NUTRIENT ADDITION AND CROP YIELD OF AN ALLEY CROPPING SYSTEM

IN THE PIEDMONT OF GEORGIA

by

ELEANOR VIRGINIA GREEN

(Under the Direction of CARL F. JORDAN)

Alley cropping, or hedgerow intercropping, is an agroforestry technique in which fast growing leguminous trees are planted in dense hedgerows, and annual crops are planted in the "alleys" between the hedges. Before planting crops, the hedges are pruned, and the leaves are added to soil as mulch. This study compared soil nutrients and crop yields of sorghum planted under four nutrient enrichment regimes including root pruned and root intact alley cropping with *Albizia julibrissin*, leguminous winter cover cropping with *Trifolium incarnatum*, and inorganic fertilizer addition. During a drought year alley cropping provided greater nitrogen additions than the other treatments and similar phosphorus additions to the cover crop treatment. Sorghum yields were highest in the fertilizer treatment and lowest in the cover crop treatment. There appeared to be root competition between the hedgerows for nutrients and moisture, but root pruning the hedgerows reduced competition.

INDEX WORDS: *Albizia julibrissin*, *Trifolium incarnatum*, Hedgerow intercropping, Green manure, Tree prunings

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DEDICATION

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CHAPTER 1

INTRODUCTION

Since the second half of the twentieth century, world crop yields have soared. Much of this increase has been due to intensification of agriculture through mechanization, use of chemical fertilizers and pesticides, irrigation, and development of high yielding crop varieties (Matson et al. 1997). This increase in food production is unprecedented and supports the world's growing human population. However, high intensity agriculture also comes with costs. Fossil fuel energy is relied upon to produce chemical fertilizers and pesticides as well as to power mechanical equipment. In some cases energy consumption exceeds food energy production by over ten to one (Kidd 1992). Such heavy reliance on nonrenewable resources may be unsustainable over the long term. Pesticides and fertilizers used in crop production have entered the environment leading to groundwater and surface water pollution. This pollution has both human health and ecosystem health effects (Perkins and Patterson 1997). When chemical nutrient inputs are combined with intensive tillage, soil organic matter decreases, especially in warm, humid areas. Soil organic matter is important because it increases the nutrient holding capacity and moisture retention of soil (Matson et al 1997). As farming becomes more intensified, fields became larger and crop diversity declines. The decline in biodiversity along with other factors, including pest resistance, has led to increases in insect damage despite increases in pesticide use (Pimentel 1997). Modern agriculture has large benefits, but it also has high environmental costs.

Concerns about the high cost of intensive industrial agriculture has led to increased interest in low-input or organic agriculture. While these farming systems also have costs, the environmental and human health aspects tend to be less damaging than in conventional farming. Organic farms are often thought of as low yielding, but properly managed organic farms can have similar yields to traditional farms after as little as four years (Drinkwater et al. 1998). The problems that chemical fertilizers solve in conventional western agriculture still remain to be solved in alternative ways. Soil amendments are needed to sustain crop yields. Adding organic residues increases retention of soil C and N (Drinkwater et al. 1998). Adding compost or manure is one option but these amendments are produced in other places and then must be transported to the farmers' fields. Interest in cover crops has revived in recent years as a method to maintain soil fertility, reduce fertilizer use, and reduce erosion (Hoyt and Hargrove 1986, Teasdale and Abdul-Baki 1998, Mueller and Kristensen 2001). However, cover crops have a few disadvantages. They must be replanted each season that they are used, and land is taken out of production if the cover crop is used as a nutrient amendment. Also inputs from herbaceous cover crops may not be sufficient at supplying nitrogen and phosphorus to a continuous cropping system. Another organic amendment option is alley cropping or leguminous hedgerow intercropping. Natural systems were guides for the development of alley cropping systems. Ecosystem services that are found in forests are brought to agroecosystems by planting trees within fields. While alley cropping has been widely promoted in the tropics as an option for subsistence farmers, few studies have been done of this technique in the temperate zone (Matta-Machado and Jordan 1995, Nair et al. 1999, Seiter et al. 1999).

