of this total area, the arid, semi-arid and dry sub-humid zones cover 12%, 18% and 10%, respectively. In Africa, drylands cover 43% of the land, and about 65% of the countries are classified as dryland countries (Ffolliott et al. 2002, IUFRO 2004).

Dryland boundaries are constantly changing, because of high inter-annual variability in the mean rainfall and the occurrence of droughts that may last for periods of several years at a time. Delineation of dryland boundaries therefore requires caution because of the processes inherent in dryland climatic regimes on the one hand, and the effects due to human activities on the other (Ffolliott et al. 2002).

On drylands, desertification and poverty are distinct but interlinked phenomena with their underlying causes and consequences. Desertification is now clearly understood as land degradation in arid, semi-arid and dry sub-humid areas resultant from various factors, including climatic variation and human activities (Middleton and Thomas 1997). Thus, it can correctly be stated that drylands are constrained by factors related to natural causes, threatened and accelerated by factors related to anthropogenic causes (IUFRO 2004).

One-half of the world's countries have portions or all of their land in dryland environments. These lands and their sub-humid margins equal to one-third of the globe's surface and are the home to almost 40 percent of the world's population (White et al. 2002). They include hotspots where land and environmental degradation is occurring at alarming rates, often leading to desertification, and threatening the livelihood of more than one billion people. Drylands vary in terms of their climate, soils, flora, fauna, land use, and people. One common feature of all dryland environments, however, is their resilience in terms of recovery from effects of drought (IUFRO 2004).

On drylands, water availability is a primary factor controlling plant growth processes and productivity (Kramer and Kozlowski 1979, Bewley and Krochko 1982). Explicitly, it has been observed that in dry environments about 90% of the diameter growth in woody plants is attributed to water availability (Zahner 1968).

One of the most important factors to consider in planning and management of dryland resources is the rainfall intensity and variability. Because the soils of dryland environments often cannot absorb all of the rain that falls in intensive storms, water is frequently lost in runoff and seepage processes. At the opposite extreme of the spectrum, the water from a rainfall of low intensity can be lost through evaporation and evapotranspiration when the rain falls on a dry soil surface. Rainfall intensity also relates to the risk of soil erosion. Individual raindrops carry enough energy capable of removing topsoil upon impact, causing splash erosion, which can degrade or destroy the soil structure over time (Brooks et al. 2003).

The water-holding capacity of the dryland soils and their ability to supply nutrients are of primary importance to planners and managers of natural and agricultural resources. Soil depth and texture largely govern the amount of water that infiltrates or can be held in a soil body. However, a hardpan layer, restricting water-holding capacities and rooting depth, often limits the depth of soils in dryland regions. These hardpans consist of $CaCO_3$ or other materials that can be continuous and occur between 5 and 60 cm below the surface. Rates of deposition, accumulation, and decomposition of organic material are low in dryland environments, hence the natural soil fertility is low. The limited organic matter that is present can be quickly lost when soils are cultivated for agricultural crop production. The extensive leaching of nutrients and intensive weathering of minerals on older exposed surfaces often characterize the soils (Brooks et al. 2003).

1.4 The gum arabic belt

"The gum arabic belt", where *A. senegal* grows naturally, coincides with the area of central Sudan mainly between latitudes 10º and 14º N. The two most conspicuous gum arabic belt areas outside these limits are the northeast (Faw-Gedaref-Kassala), and in the southeast along the Blue Nile/Upper Nile states border (Fig. 1).

The total gum belt area in Sudan amounts to 520,000 km^2, which is equal to one-fifth of the area of the country. A field survey conducted in 1989 indicated that there existed scarcely any *A. senegal* north of latitude 13º 45´ in Kordofan or Darfur (IIED and IES 1990). The gum belt provides a buffer against desertification across the vast region of the Sudano-Sahelian zone. *A. senegal* provides a variety of valuable economic and ecological functions, such as gum arabic, fodder for livestock, fuelwood and shade, as well as many indirect benefits associated with the tree. Its extensive and massive root system reduces soil erosion and runoff, and, as a leguminous tree, it fixes nitrogen which encourages grass and crop growth. The tree is also essential in sand dune fixation for these reasons; it is the preferred species in bush-fallow rotational and intercropping farming systems in the drylands of western Sudan (Barbier 2000).

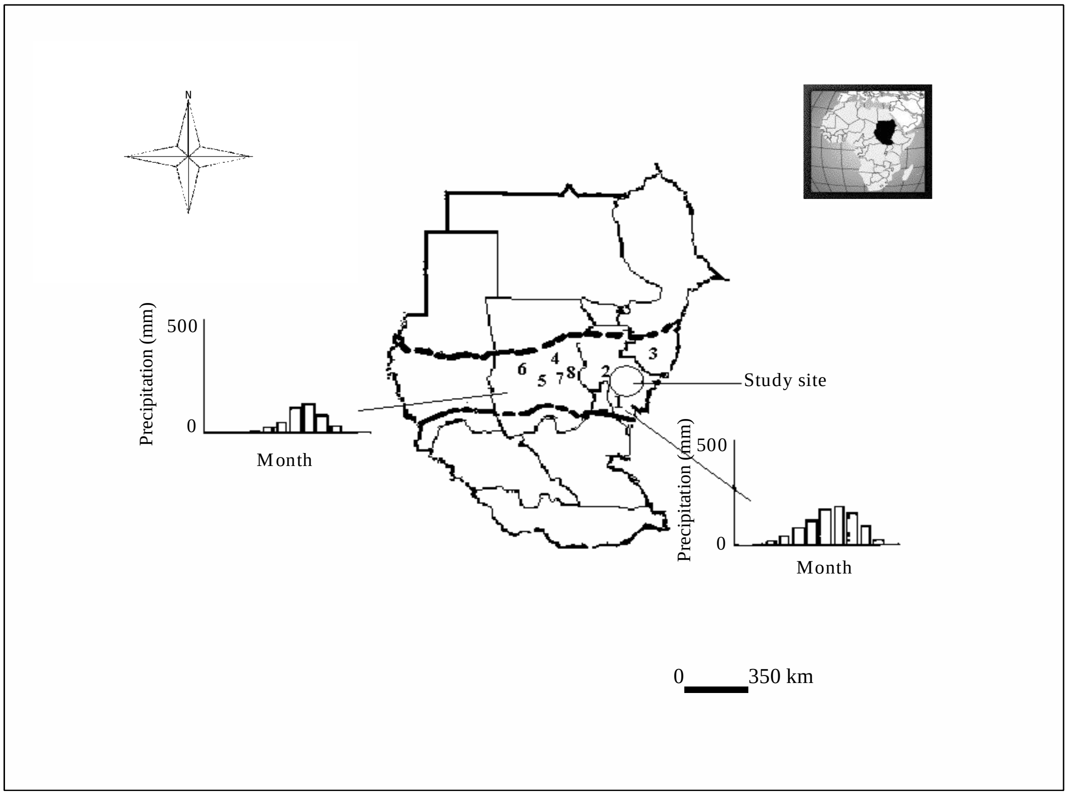

Fig. 1. Map of Sudan with *Acacia senegal* provenance locations. Broken lines show the gum arabic belt boundaries. Average monthly rainfall (mm) of the two contrasting regions for provenances is shown. Numbers 1, 2, 3, 4, 5, 6, 7 and 8 stand for provenances Bout, Mazmoom, Gedaref, Domokeya, Nabag, Saata, Rahad and Semaih, respectively (modified after FAO 2003).

1.5 Agroforestry

Agroforestry is defined as "intensive land-use management that optimizes the benefits (whether physical, biological, ecological, economic or social) from biophysical interactions created when trees and/or shrubs are deliberately combined with crops and/or livestock" (Gold et al. 2000).

Traditionally, farmers on the drylands of Africa have developed a wide range of agroforestry and soil conservation strategies to adapt their crop and livestock production systems to the marginal conditions of their lands and to minimize climatic risks to household and food supply. The strategies include deliberate preservation of selected valuable trees and shrubs in cropped fields and the use of tree/shrub biomass (leaves and twigs) as mulch on crusted or compacted soils to improve the organic matter input and soil structure. Agroforestry involves management systems that incorporate a tree or shrub component in the agricultural landscape, and it can increase both the carbon storage and biodiversity in areas where annual crops or degraded lands are predominant.

Agroforestry has shown promising results in the rehabilitation of degraded lands. With its low level of inputs and multipurpose-tree species focus, agroforestry as a land restoration strategy also shows a significant potential for small-scale subsistence farmers in dryland and developing regions. The presence of trees in an agricultural system can have a significant influence by increasing the soil fertility and ecosystem production capacity as a whole. Although agroforestry systems have been seen as a general solution for the reclamation of degraded lands, it is important to note that the ultimate success depends on the ability to increase the related knowledge among all partners involved and on the acceptance by farmers and local communities (Nair 1993, Buck et al. 1999, Eskonheimo 2006).

The traditional *A. senegal* agroforestry system practiced for centuries in the Sudano-Sahelian zone can be seen as a complex and dynamic resilient system reacting to a wide variety of long-term external changes and short-term disturbances related to climate, topography, soils, geomorphology, herbivores, fires and human intervention. An important general conclusion has been that, in dryland environments, the effects of global climate change are of increasing concern and the main attention is directed towards management and policy improvements (IUFRO 2004). Moreover, considerations for adaptation to climate change have been exemplified for Sudan in particular by Abdalla et al. (2002).

The inherent ability of dryland acacias to restore the land productivity is supported by evidence from traditional farming practices as well as from scientific research (Fries 1995). Understanding the nature of coexistence between the components of the ecosystem, which under other circumstances are mutually exclusive or unequal partners, yields theoretical insights and has practical implications for sustainable management.

The changes that occur in natural systems in the Sudano-Sahelian zone are mainly those of limited disturbance. Much competition among plants takes place below ground, where root systems influence the biogeochemistry, hydrology and primary production. In contrast, soil characteristics play a significant role in plant species distribution through their effects on root system development and, subsequently, on the establishment and growth of plant communities. As shown in related earlier studies (Gaafar et al. 2005), water is the main factor limiting plant growth; the competition is severe between the woody plants and agricultural crops for both water and nutrients.

A. senegal is a deep-rooted tree species capable of efficiently using soil resources, and its presence can increase the overall biomass productivity. However, agroforestry research especially concentrates on the competition between trees and crops in the top 50 to 60 cm soil layer (Ong et al. 1996, Livesley et al. 2002).

The diverse patterns of growth and development in natural *A. senegal* trees is presumably a result of adaptation. Little is known on how site and climatic factors influence the balance between above and below-ground components or how these factors affect the gum arabic production. Preliminary results from the earlier phases of the present research project show that the gum production per tree is higher at higher tree densities (Ballal et al. 2005). Such results are surprising, again suggesting that more research needs to be done.

On drylands, combinations of agricultural cropping, livestock production, forestry, and other types of production systems are frequently placed on the same piece of land rotationally or simultaneously. Regardless of the nature of these combinations, the goal is attaining ecological stability and sustainable benefits to the users of the land.

Land use sustainability is a challenge to the people living in dryland environments. Problems that commonly challenge these people include desertification, poverty and low levels of investment. However, people can also confront major problems in attempting to attain a level of sustainable land use because of their inadequate knowledge of alternative land use practices (Ffolliott et al. 1995, Squires and Sidahmed 1998). Many people have a "tradition" in agriculture that is not always matched by a similar attitude towards other land uses such as forestry, wildlife ranching, or ecotourism, all of which have these days become profitable enterprises in many dryland regions of the world. This lack of appreciation can be a barrier to the initiation of these land uses, especially on marginal agricultural lands. The barriers are often overcome through new land tenure arrangements, the education of people, extension services, and, most of all, through demonstrating the benefits obtained by more diversified land-use activities (IUFRO 2004).

Cannell et al. (1996) argued that agroforestry may increase the productivity, provided the trees capture resources which are under-utilized by crops. In annual systems where the land lies bare for extended periods, the residual water remaining in the soil after harvest and the off-season rainfall are often unused. For instance, in the drylands of the Blue Nile (with a mean annual rainfall of about 730 mm), substantial amounts available water remain in the top one-metre soil layer after harvesting the crops, and this water could be used by trees, thus improving the water use and productivity of the lands (Ong et al. 1996).

The drylands of the world suffer from a vicious cycle of low productivity, low levels of investment, and, as a result, poverty. Investments, apart from those made for irrigated agriculture activities, are relatively low (Marples 1986, Ffolliott et al. 1995, Squires and Sidahmed 1998). Low productivity, low levels of investment, and land degradation often leading to desertification are responsible for regional poverty and income differences. The poverty and hunger that are predominant in sub-Saharan Africa are a poignant example of this situation. Other critical problems include the inherent problems of water scarcity, tenure considerations, and ineffective developmental policies. Improving this situation requires that a variety of technical and institutional problems be solved. Among these solutions is increasing the level of investments in appropriate agriculture, alternative land use practices, and other appropriate income-generating interventions. Other solutions are designing strategies for risk management and implementing programmes for more equitable land distribution and levels of income (IUFRO 2004).

1.6 Effective rainfall

Effective rainfall is that portion of the total rainfall where part of the rain may be lost by surface runoff, deep percolation below the root zone or by evaporation of the rain intercepted by the plant foliage. The effective rainfall is assumed as 80% of the total rainfall (Doorenbos and Pruitt, 1975; Sudan Meteorological Department, 2002).

In regions where high-intensity rains occur, only a portion of the water can pass the soil and be stored in the root zone; hence the effectiveness of rain is consequently low. In case of light rains, interception by the plant foliage can be important; wet plants tend to transpire less, which is offset by increased evapotranspiration of the rainwater intercepted by the plant foliage. In practice, for conditions where the ground is fully covered, it has been assumed that intercepted light rainfall is close to 100% effective. Where crops do not cover a high percentage of the ground and the soil surface has been dry for some time before rain, evaporation from the wet soil surface can be considerable. Rainfall of 6 to 8 mm per day may essentially all be lost by evaporation. Even rains of 25 to 30 mm during initial and early crop development stages with a low percentage of ground cover may result in a net gain of only 60% of the rain received (Doorenbos and Pruitt 1975, Allen et al. 1998).

Different countries use different criteria to estimate the effective rainfall as a percentage of total rainfall. In India, one method considers 70% of the average seasonal rainfall to be effective. In another, the effective rainfall is taken as the mean rainfall but excluding a daily rainfall of less than 5 mm and in excess of 75 mm in one day and 125 mm in ten days. In Thailand, 80% of the November and 90% of the December to March rainfall is taken as effective. In Japan, for non-submerged rice, the rainfall is assumed 80% effective, but a daily rainfall below 1.85 mm and above 30 mm is discarded; when effective rainfall and residual soil water on the previous day exceeds 30 mm, the surplus is excluded from calculations.

A rough guide to estimating effective rainfall is the method of the US Bureau of the Reclamation for use in arid and semi-arid regions. Mean season precipitation of the driest one in consecutive years is used as the basis, while the effectiveness of increments of monthly rainfall ranges from 90% for the first 25 mm to 0% for precipitation greater than 150 mm (Doorenbos and Pruitt 1975).

1.7 Aims of the study

General objectives

The main aim of the present study was to provide new knowledge on the potential use of *A. senegal* in dryland agroforestry systems on clay soils, and to provide silvicultural and management tools, with consideration for agroforestry system productivity, nutrient cycling and sustainability. The study was also carried out acknowledging the fact that dryland ecosystems in the Blue Nile constitute a carbon sink potentially affected by agroforestry and other forms of land use. An ultimate general aim was to provide guidance for designing suitable agroforestry systems for clay soil in Sudan for land rehabilitation and suitable land use, so as to contribute to increased environmental, production and social benefits and services.

Specific objectives

The specific objectives were as follows:

1. To analyse the soil water characteristics associated with two agricultural crops commonly used in dryland agroforestry in Sudan, sorghum, and sesame. An attempt was made also to determine the effect of trees on crop performance and the general availability of water for agricultural crops in clay soils.

2. To clarify the growth and gum yield performance and physiological behaviour of different *A. senegal* provenances grown in agroforestry systems on clay soil in relation to conditions of their original habitats, so as to assess their genetic variability and adaptation for the purpose of finding suitable acacia stocks for sustainable land use.

3. To study and determine the nutrient cycling and balance for N, P, K and OC in the soil in relation to different production system designs represented by sole *A. senegal* stands, intercropping and sole agricultural crops.

1.8 Hypotheses of the study

The following hypotheses were set:

1. *A. senegal* competes for water with agricultural crops, and the soil water content would vary spatially depending on tree density; competition for water would also depend on tree spacing and management.

2. The microclimate created by trees in the agroforestry system would favourably affect the soil water content and improve the growth of associated crops as well as the overall productivity of this intercropping system.

3. Agroforestry systems based on *A. senegal* increase crop and tree yields given that they utilise more water and nutrients than annual cropping systems (reflecting facilitation and sharing of resources).

4. Nutrient balance and cycling in *A. senegal*-based agroforestry systems is more efficient compared to monoculture of agricultural crops; the rate at which the nutrient capital is increased in trees and surface soil during the cropping period is important in establishing a simple relationship between site nutrient enrichment and the density and age of trees.

5. Competition for resources between trees and crops occurs under the ground rather than above the ground.

6. Local clay-soil *A. senegal* provenances are well adapted to their sites, and they maintain a high water and nitrogen use efficiency and high biomass and gum productivity.

7. Water availability would influence leaf carbon isotope ratios ($\delta^{13}C$) and water relations parameters, making these also indicators for genetic adaptation in *A. senegal*.

8. Dryland agroforestry systems, through appropriate land management, are more effectual as carbon sinks as compared to crop monoculture or sole forestry systems.

2. THEORETICAL FRAMEWORK

2.1 Soil water availability and drainage

Usually, the amount of available water is low in sand, higher in clay and maximal in loamy and silt soils. In clay soils, however, the drainage is often poor; and clay soils containing less than 10 to 15% air volume at field capacity may have insufficient aeration for plant growth (Soil Survey Staff 1996).

It has been confirmed that agroforestry systems may greatly increase the rainfall utilization as compared to annual cropping systems. Nevertheless, careful consideration of the tradeoffs between the loss of crop production and the additional value provided by tree products is of paramount importance (Lott et al. 2003). Walker et al. (1981) proposed that stratification of soil water between the topsoil and subsoil may lower the competition between woody plants and grasses (since woody plants presumably have the exclusive use of subsoil water), and trees tend to utilize the available soil water in such a way that they do not prevent the establishment or survival of crops.

Tree species selection and management and their spatial arrangement is a key factor in determining the feasibility of dryland agroforestry systems. Gregory (1996) reported that *Prosopis juliflora* (Sw.) DC. reduced the soil water content in the crop-rooting zone less and had less competitive effect on sorghum than *A. nilotica* (L.) Willd. in an agroforestry system. The two tree species therefore performed differently in their specific root density and distribution. This has profound implications for modelling tree-crop competition, since most current approaches assume a direct correlation between root length and water uptake irrespective of species. The conservation of soil water by acacias is more useful during drought years as compared to normal and above-normal years of rainfall in the Blue Nile region conditions (Bukhari 1998).

The soil water content is extremely important for crop growth, and the soil water storage (SWS) before sowing of an annual crop plays an important role in crop growth and yield. Increase of SWS before sowing can enhance crops to develop larger and deeper root systems, which can add to the utilization of available soil water (Li et al. 2001).

On drylands, evaporation from the soil surface can reach up to 30-60% of the total amount of rainfall (Wallace 1991). Annual crops often use only a small fraction of the available rainfall or stored soil water reserves. Incorporation of woody perennials, such as *A. senegal*, into a farming system can increase the overall biomass productivity (Ong et al. 2000, Livesley et al. 2004).

A. senegal has a deep root system that makes it capable of efficiently using soil resources, and its presence may enhance ecosystem productivity. The diverse patterns of growth and development in natural *A. senegal* trees is presumably a result of adaptation (Gaafar et al. 2005). However, little is known of how site and climatic factors influence the balance between above-and below ground components or how these factors affect the gum production of acacia trees.

2.2 Effect of *A. senegal* on soil water

Development of dryland agroforestry systems depends on the fact that the tree species selected have few superficial lateral roots. Their root system goes deeper into the soil than that of the crop species and obtains water and nutrients inaccessible to the crop. Various tree species are assumed as suitable for agroforestry, despite limited knowledge of their root distribution. However, it has also been recognized that in many situations tree roots compete with crop roots for water and soil nutrients, and under these circumstances the system has to be modified or managed in such a way as to maintain and retain the expected positive results (Schroth 1995, Smith et al. 1999).

A general observation reported by ICRAF (1996) and Gregory (1996) has been that when soil water and nutrients are distributed evenly, trees will preferentially extract water from the top soil layer. However, one way of reducing the impact of tree roots on crop growth is to carry out root pruning, which has been found to increase the crop yield in some agroforestry systems (Yadav and Khanna 1992, Korwar and Radder 1994). A simpler management technique that may have the same effect is shoot pruning.

A well-known phenomenon which has been widely demonstrated for herbaceous and woody plants consists of the fact that when shoots are defoliated or pruned, plant growth is concentrated above the ground and the below-ground growth stops or slows down dramatically (Jones et al. 1998). This tendency of plants to maintain and keep the ratio between roots and shoot constant under a certain prevailing set of environmental conditions has been termed ‘functional equilibrium’ by Brouwer (1983). In some intercropping situations, crown pruning offers the additional benefits of reduction of shading and provision of fuelwood and fodder for the dry season. Likewise, shoot pruning is a standard and main component in managing alley cropping systems, but few data are available on the exact effect and impact of shoot pruning on root growth (Schroth and Zech 1995).

Tree root density decreases sharply with increasing soil depth, with most fine roots being found in the surface layers. In a study by (Bouillet et al. 2002) the number of fine root intersects in the 0-25 cm surface soil layer represented 16-53% of the total throughout the profile, depending on stand age and the type of profile. The percentage of root intersects in surface layers increased with stand age. This could be due to the greater concentration of nutrients in surface layers, since the highest root densities were generally observed under the stump. In the central clay plains of Sudan, the root system depth of mature trees varies from 60-80 cm. A compacted nature of the clay soil and the accumulation of soil water content in the upper soil layer could account for this pattern (Bukhari 1998).

Daily fluctuations in the soil water content seem to be greatest in the topsoil (0-15 cm) and decrease as soil depth increases. In general, little soil water manages to reach the soil layers below 45 cm (Smit and Rethman 2000). The water content in the soil suggests high rainwater losses (e.g. runoff plus interception) on plots with a high tree density and less grass cover, compared to plots with a low tree density and some grass cover. This evidence suggests that soil water extraction within the topsoil zone by the roots of trees occurs at a rate fast enough to prevent soil water from reaching deeper soil layers (Smit and Rethman 2000).

Positive and negative interactions (or facilitation and competition) between trees and herbaceous plants may occur simultaneously (Holmgren et al. 1997). Facilitation may result in increased productivity through improving the water and nutrient status beneath the canopy.

Introduction of woody plants into the system can change the water balance of a site. Replacing the grassland with forest has been reported to have a significant impact on the groundwater status and recharge by altering interception and transpiration (Le Maitre et al. 1999, Vertessy and Bessard 1999). The magnitude and impact of this change may be of great importance in regions experiencing marked seasonal rainfall variation. Due to this reason, the introduction and planting of exotic fast-growing trees could modify not only the composition and distribution of native grasses but also the local water balance (Gyenge et al. 2002).

The use of water resources by silvopastoral systems reflects the productivity of these systems. Water consumption has been found to be higher in silvopastoral systems based on pines than in an open pasture (Gyenge et al. 2002). It has also been reported that roots of *Leucaena* and maize exploit water from the same soil horizons during the rainy season, with the result that the intercropped maize captures less water than sole maize (Howard et al. 1995).

2.3 Crop yield and productivity

Agroforestry systems increase the productivity by facilitation and sharing of resources; the temporal and spatial complementarities of resource capture by trees and crops in an agroforestry system are major determinants of the ability of the system to improve crop yields and the overall productivity (Ong and Black 1995, Cannell et al. 1996, Huang 1998). In agroforestry systems trees reduce the solar heat effect on crops and decrease the wind speed and soil temperature. It has been reported that the yield of crops grown under leguminous trees is generally higher as compared to sole crops. Recognizing this fact, agroforestry has been practiced on drylands for centuries (Sharma 1998). Crop productivity is enhanced under a tree canopy because of improved soil fertility and the influence of shade leading to reduced under-storey temperature and evapotranspiration in a hot and dry environment (Bunderson et al. 1990).

Owing to its size and age, the woody component of an agroforestry system has a considerable advantage in sequestering resources from a large area and in enhancing soil physical and chemical properties under its canopy (Kessler 1992, Belsky et al. 1993). This is well demonstrated by the effects of isolated trees on the under-storey habitats and vegetation as described by Belsky et al. (1993) in the semi-arid rangelands of East Africa, in which the under-storey vegetation productivity under *Acacia tortilis* (Forssk.) Hayne and *Adansonia digitata* L. amounted to 50 and 20 % higher, respectively, as compared to outside the tree canopy. Similarly, the organic matter content and N, P, K, and Ca concentrations were significantly higher under the tree canopies than in an open area.