In the United States, alley cropping has greatest potential as a technique on small organic farms. It is easier to incorporate alley cropping into farming systems that rely on light machinery and manual labor. Seiter et al. (1999) found highest interest in alley cropping among small-scale farmers who intensively managed their land. Several factors make alley cropping appropriate for organic growers. Many organic farmers grow multiple crops in their beds. This familiarity with intercropping may make them more accepting of planting hedgerows within their fields. The greatest costs associated with alley cropping are labor costs and loss of productive land due to hedgerows. However, by adapting alley cropping techniques to mechanical methods and introducing alley cropping to areas with low land values, the techniques may be economically viable. Also organic farmers are able to absorb limited increases in costs of production because organic products are high value crops. Leguminous hedgerows provide nutrient additions similar to other on-site organic inputs and help maintain soil fertility. Hedgerows restore some ecosystem functions to fields by increasing nutrient cycling and maintaining levels of soil organic matter.

The Piedmont of Georgia is an excellent place to test the appropriateness of alley cropping in the United States. Soils in the Piedmont are similar to the tropical soils in areas where alley cropping was originally developed. Piedmont soils are old, weathered, and acidic with low nutrient holding capacities. The growing season is long which enables the hedgerows to produce large amounts of biomass in a single season. Organic farming is also a growing industry in northeast Georgia as is demonstrated by organic grocery stores, organic farmers markets, and restaurants serving organic produce. Most organic farms in northeast Georgia are small and intensively managed. In general land values are low and farmers are not land limited. Organic growers and gardeners in the Georgia piedmont are potential adopters of alley cropping techniques.

In this study we examine the ability of a mature alley cropping system to provide nutrients to a grain crop. Few, if any, studies have looked at a mature alley cropping system in the temperate zone. In order to determine the appropriateness of alley cropping, it is compared to other cropping systems. One method of soil improvement used by organic farmers is the planting of a winter cover crop. Cover cropping with a winter legume is a similar system to alley cropping because both systems add available N to the agroecosystem through the symbiotic relationship of legumes with *Rhizobia*. Alley cropping uses perennial legumes while cover cropping systems use annual legumes.

Trifolium incarnatum L., crimson clover, has a long tradition as a green manure in the southeastern United States. It has been used as a winter cover crop and green manure since the 1800s (Knight 1985). Conventional farming systems use fertilizer and lime to maintain soil fertility. In this study alley cropping is compared to cover cropping with crimson clover and to addition of inorganic fertilizers.

This study attempts to determine the effectiveness of hedgerow intercropping at providing nutrients, increasing crop yields, and improving soil quality as compared to other nutrient addition strategies. Nutrient inputs from leguminous hedgerow intercropping are compared to the other systems. N and P are focused on because these nutrients are often limiting to plant growth in the Georgia Piedmont. In order to determine the overall effectiveness of alley cropping, crop yields are compared between alley cropping, cover cropping and fertilizer treatments. One of the advantages of alley cropping is that it increases long-term sustainability by improving soil quality. Both chemical and physical soil properties are examined to determine changes in soil quality. Alley cropping is not effective if there is competition between crops and the hedgerows. Here, the effects of competition are examined by reducing root competition. Finally a brief economic examination is conducted to determine if costs of alley cropping is higher than other farming systems.