In some countries like Australia agroforestry is regarded as a means to alleviate the problems of rising water table and salinization, which affect a major proportion of the dryland areas (Eastham et al. 1994). Under adverse conditions such as sloping land, poor soil conditions, and drought stress, trees are often superior as fodder and fuel sources compared to herbaceous species (Roder 1992, Olsen et al. 2000). However, in alley cropping the competition between trees and crops may significantly reduce the yields of the crops (Ong et al. 2000). Long-term experiments with maize grown with *Erythrina poeppigiana* (Walp.) O.F. Cook, and *Gliricidia sepium* (Jacq.) Walp. hedgerows have indicated that, after seven years, the maize productivity and N uptake were more than twice as high in alley cropping with either tree species as compared to crop monoculture (Haggar et al. 1993).

There is sufficient evidence to show that the overall (biomass) productivity of an agroforestry system is generally greater than that of an annual system, although not necessarily greater than that of a forestry or grassland system. The basis for potentially higher productivity could be due to the capture of more growth resources, e.g. light or water (Ong et al. 1996), or to improved soil fertility.

Results from *Leucaena*-based systems in the tropics indicate that the competitive nature and vigorous growth of this tree usually reduce the yield of associated crops. Over-yielding and under-yielding as a result of competition usually occur simultaneously, because the trees and the crops both require water, light space and nutrients (Ong et al. 1996). The same studies also concluded that the major limiting growth resources available for a mixture of components always exceed those available for corresponding sole stands, irrespective of the proportions of species.

Complementarity exists when a full yield of one component or the other can be achieved simply by varying the proportions of the desired species.
Changes in soil structure through plant-induced increases in macro-porosity have the potential to influence the soil water dynamics, including the timing and rate of evapotranspiration and nutrient uptake, aeration, and redistribution of particles and solutes. These factors influence chemical and microbial activities in the rhizosphere and subsequently the growth and yield of the following crop (White 1997, Harrier and Watson 2003).

Sorghum (*Sorghum bicolor* (L.) Moench)

Sudan's flora includes all the three wild sorghums believed to be the ancestors of cultivated sorghum (S. *aethiopicum, S. verticilliflorum* and *S. arundinaceum*). It is also the home of five to six other wild sorghums, including *S. sudanensis* (Sudan grass) which internationally is very important as a fodder crop. Sorghum is one of the most significant and widely used grain crops in Sudan and in the Sudanese diet and economy. The germplasm of sorghum is thoroughly collected, documented and preserved. Collection started in 1914 by Punter and was later augmented with local types and exotic introduction, mainly from U.S.A in the early forties, and plant breeders kept adding to the collection (Mahmoud et al. 1996). Its productivity varies greatly from one year to another due to the fluctuation in weather and its components such as the amount of rainfall and its distribution.

Sesame (*Sesamum indicum* L.)

Sesame is one of the main oil crops in Sudan, grown under rain-fed conditions by subsistence, semi-commercial and commercial farmers. Selection by subsistence farmers has resulted in many land races adapted to different ecological areas, varying mainly in rainfall (300 to 1000 mm) and soil type (sandy to heavy clay), and to the needs of the farmer (e.g. seed colour). All cultivars have one dehiscent capsule per leaf axil, but they differ in seed colour, days to maturity, degree of branching, number of locules per capsule and capsule size, which affects the number of seeds produced (Mahmoud et al. 1996).

2.4 Tree growth improvement

2.4.1 Roots and root system

The practice of intercropping during early stages of timber plantation management is widely known as the taungya system (Ballal et al. 2005). Especially the first two years of intercropping in taungya systems have been well studied, and many authors report an increase in tree growth rates as compared to tree monoculture (e.g. Chamshama et al. 1992). However, tree growth can also be faster in monoculture trees than in agroforestry systems. This suggests that trees can be adversely affected by competition with associated crops for the above and below-ground resources during the establishment period. Nevertheless, trees in agroforestry systems later normally reach the level of growth found in solely grown trees (Ong et al. 2000).

The root system architecture is highly influenced by environmental factors. *A. senegal* has thick roots that are capable of penetrating hard clay soils. Field and laboratory studies have shown that tree species with thick roots penetrate compact soils more easily than the thin-rooted ones (Materechera et al. 1991, Salih 1998). Large pores created by thick roots are known to last longer and withstand disturbance due to tillage and land use in general, as compared to the fine pores created by thin roots (Blackwell et al. 1990).

Rapid decomposition of roots is required for quick formation of bio-pores. In addition, this rate of decomposition is determined and influenced by many factors such as the C: N ratio, and composition of sugars in the roots, microbial flora population, and moisture availability. The optimum C: N ratio for greater microbial activity and faster formation of bio-pores is about 25 (White 1997). Thick roots of woody species tend to have higher C: N ratios of between 70-106, than found in *Quercus* spp. and *Pinus* spp. (Usman et al. 2000) and a greater concentration of insoluble carbohydrates, as found in *Acacia* spp. (Peter and Lehmann 2000).

In general, the natural vegetation productivity under savanna trees increases with a decrease in rainfall; however, the opposite occurs in agroforestry. One explanation for this is that, in the savanna, the beneficial effects of microclimate improvements (e.g. lower temperature and reduction in water loss) are greater in more xeric environments. Mature savanna trees have a high proportion of woody biomass above the ground as compared to the area of foliage, whereby the amount of water saved (largely by reduction in soil evaporation) is greater compared to the water lost through transpiration by trees (Ong and Leakey 1999).

2.5 Physiological adaptation

2.5.1 General considerations

The research into physiological characters related to drought adaptation and tolerance has been fruitful over the last decades. Determination of water-use efficiency, with stable carbon isotope measurements of trees, has become common in studies on drought adaptation (Kramer 1980, Arndt et al. 2000, Li and Wang 2003). Most of the traits that explain plant adaptation to drought are related to plant development and structure and include phenology, the size and depth of the root system, xylem properties, or the storage of reserves (Passioura 2002, Chaves et al. 2003).

The physiological and morphological adjustments that take place in a plant during water deficit can be divided into short and long-term responses. These responses and their implications for field performance are controlled by the genetic characteristics of the plants and those growing conditions under which it has evolved (Jones 1980). Generally, plants adapt to drought by improving the water uptake through developing deep root systems, or by osmotic adjustment, by reducing water loss, or by maintaining a large internal storage of water (Larcher 2003).

Structural modifications, such as changes in the relationship between leaf and stem wood areas, may be of considerable importance in the end, reflecting acclimation or adaptation to the supply and demand of water under particular growing conditions. In general, a reduction of the leaf area is an efficient way to control water loss during drought (Myers and Landsberg 1989, Gibson et al. 1995, Warren and Adams 2004). The reduction of the leaf area is, however, a relatively slow and irreversible response mechanism that more affects long-term adaptation than the diurnal physiological behaviour. An extensive and deep root system is commonly associated with good drought adaptation and enables a plant to take up water efficiently (Awe et al. 1976, Grunwald and Karschon 1982).

A small leaf area, such as that commonly found in *Acacia* species, prevents water loss and enables the plant to survive drought. Similarly, prompt stomatal regulation leads to lower stomatal conductance that tends to increase the leaf area. According to Whitehead et al. (1984), the leaf area becomes smaller in dry conditions due to the greater evaporative demands.

Leguminous trees can grow and nodulate well under drought-stress conditions. Plants of the genus *Acacia* are pioneer plants that play an important role in the preservation and restoration of fertility in poor and eroded soils in Africa. Deficiency in N often limits plant growth and, hence, a symbiotic relationship has evolved between plants and a variety of N_2-fixing organisms. These plants produce an extensive, deep root system in addition to their potential to fix atmospheric N_2. For example, species representing the genera *Acacia* and *Prosopis* are widely spread in the drylands of Africa and other regions and have proved to form effective N_2-fixing nodules. Leguminous trees have been estimated to annually fix about 40-580 kg of N per ha, compared to 15-210 kg per ha for grain legumes (Fownes and Anderson 1991).

2.5.2 Adaptation and adaptive attributes

Adaptation is defined as inherent modification in structures or functions that increase the probability of an organism surviving and reproducing in a particular environment (Kramer 1980). Adaptive responses to water availability include physiological and morphological changes affecting, for instance, plant structure, growth rate, water-use efficiency (WUE), tissue osmotic potential and stomatal conductance (Begg and Turner 1980, Li and Wang 2003). The extremes of dryland climates mainly determine the form of the physiological adaptations and ecological requirements of plants occurring in dryland areas. Stem and leaf structures, physiological control of transpiration and metabolic rates, water and food storage organs, and thorns are further examples of characteristics reflecting adaptation to drought. Such specializations become less marked as aridity becomes moderate and less acute and the conditions for plant establishment and growth become more favourable (Turner and Kramer 1980, Ffolliott et al. 2002, Chaves et al. 2003).

2.5.3 Water use efficiency

Water use efficiency (WUE) can be defined as the ratio of biomass yield to evapotranspiration, or net photosynthesis to transpiration, or carbon gained per unit of water lost to transpiration (Cowan 1982). It is an important index of water relations, and a high WUE is usually considered beneficial in water-limited environments. "Water-wasting trees" are trees with a high degree of transpiration and a relatively low photosynthetic rate. Alternatively, as the ratio of dry matter accumulation and water consumption (B/W) is determined over a season, plants can achieve a high WUE either through high net photosynthesis rate while growing, or low transpiration rate, or both. Both processes are at least partially regulated by stomatal conductance (Cowan 1982).

Many authors have suggested that two types of water-use behaviour are operational in woody plants. A prodigal water use behaviour is beneficial in conditions where the water supply is interrupted for short periods only and where there is little danger of serious desiccation despite rapid water use; it enables the plant to grow quickly. In contrast, a conservative water use behaviour is beneficial in conditions where a long dry period prevails under which a plant uses the available water efficiently, leading to availability of soil water for use later during the dry season (e.g. Li and Wang 2003).

Climate change has now become a serious issue of the world's attention. It refers to shifts in climate occurring because of natural processes and human intervention, e.g. through land-use changes and increased carbon dioxide in the atmosphere (Wigley 1999). Scientific consensus today has suggested that the relative contribution of anthropogenic factors to the change in natural climate is significant (Hare 1993, Wigley 1999).

An increase in water-use efficiency paralleling the trend of CO_2 concentration increase in the atmosphere, commonly found in trees, might also increase the transpiration efficiency in dryland acacias (cf. Luukkanen 1991). This would allow dryland trees to grow rapidly and act as an effective carbon sink for the anthropogenic CO_2 even during the anticipated global climate change (Feng 1999, Koskela et al. 2000).

2.6 Dry-matter production

The production rate of single plants can be given in terms of the net assimilation rate (NAR) or the relative growth rate (RGR). The magnitudes of the highest possible and average net assimilation rate depend mainly on the morphological and physiological constitution of the plant. Similarly to the photosynthesis rate, dry-matter production exhibits a temperature optimum, and both a water deficit and an inadequate or unbalanced provision of nutrients can reduce the production of dry matter (Larcher 2003).

2.7 Nutrient and organic matter accumulation

2.7.1 Nutrient cycling

The concepts and practices of soil amelioration by trees have been extensively reviewed by several authors (Ingram 1990, Buresh and Tian 1998, Deans et al. 1999, Lal 2001, and many others). Many studies have postulated that soil improvement is linked to the growth of deep-rooted trees and shrubs which recycle plant nutrients from lower soil strata and build up the soil organic matter (Schroth 1995, Buresh and Tian 1998). Sprent (1995) suggested that the key to success of the Mimosoideae subfamily trees in dry/saline environments is more likely attributed to their deep roots than to their nitrogen fixation. The general vertical distributions of nutrients from shallowest to deepest ranked in the following order: $P > K > Ca > Mg > Na = Cl = SO_4$. Nutrients efficiently cycled by plants, such as P and K, were more concentrated in the topsoil (upper 20 cm layer) as compared to nutrients less limiting to plant growth, such as Na (Jobbagy and Jackson 2001).

Numerous studies have reported higher soil organic material (SOM) contents in topsoil under trees than in open areas (Breman and Kessler 1995, Young 1997, Lal 2002). Mordelet et al. (1993), for example, reported higher soil organic C under trees than in open grassland in a humid savanna in Ivory Coast. Trouve et al. (1994) found a progressive increase in SOM under *Eucalyptus* sp. and *Pinus caribaea* Morelet in plantations on sandy soil in the Congo, and Belsky et al. (1993) showed an accumulation of SOM at 0-15 cm depth under *Acacia tortilis* and *Adansonia digitata* on a savanna in Kenya. Kang (1997) reported that soil organic C at 0-15 cm depth after 5-year hedgerow intercropping with *Leucaena leucocephala* (Lam.) De Wit was 12.3 g kg^{-1} under the hedgerow and 9.4 g kg^{-1} between the hedgerows, as compared to 5.9 g kg^{-1} in the control without a hedgerow. In semi-arid ecosystems, soils under tree canopies evidently have greater levels of organic matter and nutrients such as Ca, K, Mg and P than those in open grassland systems (Belsky et al. 1993, Campbell et al. 1994).

Nutrient release from SOM is usually more dependent on the portion of the SOM in biologically active fractions than on the total amount of SOM. Trees can augment the inorganic soil N, N mineralization and the quantity of N in light-fraction SOM. Among six tree fallows of 2 and 3-year duration in Zambia, the inorganic N content and N mineralization were found to be higher in leaf litter of tree species with a low (lignin + polyphenol) to N ratio as compared to tree species with a high ratio (Barrios et al. 1997, Buresh and Tian 1998).

In Sudan, *A. senegal* occurs widely and is used to restore the soil fertility in sandy areas in traditional bush-fallow systems, but it has also been artificially established to restore the soil fertility in the large-scale rain-fed sorghum production area of the Blue Nile region (El Houri 1986). Singh and Singh (1993) also pointed out that short-lived components such as annual herbs and grasses have a major role in the aspects of productivity and nutrient cycling in dry tropical forests.

Research in western Kenya has shown that fast-growing trees with a high N demand take up subsoil nitrate accumulated below the rooting depth of annual crops. *Sesbania sesban* (L.) Merr. was also more effective than a natural grass fallow in extracting subsoil water, suggesting lower leaching loss of nutrients under *S. sesban* than under natural uncultivated fallows (Buresh and Tian 1998).

Trees can increase the availability of nutrients through increased release of nutrients from soil organic matter (SOM) and recycled organic residues. Some agroforestry trees (e.g. *Leucaena leucocephala*, *Sesbania sesban*, *Acacia* spp., *Gliricidia sepium*) have a potential to provide N in quantities sufficient to support moderate crop yields through (1) N inputs from biological N_2 fixation and retrieval of nitrate from deep soil layers and cycling of N from plant residues and manure, (2) retrieval of nutrients from below the rooting zone of crops, and (3) reduction in nutrient losses due to processes such as leaching and erosion (cf. Fig. 2). Cycling of P from organic material is normally insufficient to meet the P requirements of crops. Sustained crop production with agroforestry on P-deficient soils will frequently require external P inputs (Buresh and Tian 1998, Jobbagy and Jackson 2001).

Deep capture and uptake of nutrients

Trees having deep roots can potentially intercept and prevent nutrients from leaching down the soil profile and ‘capture’ nutrients accumulated in the subsoil below the rooting depth of annual crops (Van Noordwijk et al. 1996). Nutrients taken up by trees from below the rooting zone of annual crops will later return as an input when transferred to surface soil through leaf litter, roots, and pruning of tree leaves and branches (Schroth 1995). The lateral extension of tree roots can be significant, particularly in dryland areas (Breman and Kessler 1995). The lateral capture and uptake of nutrients from within the rooting zone of crops, nonetheless, represents a reallocation of nutrients within the soil-plant system rather than an input. Trees could also affect the restoration of the soil fauna, which is essential for SOM and plant residues decomposition (Buresh and Tian 1998).

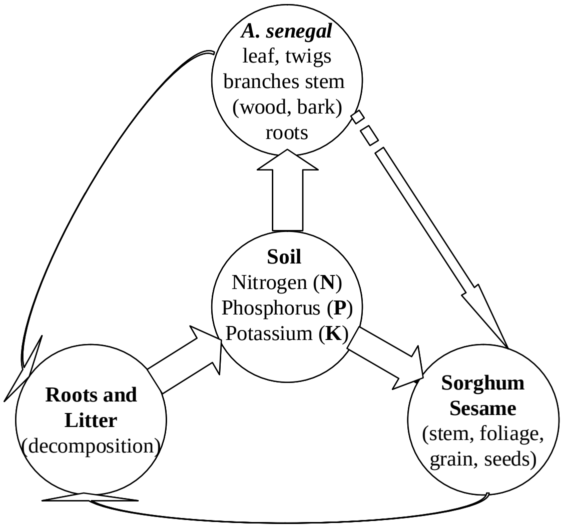

Fig. 2. Conceptual model for nutrient uptake, transport, and above-ground cycling through litter fall in *Acacia senegal* agroforestry systems.

Generally, tree roots can extend beyond the rooting depth of annual crops (Stone and Kalisz 1991, Torquebiau and Kwesiga 1996, Mekonnen et al. 1997, Ludwig et al. 2004), and the spatial distribution and temporal patterns of root growth vary among different tree species (Ruhigwa et al. 1992, Hauser 1993). The extent to which tree roots in deep soil layers contribute to the overall uptake of nutrients is, however, less clear and less frequently documented. In his critical review of the literature, Buresh (1995) concluded that the potential of trees to retrieve subsoil nutrients is generally greatest when (1) trees have deep rooting systems and a higher uptake of nutrients, (2) the surface soil experiences water and/or nutrient stress, and (3) significant reserves of plant-available nutrients or weatherable minerals occur in the subsoil. Larger capture of subsoil resources by roots would be anticipated for water and for mobile nutrients such as nitrate, than for less mobile nutrients such as P. There is consistently little potential of trees to capture P from beneath the rooting depth of crops (IAEA 1975), presumably because the plant-extractable P concentration is normally low in the subsoil (Breman and Kessler 1995).

2.7.2 Nitrogen dynamics

Nitrogen is the primary element that most often limits plant growth in many terrestrial ecosystems, and the competition between plants and microbes for this nutrient is powerful (Hodge et al. 2000). Most of the soil N occurs in organically bound forms, which need to be mineralized to simpler compounds such as ammonium or nitrate to be ready for uptake by plants. In reality, a small fraction of the total N (< 10% in most cases) may be mineralized during the short rotation of a fast-growing tree plantation (Miller 1995, Hawkins et al. 2000).

In mixed-species plantations under short rotation, the amount and time of N transfer from N_2-fixing trees to non-N_2-fixing trees are essential issues to be taken into account when attempting to develop optional nutrient management strategies. According to the limited information available mainly from trials in Southeast Asia, it emerges that the acacia species fix substantial amounts of N during the first few years of establishment and a significant amount of that N can be transferred to adjacent eucalypts, thereby ameliorating the growth and nutrition of the eucalypts. The postulated transfer of N from acacia to eucalypts during an early stage of plantation development is probably due to a below-ground turnover of roots and nodule senescence, since the above-ground litter decomposition is slight and contributes little to the overall N dynamics at this stage (Khanna 1998).

Green plants utilize inorganically bound nitrogen, that is, they are autotrophic with respect to nitrogen as well as to carbon. Nitrogen is taken up from the soil as nitrate or ammonium ions. Most plants can meet their nitrogen requirements with either NO_3^- or NH_4^+, as long as the pH in the space occupied by the roots is suitable. Like all ion absorption, that of inorganic nitrogen requires energy and is thus dependent on respiration; consequently, plants growing in cold, poorly aerated soils often suffer from nitrogen deficiency (Larcher 2003). Controlled fallow with nitrogen-fixing legumes and possibly with rock phosphate application are cited as key soil fertility restoration options (ICRAF 1996).

A. senegal, known for long as a nitrogen-fixing species, is important and has its significant effects in reclaiming degraded lands in the tropics through amelioration of soil properties, as also has been observed in Sudan (Alstad 1991, Njiti and Galiana 1996). Jewitt and Manton (1954, cited by Ardö and Olsson 2003) compared an exhausted site that had been under continuous cultivation for 30 years with an area taken out of cultivation and allowed to regenerate as a gum forest (*A. senegal*). Organic N, exchangeable calcium and pH were much higher in the gum forest. The N concentration of the upper 15 cm soil stratum was 0.019% in the gum forest and 0.009% on the exhausted site. After clearing of the gum forest, the two sites were cultivated with sesame and groundnuts (*Arachis hypogaea* L.). The sesame yield was five times higher and the groundnut yield one and half times higher for the cleared forest as compared to the exhausted site.

2.7.3 Phosphorus dynamics

Phosphorus (P) is the most limiting nutrient for plants in many areas of the tropics. It is an important plant macronutrient, which constitutes 0.2% of a plant's dry weight. Low availability of P in bulk soil restricts plant uptake (Harrier and Watson 2003). Nonetheless, there have been few studies that have assessed the extent and effectiveness of tree root exudates in P mobilization for crop uptake under field conditions. If trees in an agroforestry system exhibit P-mobilizing adaptations, then these species would acquire P from sources that are not in competition with the crop. Moreover, if the rhizospheres of tree and crop roots overlap, and if they do not exclude each other, there is a potential for the crop to benefit from the increased P availability in tree rhizosphere soil (Van Noordwijk et al. 1999).

The most important modifications to low P availability that trees may exhibit, and which may profit the crops, are related to mobilization and hydrolysis of P in the rhizosphere through organic-anion exudation (Dinkelaker et al. 1989, Radersma and Grierson 2004), increased phosphate activity (Mc Lachlan 1980, Chen et al. 2003), iron reduction (Gardner et al. 1983, Grierson and Attiwill 1989), pH increase or decrease (Hinsinger 2001), or rhizosphere microbial effects (Bowen and Rovira 1999, Hawkins et al. 2000).

The cycling of P from organic materials is normally insufficient to meet the P requirements of crops. Sustained crop production with agroforestry on P-deficient soils will significantly require external P input (Buresh and Tian 1998, Khanna 1998). Most studies have found little or no benefit of trees on extractable inorganic soil P. Siaw et al. (1991) and Weil and Mughogho (1993) found no significant difference in available soil P under hedgerow intercropping with *L. leucocephala* and *Dactyladenia barteri* as compared to a control without trees or with *Faidherbia albida*. Some studies have reported a decrease in extractable inorganic P under trees, probably because of sequestration of P in tree biomass (Haggar et al. 1991). Kang et al. (1997) found a slight favourable effect of 4-year old trees (*Senna siamea*, *L. leucocephala*, *Acacia leptocarpa* and *Acacia auriculiformis*) on extractable P at 0-15 cm soil depth during the fallow phase.

Trees might have access to soil P from unstable pools inaccessible or exploited by crops (Hands et al. 1995). Many tree species in the tropics form associations with ectomycorrhizal (ECM) or vesicular-arbuscular mycorrhizal (VAM) fungi (Mason and Wilson 1994, Chen et al. 2003). This association may enhance P uptake by the tree through the extensive proliferation of mycorrhizal hyphae, which results in the effective exploration of large soil volume. Mycorrhizal fungi can also contribute to the synthesis and production of phosphatase enzyme and organic acids that ameliorate and upgrade the availability of soil P (Bolan 1991, Handreck 1997).

Buresh et al. (1997) reported in western Kenya that rotation of unfertilized maize with *Sesbania sesban* rather than continuous maize cropping could to a small degree increase the availability of P. The *S. sesban* fallow also increased the maize yield on this P-deficient soil, but it did not exclude P deficiency in subsequent maize crops. The balance of P is mainly a consequence of adsorption and precipitation reactions with sesquioxides (e.g. Al_2O_3/ Fe_2O_3) rather than low amounts of total P (Sanchez 1976, Hue 1991). Likewise, a main challenge of agroforestry research is to identify species that are able to transform unavailable P into forms that may be utilized by the crop, through nutrient cycling or by direct root effects; in the end, that will result in improved crop performance and productivity.

It is postulated that increased exudation activity of organic acids in *A. senegal* tree roots may have a role in increasing hydrolysis and solubility of organic P and then the availability of organic P for microbial interactions in the rhizosphere. This may also be to some extent responsible for enhancing the mineralization of organic P.

2.7.4 Potassium dynamics

The total amount of potassium (K) in soils varies broadly from less than 0.01% to about 4%, and is usually about 1%. Clays may contain 2 to 4% K. The direct source of K for crops is that in the soil solution. Its availability to a plant mainly depends on the K^+ ion concentration close to the root zone, on the rate at which K^+ ions are transported through the soil solution to the root surface, on the replenishment of the solution by desorption from exchange sites on the soil colloids, and on the level to which the plant roots ramify through the soil (Wild 1988).

Deans et al. (1999), working with *A. senegal* agroforestry in Senegal, showed that the increase of N and K in surface soil as plantations aged could be predictable by multiple regression equations in which plantation age and inter-tree spacing were used as variables. The accumulation of N in 15 years of fallow period would provide good sorghum yields for at least four successive cropping seasons. Accordingly, the amounts of K in trees exceeded those in the upper soil strata, suggesting that harvesting of trees poses a greater threat to the site K budget as compared to the site N budget, and harvesting of tree fruits and leaves for fodder pose a heavier risk to site fertility than removal of wood at the end of the rotations.

The central reasons for adoption and practicing of agroforestry systems in areas where commercial fertilizers are expensive or even unavailable is the inherent capacity of such systems to recover, recycle, and utilise nutrients. This is often linked to mechanisms associated with woody perennial species. Agroforestry systems could be profitable if established directly after forest removal. Under conditions of degraded lands, a number of years are required for soil recovery. However, for this reason, farmers with limited capital and poor soils may require subsides and support to establish agroforestry systems (Montagnini et al. 2000).

2.8 Plant nitrogen isotope composition

The forms of nitrogen absorbed by plants can have different isotope compositions, and many studies now routinely measure foliar $\delta^{15}N$ in an attempt to understand differences in patterns of nitrogen use among co-occurring species. Many studies assume that ^{15}N at natural abundance levels acts as a tracer (Boddey et al. 2000), i.e. the isotope ratio of source nitrogen is preserved during nitrogen absorption, assimilation and translocation, and that the $\delta^{15}N$ of leaf tissue reflects that of the nitrogen source in the soil.

Few studies have addressed the genetic variation in physiological traits that could cause differences in whole plant and foliar $\delta^{15}N$ (Evans 2001). Legumes obtain their N requirements from two major sources: from the soil and through symbiotic N_2 fixation. These two N sources often differ in ^{15}N abundance, whereby an N-fixing plant, which depends on both soil N and symbiotic N_2 fixation, is less abundant in ^{15}N than a non-N_2-fixing plant grown at the same site (Shearer and Kohl 1986, Danso et al. 1993, Handley and Scrimgeour 1997, Evans 2001). Plants dependent on soil N have more positive $\delta^{15}N$ values that are close to those of soil nitrogen. In N-fixing plants, significant amounts of N are derived from the atmosphere and therefore dilute the $\delta^{15}N$ concentration derived from the soil.

There is relatively little information on the genetic variation in N_2 fixation by herbaceous legumes, and even fewer measurements have been made with trees (for *Gliricidia sepium*, cf. Liyanage et al. 1994). Many authors have shown a strong relationship between precipitation and ^{15}N. These suggest that the annual rainfall may be an important component controlling ecosystem nitrogen cycling (Austin and Vitousek 1998, Austin and Sala 1999).

2.9 Carbon isotope composition

Stable carbon isotope ratios are measured using an isotope ratio mass spectrometer, which measures the ratio between different isotopes in a sample and compares this with a standard. In principle, one can measure the absolute abundance of an isotope within a sample; however, the total variation is naturally quite small and subject to errors caused by sample heterogeneity, daily fluctuations within the mass spectrometer and by sample preparation procedure (Lajtha and Michener 1994). Therefore, in practice, the isotope ratio of a sample (R_{sample}) is compared to a standard (R_{standard}), so that any fluctuations will be reflected evenly both in the standard and in the sample. R is expressed as the ratio of a heavy to a light isotope. The differences (δ) in ratios have units of per mill (‰):

$$\delta^{13}C = \left\{ \frac{R_{sample}}{R_{s\tan dard}} - 1 \right\} \times 1000 \tag{1}$$

Ecologists are much concerned with the stable isotopes of carbon ($^{13}C/^{12}C$), nitrogen ($^{15}N/^{14}N$), sulphur ($^{34}S/^{32}S$), oxygen ($^{18}O/^{16}O$) and hydrogen ($^{2}H/^{1}H$). In this study, we are primarily concerned with the first two pairs of isotopes. Common thought is that samples containing more of the heavy isotope are referred to as 'enriched' or are 'heavier' than other samples. Those that contain less of the heavy isotope are 'depleted' and are 'lighter' than other samples (Chaves et al. 2003). Many chemical and physical processes have a significant isotopic fractionation, which generally refers to an enrichment or depletion of the heavy isotope. For example, plants contain less ^{13}C than atmospheric CO_2, because processes involved in both diffusion of CO_2 and enzymatic reactions discriminate against the heavier $^{13}CO_2$.

Isotopes and plant water-use efficiency

The most ordinary ecological use of carbon isotope ratios at natural abundance levels is as an indication of photosynthetic WUE in C_3 species. The use of $\delta^{13}C$ analysis to estimate long-term WUE has been subjected to thorough reviewing and is becoming almost a routine (Ehleringer and Osmond 1989, Farquhar et al. 1989, Ehleringer 1991, Ehleringer et al. 1993). A common application of isotope ratios has been for screening cultivars of dryland crop and rangeland grass species. The isotope data have corresponded well with various other methods of estimating WUE, and the results have been remarkably consistent across altering environments (Ehleringer et al. 1990, Read and Farquhar 1991).

Reported heritability values in WUE are often high (Hubick et al. 1988, Hall et al. 1990, Ehdaie et al. 1991), signifying that WUE is a trait for which breeding programmes can be readily designed. Research on carbon isotope ratios in natural ecosystems has focused on WUE in desert ecosystems or across gradients of water availability in mesic systems. Comstock and Ehleringer (1988) compared WUE in desert species that had photosynthetic stems as well as leaves, and established that $\delta^{13}C$ values were more positive, and thus WUE values higher, in stem than in leaf tissue. Comparing different species within a habitat, Smedley et al. (1991) found that short-lived annuals or herbaceous species had significantly lower values than long-lived perennial species; they reported that $\delta^{13}C$ incorporates physiological processes over time and enables seasonal variation in processes such as WUE to be evaluated.

Species active during wetter, more favourable months discriminate against ^{13}C more than do species that persist over dry seasons, indicating a higher WUE in the more drought-tolerant species. A comparison of plants over a wider environmental gradient for their $\delta^{13}C$ showed that those from drier conditions had more positive $\delta^{13}C$ values than those originating from wetter areas. Similarly, foliar $\delta^{13}C$ was more positive during a dry year than a wet year (Garten and Taylor 1992). In *Acer negundo* L. it has been reported that during wet years female trees display higher growth rates and lower carbon isotope ratios, which indicates their less conservative water use as compared to males (Ward et al. 2002).

Sharp differences in water use and carbon gain strategies among plants in a habitat with environmental heterogeneity have been observed. Superior plants with lower discrimination values indicate decreased ratios between the inter-cellular and atmospheric CO_2 concentrations that appear to result from a decrease of stomatal conductance following a drop in water availability (Sandquist and Ehleringer 2003). Clay et al. (2003) stated that stable isotopic $\delta^{13}C$ is helpful in evaluation of the factors that determine yield variability in wheat, corn and soybean. A negative value indicates that a sample has a lower $^{13}C/^{12}C$ ratio than the standard, PDB (Pee Dee Belemnite). WUE and leaf $\delta^{13}C$ are negatively related with Ci/Ca, the proportion of leaf intercellular and ambient CO_2 concentrations, and thus dependent on factors that influence stomatal conductance and leaf photosynthetic rate. WUE and $\delta^{13}C$ differ with soil and atmospheric moisture conditions (Farquhar et al. 1989). However, Read and Farquhar (1991) found that $\delta^{13}C$ in species of the genus *Nothofagus* was inversely related to the rainfall at the site of origin. $\delta\ ^{13}C$ measured in a common environment with sufficient resources is the most feasible measure of the genetic (or adaptive) value for WUE (cf. Condon and Richards 1992, Handley et al. 1994).

Selection of plants for higher transpiration efficiency by measuring their carbon isotope discrimination has been recommended (Wright et al. 1993, Hall et al. 1994, Lu et al. 1996). It may also be a hopeful approach in tree breeding, because changes in carbon isotope discrimination can be independent of shifts in root-to shoot allocation (Zhang et al. 1996). The selection for trees with low $\delta^{13}C$ and, therefore, high transpiration efficiency, has the potential to increase total tree biomass growth in water-limited arid environments, such as those occurring in the Blue Nile area of the Sudan.

Previous studies (e.g. Devitt et al. 1997) have reported that average leaf WUE values in live oak (*Quercus virginiana* Mill.) and tall fescue (*Festuca arundinacea* Schreb.) were correlated with average leaf carbon isotope ratios, and in tall fescue the leaf WUE increased as the leaf carbon isotope ratio become more negative. It was verified that leaf carbon isotope ratios could be used as a method of screening for plant response towards low water-use. However, plant water-use efficiency is a complex function of the CO_2 concentration of the atmosphere. It can increase, remain constant, or decrease with an increase of the atmospheric CO_2 concentration (Feng and Epstein (1995).

Usually, there is a strong relationship between δ ^{13}C and modelled soil water availability or transpiration (Dupouey et al. 1993, McNulty and Swank 1995, Walcroft et al. 1997). Accordingly, δ ^{13}C may well be a useful indicator of drought stress, but only in seasonally dry climates (P/E< 1), where the variation in other environmental factors remains unchanged. Likewise, a more drought-tolerant tree species, for instance *Pinus pinaster* Aiton, can be inefficient in the use of water (Warren et al. 2001).

It can be concluded that high transpiration efficiency (dry matter produced per unit of water transpired) is a useful trait for plants adapted to dry regions. Genetic variation in δ ^{13}C of different woody plant species has been linked to the distribution of genotypes across gradients in air humidity and soil water availability (e.g. Pennington et al. 1999). Earlier studies have assessed the genetic variability of δ^{13}C and nutrient concentrations in woody plant species and revealed a high degree of variation between the species studied (Prasolova et al. 2001).

3. MATERIAL AND METHODS

3.1 Research site

The research site was located in the Blue Nile State near Ed Damazin town (34° 23′, 11° 47′, 470 m above sea level). The climate at the trial site is semi-arid with a mean annual rainfall (May-October) of 736 mm. The mean annual temperature is 28.1 ºC, and the length of the growing season for main agricultural crops is 82 days. The soil consists of dark cracking clay (Vertisol) which extends to at least 15 m in depth. The natural vegetation is woodland savanna dominated by *Acacia seyal, A. polyacantha* Willd. *A. senegal*, *Balanites aegyptiaca* (L.) Del., *Combretum* spp., and *Dichrostachys cinerea* (L.) Wight & Arn. as characteristic tree species (El Amin 1990).

The site was first cleared of trees shrubs and grass, and then deep-ploughed with a chisel plough, followed twice by a wide level disc plough.

3.2 Experimental design

3.2.1 Effect of **Acacia senegal** *on two field crops*

Seeds of *A. senegal* originating from Bout (local provenance) were directly sown on agricultural land on 20 July 1999 at a spacing of 5 x 5 m (400 trees ha^{-1}) and 10 x 10 m (100 trees ha^{-1}) Simultaneously, agricultural crops were sown between the acacia trees. Sorghum 'Wad Ahmed' variety was sown at 0.75 m spacing between rows and 0.3-0.5 m within rows, and sesame variety 'Kenana 2' at 0.75 m spacing between rows and

0.2-0.3 m within rows. This intercropping with sorghum and sesame was repeated annually between 1999 and 2002 in a rotational manner. Pure crops and sole *A. senegal* stands were also established using the same spacings, so as to provide control treatments; plot size was 30 x 30 m. Weeding was carried out annually as required during the growing season (Study **I**). No fertilizers were applied. Trees were managed annually by removing the lower branches, and the first systematic pruning was applied when trees were three years old. Growth variables indicating height (H), basal diameter (BD) and crown diameter (CD), were measured annually at the end of the growing season. Trees were tapped for gum arabic using the traditional axe for the first time when they were three and a half years old (Studies **I**, **IV**).

Annual crops in the experimental plots were harvested at physiological maturity. Small plots (6×6 m, representing 4% of the plot area for crop harvest) were laid out at the centre of each plot. Heads were harvested, sun-dried and threshed, and later the grain and seed yields were calculated (in kg ha^{-1}); this was done annually. About ten plants were randomly selected from these sample plots for measurements of plant height, the number of tillers in sorghum, and, in sesame the number of branches and number of capsules.

The experimental design used was a randomized complete block design (RCBD) with four replications (Studies **I**, **II**). The treatments were as follows: *A. senegal* 5 x 5 m/sorghum (Sg5), *A. senegal* 10 x 10 m/sorghum (Sg10), *A. senegal* 5 x 5 m /sesame (Se5), *A. senegal* 10 x 10 m/sesame (Se10), Sorghum (SgC), Sesame (SeC), *A. senegal* 5 x 5 m (C5), and *A. senegal* 10 x 10 m (C10).

3.2.2 Physical soil analysis and soil water content

At the establishment of the field trials in 1999, soil samples were taken from different soil depths (0-25, 25-50, 50-75 cm) for complete soil analysis in the Land and Water Research Centre, ARC, Wad Medani, Sudan (Table 1). Soil water content was determined gravimetrically and with neutron probe (Model 4300 depth moisture gauge, type Troxler, USA). Pits were dug using metal cores (Eijkel Kamp, Giesbeek), and aluminium access tubes were installed to 1.2 m soil depth. Tubes were installed at 0.3 m distance from the nearest tree in the centre of the plots. Measurements were taken during the morning for 0-25 cm, 25-50 cm and 50-75 cm depth, at different crop stages (early, mid, and late); they required about one hour to finish. Neutron probe counts were converted to soil water content (mm) based on a calibration performed using soil water content samples. Initial and late soil bulk densities for the same three depths were determined by the cylinder method; undisturbed soil samples were collected by means of metal core sampling cylinders of known volume and then oven dried at 105°C for 48 hours. The oven-dried weight of the soil sample was divided by the volume of the cylinder to obtain the bulk density, expressed as g cm^{-3} (Mg m^{-3}) (Blake and Hartge 1986). The rainfall at the site was also recorded for the whole period of the study (1999-2003) using a rain gauge (Fig. 3; Studies **I**, **II**).

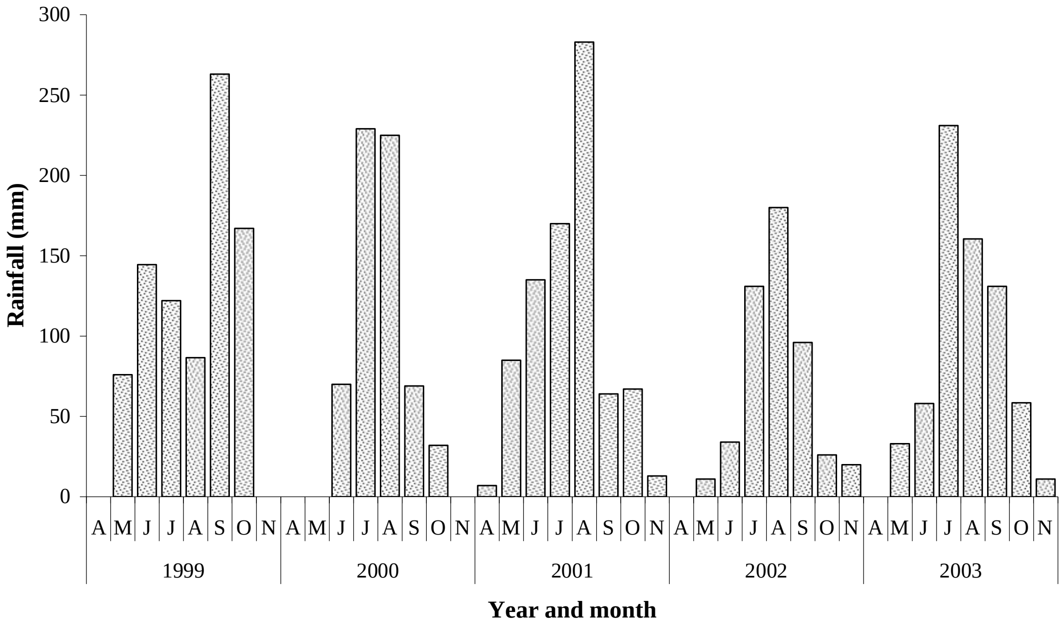

Fig. 3. Monthly rainfall during the growing season at the experimental site in the Blue Nile region over the study period 1999-2002.

3.2.3 Provenance testing

Nursery stage (Study **III**)

Seeds of eight *A. senegal* provenances, namely Bout (BO), Mazmoom (MZ), Gedaref (GE), Domokeya (DO), Nabag (NA), Saata (SA), Rahad (RH), and Semaih (SE), were collected from different geographical regions in the gum belt of the Sudan; the first three were collected from the clay plain and the latter five from the sand plain (Fig. 1, Table 1, Studies **III**, **IV** and **V**). These provenances were representative of wide natural ecological and geographical distribution with contrasting environmental conditions, corresponding to the elite production range of the species through the gum belt. The seeds were sown in the nursery in 10 x 20 cm polyethylene bags filled with a mixture of silt and sand in 2:1 ratio by volume, on 1 April 1999. Flood irrigation was used over the whole period. Data on seedlings growth parameters and biomass production were collected regularly at three-week intervals.

Field stage (Studies **III-IV**)

Seventeen weeks after sowing, the seedlings representing the different provenances were transported to the field and planted on 29 July 1999, at 3 x 3 m spacing in plots of 27 x 27 m, giving 100 trees per plot (1111 trees ha^{-1}); following a randomised complete block design with four replications. The same layout of the trial as used in the nursery was maintained in the field. The site was hand-weeded as required during the first growing season. Later, strip weeding was performed annually for the whole experimental period.

3.3 Plant and soil samples

Plant samples from sesame and sorghum (complete plant) were collected from all treatments and taken for nutrient analysis (Study **I**). Likewise, composite samples of tree leaves plus twigs were also collected (three samples of each component were taken from the upper, middle and lower plant parts and mixed together to form a composite sample).

A tree from each treatment plot was selected from the inner ones, cut at the ground level and separated into stem, branches, leaves and roots. Samples from each part were taken for analyses (5 replicates). The water content (WC) for trees were estimated by oven-drying subsamples at 70 ^{o}C to constant weight. The biomass of tree parts was corrected accordingly to obtain the dry weight of each part in kg. Nitrogen, phosphorus, potassium and organic carbon were determined every year at the end of the cropping season.

Soil samples were taken from the middle of the experimental plots by augering at crop harvest to depths of 0-25, 25-50, 50-75 and 100 cm. Composite soil samples from the four depths were taken annually for nutrient analysis in all treatments (described in details in Study **I**).

3.4 Nutrients analyses

The chemical composition of the plant tissue (trees and crops; Study **I**) was determined after oven drying at 70 ^{o}C for 24 hours to a constant weight and grinding in a Wiley mill with stainless steel points to pass a 40-mesh screen. Total nitrogen and C in the plant tissues and soil were determined by dry combustion on a LECO® CNS-1000

Carbon, Sulphur and Nitrogen Analyser. Phosphorus and potassium were extracted by wet aching of 1g plant material in acid mixture consisting of 10 ml H_2SO_4, 3 ml HNO_3 and 1 ml $HClO_4$ following the methods of Olsen and Sommers (1982) and Allen (1989). Phosphorus was determined from the extract using a spectrophotometer and potassium using a flame photometer (described in detail in Study **I**).

3.5 Nutrient uptake

Soil volume of the uppermost 25 cm soil slice per hectare was multiplied by the respective average bulk density to obtain its weight; this weight was in turn multiplied by corresponding nutrient concentration (N, P, K and C) to obtain the amount of soil nutrients content in kg per hectare. The nutrient contents of the trees were computed by multiplying the dry weight of each part by its respective mean nutrient concentration, and then summed to obtain the total standing amount of nutrients in the above-ground tree biomass.

3.6 Discrimination measurements of carbon and nitrogen isotopes

Plant samples (consisting of current fully expanded leaves including petioles, twigs and small branches) were collected from about ten trees in each replication in all *Acacia* provenances annually at the end of the rainy season when trees were at maximum foliage. Leaves from the upper, middle and lower plant parts were pooled to form a single sample (Studies **IV, V**). Samples were dried at 70 °C. Values of $\delta^{13}C$ were measured using a mass spectrometer (Finnigan Delta + XL, Thermofinnigan, Bremen, Germany), connected on-line to an elemental analyser type NC 2500 (CE Instruments, Milan, Italy) by an interface ConFlow III (Thermofinnigan, Bremen, Germany).

The carbon isotope results were given as delta values in per mil (‰) deviation from the V-PDB (Pee Dee Belemnite), the usual standard against which all measurements are referred, namely CO_2 obtained from the carbonate shell of a Cretaceous mollusc, *Belemnitella americana* from the Pee Dee Formation in South Carolina (Craig 1957, cited by Feng 1999), as described in detail in Study **IV**:

$$\delta^{13}C = \left\{ \frac{R_{sample}}{R_{s\tan dard}} - 1 \right\} \times 1000 \qquad (1)$$

where R is the carbon isotope ratio $^{13}C/^{12}C$ for sample and standard, respectively. The error for the $\delta\,^{13}C$ values was estimated to be ± 0.2 ‰ or less.

3.7 Estimates of N_2 fixation

Plant samples collected as described above were used. Trees of *Balanites aegyptiaca* growing naturally at the planting site were used as non-N_2-fixing reference material. Ten individual samples from the reference tree species were similarly collected and pooled.

The natural abundance ($\delta^{15}N$) method (Shearer and Kohl 1986, Högberg 1997, Boddey et al. 2000) was used, since it is suitable for measuring N_2 fixation in natural ecosystems (Kurdali et al. 1993, Yoneyama et al. 1993). These measurements, made with ^{15}N, were considered more reliable than the acetylene reduction assay. Plant $\delta^{15}N$ reflects the potentially variable $\delta^{15}N$ values of external N sources and $^{15}N/^{14}N$ fractions, which occur during the assimilation, transport and loss of N.

The plant tissue was oven-dried at 70 ^{0}C to constant weight and milled into fine powder. Subsamples of ground material were finely reground in a rotating ball bearing mill. Analysis of powdered samples was conducted at the Radio Carbon Dating Laboratory of the University of Helsinki, Finland. The $^{15}N/^{14}N$ isotope ratio was determined by a mass spectrometer (Finnegan Delta + Advantage, Thermofinnigan, Bremen, Germany) described in detail in Study **V**. The deviation of the sample $^{15}N/^{14}N$ ratio from that of the atmosphere ($\delta\ ^{15}N$) was calculated as follows:

$$\delta^{15}N = \left\{ \frac{R_{sample}}{R_{standard}} - 1 \right\} \times 1000 \qquad (2)$$

3.8 Leaf biomass estimates

To estimate the total leaf biomass in *A. senegal*, destructive sampling of trees was used to develop an allometric equation based on the tree basal diameter (BD) at ground level (Study **V**). A total of 30 trees were cut at the ground level, and the dry weights of leaves, stems and branches were determined. A regression equation was derived based on (BD) as the independent variable**:**

$$Y = -0.8019 + 0.31272BD,\ R^2 = 0.76,\ (P < 0.0001) \qquad (3)$$

3.9 Data analysis

Analysis of variance was performed, whenever needed, using the General Linear Model (GLM) procedure of the statistical software SPSS 10 for Windows 2000. Regression analysis was done using the JMP 3.2 statistical package (SAS 1997). Tukey's HSD test and Student t-tests (Steel and Torrie 1980) were performed to determine the possible differences between the means. Significance levels, if not otherwise mentioned, were $P < 0.05$.

Table 1. Soil characteristics of the study site in the Blue Nile region, Sudan.

Parameter	Soil depth		
	0-25 cm	25-50 cm	50-75 cm
Particle size distribution			
Coarse sand (%)	34	32	40
Fine sand (%)	7	10	10
Silt (%)	19	14	12
Clay (%)	40	41	38
Bulk density (g cm^{-3})	1.4	1.6	1.64
$CaCO_3$ (%)	0.0	0.0	0.6
Exchangeable bases			
Na (cmol kg^{-1})	0.91	2.35	2.3
K (cmol kg^{-1})	0.48	0.38	0.43
CEC (cmol kg^{-1})	38	40	36
OC (%)	0.324	0.312	0.312
N (%)	0.024	0.022	0.021
C/N ratio	14	14	15
Available P (mg kg^{-1})	4.0	2.4	2.6
Total P (mg kg^{-1})	393.0	268.0	228.5
pH paste	7.2	7.5	7.7
EC (ds m^{-1})	0.46	0.50	0.70
SAR	2	2	3
ESP (%)	2	5	6
Soluble cations and anions meq L^{-1} (saturation extract)			
Na	1.8	2.4	3.7
Ca	1.5	1.5	2.5
Mg	0.5	0.5	0.5
Cl	1.4	1.8	3.4
CO_3	0.0	0.0	0.0
HCO_3	1.9	2.0	2.5

Particle size distribution: coarse sand 2 to 0.2 mm, fine sand 0.2 to 0.02 mm, silt 0.02 to 0.002 mm, and clay <0.002 mm. CEC = cation exchange capacity, EC = electrical conductivity, SAR = Sodium adsorption ratio, ESP = exchange sodium percentage.

4. RESULTS

4.1 Soil conditions

The soil at the experimental site consisted of dark cracking clay, representative of the Central Clay Plain of Sudan. This soil, because of its high montmorillonitic content, swells during the wet season and shrinks, forming deep cracks (> 1m deep), during the dry season. The infiltration rate is very slow (< 0.5 cm/hr), and the soil is thus highly prone to waterlogging. The soil is inherently deficient in nitrogen, available phosphorus and carbon (Table 1). The water-holding capacity is high and so is the permanent wilting point (45% and 21%, respectively), and therefore the available water content is about 24%.

The soil at the research site was also rich in bases but poor in N and organic matter. The soil was alkaline, with a pH value ranging between 7.2 and 7.7 in the topsoil layer (0-75 cm) (Table1).

4.2 Water use

Water use (WU), defined as the initial soil water content minus the final soil water content added with precipitation, was calculated for the whole system from the measured soil water content in all treatments. There were no significant differences in WU caused by types of intercropping, but highly significant ($P \leq 0.0001$) differences between years existed. Years 1999 and 2001 (i.e. the years with a high amount of annual rainfall) showed the highest water use, while the WU was very low in 2002 when the rainfall was exceptionally low (498 mm; Fig. 4).

4.3 Effect of *Acacia senegal* on crop yield (Studies **I, II**)

Yields of grain and straw of sorghum or sesame seeds and stalks showed no significant differences between different treatments compared to the control plots. The yield of sesame stalks, however, seemed to vary in the different treatments, but this variation was not significant (Table 2). Grain production in sorghum was significantly influenced by the variation in the annual rainfall between the years ($P = 0.02$). The highest yield of sorghum grain was obtained when sorghum was intercropped with *A. senegal* at the spacing of 5x5 m. The highest sorghum grain yield was realized during the first and second year (1999, 2000; 2.04 t ha^{-1} and 1.48 t ha^{-1}, respectively). Sesame seed and stalk production varied significantly during the different years of study (1999-2002). This obviously also reflects the sensitivity of sesame to excess water availability. The highest and lowest seed yields were observed in 1999 and 2001 (0.64 t ha^{-1} and 0.14 t ha^{-1}, $P \leq 0.0001$), respectively.

4.4 Effect of crops on trees

Tree biomass

Tree height (H), basal diameter (BD) and crown diameter (CD) were significantly ($P \leq 0.0001$) affected by the treatments; however, the crop type had no effect on tree growth parameters, although tree growth varied between the years (Fig. 5 d, e, f).

Intercropping increased the tree height at a spacing of 5 x 5m, relative to control trees grown without agricultural crops (Fig. 5 a). The tree height increased rapidly during the study period and thus showed significant variation between the years ($P \leq 0.0001$). Intercropping with sorghum at a spacing of 5 x 5 m produced the tallest trees, whereas trees grown at 10 x 10 m spacing and intercropped with sesame were the shortest (1.77 and 1.46 m, respectively).

The basal diameter (BD) of trees also varied significantly among the treatments ($P \leq 0.0001$). Similarly to tree height, the BD was largest in trees grown at the 5 x 5 m spacing intercropped with sorghum or sesame (6.24 and 6.03 cm) and smallest (5.08 cm) at the 10 x 10 m spacing intercropped with sesame (Fig. 5 c). Following the same pattern, the tree crown diameter was also significantly affected by the treatments ($P \leq 0.0001$). Trees grown at 5 x 5 m or 10 x 10 m spacing and intercropped with sesame produced the largest and the smallest tree crown diameters (2.63 m 2.14 m, respectively, Fig. 5 b).

4.5 Tree gum yield (Studies **I, IV**)

Trees were tapped for gum production for the first time when three and a half years old. Gum yield per tree showed no significant variation among different intercropping systems (Study **I**), but the gum production per hectare varied ($P < 0.0001$) due to the different tree densities used. Gum yields were 33.0 kg ha^{-1} and 7.0 kg ha^{-1} at the first round of tapping of trees 3.5 years old, grown in spacing of 5 x 5 m or 10 x 10 m, respectively. A significant positive correlation existed between the second or third picking of gum on the one hand and the total gum yield per tree on the other ($R^2 = 0.74$, $P < 0.0001$; $R^2 = 0.48$, $P = 0.0002$, respectively; Fig. 6 a, c). The data suggest that the second gum picking seems to be a decisive factor in gum production and could be used as an indicator for the prediction of the total gum yield.

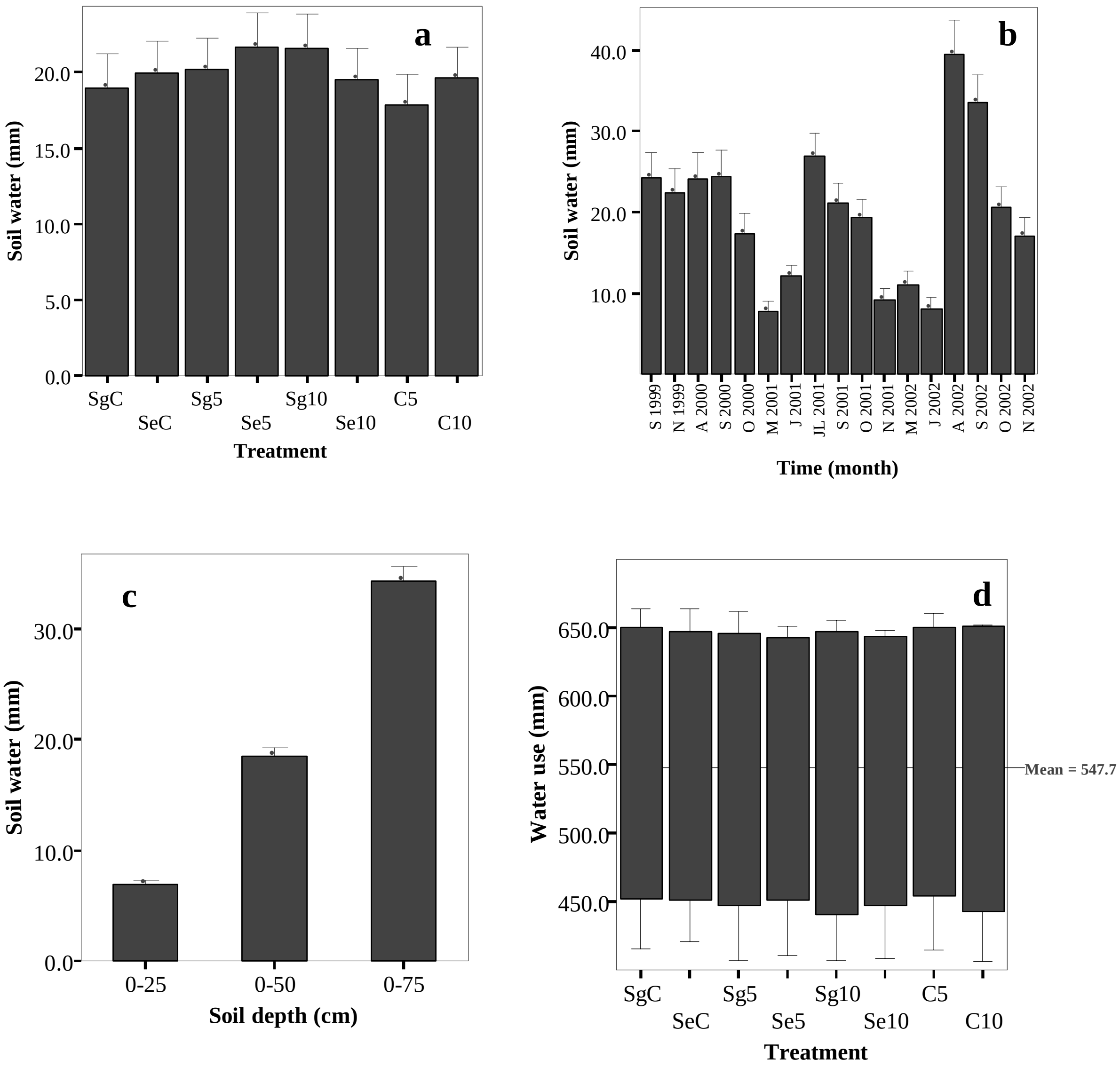

Fig. 4. Soil water content averaged over the profile as affected by different agroforestry systems (a), date of measurement (b) and soil depth (c), and the water use of *A. senegal* in different agroforestry systems (d). In (a) and (d) Sg = sorghum, Se = sesame, C = control, 5 = 5x5 m spacing, 10 = 10x10 m spacing. Trees were grown in the Blue Nile region, Sudan, during the study period from 1999 to 2002. Bars indicate standard errors.

Table 2. Sorghum and sesame yields in agroforestry systems in the Blue Nile region, Sudan in 1999-2002. Two spacings of *A. senegal* (5x5 m and 10x10 m) and the sole crop as a control were used. The annual rainfall at the site is also indicated.

Agroforestry system	Yield (t ha^{-1})									
	1999		2000		2001		2002		Average	
	Grain /seed	Stover /stalk	Grain /seed	Stover /stalk	Grain /seed	Stover /stalk	Grain /seed	Stover /stalk	Grain /seed	Stover /stalk
Sorghum										
5x5 m	1.68	5.01	1.74	3.33	1.39	4.20	1.00	3.71	1.45 ±0.17	4.06 ±0.36
10x10 m	1.30	4.48	2.10	4.12	1.45	4.63	1.64	4.46	1.62 ±0.17	4.42 ±0.12
Control	1.47	5.37	2.3	4.93	1.04	3.37	1.36	4.24	1.54 ±0.27	4.48 ±0.44
Sesame										
5x5 m	0.61	1.50	0.35	0.80	0.11	0.36	0.43	0.77	0.38 ±0.10	0.86 ±0.24
10x10 m	0.55	1.30	0.31	0.87	0.12	0.28	0.50	0.84	0.37 ±0.10	0.82 ±0.21
Control	0.76	1.90	0.30	0.74	0.20	0.49	0.40	0.71	0.42 ±0.12	0.96 ±0.32
Rainfall (mm)	859		625		824		498			

There were no differences in yield among treatments in a particular year ($P < 0.05$). Means and standard errors are indicated (n = 4).

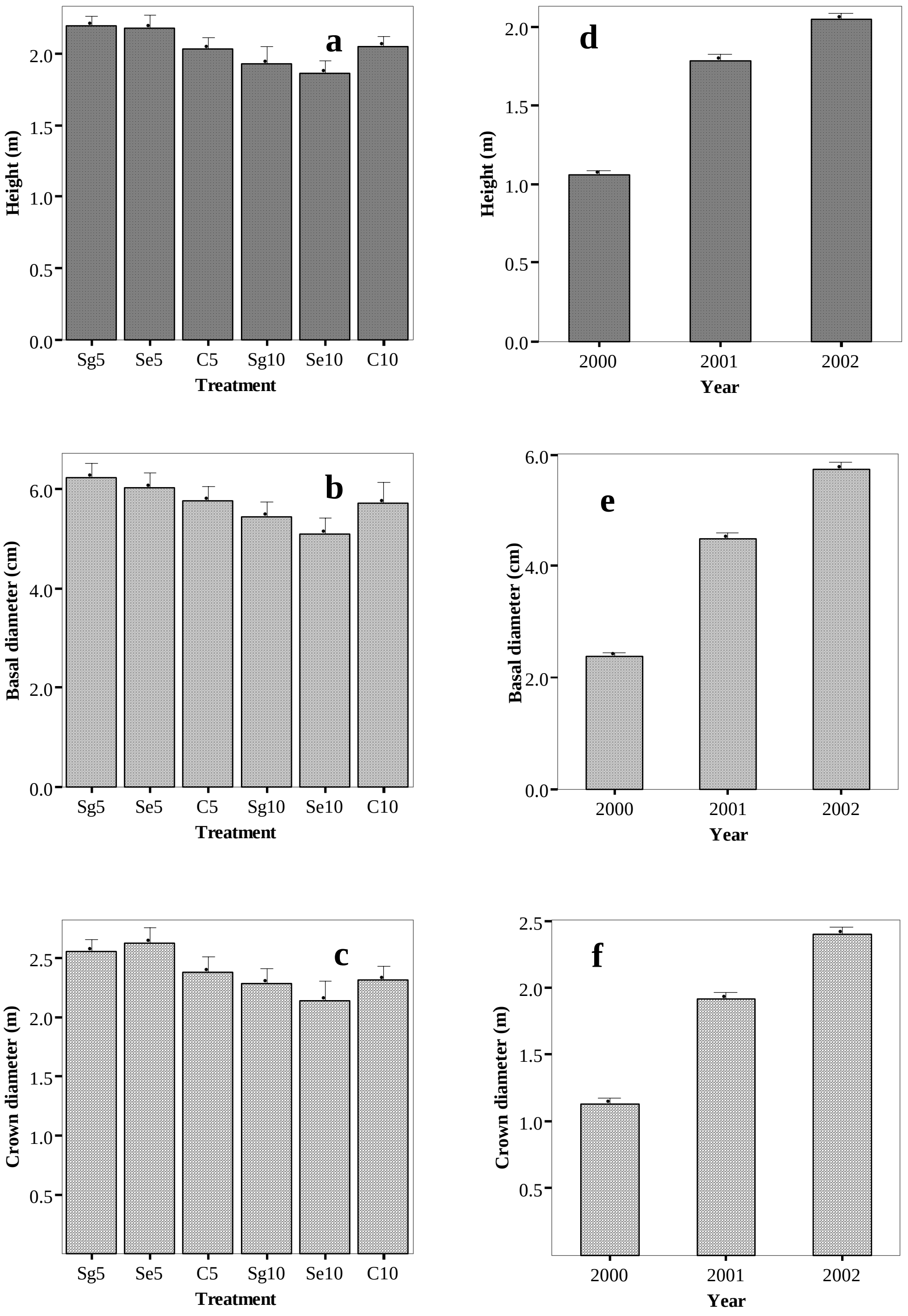

Fig. 5. Height (a), crown diameter (b) and basal diameter (c) of *Acacia senegal* trees grown in agroforestry systems and on average in three successive years (d, e, f). Sg = sorghum, Se = sesame, C = control (no crop), 5 = 5x5 m spacing, 10 = 10x10 m spacing. Bars indicate standard errors. Adopted from Study (**I**).

The gum yield of young trees showed no significant differences among provenances (Study **IV**), but clay provenances generally ranked higher compared to the sand provenances in gum yield per tree. As found in the agroforestry experiments, a significant positive relationship existed between the yield from the second or third picking of gum on the one hand, and the total gum yield per tree on the other ($P <$ 0.0001; $R^2 = 0.78, 0.31$, respectively; Fig. 6 b). As in the previous case, the data show that the second gum picking was the main contributor to total gum production and that it probably can be used as an indicator for the total gum yield. A strong negative relationship was observed between the per-tree gum yield and $\delta^{13}C$ ($P < 0.03$, $R^2 =$ 0.54, Fig. 6, Study **IV**). A positive relationship existed between soil water content and gum yield per tree ($P < 0.0001$, $R^2 = 0.47, 0.53, 0.52$, and 0.49) for soil depths 0-25, 25-50, 50-75, and 70-100 cm, respectively.

4.6 Nutrient content (Study **I**)

4.6.1 Nutrients amounts in the soil

Results for soil nutrient amount after four years of intercropping are presented in Fig. 7 a-c, (see also Fig. 4, Study **I**). The total soil organic carbon amount was not significantly affected by the agricultural crops. Therefore, the data for agroforestry systems having the same tree spacing were grouped together. The soil carbon content was however, highly affected by the year of observation ($F = 10.08$, $P < 0.0001$). Year 2001 with high rainfall (824 mm) showed the highest amount of soil organic carbon. This variation was also significant in relation to soil depth: the amount of carbon in the 0-25 cm stratum was greater than that for the other depths ($F = 4.12$, $P = 0.02$).

The total N in the soil did not vary significantly among treatments, but it tended to be slightly higher when trees were grown at 5 x 5 m spacing and intercropped with sesame (Fig. 7 b). Amount of N varied between years ($F = 6.29$, $P = 0.0006$), probably due to successive input from the trees by N_2 fixation and mineralization of organic matter. The total N amount was highest in the uppermost stratum and decreased successively with depth ($F = 4.84$, $P = 0.01$).

The amount of exchangeable K varied significantly between years and was highest in 2000 (0.53 ± 0.017%, $P < 0.0001$). No significant differences in K were observed in relation to treatments or soil depth. Amounts of exchangeable P also varied significantly between years, being highest in 2001 with its high annual rainfall, (4.42 ± 0.105%, $P < 0.0001$), followed by 2002.

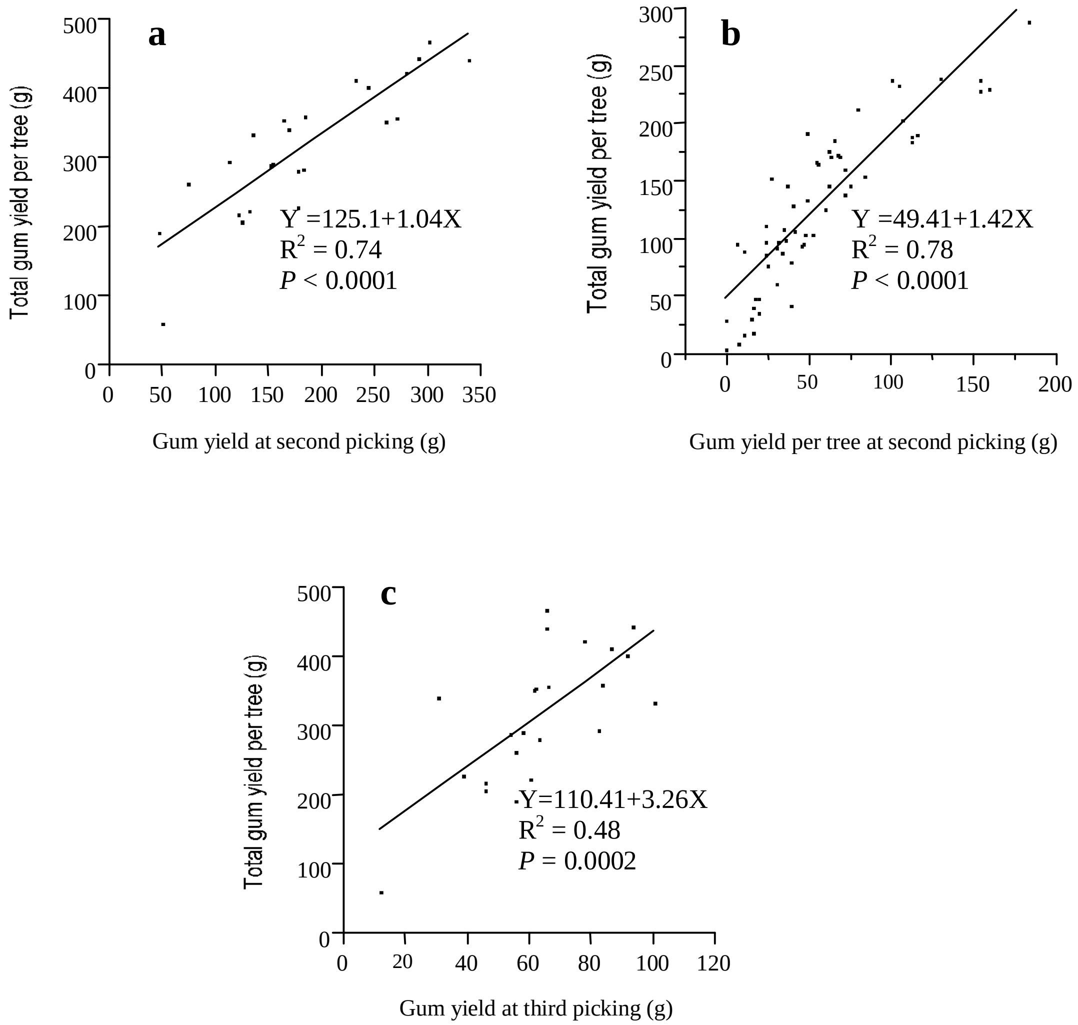

Fig. 6. Relationship between gum yield per tree at separate pickings and total gum yield per tree (a, c in agroforestry and b in provenance trial). Data were collected during two years (2002 and 2003; trees were three and four years old, respectively).

The C/N ratio was relatively low in 2002, which could be due to the effect of agricultural crops and an increase of N in the topsoil through N_2 fixation by trees (average decreases in the C/N ratios were 19.1%, 11.8% and 6.8% in the agroforestry, pure crop and sole *A. senegal* treatments, respectively). Soil exchangeable P showed no significant variation among treatments or soil depth, but in general P tended to decrease with an increasing soil depth and time (Fig. 7 c). The same trend was observed for total soil C.

4.6.2 Nutrient and C concentrations of trees

Concentrations of N, P, K and C in trees grown in the intercropping treatments were determined for samples of tree leaves and twigs collected annually after the end of the rainy season and before trees shed their leaves. Different tree parts (leaves, branches, stem and roots) were also analysed for sample trees cut at ground level at age four.

Significant differences between tree parts were found in the P and K values (Fig. 8 a-c). The concentration of P in tree leaves was highest in the leaves of sole or intercropped acacias, except for the treatment where *A. senegal* was intercropped with sorghum at a spacing of 5 x 5 m. No significant variation among treatments was observed in N or C. Highly significant differences were observed between years in the case of N, P, and C ($P \leq 0.0001$). Year 2002 resulted in the highest level of tree N; this could be because, as trees grew older, they accumulated more N in their total leaf mass. On the other hand, the same year showed the lowest P concentrations in tree leaves. This was a trend different from the one found in the other nutrients. A decrease in P could have been due to the ageing of trees; as they grew older, the P concentrations decreased or there was some P translocation to other tree parts.

The total C concentration in trees was high during the second year and low during the last year of observation. K showed no significant variation. The interaction between treatments and years was significant only for the K and C concentrations (F = 2.03, 2.19, $P \leq 0.048$ and $P \leq 0.03$, respectively). After four years of intercropping, the above-ground biomass of *A. senegal* (on average, for trees with 5 m or 10 m spacing) had accumulated N ca. 18 kg ha^{-1}, P 1.21 kg ha^{-1}, K 7.8 kg ha^{-1} and OC 972 kg ha^{-1} (Table 3).

4.6.3 Nutrient amount of crops (Study **I**)

In Study **I**, in agricultural crops, the N and C amounts varied among treatments (averages for N were 21.97 ± 2.8, 51.75 ± 2.51 kg ha^{-1}, and for C 598.9 ± 89.95, 2576.1 ± 106.53 kg ha^{-1} for sesame and sorghum, respectively). The N and C amounts were higher in sesame than in sorghum. No significant variation among treatments was observed in P or K (the averages were 2.46 ± 0.53 and 11.11 ± 1.14 for sesame, and 9.81 ± 1.5 and 46.6 ± 2.4 kg ha^{-1} for sorghum, respectively). However, the values varied considerably between years. N, P and K levels were higher in 2000 as compared to the other years. At the same time, the C amount in crops was low in that particular year and high during the rest of the period. The variation between years and the interaction among treatments and years were highly significant ($P \leq 0.0001$ for P and K; $P = 0.006$ for N, and $P \leq 0.05$ for C; Table 4).

4.7 Tree provenance variation (Studies **III, IV, V**)

Soil water

In the study of *Acacia senegal* provenance variation, significant ($P < 0.0001$) differences in soil water content at different soil depths were recorded. Trees tended to use water in the 0-50 cm topsoil during the wet season and depend on water from the subsoil layers in the dry season. No variation in water use among the provenances was observed ($P > 0.97$). However, the soil water balance under different *A. senegal* provenances showed significant variation ($P < 0.0001$) which depended on the sampling date (Fig. 1, Study **IV**).

Tree height

The *Acacia senegal* provenances observed in the present studies did not differ significantly in height, basal diameter or the number of branches during the first year, but later, with time, clear-cut significant differences among provenances were observed (Fig. 2 a, Study **IV**).

Provenances originating from the clay soil area maintained a taller height ($F = 5.29$, $P < 0.02$) as compared to provenances from the sand soil area; respective average heights were 1.94 ± 0.04 and, 1.82 ± 0.03 m at the end of the four-year observation period. Provenance Bout (BO) ranked highest, followed by Mazmoom (MZ), while provenance Semaih (SE) produced the smallest height (1.98, 1.96, and 1.75 m, respectively). These were 5.9% and 4.8% above, and 6.4% below the overall average of 1.87 m, respectively.

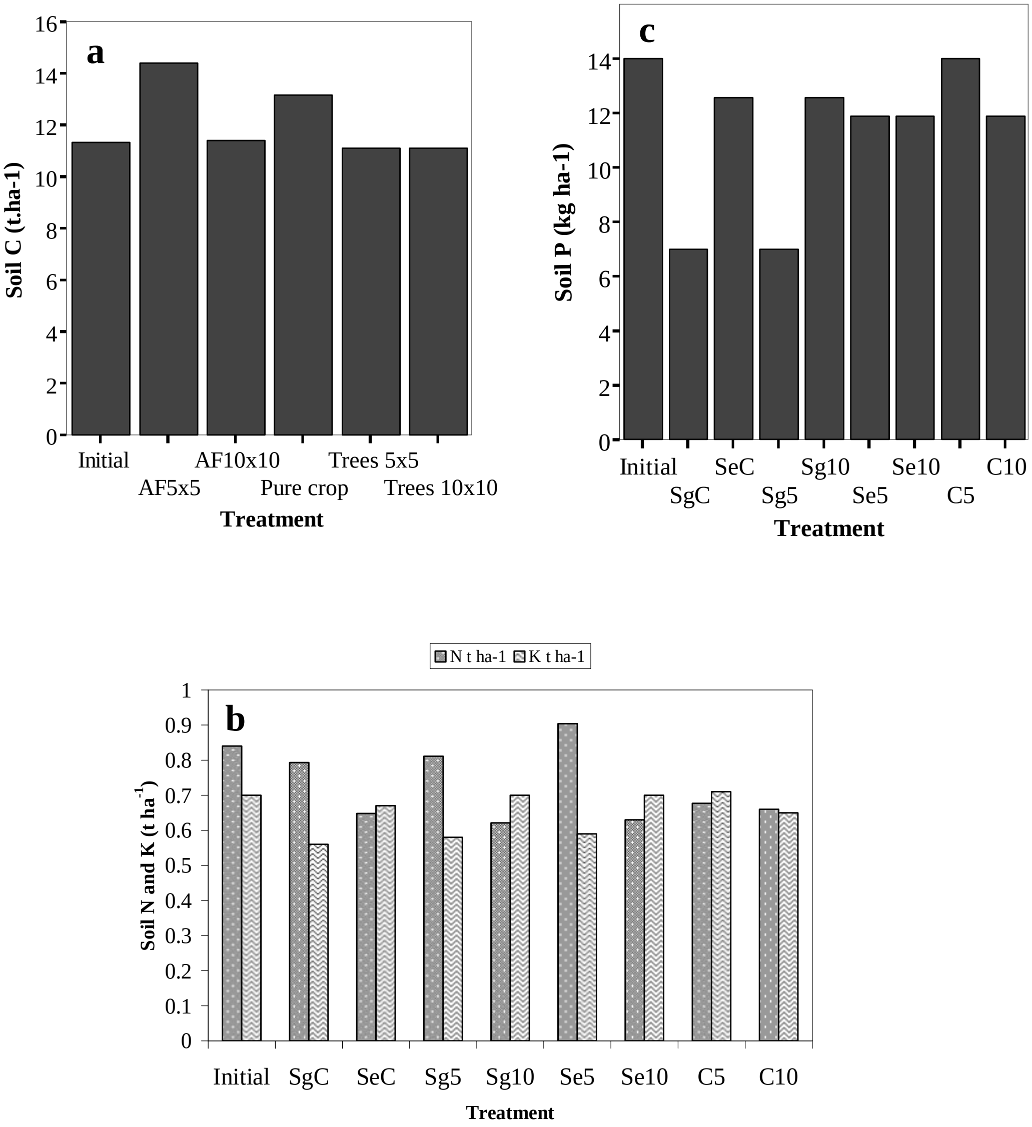

Fig. 7. (a) Total soil carbon, (b) total soil N and exchangeable K, and (c) exchangeable P in 0-25 cm soil stratum after 4 years of *Acacia senegal* intercropping with sorghum or sesame. In (a) AF = agroforestry, 5x5 and 10x10 refer to tree spacing (m), initial = before the start of the intercropping treatments. In (b) and (c), for acronyms, cf. Fig. 4.

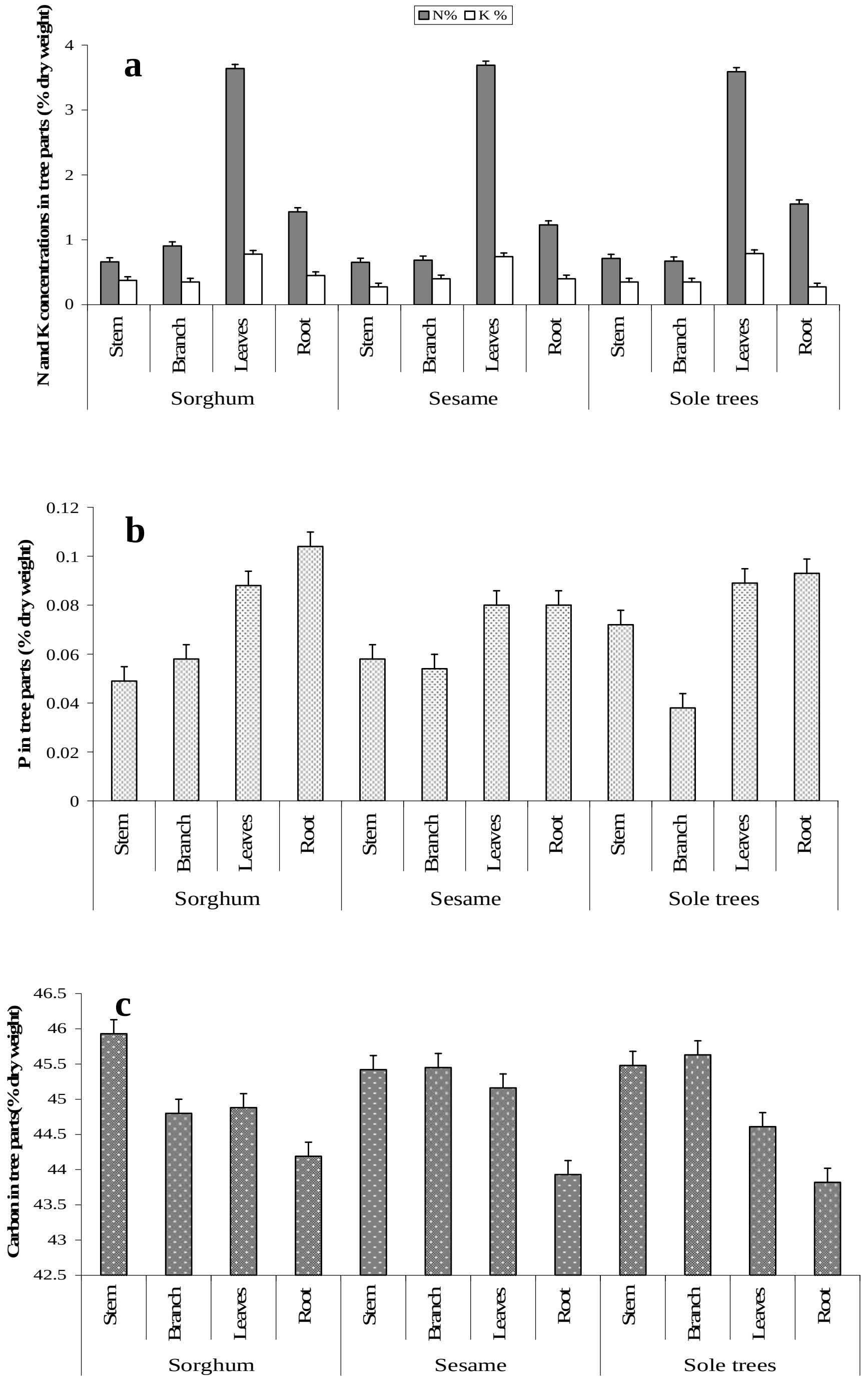

Fig.8. Nutrient and carbon concentrations in tree parts in *A. senegal* (stem, branches, leaves and roots). (a) nitrogen and potassium, (b) phosphorus, and (c) total C; after 4 years of intercropping with sorghum or sesame. Bars indicate standard errors.

Table 3. Above-ground nutrient (N, P, K) and carbon (OC) accumulation per hectare in *Acacia senegal* trees in agroforestry systems and without intercropping at two spacings after 4 years of growth.

Treatment	N (kg ha^{-1})	K (kg ha^{-1})	P (kg ha^{-1})	OC (kg ha^{-1})
Spacing 5x5 m	30.2	12.54	1.98	1590.6
Spacing 10x10 m	5.3	2.97	0.43	353.3
Sole trees (control) 5x5 m	14.0	5.98	0.93	930.1
Sole trees (control) 10x10 m	3.5	1.50	0.23	232.5

Table 4. Soil nutrient balance (kg ha^{-1}; top 25-cm layer) in *Acacia senegal* agroforestry systems and control treatments (sole trees or crops) after 4 years of measurement.

Treatment[1]	Nutrient	Crop export (harvest)	Trees (above ground biomass)	Changes in soil after 4 years	Output	Initial input from soil	Net nutrient gain (+) or loss (-)
Sg5	N	206	30	811	1017	840	-147
Sg10	N	202	5	621	823	840	+22
SgC	N	214	-	793	1007	840	-167
Se5	N	89	30	904	993	840	-123
Se10	N	86	5	630	716	840	+129
SeC	N	89	-	648	737	840	+103
C5	N	-	14	677	677	840	+177
C10	N	-	4	660	660	840	+184
Sg5	K	40	125	580	620	700	+205
Sg10	K	47	30	700	747	700	-17
SgC	K	56	-	560	616	700	+84
Se5	K	7	125	590	597	700	+228
Se10	K	8	30	700	708	700	+22
SeC	K	8	-	670	678	700	+22
C5	K	-	60	710	710	700	+50
C10	K	-	15	670	670	700	+45
Sg5	P	5	2	7	12	14	+4
Sg10	P	6	0	13	19	14	-4
SgC	P	6	-	7	13	14	+1
Se5	P	1	2	12	13	14	+3
Se10	P	3	1	12	15	14	0
SeC	P	2	-	13	15	14	-1
C5	P	-	1	14	14	14	+1
C10	P	-	1	12	12	14	+3

[1] Sg = sorghum, Se = sesame, C = control, 5 = 5x5 m spacing, 10 = 10x10 m. Initial input refers to the situation before the start of intercropping treatments.

Crown diameter

Statistical analysis showed that the effect of provenance was highly significant on crown diameter development ($P < 0.0001$). The average crown diameter varied between 1.79 m (± 0.058) and 1.47 m (± 0.058), while provenance Bout (BO) had the widest and provenances Domokeya (DO) and Semaih (SE) the narrowest crowns (1.79 m and 1.47 m; 11.32% and 8.58% above and below the overall average of 1.61m, respectively; cf. Fig. 2 b, Study **IV**).

Annual growth

No significant differences existed among the provenances in the annual growth rate in height, basal diameter or crown diameter. However, significant differences were found in growth rates between the four years (F = 20.34, 69.01 and 16.39, $P < 0.0001$, respectively) for tree height, tree crown diameter and tree basal diameter. The annual growth was good for height in 2001 and for basal diameter in 2001 and 2003. The rainfall in 2001 and 2003 was relatively high (824 and 683 mm, respectively).

4.7.1 Carbon isotope composition (δ^{13}C)

Leaf isotope composition (Study **IV**)

No significant differences were observed in δ^{13}C in leaves ($P < 0.076$) among trees representing different provenances or the two soil type groups. Clay provenances, however, tended to be more depleted (more negative) as compared to the sand group. The averages were -29.11 ± 0.169‰ (n = 3) and -28.88 ± 0.098‰ (n = 5) for the clay and sand groups, respectively. The ranking order for provenances (from less to more negative values) is given in Fig. 10 a. In contrast, significant differences in δ^{13}C were found ($P < 0.0001$, $R^2 = 0.73$) between different years. A positive correlation existed between leaf δ^{13}C and the leaf N content.

Wood isotope composition

In contrast to the results obtained from leaves, in branch wood samples significant differences in δ^{13}C ($P < 0.021$, $R^2 = 0.47$) were evident among the provenances, and the δ^{13}C values ranged between -28.07‰ and -29.31‰. The same pattern as tentatively found in leaves was now confirmed: the clay provenances were more significantly depleted than those of the sand group. Provenance Bout (BO) displayed the maximum negative value (-29.31‰, most depleted), while provenance Rahad (RH) had the least negative value (-28.07‰) and the others remained intermediate. The ranking order was slightly different from that based on leaf samples (Fig. 10 b). In this case, the clay-soil provenance Mazmoom (MZ) resembled the sand group, which suggests that the seeds might actually have been collected from trees growing on sand.

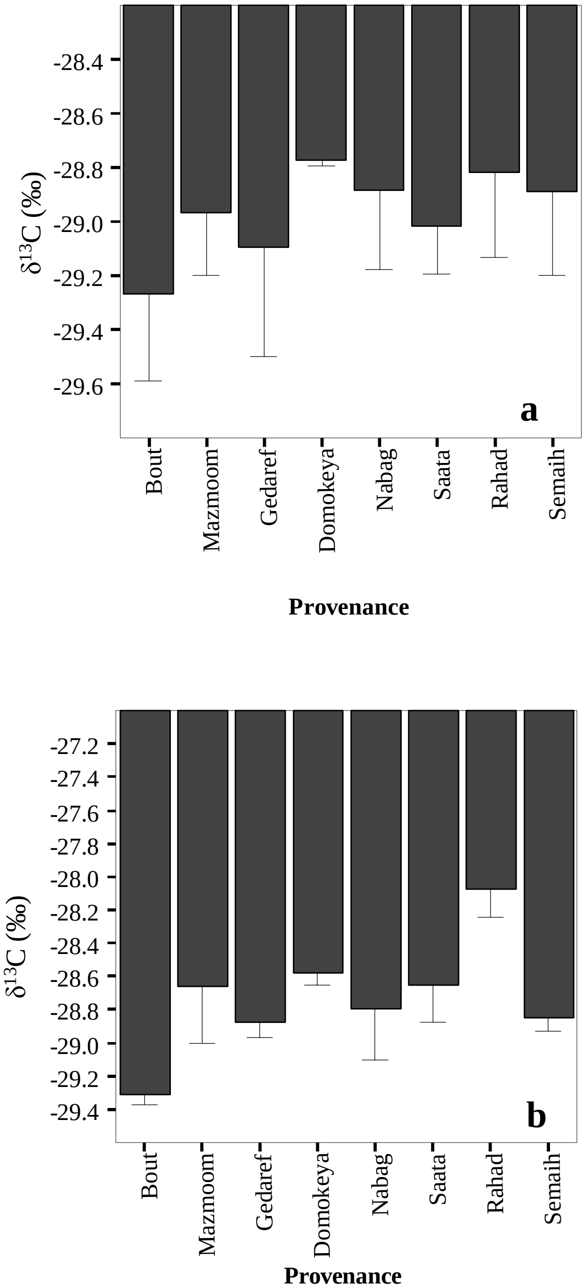

Fig. 10. (a) Mean $\delta^{13}C$ in leaves of different *Acacia senegal* provenances in 2000–2002 and (b) that in wood in 2002 (summer). Trees were grown on clay soil in the Blue Nile region, Sudan. Bars indicate standard error. The first three provenances originate from clay soil and the others from sand soil areas.

A positive relationship between $\delta^{13}C$ in the year 2000 and that in the subsequent year 2001 existed ($P = 0.024$, $R^2 = 0.76$). There were temporal changes in $\delta^{13}C$: values were, on average, most depleted in 2001. The variation in depletion associated with time was the small but significant.

4.7.2 Estimates of biological N_2 fixation (Study **V**)

The leaf nitrogen concentration ($\delta^{15}N$-total concentration) as found in the *A. senegal* provenances is presented in Fig. 11 a-b. The $\delta^{15}N$ in the leaves differed significantly ($P = 0.026$) between the *A. senegal* provenances and the reference tree species (*B. aegyptiaca*). In acacias, the highest and lowest mean $\delta^{15}N$ values were 5.65 ± 0.428‰ and 3.81 ± 0.328‰, respectively, whereas the corresponding value for the reference tree species was 7.02 ± 0.012‰. There were no significant differences ($P = 0.32$) among provenances. Provenance Rahad (RH) exhibited the lowest and provenance Bout (BO) the highest $\delta^{15}N$. There was no significant difference in $\delta^{15}N$ between the two provenance groups based on soil type. A highly significant ($P < 0.001$) variation in $\delta^{15}N$ existed among years. The highest amount of N fixed seemed to be associated with the highest annual rainfall (824 mm in 2001).

All acacia provenances showed a decrease in $\delta^{15}N$ indicating increase in N_2 fixation with age (Fig. 11 a). The $\%N_{dfa}$ values for provenance Rahad (RH), showing the highest average N_2 fixation, were 28, 48 and 61, or 22, 37 and 48, and those in provenance Bout (BO), showing the lowest N_2 fixation, 0, 30 and 34 or 0, 23 and 26 using assumption 1 or 2 for the three different years, respectively (Table 5).

In acacias, there were significant differences in $\%N_{dfa}$ between years ($P = 0.001$, Figs. 12, and 4 in Study **V**). The mean $\%N_{dfa}$ values, with assumption 1, for the different years were 16 ± 3.7, 32 ± 2.8 and 40 ± 3.7, and with assumption 2, 13 ± 3.1, 26 ± 3.1 and 31 ± 3.1, respectively (Fig. 4 a, b in Study **V**).

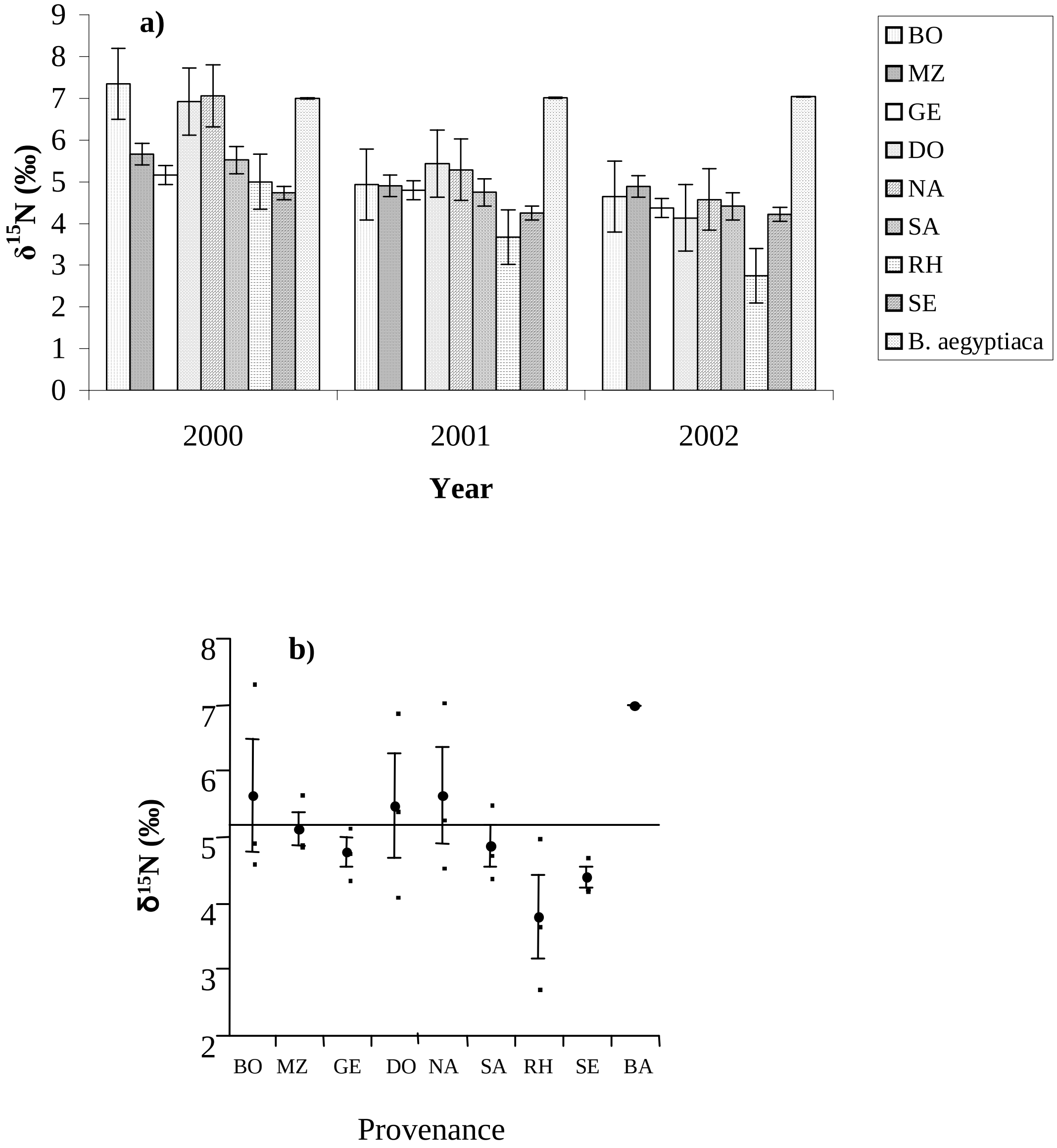

Fig. 11. (a) Variation in $\delta^{15}N$ in *Acacia senegal* provenances and *Balanites aegyptiaca* (BA) in different years, and (b) that in three successive years combined. (For provenance acronyms, cf. Table 1). Bars indicate standard error. The horizontal line refers to total response sample mean. Adapted from Study V.

Table 5. Estimates of the contribution of N_2 fixed from the atmosphere (%N_{dfa}) by *Acacia senegal* provenances calculated with the ^{15}N natural-abundance method using *Balanites aegyptiaca* as non-N_2-fixing reference. Trees were grown on clay soil in the Blue Nile region, Sudan. $\delta^{15}N_a$ values of 0‰ and -2‰ were used for assumptions 1 and 2, respectively. n = 3.

Provenance	%N_{dfa}					
	Year 2000		Year 2001		Year 2002	
	$\delta^{15}N_{\text{N-free}}$ assumption					
	0‰	-2‰	0‰	-2‰	0‰	-2‰
Bout (BO)	0	0	30	23	34	26
Mazmoom (MZ)	19	15	30	23	31	24
Gedaref (GE)	26	20	32	25	38	29
Domokeya (DO)	1	1	23	18	41	32
Nabag (NA)	0	0	25	19	35	27
Saata (SA)	21	16	32	25	37	29
Rahad (RH)	28	22	48	37	61	48
Semaih (SE)	32	25	39	31	40	31

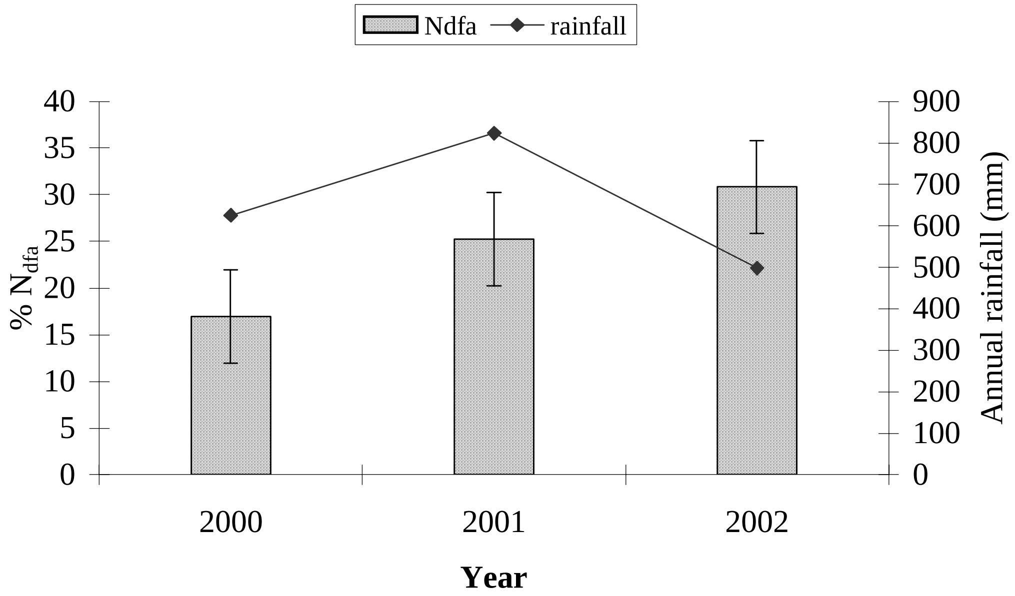

Fig. 12. Average %N_{dfa} pooled over eight *Acacia senegal* provenances in 2000-2002. Bars indicate standard error. The annual rainfall is also indicated.

Estimates of nitrogen amount in leaves

The total amount of leaf N was estimated from the leaf N concentration. There were no significant (*P* = 0.74) differences between different acacia provenances, whereas the years showed a highly significant variation (*P* = 0.0013). Year 2001, with a high annual rainfall (824 mm), ranked high compared to the rest. Highest amounts observed were, in 2002, 46.7 and 36.4 kg of leaf N in provenance Rahad (RH). Provenance Bout (BO), which was native to the region, yielded 32.8, or 25.47 kg ha^{-1} of leaf N, based on assumptions 1 or 2, respectively (Table 3, Study **V**). These results suggest a mean annual contribution of 21.6 and 20.0 kg ha^{-1} of fixed N_2 to the total leaf N by the clay and sand soil provenance groups, respectively, when grown on the present clay-soil experimental site.

The average amount of N accumulated in *A. senegal* leaves in four years equalled 0.077 kg N per tree, which was equivalent to 85.8 kg N ha^{-1} in provenance Bout (BO) and 0.059 kg N per tree, equivalent to 66.1 kg N ha^{-1}, in provenance Rahad (RH).

5. DISCUSSION

5.1 Effect of *Acacia senegal* on crop yield

In this study, the crop grain or seed yields were not influenced by intercropping with trees, regardless of agricultural crop type or tree density. This probably reflects the fact that the agroforestry systems tested were still young. Based on general information available from the Blue Nile, intercropping with *A. senegal* could possibly continue for more than five years without a risk of crop yield reduction. Obviously, there was little competition for water between trees and crops, even if water is normally the limiting factor for crop growth on dryland (Feng and Epstein 1995). The results show a sensitivity of sesame to excessive water: a low sesame yield was observed during years of high rainfall.

As trees grew older, their water use increased. Dawson (1996) has confirmed that larger trees use more water than smaller ones, suggesting also water use by trees of different size is proportional to their leaf area.

Trees seem to utilise the water in the topsoil rather than that below. However, the present data show that there is no detrimental effect of competition between trees and crops during an early stage of agroforestry system development. Under an *A. senegal* agroforestry system with trees four years of age, the clay soil had enough water to support the crop plant growth for the whole growing season up to crop maturation and harvest.

Kaushik and Kumar (2003) observed high yields from pearl millet (*Pennisetum typhoides* Rich), cluster bean (Guar bean) and cowpea (*Vigna unguiculata* (L.) Walp.) in association with “khejri” (*Prosopis cineraria* (L.) Druce trees. Increased crop returns from a tree-crop combination as compared to sole crops have been reported by Reddy and Sudha (1989). Droppelmann et al. (2000) observed similar results, and Ong et al. (2000) reported that the yields of intercrops (*Sorghum* or *Vigna*) in combination with pruned trees were similar to crop yields obtained without trees. This shows that there can be complementarity in resource use between different agroforestry systems components. Negative effects of tree hedges and alley cropping designs on the yields of annual intercrops have been found at the tree/ crop interface in most studies in semiarid regions under rain-fed conditions (cf. Rao et al. 1991, Jama et al. 1995, Govindarajan et al. 1996, Heinemann et al. 1997).

In the present study the soil nutrients were also sufficient to support crop growth in combination with trees; this shows that there is facilitation and complementarity in resource sharing and use between agricultural crops and *A. senegal*.

The reduction in sesame yield during two years of high rainfall (with 625 and 824 mm of precipitation) was probably due to the fact that sesame does not grow well in poorly drained and heavy clay soil like that commonly found in the Blue Nile region. Oplinger et al. (1990) and Langham and Wiemers (2002) reported that, in sesame, excessive moisture is not beneficial, and extended periods of rainfall or high air humidity may cause leaf diseases. Sesame plants standing in water for more than a few hours may be killed. In contrast, sesame could do well in areas of 400-500 mm of annual precipitation, and it will respond to irrigation if applied properly (Langham and Wiemers 2002). In the present study, sorghum failed to produce a higher than average grain yield in 2001. That was a year with a long rainy season and high annual rainfall (824mm). The erratic rainfall in July and August in that year, however, may have affected the sorghum yield negatively.

A varying quantity and distribution of the annual rainfall and an increasing maturity of the trees thus seemed to result in changes in tree/crop interactions. The present studies suggest that intercropping of *A. senegal* with annual crops is advantageous in terms of crop yield and diversity. In contrast to sole stands of trees or crop monoculture, in an *A. senegal* agroforestry system the farmer can get from the same piece of land two different crops at different times of the year. The use of optimal tree spacing seems to be an effective management tool to increase the overall biomass and productivity per area in rainfed dryland farming and in restocking of the gum belt.

5.2 Tree growth parameters

In this study the growth rate of trees was affected positively by association with annual crops. This could be explained by the fact that trees also benefited from crop management practices. The slow tree growth in sesame plots with a wider tree spacing could be due to the fact that trees were not competing for resources with sesame during their initial years of growth or to the low tree density of 100 trees ha^{-1}. In comparison, Ong et al. (2000) reported that crops affected the growth of *Grevillea robusta* negatively during early stages of intercropping due to competition for the available resources.

Plants compete for resources irrespective of whether they grow in sole stands or as species mixture. The degree of competition between individual plants depends on the demand for and the availability of growth resources, as well as on the ability of the component species to exploit a shared resource pool. Therefore, a production system that makes optimal use of the resources shows the highest productivity. In the present studies, it was found that the highest overall productivity was reached when *A. senegal* was planted at a high density with annual crops.

The temporal variation in the growth rate of trees between years was obviously mainly due to annual rainfall fluctuations and subsequent variations in the net assimilation rate. The highest relative growth rate was recorded during years with good rainfall. The growth rate was not consistent over time, showing variation between years.

5.3 Nutrient concentrations and uptake by trees

Concentrations of nutrients in tree tissues found in this study were similar to those reported for *A. senegal* by Breman and Kessler (1995) and Deans et al. (1999). Bernhand-Reversat and Poupon (1980) found N concentrations of 0.5%, 0.6% and 3.0% in stems, branches, twigs and leaves, respectively.
The reported range of tissue-nutrient concentrations in *A. senegal* seedlings has been observed to increase with increasing soil fertility (Colonna et al. 1991). Concentration ranges, obtained by these authors, were 3.1-4.2%, 0.11-0.21% and 1.1-1.6% for foliar N, P, and K, respectively, and their data indicated that the soils in which the trees grew were under nutrient deficiency, approaching the lower soil-fertility range. Ong et al. (2000) have reported that the foliar P amount was lower in sole crop plots than in *Grevillea robusta* agroforestry systems.

In the present investigation, the P concentration of woody tissues decreased as the trees aged, and it was higher in tree roots as compared to above-ground parts. Deans et al. (1999) reported similar results. Sterck et al. (1991), studying *Faidherbia albida* (Del.) A. Chev., observed decreasing internal concentrations of both N and P as the tree parts aged. These results suggest considerable internal translocation of P from woody tissues. Similar results on P translocation in *A. senegal* were reported by Deans et al. (1999). Considerable internal translocations of P and K from woody parts were reported for many species by various authors (cf. Pierre 2002). Thus, it seems that trees contain sufficient reserves of P in their tissues to maintain growth in the future even when the soil P level is a limiting factor. In addition, limitations in P availability are balanced by cycling of this nutrient through litter fall.

An increase in N in tree tissues as result of a high density of trees intercropped with sesame in the present studies was possibly explained by the fact that *A. senegal* obtains N from symbiotic N_2 fixation (34-61% of total N). A higher total nutrient uptake by trees in agroforestry systems can be interpreted as more efficient resource use as compared to monoculture.

Present results on exchangeable K suggest that trees can tap it from deeper soil sources, since the site now studied was rich in K. Recycling of nutrients from deeper soil layers was the most likely cause for increase in topsoil fertility associated with the presence of trees. Similar results for legume trees were observed by Palm (1995) and Sprent (1995) and for the *A. senegal* growing in Senegal by Deans et al. (1999).

Intercropped trees not only take up less nutrients from the topsoil than a crop monoculture but they also contribute to an increase in the N concentration of the soil under agroforestry. Root and nodule turnover could also be held responsible for this, as reported by Lehmann and Zech (1998).

5.4 Nutrient concentration and uptake in crops

The uptake of nutrients by sorghum or sesame did not considerably affect the site nutrient budget during the four cropping seasons of the present investigation. In contrast, the annual rainfall seemed to have a clear effect. The uptake increased during years with high total rainfall and good rainfall distribution. A high annual rainfall with an erratic temporal distribution decreased the uptake of nutrients by sesame. In particular, that was obvious in year 2001 with an annual rainfall of 824mm. The uptake of all nutrients was higher in agroforestry systems than in sole crops, suggesting that the resource use was more intensive in agroforestry system than in monoculture. Similar results have been reported by Lehmann et al. (1999) in an agroforestry system combining sorghum and *Acacia saligna* in northern Kenya.

Of the different tree parts in *A. senegal* the N concentration was highest in the leaves, and since the leaves are shed on to the site and captured in clay cracks (unlike the situation on sandy soil), this has positive effects on N cycling. On the other hand, the K concentrations were highest in the roots, stems and branches. Even if there was no risk for depletion of K on the present site, that could pose a risk at the end of the tree rotation, especially if the trees are to be taken away from the site.

5.5 Nutrient dynamics under cultivation

When land is opened up for farming, the soil N content usually decreases. This is mainly a consequence of an increased rate of oxidation of the soil organic matter (Wild 1988). In subsequent years, the annual loss can be lower, and almost all of it can be balanced by the nitrogen fixed by the trees.

In soil profiles most of the phosphate is usually located in the surface soil strata. In uncultivated soils, the phosphate will accumulate near the soil surface because of its cycling through vegetation and deposition in litter. Hence the circulation that leads to increased soil organic matter contents also generally leads to increased soil organic phosphorus concentrations. It is commonly assumed that the soil organic P is derived directly in or after biochemical transformations, from crop residues and leaf litter, where P is present in organic compounds (Wild 1988).

In the present studies, the nutrient balance was slightly negative for N, and also for P if all the above-ground annual crop biomass was exported (Table 4). Any improvement of the soil nutrient status under these systems would need a long enough time to occur (cf. Ong and Leakey 1999). When the long-term tree or crop production potential is considered, the supply of P seems to be a critical factor. The integration of *A. senegal* into this cropping system seems to ensure high nutrient use efficiency. Similar results were reported by Lehmann et al. (1999) and Deans et al. (1999). An increase in water use-efficiency paralleling for most trees the trend of CO_2 concentration increase in the atmosphere might also improve the transpiration efficiency in acacias (Luukkanen 1991). This would allow dryland trees to grow rapidly and act as an effective carbon sink for the anthropogenic CO_2 (Feng 1999, Koskela et al. 2000).

Estimates from the present study indicate that ca. 217 kg ha^{-1} of K and 1500 kg ha^{-1} of OC were added to the top 25-cm of soil during four years of annual crop cultivation in a mixture with *A. senegal* at 5 x 5 m spacing (corresponding to 400 trees ha^{-1}). However, the below-ground biomass was not included in these calculations, due to difficulties in excavating the root system in clay soil.

5.6 Nitrogen input of *A. senegal*

Previous research is not available on the variation in leaf biomass of *A. senegal* in its natural habitat. In the present work, an allometric equation similar to that used by Puig et al. (1990) was applied. The amount of leaf biomass in the present studies ranged from 1.3 to 2.6 t ha^{-1} (Equation 3). Due to small variation in basal diameter values among the acacia provenances, there were only small differences in the leaf biomass estimates observed (the tree stand density was similar for all the provenances, 1,111 trees ha^{-1}). These biomass estimates were consistent with those reported earlier, in N_2-fixing legumes and *Pterocarpus lucens*, by Puig et al. (1990), and by Roggy et al. (1999) and Sylla et al. (2002) in other tropical semi-arid ecosystems similar to those of the present investigation.

Root nodules were found in the nursery, but they were not detected under field conditions. Johnson and Mayeux (1990) postulated that nodules cannot be detected in some N_2-fixing tree roots at certain of sites, even when compatible rhizobia are present in the soil, because they decompose rapidly or are too small to be detected, or because they are located at 5-10 m depth.

The value for $\delta^{15}N$ was higher (5.19‰), but not significantly, in the clay soil group of provenances, as compared to that in the group originating from the sandy soil areas (4.85‰). This probably reflects the fact that *A. senegal* trees growing on clay initially depend on the soil N for growth and start their symbiotic N_2 fixation later. This was observed for the whole provenance group from the clay plain. In contrast, provenances collected from the area of N-poor sandy soils obviously started the N_2 fixation earlier. Provenance Rahad (RH) showed low $\delta^{15}N$ values and high $\%N_{dfa}$ values. The influence of rainfall in the process of N_2 fixation was not highly evident, suggesting that adequate soil water was available during the growing seasons throughout the study.

The difference in $\delta^{15}N$ values between *Balanites aegyptiaca* and the *A. senegal* provenances was significant enough to detect acacia trees with only a slight contribution of N_2 fixation to their total nitrogen. These estimates of N_2 fixation (with low standard errors) were similar to those reported by Roggy et al. (1999) in oxisols. In the present study, only the leaf ^{15}N abundance was used, since the variation in ^{15}N between different tree organs is usually very small. Ladha et al. (1993) reported no differences in ^{15}N abundance between the trunk, branch or leaf samples taken from nodulated *Gliricidia sepium* or from *Senna spectabilis*. Ndoye et al. (1995), when studying different acacias including *A. senegal* using the ^{15}N isotope dilution technique, found that leaves and stems showed similar ^{15}N enrichment. Similarly, other estimates of $\%N_{dfa}$ do not seem to differ significantly between different plant parts, or between whole trees grown in greenhouse or in the field (Danso et al. 1995, Gueye et al. 1997, Sylla et al. 1998). However, some authors have reported differences in ^{15}N between different plant parts (Boddey et al. 2000).

In the present study, *B. aegyptiaca* had a high leaf $\delta^{15}N$ value (7.04‰), whereas *A. senegal* showed lowered ones, e.g. 3.81‰ in provenance Rahad (RH) and 5.65‰ in provenance Bout (BO). This suggests that *A. senegal* is less dependent on soil N, as compared to *B. aegyptiaca*, due to its ability to fix N in natural conditions. Amounts of N_{dfa} in the leaves of *A. senegal* provenances indicate that N_{dfa} represented 26 to 34% of the total nitrogen accumulated in provenance Bout (BO) and 48 to 61% in provenance Rahad (RH) using assumptions 1 and 2, respectively, in the four-year-old trees. These proportions are higher than those reported for *Pterocarpus lucens* by Sylla et al. (2002). Interestingly, Ndoye et al. (1995) reported 34.4% N_{dfa} in 5-month-old potted *A. senegal* plants.

Schulze et al. (1991) estimated the percentage of N_{dfa} as ranging from 10 to 30% in woody Mimosaceae species along an aridity gradient in Namibia. Shearer et al. (1983) reported that N_2 fixation might contribute 43-61% of the nitrogen in *Prosopis* spp. under conditions of very low mineral nutrient availability. The present results are in line with the findings of Ovalle et al. (1996) and Ndoye et al. (1995) and suggest that African acacias are potentially good N_2-fixers, in contrast to the common belief that they are poor ones (cf. Dommergues 1987). The present results also suggest that the *A. senegal* provenance Bout (BO) has a good potential for reforestation and agroforestry programmes in the clay plain of the gum belt.

5.7 Provenance variation and adaptation

In the present study, significant differences were evident in the soil water balance at different soil depths. Trees tended to use the water in the 0-50 cm topsoil stratum and very little of that from the sub-soil during the rainy season. The water use was greater during the rainy season than during the dry season, as can be expected as a result from water availability. Trees from the wetter clay regions had a less conservative water-use behaviour, grew faster, and produced more gum, as compared to those from the drier, sand soil regions. This agrees with earlier findings by Devitt et al. (1997) and Raebild et al. (2003).

The present results suggest that provenances from the eastern clay-soil part of the gum belt are well adapted to that region and take the advantage of the short but intensive rainfall season by growing faster with a high photosynthetic rate and less conservative water-use, which also results in superior growth and good gum production.

Tree height is usually considered an important variable in the evaluation of the variation in performance among tree species and provenances. Height may also be seen as a measure of the adaptation of tree to its environment. This was in the present study demonstrated by the local provenance Bout (BO), which was superior to the others in terms of height (Fig. 2 a, Study **IV**).

The variability in adaptation between provenances is under genetic control. In this study, the environmental effects on performance were small, since the provenances were grown under identical field conditions. For studying the interaction between environment and genotype, which may be present, field studies covering both soil types are needed.

Significant differences in basal diameter and crown diameter were found among individual provenances and in height, growth rate, δ^{13}C, and gum production between the two provenance groups representing sand and clay soil. The differences detected in growth variables, gum production and δ^{13}C may reflect specific adaptation mechanisms in *A. senegal.* Physiological and morphological adjustments that take place in a plant during water deficit can be divided into short and long-term responses. Their implications for field performance are controlled by the genetic characteristics of the tree and the growing conditions under which it has evolved (Verzino et al. 2003). The variation in annual growth between years was due to annual rainfall fluctuations that affected the relative growth rate (RGR). The highest annual growth rate was recorded during the years with good rainfall (2001 and 2003).

Antunez et al. (2001) stated that the variation in RGR among woody species is due to the variation in leaf area ratio (LAR, whole plant area related to complete plant dry weight) which is also greater in deciduous species as compared to evergreens. They suggested that the specific leaf area (SLA), more than RGR, could be a significant parameter in determining the adaptive advantages of evergreens in dry or nutrient-poor environments and deciduous species growing on fertile soils. The differences in the net rate of production per unit of dry weight (RGR) in plants can be attributed either to environmental conditions, or to inherent genetic traits (Poorter 1990). It has been reported (Warren and Adams 2004) that species originating from more arid habitats have a higher specific leaf density and nitrogen content, as also was the case demonstrated here by the acacia provenances from the sand soil areas.

5.8 Carbon isotope composition

In the present studies, *A. senegal* provenances from the clay part of the gum belt had consistently more negative $\delta^{13}C$ values and a higher growth rate than those from the sand areas. This indicates a conservative water use behaviour in the latter group (less negative $\delta^{13}C$). A lower $\delta^{13}C$ (higher intrinsic water use efficiency) could be due to higher rate of carbon assimilation. These differences were maintained over the whole experimental period.

In this investigation, the carbon isotope composition of leaves and branch wood was determined separately. It has been reported by a number of investigators that in a tree, woody parts are often more enriched in ^{13}C than the leaves. The present data show that leaves and branches differed in their $\delta^{13}C$ composition, with the branches having high $\delta^{13}C$ values. Variation in $\delta^{13}C$ with tissue type has been reported in earlier tree studies (Schleser 1990, Newton et al. 1996), which reinforces the need for consistent sampling of tissues. Variation in $\delta^{13}C$ could be due to inherent provenance and species differences in isotope discrimination, or to variation in sites factors such as water availability (Warren et al. 2001). Values of $\delta^{13}C$ measured in a common environment with ample resources are the best measure of the genetic or adaptive indicator for WUE (Condon and Richards 1992, Handley et al. 1994). This offers potential for evaluation and screening of tree species and to identify suitable genotypes for reforestation and rehabilitation of degraded dryland (e.g. Griffiths 1993, Newton et al. 1996).

Perennial plants having their genetic origin in drier environments often have higher WUE values than individuals of the same species from wetter environments (O’Leary 1988, Ehleringer and Cooper 1988, Comstock and Ehleringer 1992). The strong negative relationship now found between $\delta^{13}C$ and gum yield explains the fact that $\delta^{13}C$ was negatively correlated with variables that are normally positively related to growth, such as net photosynthesis, transpiration and total biomass (cf. Li and Wang 2003).

Carbon isotope composition can be used to determine the water availability to plant communities (Steward et al. 1995) or the genetic adaptation of plants to particular conditions of water supply (Anderson et al. 1996). A narrow crown, small leaf size and early shedding of leaves that reduces the transpiration demand, are more characteristics of the sand provenances of *A. senegal* as compared to the clay ones. The results suggest that the natural selection associated with the rainfall gradient, soil type and climatic factors has resulted in genetic variation in physiological factors involved in $\delta^{13}C$ patterns for these populations. In *A. senegal* distinct differences in water-use and carbon gain strategies among provenances thus appear to exist.

The gum production process in *A. senegal* seems to be highly affected by the soil water content (SWC) at different soil depths (cf. Gaafar 2005). The soil water contents at depths of 25-50 and 50-75 cm in particular had a strong effect on this process. In clay soil, cracks appear soon after the end of the rains, and most of the water in the topsoil then evaporates. This explains the particular uptake of water from the subsequent deeper layers. In clay soils, the soil water content at 100 cm depth seems to have little effect on the process of gum production, and trees seem not to be able to use the water from this depth, which explains the weak relationship. However, the situation may change as trees age. In sandy soils, the situation is completely different and trees use water from deep soil strata (Gaafar 2005).

The local provenance Bout (BO) was efficient in the use of water available during the short rainy season; this was reflected in its superior growth, high photosynthetic rate and high gum yield. As found in earlier studies, an increase in biomass may be expected with an increase in water-use efficiency in dryland conditions where water availability limits the plant growth (Feng and Epstein 1995).

Present results prove that a more drought-tolerant *A. senegal* genotype is more conservative in its use of water. This was the case in the sand provenances, in agreement with earlier findings on conifers by Warren et al. (2001). Less conservative water-use is a characteristic trait for *A. senegal* provenances adapted to the Blue Nile region, as exemplified by the local provenance Bout (BO) in the present study.

The changes in $\delta^{13}C$ values with time were small but significant, reflecting the fact that the growing conditions, particularly the rainfall patterns, were very different, for instance, in 2000 and 2001. An increase in water use-efficiency in trees in general as a consequence of an increase of the CO_2 concentration in the atmosphere might also improve the biomass growth and consequently the gum yield in *A. senegal* (cf. Luukkanen 1991). This would also allow dryland trees such as *A. senegal* to act as a successively more effective carbon sinks for the increased anthropogenic CO_2 under the predicted global atmospheric change (Feng 1999, Koskela et al. 2000).

6. CONCLUSIONS

No increase or decrease was observed in agricultural crop yield as a result of intercropping with *A. senegal* at an early stage of agroforestry system management. However, patterns of resource capture by trees and crops may change as the agroforestry system matures; any reduction in crop yields could be compensated by the production of gum arabic from the acacia trees. Gum yields were 33.0 kg ha^{-1} and 7.0 kg ha^{-1} at the first tapping of trees when three-and-a-half years old and grown in spacing of 5 x 5 m or 10 x 10 m, respectively.

This simultaneous agroforestry system could be an alternative, or at least a variant, of the more traditional *A. senegal* fallowing system. The simultaneous system has the advantage of crop outputs at the start of the rotation when nothing can be harvested from the trees.

Levels of N and K in trees were high, suggesting that lopping of branches and removing them from the site or overgrazing in the dry season poses a potential threat to N and K budgets in the agroforestry systems.

There was little evidence that P increased in the topsoil as the agroforestry plantations aged. The P uptake by roots appeared to be more or less balanced by losses through litterfall and root turnover of system components. However, *A. senegal* could have a role in the mineralization of the total P.

The soil carbon sink was considerable in the young agroforestry systems now studied. This indicates a potential of dryland agroforestry for long-term carbon sequestration in the attempts to prevent a global climate change.

The total gum arabic production per tree in a certain year can be predicted from the yield in the second gum picking; this relationship can be used in planning and implementing the annual gum harvest, for instance, in relation to fluctuations in agricultural crop production.

Intercropping of *A. senegal* with sorghum or sesame is an effective measure in reforestation and land rehabilitation for farming purposes in the central clay plain of the gum belt in Sudan.

Tree management and especially the application of appropriate tree spacing is an important factor in determining the feasibility and success of agroforestry systems in the drylands of the Blue Nile region.

A. senegal provenances formed two distinctly different groups that exhibited variability in their morphological growth parameters at the nursery and during the early field stage. The most outstanding result was the superior performance in terms of height growth, branch number and basal diameter of the clay provenances. This suggests adaptation of provenances in this group to their local environment. The early fast height growth increases their importance for agroforestry and soil conservation in the drylands of the Blue Nile, since their superior traits can shorten the establishment period and protect the soil from excessive erosion by rains and overheating that increases the soil water evaporation and soil cracking.

Tree height, basal diameter and branch number are suitable indicators for the selection of *A. senegal* genotypes for use in reforestation and agroforestry systems in the clay part of the gum belt. Branch number which is very important traditional criterion used by farmers, indicates growth vigour and potential for gum production.

There is a genetic divergence in the carbon isotope composition between *A. senegal* provenances from clay and sand soil areas of the gum belt in Sudan. This can be related to the variation in the amount and timing of water availability and other climatic and environmental factors, leading to intra-specific variation in adaptation mechanisms. Trees from the sandy part of the gum belt with a low and erratic rainfall have less negative carbon isotope discrimination values. This indicates a conservative water-use behaviour that results in slow growth rate.

Trees from the eastern, clay soil part of the gum belt where the rainfall is higher and the conditions are more predictable have lower (more depleted) carbon isotope discrimination values, thus displaying a less conservative water-use behaviour which, under the prevailing conditions, results in higher biomass and gum productivity and better adaptability to the specific Blue Nile clay plain environments. The present investigation suggests that the carbon isotope discrimination method is helpful in evaluating the performance and productivity of planted *A. senegal* provenances on different sites. The method also offers potential for evaluating the water use efficiency of this species so as to identify appropriate genotypes that can be used in reforestation, rehabilitation and agroforestry programmes.

Growth traits, physiological characteristics and gum production can be used separately as criteria for genotype selection of *A. senegal*, since they are mutually correlated.

Selection and planting of the local clay provenances of *A. senegal*, as compared to unrelated material, in the Blue Nile region will lead to increases in biomass growth and gum production. Until more experimental field work on both soil types is conducted, planting of sand soil provenances is recommended for drought tolerance in the sandy part of the gum belt where water is a more severe limiting factor.

Further research should look into the genotype x environment interaction in *A. senegal* at different test sites over a wider range of environmental conditions within the gum belt of central Sudan and ultimately over the entire gum belt of Sudano-Sahelian Africa.

REFERENCES

Abdalla, A.T., Stigter, C.J., Bakhiet, N.I., Gough, M.C., Mohamed, H.A., Mohammed, A.E. & Ahmed, M.A. 2002. Traditional underground grain storage in clay soils in Sudan improved by recent innovations. Tropicultura 20: 170-175.

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M. 1998. Crop evapotranspiration, Guidelines for computing crop water requirements. Irrigation and Drainage Paper No. 56, FAO, Rome, Italy. 300 p.

Allen, S.E. (Ed). 1989. Chemical Analysis of Ecological Materials. Blackwell Scientific Publications. Oxford. 368 p.

Alstad, G. 1991. The Influence of *Acacia tortilis* on Soil in Arid North-eastern Sudan. Bergen, Norway: University of Bergen. 79 p.

Anderson, J.E., William, J., Kriedemann, P., Austin, M.P., & Farquhar, G.D. 1996. Correlations between carbon isotope discrimination and climate of native habitats for diverse eucalypt taxa growing in common garden. Australian Journal of Plant Physiology 23: 311-320.

Antunez, I., Retamosa, E.C. & Villar, R. 2001. Relative growth rate in phylogenetically related deciduous and evergreen woody species. Oecologia 128: 172-180.

Ardö, J. & Olsson, L. 2003. Assessment of soil organic carbon in semi-arid Sudan using GIS and the GENTURY model. Journal of Arid Environments 54: 633-651.

Arndt, S.K., Wanek, W., Clifford, S.C. & Popp, M. 2000. Contrasting adaptations to drought stress in field- grown *Ziziphus mauritiana* and *Prunus persica* trees: water relations, osmotic adjustment and carbon isotope composition. Australian Journal of Plant Physiology 27: 985-996.

Austin, A.T. & Sala, O.E. 1999. Foliar δ^{15}N is negatively correlated with rainfall along the IGBP transect in Australia. Australian Journal of Plant Physiology 26: 293-295.

Austin, A.T. & Vitousek, P.M. 1998. Nutrient dynamics on rainfall gradient in Hawaii. Oecologia 133: 519-529.

Awe, J.O., Shepherd, K.R. & Florence, R.G. 1976. Root development in provenances of *Eucalyptus camaldulensis* Dehn. Australian Forest Research 39: 201-209.

Ballal, M.E. 2002. Yield trends of gum arabic from *Acacia senegal* as related to some environmental and managerial factors: Doctoral thesis, Faculty of Forestry, University of Khartoum. Sudan. 105 p.

Ballal, M.E., El Siddig, E.A., Elfadl, M.A. & Luukkanen, O. 2005. Gum arabic yield in differently managed *Acacia senegal* stands in western Sudan. Agroforestry Forum 63: 237-245.

Barbier, E.B. 2000. The economic linkages between rural poverty and land degradation: some evidence from Africa. Agriculture Ecosystems & Environment 82: 355-370.

Barrios, E., Kwesiga, F., Buresh, R.J. & Sprent, J.I. 1997. Light fraction soil organic matter and available nitrogen following trees and maize. Soil Science Society of America Journal 61: 826-831.

Begg, J.E. & Turner, N.C. 1980. Morphological adaptations to water stress. *In*: Turner, N.C. & Kramer, P.J. (Eds.), Adaptation of plants to water and high temperature stress, pp. 31-42. John Wiley & Sons, New York.

Belsky, A.J., Mwonga, S.M., Amundson, R.G., Duxbury, J.M. & Ali, A.R. 1993. Comparative effects of isolated trees on their under canopy environments in high- and low-rainfall savannas. Journal of Applied Ecology 30: 143-155.

Bernhard-Reversat, F. & Poupon, H. 1980. Nitrogen cycling in a soil-tree system in a Sahelian savanna. Example of *Acacia senegal*. *In*: Rowsswall, T. (Ed.), Nitrogen Cycling in West African Ecosystems. Proc. Workshop SCOPE/UNEP International Nitrogen Unit, MAB (UNESCO) and IITA, Ibadan, Nigeria, 11-15 Dec. 1978. pp. 363-369.

Bewley, J.D. & Krochko, J.E. 1982. Desiccation- tolerance. *In*: lange, O.L., Nobel, P.S., Osmond, C.B. & Ziegler, H. (Eds.) Physiological Plant Ecology 2. Water Relation and Carbon Assimilation, pp. 325-378. Encyclopedia of Plant Physiology, New Series, Volume 12 B. Springer, Berlin.

Blackwell, P.S., Green, T.W. & Mason, W.K. 1990. Responses of biopore channels from roots to compression by vertical stresses. Soil Science Society of America Journal 54: 1088-1091.

Blake, G.R. & Hartge, K.H. 1986. Bulk density. *In*: Klute, A. (Ed.), Methods of soil analysis, Part 1, 2nd ed. Agronomy 9, pp. 363-375.

Boddey, R.M., Peoples, M.B., Palmer, B. & Dart, P.J. 2000. Use of the ^{15}N natural abundance technique to quantify biological nitrogen fixation by woody perennials. Nutrient Cycling in Agro-ecosystems 57: 235-270.

Bolan, N.S. 1991. A critical review on the role of mycorrhizal fungi in the uptake of phosphorus by plants. Plant and Soil 134: 189-207.

Bouillet, J.P., Laclau, J.P., Arnaud, M., M'Bou, A.T., Andre, L.S. & Jourdan, C. 2002. Changes with age in spatial distribution of roots of Eucalyptus clone in Congo Impact on water and nutrient uptake. Forest Ecology and Management 171: 43-57.

Bowen, G.D. & Rovira, A.D. 1999. The rhizosphere and its management to improve plant growth. Advances in Agronomy 66: 1-102.

Breman, H. & Kessler, J.J. 1995. Woody plants in agro-ecosystems of semi-arid regions. Springer-Verlag, Berlin, Germany. 340 p.

Brooks, K.N., Ffolliott, P.F., Gregersen, H.M. & DeBano, L.F. 2003. Hydrology and the management of watersheds. 3rd ed. Ames: Iowa: Iowa State University Press. pp. 373-384.

Brouwer, R. 1983. Functional equilibrium: sense or nonsense? Netherlands Journal of Agricultural Science 31: 335-348.

Buck, L.E., Lassoie, J.P., & Fernandes, E.C.M. (Eds.). 1999. Agroforestry in sustainable agricultural systems. Boca Raton, Florida: Lewis Publishers. 416 p.

Bukhari, Y.M. 1998. Tree-root influence on soil physical conditions, seedling establishment and natural thinning of *Acacia seyal* var. *seyal* on clays of central Sudan. Agroforestry Systems 42: 33-43.

Bunderson, W.T., Wakeel, A.El., Saad, Z. & Hashim, I. 1990. Agroforestry and potential in Western Sudan. *In*: Budd, W., et al. (Eds.), Planning for Agroforestry. New York, Elsevier Science Publisher.

Bunting, A.H. & Lea, J.D. 1962. The soils and vegetation of the Fung, East Central Sudan. Journal of Ecology 50: 529-558.

Buresh, R.J. & Tian, G., 1998. Soil improvement by trees in sub-Saharan Africa. Agroforestry Systems 38: 51-76.

Buresh, R.J. 1995. Nutrient cycling and nutrient supply in agroforestry systems. *In*: Dudal, R. & Roy, R.N. (Eds.), Integrated Plant Nutrition Systems, pp 155–164. FAO Fertilizer and Plant Nutrition Bulletin No. 12. Rome, Italy

Buresh, R.J., Smithson, P.C. & Hellums, D.T. 1997. Building soil P capital in sub-Saharan Africa. *In*: Buresh, R.J. & Sanchez, P.A. (Eds.), Replenishing Soil Fertility in Africa. SSSA Special Publication. 51. SSSA and ASA, Madison, WI, USA. pp. 111-149.

Campbell, B.M., Frost, P., King, J.A., Mawanza, M. & Mhlanga, L. 1994. The influence of trees on soil fertility on two contrasting semiarid soil types at Matopos, Zimbabwe. Agroforestry Systems 28: 159-172.

Cannell, M.G.R., Van Noordwijk, M. & Ong, C.K. 1996. The central agroforestry hypothesis: the trees must acquire resources that the crop would not otherwise acquire. Agroforestry Systems 34: 27-31.

Chamshama, S.A.O., Monela, G.C., Sekiete, K.E.A. & Persson, A. 1992 Sustainability of taungya system at North Kilimanjaro forest plantation, Tanzania. Agroforestry Systems 17: 1-11.

Chaves, M.M., Maroco, J.B. & Pereira, J.S. 2003. Understanding plant responses to drought from genes to the whole plant. Functional Plant Biology 30: 239-264.

Chen, C.R, Condron, L.M., Sinaj, S., Davis, M.R., Sherlock, R.R. & Frossard, E. 2003. Effects of plant species on phosphorus availability in a range of grassland soils. Plant and Soil 256: 115-130.

Clay, D.E., Clay, S.A., Jackson, J. Dalsted, K., Reese, C., Liu, Z., Malo, D.D. & Carlson, C.G. 2003. Carbon-13 discrimination can be used to evaluate soybean yield variability. Agronomy Journal 95: 430-435.

Colonna, J.P., Thoen, D., Ducosso, M., & Badji, S. 1991. Comparative effects of Glomus mosseae and P fertilizer on foliar mineral composition of *Acacia senegal* seedlings inoculated with Rhizobium. Mycorrhiza 1: 35-38.

Comstock, J.P. & Ehleringer, J.R. 1988. Contrasting photosynthetic behaviour in leaves and twigs of *Hymenoclea salsola*, a green-twigged, warm desert shrub. American Journal of Botany 75: 136-1370.

Comstock, J.P. & Ehleringer, J.R. 1992. Correlating genetic variation in carbon isotopic composition with complex climatic gradients. Proc. Natl. Acad. Sci. 89: 7747-7751.

Condon, A.G. & Richards, R.A. 1992. Broad sense heritability and genotype x environment interaction for carbon isotope discrimination in field-grown wheat. Australian Journal of Agricultural Research 43: 921-934.

Cowan, I.R. 1982. Regulation of water use in relation to carbon gain in higher plants. *In*: Lange, O.L., Nobel, C.B., Osmond, C.B. & Ziegler, H. (Eds.), Physiological Plant Ecology II. Water Relations and Carbon Assimilation. pp 489-613. Encyclopedia of Plant Physiology, New series, Volume 12B. Springer-Verlag, Berlin Heidelberg, New York.

Craig, H. 1957. Isotopic standards for carbon and oxygen and correction factors for mass spectrometric analysis of carbon dioxide. Geochimica et Cosmochimica Acta. 12: 133-149.

Danso, S.K.A., Hardarson, G. & Zapata, F. 1993. Misconceptions and practical problems in the use of ^{15}N soil enrichment techniques for estimating N_2. Plant and Soil 152: 25-52.

Danso, S.K.A., Zapata, F. & Awonaike, K.O. 1995. Measurement of biological N_2 fixation in field-grown *Robinia* pseudo acacia L. Soil Biology and Biochemistry 27: 415-419.

Dawson, T.E. 1996. Determining water use by trees and forests from isotopic, energy balance and transpiration analysis: the roles of tree size and hydraulic lift. Tree Physiology 16: 263-272.

Deans, J.D., Diagne, O., Lindley, D.K., Dione, M. & Parkinson, J.A. 1999. Nutrients and organic-matter accumulation in *Acacia senegal* fallows over 18 years. Forest Ecology and Management 124: 153-167.

Devitt, D.A., Smith, S.D. & Neuman, D.S. 1997. Leaf carbon isotope ratios in three landscape species growing in an arid environment. Journal of Arid Environments 36: 249-257.

Dinkelaker, B., Römheld, V. & Marschner, H. 1989. Citric acid excretion and precipitation of calcium citrate in the rhizosphere of white lupin (*Lupinus albus* L.). Plant Cell Environment 12: 285-292.

Dommergues, Y. 1987. The role of biological nitrogen fixation in agroforestry. *In*: Steppler, H.A. & Nair, P.K.A. (Eds.), Agroforestry. A Decade of Development, pp. 245-271. ICRAF, Nairobi, Kenya.

Doorenbos, J. & Pruitt, W.O. 1975. Crop water requirements. FAO Irrigation and Drainage Paper 24, (revised), Rome, Italy. 144 p.

Droppelmann, K.J., Ephrath, J.E. & Berliner, P.R. 2000. Tree/crop complementarity in an arid zone runoff agroforestry system in Northern Kenya. Agroforestry Systems 50: 1-16.

Dupouey, J.S., Leavitt, S.W., Choisnel, E. & Jourdain, S. 1993. Modelling carbon isotope fractionation in tree rings based on effective evapotranspiration and soil water status. Plant Cell and Environment 16: 939-947.

Eastham, J., Scott, P.R. & Steckis, R. 1994. Components of the water balance of tree species under evaluation for agroforestry to control salinity in the wheat belt of Western Australia. Agroforestry Systems 26: 157-170.

Ehdaie, B., Hall, A.E., Farquhar, G.D., Nguyen, H.T. & Waines, J.G. 1991. Water-use efficiency and carbon isotope discrimination in wheat. Crop Science 31: 1282-1288.

Ehleringer, J.R. & Cooper, T.A. 1988. Correlations between carbon isotope ratio and microhabitat in desert plants. Oecologia 76: 562-566.

Ehleringer, J.R. & Osmond, C.B. 1989. Stable isotopes *In*: Pearcy, R.W., Ehleringer, J., Mooney, H.A. & Rundel, P.W. (Eds.), Plant Physiological Ecology: field methods and instrumentation, pp. 281-300. London: Chapman and Hall. 448 p.

Ehleringer, J.R. 1991. $^{13}C/^{12}C$ fractionation and its utility in terrestrial plant studies. *In*: Coleman, D.C. & Fry, B. (Eds.), Carbon Isotope Techniques. Academic Press, New York, pp.187-200.

Ehleringer, J.R., White, J.W., Johnson, D.A. & Brick, M. 1990. Carbon isotope discrimination, photosynthetic gas exchange, and water-use efficiency in common bean and range grasses. Acta Oecologia 11: 611-25.

Ehlerringer, J.R., Hall, A.E., & Farquhar, G.D. (Eds.), 1993. Stable isotopes and plant carbon-water relations. Academic Press, San Diego, California, USA. 555 p.

El Amin, H.M. 1990. Trees and Shrubs of the Sudan. ISBN. Ithaca Press England. 484 p.

El Houri, A.A. 1986. Some aspect of dryland afforestation in the Sudan with special reference to *Acacia tortilis* (Forks.) Hayne, *Acacia senegal* Willd. and *Prosopis chilensis* (Molina) Stuntz. Forest Ecology and Management 16: 209-221.

Eskonheimo, A. 2006. Women, environmental changes and forestry-related development: Gender-affected roles of rural people in land degradation and environmental rehabilitation in a dry region of Sudan. PhD Thesis. University of Helsinki Tropical Forestry Reports 29. 214 p.

Evans, R.D. 2001 Physiological mechanisms influencing plant nitrogen isotope composition. Trends in Plant Science 6: 121-126.

FAO. 1998. World reference base for soil resources. Report 84. <http://www.fao.org/docrep/w8594e00.htm> (05.06.2006).

FAO. 2003. <http://www.fao.org/countryprofiles/index.asp?> (10.07.2003).

Farquhar, G.D., Ehleringer, J.R. & Hubick, K.T. 1989. Carbon isotope discrimination and photosynthesis. Annual Review Plant Physiology. Plant Molecular Biology 40: 503-537.

Feng, X. & Epstein, S. 1995. Carbon isotope of trees from arid environments and implications for reconstructing atmospheric CO_2 concentration. Geochimica et Cosmochimica Acta 59: 2599-2608.

Feng, X. 1999. Trends in intrinsic water-use efficiency of natural trees for past 100-200 years: a response to atmospheric CO_2 concentration. Geochimica et Cosmochimica Acta 63: 1891-903.

Ffolliott, P.F., Brooks, K.N., Gregersen, H.M. & Lundgren, A.L. 1995. Dryland forestry: Planning and management. New York: John Wiley & Sons.

Ffolliott, P.F., Jeffrey, O.D., James, T.F., Itshack, M., Timothy, E.F., Abdullah, A.M., Carter, J. & Paul, V. 2002. Assessing capabilities of soil and water resources in drylands: The role of information retrieval and dissemination technologies IALC Conference. Arid Lands Newsletter, Issue No. 52, November/ December 2002.

Fownes, J.H. & Anderson, D.G., 1991. Change in nodule and root biomass of *Sesbania sesban* and *Leucaena leucocephala* following coppicing. Plant Soil 138: 9-16.

Fries, J. 1995. Management of natural forests in the semi-arid areas of Africa: Present knowledge and research needs. IRDC. Swedish University of Agricultural Sciences, Uppsala. 119 p.

Gaafar, A.M. 2005. Improvement of traditional *Acacia senegal* agroforestry: Ecophysiological characteristics as indicators for tree-crop interaction on sandy soil in western Sudan. PhD Thesis. University of Helsinki Tropical Forestry Reports 26. 100 p.

Gardner, W.K., Barber, D.A. & Parbery, D.G. 1983. The acquisition of phosphorous by *Lupinus albus* L. III. The probable mechanism by which phosphorous movement in the soil/root interface is enhanced. Plant and Soil 70: 107-124.

Garten, C.T. & Taylor, G.E., 1992. Foliar $\delta^{13}C$ within a temperature deciduous forest: spatial, temporal, and species sources of variation. Oecologia 90: 1-7.

Gibson, A., Bachelard, E.P. & Hubick, K.T. 1995. Relationship between climate and provenance variation in *Eucalyptus camaldulensis* Dehnh. Australian Journal of Plant Physiology 22: 453-460.

Gold, M.A., Rietveld, W.J., Garrett, H.E. & Fisher, R.F. 2000. Agroforestry nomenclature, concepts, and practices for the USA. *In*: Garrett, H. E., Rietveld, W.J. & Fisher, R.F. (Eds.), North American Agroforestry: An Integrated Science and Practice, ASA, Madison, WI, USA. pp. 63-76.

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 88: 513-520.

Gregory, P.J. 1996. Approaches to modelling the uptake of water and nutrients in agroforestry systems. Agroforestry Systems 34: 51-65.

Grierson, P.F. & Attiwill, P.M. 1989. Chemical characteristics of proteoid root mat of *Banksia integrifolia* L.f. Australian Journal of Botany 37: 137-143.

Griffiths, H. 1993. Carbon isotope discrimination. *In*: Hall, D.O., Scurlock, J.M.O., Bolhar-Nordenkampf, H.H., Leegood, R.C. & Long, S.P. (Eds.), Photosynthesis and Production in a Changing Environment: a field and laboratory manual, pp. 193-206. London: Chapman and Hall. 464 p.

Grunwald, C. & Karschon, R. 1982. Leaf xylem water potentials and water saturation deficits as related to seed origin of *Eucalyptus camaldulensis* Dehnh. Australian Forest Research 12: 175-181.

Gueye, M., Ndoye, I., Diand, A.M., Danso, S.K.A. & Dreyfus, B. 1997. Active N_2 fixation in several *Faidherbia albida* provenances. Arid Soil Research and Rehabilitation 11: 63-70.

Gyenge, J.E., Fernandez, M.E., Salda, G.D. & Schlichter, T.M. 2002. Silvopastoral systems in North-western Patagonia II: water balance and water potential in a stand of *Pinus ponderosa* and native grassland. Agroforestry Systems 55: 47-55.

Haggar, J.P., Tanner, E.V.J., Beer, J.W. & Kass, D.C.L. 1993. Nitrogen dynamics of tropical agroforestry and annual cropping systems. Soil Biology and Biochemistry 25: 1363-1378.

Haggar, J.P., Warren, G.P., Beer, J.W. & Kass, D. 1991. Phosphorus availability under alley cropping and mulched and un-mulched sole cropping systems in Costa Rica. Plant and Soil 137: 275-283.

Hall, A.E., Mutters, R.G., Hubick, K.T. & Farquhar, G.D. 1990. Genotypic differences in carbon isotope discrimination by cowpea under wet and dry field conditions. Crop Science 30: 300-305.

Hall, A.E., Richards, R.A., Condon, A.G., Wright, G.C. & Farquhar, G.D. 1994. Carbon isotope discrimination and plant breeding. Plant Breeding Review 12: 81-113.

Handley, L.L. & Scrimgeour, C.M. 1997. Terrestrial plant ecology and ^{15}N natural abundance: the present limits to interpretation for uncultivated systems with original data from a Scottish old field. Advances in Ecological Research 27: 133-212.

Handley, L.L., Nevo, E., Ravan, J.A., Martinez-Carrasco, R., Scrimgeour, C.M., Pakniyat, H. & Forster, B.P. 1994. Chromosome 4 controls potential water use efficiency (Δ^{13}C) in barley. Journal of Experimental Botany 280: 1661-1663.

Handreck, K.A. 1997. Phosphorus requirements of Australian native plants. Australian Journal of Soil Research 35: 241-289.

Hands, M.R., Harrison, A.F. & Bayliss-Smith, T. 1995. Phosphorus dynamics in slash-and burn and alley cropping systems of the humid tropics. *In*: Tiessen, H. (Ed.), Phosphorus in the Global Environment; Transfer, Cycles and Management. Scope 54, pp. 155-170. John Wiley & Sons Ltd, New York.

Hare, F.K. 1993. Climate variations, drought and desertification. WMO-No. 653. 44 p.

Harrier, L.A. & Watson, C.A. 2003. The role of arbuscular mycorrhizal fungi in sustainable cropping systems. Advances in Agronomy 79: 185-225.

Hauser, S. 1993. Effect of *Acioa barteri*, *Cassia siamea*, *Flemingia macrophylla* and *Gmelina arborea* leaves on germination and early development of maize and cassava. Agriculture Ecosystems & Environment 45: 263-273.

Hawkins, H., Johansen, A., & George, E. 2000. Uptake and transport of organic and inorganic nitrogen by arbuscular mycorrhizal fungi. Plant and Soil 226: 275-285.

Heinemann, A.M., Otieno, H.J.O., Mengick, E.K. & Amadelo, B.A. 1997. Growth and yield of eight agroforestry tree species in line plantings in western Kenya and their effect on maize yields and soil properties. Forest Ecology and Management 91: 103-135.

Hinsinger, P. 2001. Bioavailability of soil inorganic P in the rhizosphere as affected by root induced chemical changes: a review. Plant Soil 237: 173-195.

Hodge, A., Robinson, D. & Fitter, A. 2000. Are micro-organisms more effective than plants at competing for nitrogen? Trends in Plant Sciences 5: 304-308.

Högberg, P. 1997. ^{15}N natural abundance in soil-plant systems. New Phytologist 137: 179-203.

Holmgren, M. Scheffer, M. & Huston, M.A. 1997. The interplay of facilitation and competition in plant communities. Ecology 78(7): 1966-1975.

Howard, S.B., Ong, C.K., Rao, M.R., Mathuva, M. & Black, C.R., 1995. The partitioning of light and water in *Leucaena*-maize agroforestry systems. *In*: Sinoquet, H., Cruz, P. (Eds.), Ecophysiology of Tropical Crops. INRA, Paris. pp. 123-136.

Huang, W. 1998. Productive coexistence and gain in agroforestry systems. Doctoral Thesis. Acta Forestalia Fennica No. 260. 72 p.

Hubick, K.T., Shorter, R. & Farquhar, G.D. 1988. Heritability and genotype x environment interactions of carbon isotope discrimination and transpiration efficiency in peanut (*Arachis hypogaea* L.) Australian Journal of Plant Physiology 15: 799-813.

Hue, N.V. 1991. Effects of Organic Acids/ Anions on P sorption and Phytoavailability in Soils with Different Mineralogies. Soil Science 152: 463-471.

IAEA .1975. Root activity patterns of some tree crops. Technical Report Series No. 170. International Atomic Energy Agency, Vienna, Austria 154 p.

ICRAF. 1996. Annual report 1995. International Centre for Research In Agroforestry, Nairobi, Kenya.

IIED. & IES. 1990. Gum Arabic Belt Rehabilitation In the Republic of the Sudan Report, Ministry of Finance and Economic Planning (Planning) of the Government of the Sudan, Vol.1.159 p.

Ingram, J. 1990. The role of trees in maintaining and improving soil productivity- review of literature. *In*: Prinsley, R.T. (Ed.), Agroforestry for Sustainable Production. Commonwealth Science Council, London. pp. 243-303.

IUFRO, 2004. Trees, Agroforestry and Global Change in Dryland Africa (TACCDA). Proceedings from VITRI/ ETFRN/ IUFRO workshop, 31 July-4 August 2003, Hyytiälä, Finland. www.etfrn.org.

Jama, B.A., Nair, P.K.R. & Rao, M.R. 1995. Productivity of hedgerow shrubs and maize under alley cropping and block planting systems in semiarid Kenya. Agroforestry Systems 31: 257-274.

Jewitt, T.N. & Manton, J.S. 1954. Soil exhaustion in the Goz sands of the Sudan. Congres international de la science du sol, leopodville, pp. 413-416.

Jobbagy, E.G. & Jackson, R.B. 2001. The distribution of soil nutrients with depth: Global patterns and the imprint of plants. Biochemistry 53: 51-77.

Johson, H.B. & Mayeux, H.S. 1990. *Prosopis glandulosa* and the nitrogen balance of range lands: extent and occurrence of nodulation. Oecologia 84: 176-185.

Jones, H.G. 1980. Interaction and integration of adaptive responses to water stress: The implication of an unpredictable environment. *In*: Turner, N.C. and Kramer, P.J. (Eds.), Adaptation of plants to water and high temperature stress, pp. 353-365. John Wiley & Sons, New York.

Jones, M., Sinclair, F.L. & Grime, V.L. 1998. Effect of tree species and crown pruning on root length and soil water content in semi-arid agroforestry. Plant and Soil 201: 197-207.

Kang, B.T. 1997. Alley cropping–soil productivity and nutrient recycling. Forest Ecology and Management 91: 75–82.

Kang, B.T., Salako, F.K., Akobundu, I.O., Pleysier, J.L. & Chianu, J.N. 1997. Amelioration of a degraded Oxic Paleustalf by leguminous and natural fallows. Soil Use and Management 13: 130-135.

Kaushik, N. & Kumar, V. 2003. Khejri (*Prosopis cineraria*)-based agroforestry system for arid Haryana, India. Journal of Arid Environments 55: 433-440.

Kessler, J.J. 1992. The influence of Karite (*Vitellaria paradox*) and nere (*Parkia biglobosa*) trees on sorghum production in Burkina Faso. Agroforestry Systems 17: 97-134.

Khanna, P.K. 1998. Nutrient cycling under mixed-species tree systems in Southeast Asia. Agroforestry Systems 38: 99-120.

Korwar, G.R. & Radder, G.D. 1994. Influence of root pruning and cutting interval of *Leucaena* hedgerows on performance of alley cropped *rabi* sorghum. Agroforestry Systems 25: 95-109.

Koskela, J., Nygren, P., Berninger, F. & Luukkanen, O. 2000. Implications of the Kyoto Protocol for tropical forest management and land use: prospects and pitfalls. University of Helsinki Tropical Forestry Reports 22. 103 p.

Kramer, P.J. & Kozlowski, T.T. 1979. Physiology of woody plants. Academic press, New York. 811 p.

Kramer, P.J. 1980. Drought, Stress, and the origin of adaptations *In*: Turner, N.C. & Kramer, P.J. (Eds.), Adaptation of plants to water and high temperature stress, John Wiley & Sons, New York. pp. 7-20.

Kurdali, F., Domenach, A.M., Bouvarel, L. & Moiroud, A. 1993. Field comparison of d15N values and growth of alder provenances and species. Soil Science Plant Nutrition 39: 635-643.

Ladha, J.K., Peoples, M.B., Garrity, D.P., Capuno, V.T. & Dart, P.J. 1993. Estimating dinitrogen fixation of hedgerow vegetation using the ^{15}N natural abundance method. Soil Science Society of America Journal 57: 732-737.

Lajtha, K. & Michener, R.H., Eds.1994. Stable Isotopes in Ecology and Environmental Science. Oxford: Blackwell Scientific Publications. London, 316 p.

Lal, R. 2001. Managing world soils for food security and environmental quality. Advances in Agronomy 74: 155-192.

Lal, R. 2002. The Potential of soils of the tropics to sequester carbon and mitigate the greenhouse effect. Advances in Agronomy 76: 1-3.

Langham, D.R. & Wiemers, T. 2002. Progress in mechanizing sesame in the US through breeding. *In*: Janick, J. & Whipkey, A. (Eds.), Trends in new crops and new uses. ASHS Press, Alexandria, VA. pp. 157-173.

Larcher, W. 2003. Physiological Plant Ecology. Ecophysiology and Stress Physiology of Functional Groups, 4th ed. Springer-Verlag, Berlin, Heidelberg. 513 p.

Le Maitre, D.C., Scott, D.F. & Colvin, C. 1999. A review of information on interaction between vegetation and groundwater. Water S. A. 25 (2): 137-152.

Lehmann, J. & Zech, W. 1998. Fine root turnover in hedgerow intercropping in Northern Kenya. Plant Soil 198: 19-31.

Lehmann, J., Weigl, D., Droppelmann, K., Huwe, B. & Zech, W. 1999. Nutrient cycling in an agroforestry system with runoff irrigation in Northern Kenya. Agroforestry Systems 43: 49-70.

Li, C. & Wang, K. 2003. Differences in drought responses of three contrasting *Eucalyptus microtheca* F. Muell. Populations. Forest Ecology and Management 179: 377-385.

Li, F.M., Song, Q.H., Liu, H.S., Li, F.R. & Liu, X.L. 2001. Effects of pre-sowing irrigation and phosphorus application on water use and yield of spring wheat under semi-arid conditions. Agricultural Water Management 49: 173-183.

Livesley, S.J., Gregory, P.J. & Buresh, R.J. 2002. Competition in tree row agroforestry systems. 2. Distribution, dynamics and uptake of soil inorganic N. Plant and Soil 247: 177-187.

Livesley, S.J., Gregory, P.J. & Buresh, R.J. 2004. Competition in tree row agroforestry systems. Soil water distribution and dynamics. Plant and Soil 264: 129-139.

Liyanage, M.de S., Danso, S.K.A. & Jayasundara, H.P.S. 1994. Biological nitrogen fixation in four *Gliricidia sepium* genotypes. Plant and Soil 161: 267-274.

Lott, J.E., Khan, A.A.H., Black, C.R. & Ong, C.K. 2003. Water use in *Grevillea robusta*-maize over story agroforestry system in semi-arid Kenya. Forest Ecology and Management 180: 45-59.

Lu, Z., Chen, J., Percy, R.G., Sharifi, M.R., Rundel, P.W. & Zeiger, E. 1996. Genetic variation in carbon isotope discrimination and its relation to stomatal conductance in Pima cotton (*Gossypium barbadense*). Australian Journal of Plant Physiology 23: 127-132.

Ludwig, F., Dawson, T.E., Prins, H.H.T., Berendse, F. & De Kroon, H. 2004. Below-ground competition between trees and grasses may overwhelm the facilitative effects of hydraulic lift 7: 623-631.

Luukkanen, O. 1991. Global change and the eco-physiology of tropical trees. Proc. Conference Global Change: Effects on Tropical Forest, Agricultural, Urban and Industrial Ecosystems, Bangkok, 22-24 Oct. 1990, pp. 66-71. ITTO Tech. Series 6.

Mahmoud, A.M., Khidir, M.O., Khalifa, M.A., El Ahmadi, A.B., Musnad, H.A.R. & Mohamed, E.I. 1996. Sudan country report to the FAO international technical conference on plant genetic resources. Leipzig, Germany. 86 p.

Marples, S. 1986. Production and investment in marginal areas. In Development of rain-fed agriculture under arid and semiarid conditions, Ed. Davis, T.J. 87. Washington, DC: The World Bank.

Mason, P.A. & Wilson, J. 1994. Harnessing symbiotic association: vesicular-arbuscular mycorrhizas. *In*: Leaky, R.R.B., & Newton, A.C. (Eds.), Tropical Trees: The Potential for Domestication and the Rebuilding of Forest Resources, HSMO, London, UK. pp 165-175.

Materechera, S.A., Dexter, A.R. & Alston, A.M. 1991. Penetration of very strong soils by seedling roots of different plant species. Plant Soil 135: 31-41.

Mc Lachlan, K.D. 1980. Acid phosphate activity of intact roots and phosphorous nutrition of plants. I. Assay conditions and phosphate activity. Australian Journal of Agricultural Research 31: 429-440.

Mc Nulty, S.G. & Swank, W.T. 1995. Wood $\delta^{13}C$ as a measure of annual basal area growth and soil water stress in a *Pinus strobus* forest. Ecology 76: 1581-1586.

Mekonnen, K., Buresh, R.J. & Jama, B. 1997. Root and inorganic nitrogen distributions in *Sesbania* fallow, natural fallow and maize. Plant Soil 188: 319-327.

Middleton, N.J. & Thomas, D.S.G. 1997. World Atlas of Desertification. UNEP. Arnold, London. UK. 182 p.

Miller, H.G. 1995. The influence of stand development on nutrient demand, growth and allocation. Plant Soil 168/169: 225-232.

Montagnini, F., Jordan, C.F. & Machado, R.M. 2000. Nutrient cycling and nutrient use efficiency in agroforestry systems, *In*: Ashton, M.S., & Montagnini, F. (Eds.). The silvicultural basis for agroforestry systems. CRC Press, Boca Raton, FL, USA. pp. 131-160.

Mordelet, P., Abbadie, L. & Menaut, J.C. 1993. Effects of tree stumps on soil characteristics in a humid savanna of West Africa (Lamto, Cote d' Ivoire). Plant and Soil 153: 103-111.

Myers, B.J. & Landsberg, J.J. 1989. Water stress and seedling growth of two eucalyptus species from contrasting habitats. Tree Physiology 5: 207- 218.

Nair, P.K.R. 1993. An Introduction to Agroforestry. Kluwer Academic Publishers, Dordrecht, the Netherlands. 499 p.

Ndoye, I., Gueye, M., & Danso, S.K.A. 1995. Nitrogen fixation in *Faidherbia albida*, *Acacia raddiana*, *Acacia senegal* and *Acacia seyal* estimated using the ^{15}N isotope dilution technique. Plant and Soil 172: 175-180.

Newton, A.C., Dick, J. McP. & Heaton, T.H.E. 1996. Stable carbon isotope composition ($\delta^{13}C$) on *Acacia tortilis* subsp. s*pirocarpa* (A. Rich.) Brenan growing at three semi-arid sites in Kenya. Journal of Arid Environments 34: 325-330.

Njiti, C.F. & Galiana, A. 1996. Symbiotic properties and rhizobium requirements for effective nodulation of five tropical dry zone acacias. Agroforestry Systems 43: 265-275.

O'Leary, M.H. 1988. Carbon isotopes in photosynthesis. Bioscience 38: 325-336.

Olsen, R.K., Schoeneberger, M.M. & Aschmann, S.G. 2000. An ecological foundation for temperate agroforestry. *In*: Garrett, H.E., Rietveld, W.J. & Fisher, R.F. (Eds.), North American Agroforestry: An Integrated Science and Practice. ASA, Madison, Wisconsin, USA, pp. 31-61.

Olsen, S.R. & Sommers, L.E. 1982. Phosphorus. *In*: Page A.L., Miller R.H. and Keeney D.R. (Eds.), Methods of Soil Analysis: Part 2 Chemical and Microbiological Properties, American Society of Agronomy, Madison, Wisconsin, USA. pp. 403-430.

Ong, C.K. & Black, C.R., 1995. Complementarity in resource use in agroforestry systems. *In*: Kang, B.T., Osiname, A.O. & Osiname Larbi, Osiname. (Eds.), alley farming-Research and Development. IITA, Ibadan, Nigeria. pp. 73-89.

Ong, C.K. & Leakey, R.R.B. 1999. Why tree-crop interactions in agroforestry appear at odds with tree-grass interactions in tropical savannahs. Agroforestry Systems 45: 109-129.

Ong, C.K., Black, C.R., Marshall, F.M. & Corlett, J.E. 1996. Principal of resource capture and utilization of light and water. *In*: Ong, C.K. & Huxley, P. (Eds.) Tree-Crop interactions a Physiological Approach. CAB International, Oxon, UK. pp. 73-158.

Ong, C.K., Black, C.R., Wallace, J.S., Khan, A.A.H., Lott, J.E., Jackson, N.A., Howard, S.B. & Smith, D.M. 2000. Productivity, microclimate and water use in *Grevillea robusta*-based agroforestry systems on hill slopes in semi-arid Kenya. Agriculture Ecosystems & Environment 80: 121-141.

Oplinger, E.S., Putnam, D.H., Kaminski, A.R., Hanson, C.V., Oelke, E.A., Schulte, E.E. & Doll, J.D. 1990. In Alternative Field Crops Manual, Sesame Home. http://www.hort.purdue.edu/newcrop/afcm/spelt.html. (26.4.04).

Ovalle, C., Longeri, L., Aronson, J. 1996. N_2 fixation, nodule efficiency and biomass accumulation after two years in three Chilean legume trees and Tagasaste *Chamaecytisus proliferus* subsp. *palmensis*. Plant and Soil 179: 131-140.

Palm, C.A. 1995. Contribution of agroforestry trees to nutrient requirements of intercropped plants. Agriculture Ecosystems and Environment 30: 105-124.

Passioura, J.B. 2002. Environmental plant biology and crop improvement. Functional Plant Biology 29: 537-546.

Pennington, R.E., Tischler, C.R., Johnson, H.B. & Polley, H.W. 1999. Genetic variation for carbon isotope composition in honey mesquite (*Prosopis glandulosa*). Tree Physiology 19: 583-589.

Peter, I. & Lehmann, J. 2000. Pruning effects on root distribution and nutrient dynamics in an acacia hedgerow planting in northern Kenya. Agroforestry Systems 50: 59-75.

Pierre, M. 2002. Mineral nutrient concentrations in sapwood and heartwood: a literature review. Annals of Forest Science 59: 713-722.

Poorter, H., & Remkes, C. 1990. Leaf area ratio and assimilation rate of 24 wild species differing in relative growth rate. Oecologia 83: 553-559.

Prasolova, N.V., Xu, Z.H., Farquhar, G.D., Saffigna, P.G. & Dieters, M.J. 2001. Canopy carbon and oxygen isotope composition of 9-year-old hoop pine families in relation to seedling carbon isotope composition and growth, field growth performance and canopy nitrogen concentration. Canadian Journal of Forest Research 31: 673-681.

Puig, H., Riera, B. & Lescure, I.P. 1990. Phytomasse et productivite'. Bois et Forets des Tropiques 220: 25-32.

Raddad, E.Y. 1987. Physiological studies and seedlings survival of some forest trees in the Sudan. M.Sc. thesis, Faculty of Science, University of Khartoum, Sudan. 120 p.

Radersma, S., & Grierson, P.F. 2004. Phosphorus mobilization in agroforestry: Organic anions, phosphatase activity and phosphorus fractions in the rhizosphere. Plant and Soil 259: 209-219.

Raebild, A., Graudal, L. & Ouedraogo, L.G. 2003. Evaluation of provenance trial of *Acacia senegal* at Dori, Burkina Faso. Trail No. 8 in the arid zone series. Results and documentation No.3. DANIDA Forest Seed Centre, Denmark.

Rao, M.R., Ong, C.K., Pathak, P., & Sharma, M.M. 1991. Productivity of annual cropping systems on a shallow alfisol in semi-arid India. Agroforestry Systems 15: 51-63.

Read, J. & Farquhar, G.D. 1991. Comparative studies in *Nothofagus* (Fagaceace). I. Leaf carbon isotope discrimination. Functional Ecology 5: 684-695.

Reddy, Y.V.R., & Sudha, M. 1989. Economics of agroforestry system-CRIDAs experience. *In*: Singh, R.P., Ahlwat, I.P.S., Ganga, S. (Eds.), Agroforestry Systems in India-Research and Development. Indian Society of Agronomy, New Delhi, pp. 179-186.

Roder, W. 1992. Experiences with tree fodder's in temperate regions of Bhutan. Agroforestry Systems 17: 263-270.

Roggy, J.C., Prevost, M.F., Garbaye, J. & Domenach, A.M. 1999. Nitrogen cycling in the tropical rain forest of French Guiana: comparison of two sites with contrasting soil types using δ^{15}N. Journal of Tropical Ecology 15: 1-22.

Ruhigwa, B.A., Gichuru, M.P., Mambani, B. & Tariah, N.M. 1992. Root distribution of *Acioa barteri*, *Alchornea cordifolia*, *Cassia siamea* and *Gmelina arborea* in an acid Ultisol. Agroforestry Systems 19: 67-78.

Salih, A.A. 1998. Root and shoot growth of *Prosopis chilensis* in response to soil impedance and soil matric potential. Journal of Arid Environments 40: 43-52.

Sanchez, P.A. 1976. Properties and Management of Soils in the Tropics. John Wiley & Sons, New York. 618 p.

Sandquist, D.R. & Ehleringer, J.R. 2003. Carbon isotope discrimination differences within and between contrasting populations of *Encelia farinosa* raised under common-environment conditions. Oecologia 134: 463-470.

SAS. 1997. JMP statistical package. SAS Institute, Inc, Cary, N.C.

Schleser, G. 1990. Investigation of the δ^{13}C pattern in leaves of *Fagus sylvatica* L. Journal of Experimental Botany 41: 564-572.

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

Schroth, G. 1995. Tree roots characteristics as criteria for species selection and systems design in agroforestry. Agroforestry Systems 30: 125-143.

Schulze, E.D., Gebauer, G., Ziegler, H. & Lange, O.L. 1991. Estimates of nitrogen fixation by trees on an aridity gradient in Namibia. Oecologia 88: 451-455.

Sharma, A.K. 1998. Reaping the benefits of non wood forest products and services. Agroforestry Today 10 (1): 23-24.

Shearer, G. & Kohl, D.H. 1986. N_2 fixation in field settings: estimation based on natural ^{15}N abundance. Australian Journal of Plant Physiology 13: 699-756.

Shearer, G., Kohl, D.H., Virginia, R.A., Skeeters, J.L., Nilsen, E.T., Sharif, M.R. & Rundel, P.W. 1983. Estimates of N_2 fixation from variation in the natural abundance of ^{15}N in Sonorian desert ecosystem. Oecologia (Berlin) 56: 365-373.

Siaw, D.E.K.A., Kang, B.T. & Okali, D.U.U. 1991. Alley cropping with *Leucaena leucocephala* (Lam.) De Wit and *Acioa barteri* (Hook. F.) Engl. Agroforestry Systems 14: 219-231.

Singh, L. & Singh, J.S. 1993. Importance of short-lived components of a dry tropical forest for biomass production and nutrient cycling. Journal of Vegetation Science 4: 681-686.

Smedley, M.P., Dawson, T.E., Comstock, J.P., Donovan, L.A., Sherrill, D.E., Cook, C.S. & Ehleringer, J.R. 1991. Seasonal carbon isotope discrimination in grassland community. Oecologia 85: 314-320.

Smit, G.N. & Rethman, N.F.G. 2000. The influence of thinning on soil water in a semi-arid savanna of southern Africa. Journal of Arid Environments 44: 41-59.

Smith, D.M., Jackson, N.A., Roberts, J.M. & Ong, C.K. 1999. Root distribution in a *Grevillea robusta*-maize agroforestry system in semi-arid Kenya. Plant and Soil 211: 191-205.

Soil Survey Staff. 1996. Keys to Soil Taxonomy. SMSS Technical Monograph No. 19, 6th ed. Pocahontas press, Inc. Blacksburg, Virginia, U.S.A.

Sprent J. 1995. Legume trees and shrubs in the tropics: N_2-fixation in perspective. Soil Biology and Biochemistry 27: 401-407.

Squires, V.R. & Sidahmed, A.E. 1998. Drylands: Sustainable use of rangelands into the twenty-first century. Rome: International Fund for Agricultural Development.

Steel, R.G.D. & Torrie, J.H. 1980. Principles and Procedures of Statistics second ed. McGraw-Hill, New York.633 p.

Steward, G.R., Turnbull, M.H., Schmildt, S., Erskine, P.D. 1995. C natural abundance in plant communities along a rainfall gradient: a biological integrator of water availability. Australian Journal of Plant Physiology 22: 51-55.

Stone, E.L. & Kalisz, P.J. 1991. On the maximum extent of tree roots. Forest Ecology and Management 46: 59-102.

Sterck, F.J., Van der Zandt, G.J.A.W., & Oldemann, R.A.A. 1991. Architectural development of *Faidherbia albida* (Del.) A. Chev. Physiologie des arbres et arbustes en zones arides et semi-arides. Group d'Etude de l'Arbre, Paris. pp. 249-256.

Sudan Meteorological Department, 2002. Annual reports (1982-2002), Khartoum, Sudan.

Sylla, S.N., Ndoye, I., Ba, A.T., Gueye, M. & Dreyfus, B. 1998. Assessment of nitrogen fixation in *Pterocarpus erinaceous* and *P. lucens* using the ^{15}N labelling methods. Arid Soil Research and Rehabilitation 12: 257-253.

Sylla, S.N., Ndoye, I., Gueye, M., Ba, A.T. & Dreyfus, B. 2002. Estimates of biological nitrogen fixation by *Pterocarpus lucens* in a semi arid natural forest park in Senegal using ^{15}N natural abundance method. African Journal of Biotechnology 1: 50-56.

Torquebiau, E.F. & Kwesiga, F. 1996. Root development in *Sesbania sesban* fallow-maize system in Eastern Zambia. Agroforestry Systems 34: 193-211.

Trouve, C., Mariott, A., Schwartz, D. & Gguillet, B. 1994. Soil organic carbon dynamics under *Eucalyptus* and *Pinus* planted on savannas in the Congo. Soil Biology and Biochemistry 26: 287-295.

Turner, N.C. & Kramer, P.J. 1980. Adaptation of plants to water and high temperature stress, John Wiley & Sons, New York. 482 p.

UNDP/UNSO. 1997. Aridity zones and Dryland populations: An Assessment of population Levels in the World's Drylands. UNSO/UNDP, New York.

Usman, S., Singh, S.P., Rawat, Y.S. & Bargali, S.S. 2000. Fine root decomposition and nitrogen mineralization patterns in *Quercus leucotrichophora* and *Pinus roxburghii* forests in central Himalaya. Forest Ecology and Management 131: 191-199.

Van Noordwijk, M., Lawson, G., Soumare, A., Groot, J.J. & Hariah, K. 1996. Root distribution of trees and crops competition and /or complementarity. *In*: Ong, C.K. & Huxley, P. (Eds.), Tree Crop Interactions-A Physiological Approach. CAB International, Wallingford, UK. pp. 319-364.

Van Noordwijk, M.Radersma, S. & Lusiana, B.1999. Modelling root architecture and phosphorus uptake in agroforestry. Agroforestry Forum 9: 28-30.

Vertessy, R.A. & Bessard, Y. 1999. Conservation of grasslands to plantations: anticipating the negative hydrologic effects. *In*: VI International Rangeland Congress Proceedings (2). Townsville, QLD., Australia, pp. 679-683.

Verzino, G., Carranza, C., Ledesma, M., Joseau, J. & Di Rienzo, J. 2003. Adaptive genetic variation of *Prosopis chilensis* (Molina) Stuntz. Preliminary results from one test-site. Forest Ecology and Management 175: 119-129.

Walcroft, A.S., Silvister, W.B., Whitehead, D. & Kelliher, F.M. 1997. Seasonal changes in stable carbon isotope ratios within annual rings of *Pinus radiata* reflect environmental regulation of growth processes. Australian Journal of Plant Physiology 24: 57-68.

Walker, B.H., Ludwig, D., Holling, C.S. & Peterman, R.M. 1981. Stability of semi-arid savanna grazing systems. Journal of Ecology 69: 473-498.

Wallace, J.S. 1991. The measurement and modelling of evaporation from semi-arid land. *In*: Sivakumar, M.V.K., Wallace, J.S., Renard, C. & Giroux, C. (Eds.), Soil water balance in Sudano-Sahelian Zone. IAHS, No 199. pp. 131-148.

Ward, J.K., Dawson, T.E. & Ehleringer, J.R. 2002. Responses of *Acer negundo* genders to inter-annual differences in water availability determined from carbon isotope ratios of tree ring cellulose. Tree Physiology 22: 339-46.

Warren, C.R. & Adams, M.A. 2004. What determines rates of photosynthesis per unit nitrogen in *Eucalyptus* seedlings? Functional Plant Biology 31: 1169-1178.

Warren, C.R., McGrath, J.F. & Adams, M.A. 2001. Water availability and carbon isotope discrimination in conifers, Oecologia 127: 476-486.

Weil, R.R. & Mughogho, S.K. 1993. Nutrient cycling by *Acacia albida* (syn. *Faidherbia albida*) in agroforestry systems. *In*: Ragland, J. & Lal, R. (Eds.), Technologies for Sustainable Agriculture in the Tropics. ASA Special Publication. 56, ASA, CSSA and SSSA, Madison, WI. pp 97-108.

White, R.E. 1997. Principles and Practices of Soil Science: The soils as a natural resource. Third edition. Blackwell Science, Melbourne. 348 p.

White, R.P., Tunstall, D. & Henninger, N. 2002. An ecosystem approach to drylands: Building support for new development policies. Information Policy Brief 1. Washington, DC: World Resources Institute.

Whitehead, D., Edwards, W.R.N. & Jarvis, P.G. 1984. Conducting sapwood area, foliage area, and permeability in mature trees of *Picea sitchensis* and *Pinus contorta*. Canadian Journal of Forest Research 14: 940-947.

Wickens, G.E., Seif El Din, A.G., Sita, G. & Nahal, I. 1995. Role of *Acacia* species in the rural economy of dry Africa and the Near East. FAO Conservation Guide 27. 85 p.

Wigley, T.M.L. 1999. The science of climate change: global and U.S. perspectives. Arlington, Virginia: Pew Centre on Global Climate Change. 48 p.

Wild, A. (Ed). 1988. Russell's soil conditions and plant growth. 11th edn. Longman Scientific & Technical. John Wiley & Sons, Inc., New York. 991 p.

Wright, G., Hubick, K.T., Farquhar, G.D. & Rao, R.C.N. 1993. Genetic and environmental variation in transpiration efficiency and its correlation with carbon isotope discrimination and specific leaf area in peanut. *In*: Ehleringer, J.R. Hall, A.E. & Farquhar, G.D. (Eds.), Stable Isotopes and Plant Water Relations. Academic Press, pp. 247-255.

Yadav, J.P. & Khanna, P. 1992. Root pruning enhances crop production under *Prosopis cineraria*. Agroforestry Today 4(4): 13-14.

Yoneyama, T., Muraoka, T., Murakami, T. & Boonkerd, N. 1993. Natural abundance of ^{15}N in tropical plants with emphasis on tree legumes. Plant Soil 153: 295-304.

Young, J. 1997. Agroforestry for Soil Management. CABI / ICRAF, Wallingford, UK.

Zahner, R. 1968. Water deficits and growth of trees. *In*: Kozlowski, T.T. (Ed.), water deficits and plant growth II, Academic Press New York. pp. 191-254.

Zhang, J., Marshall, J.D. & Fins, L. 1996. Correlated population differences in dry matter accumulation, allocation, and water-use efficiency in three sympatric conifer species. Forest Science 42: 242-249.

Total of 245 references