CHAPTER 2

LITERATURE REVIEW

A Need for Agroforestry

Soil degradation is a worldwide problem. Some areas of sub-Saharan Africa have lost over 650 kg N ha^{-1} in the last 30 years (Brady and Weil 1999). Much of the decline in soil quality is linked to human population growth. As populations increase, demands for natural resources and agricultural products also increase. Population growth sparks several major trends including deforestation, high rates of urbanization, reduction of fallow periods, and increased cultivation of marginal lands (Cooper et al. 1996). All of these trends lead to soil degradation. When forests are cleared, nutrients are removed, nutrient conserving mechanisms are lost, and soils degrade as nutrients leach out (Jordan 1985). Urbanization leads to the conversion of arable land to urban land and increases local demand for agricultural products. As the amount of high quality arable land decreases and the demand for agricultural products increases, external inputs are added to increase yields, fallow periods are shortened and marginal land is brought into cultivation. Marginal lands degrade quickly, and shortened fallow periods prevent soil nutrients from building back up (Stoorvogel et al. 1993). As crop yields on degraded lands decline, fallow periods are shortened even more, and additional marginal land is converted to agricultural land.

In developed countries, farmers increase crop yields by using external inputs, increasing the scale of farms, using mechanization, and using improved crop varieties. Crop yields have increased dramatically, but there are also costs associated with intensive agriculture. Mechanization leads to erosion, pollution of rivers and streams with sediment, and filling reservoirs (Soule and Piper 1992). Increased chemical use has led to pollution of water supplies, chemical residues on foods, and increased pesticide resistance. Nitrate, from fertilizers, animal wastes, and crop residues is the most prevalent chemical pollutant. It seeps into shallow and deep aquifers and pollutes ground water. Both nitrate and phosphorus are easily transported in runoff and contribute to eutrophication (Tilman 1998). Nitrate runoff can lead to eutrophication of estuarine and nearshore ecosystems affecting coastal fisheries (Vitousek et al. 1997). Though pesticide runoff is often low, it can affect other crops, aquatic systems, and top predators (Soule et al. 1990). Many of the costs of high input farming are societal costs that are not factored into the monetary cost of food or its production (Mäder et al. 1999)

With the Green Revolution, developed countries tried to help developing countries by exporting new crop strains, agricultural equipment, and chemicals. Crop yields did increase, especially in Asia, but there were questions about the long-term sustainability of the technologies introduced (Garett and Buck 1997, Matson et al. 1997, Jordan 1998). Besides the problems that where found in developing countries, other aspects of Green Revolution technology tempered its success in the developing world. Many subsistence farmers were unable to take part in the capital-intensive technology of the Green Revolution. High input agricultural technology was inappropriate for farmers unable to afford the technology (Nair, 1993). In some cases the advanced technologies were made available through subsidies, but when these subsidies were reduced, agricultural costs increased dramatically for farmers (Matson et al. 1998). Changes in the crops grown put new strains on limited resources such as water and sometimes lead to aquifer depletion, salinization, or waterlogging (Matson et al. 1997). After the shine of the Green Revolution began to dull, system oriented, low-tech strategies were developed. One of the new emerging fields was agroforestry.

Agroforestry techniques are based on the idea that trees increase nutrient cycling, improve soil fertility, and support the growth of crops (Nair et al. 1999). There are many cropping systems that fall under the umbrella of agroforestry. Some of these systems are taungya, silvo-pastoral, improved fallows, shaded perennial-crop, parkland systems, and alley cropping. Taungya is a system developed in southeast Asia. Subsistence food crops are planted between juvenile timber trees, such as teak (Boonkird et al. 1984). More recently this system has been introduced into Latin America (Schlönvoigt and Beer 2001). Silvo-pastoral systems include planting leguminous trees and allowing animals to graze directly on the trees, or cutting and carrying the leaves from leguminous trees to animals (Cooper et al. 1996). Perennial crops such as coffee or cacao are planted under a canopy of trees, often leguminous, in a shade perennial-crop system. The trees may be coppiced periodically with the leaves used as mulch for the perennial crop or fed to animals (Beer et al. 1997). In parkland systems, crops are grown under an open, managed canopy of mature, often naturally occurring, trees (Kater et al. 1992, Vandenbelt and Williams 1992, Rhoades 1997).

Alley cropping or hedgerow intercropping, first developed in the 1970s, is a departure from traditional farming systems (Kang and Wilson 1987). Many traditional farming practices incorporate scattered trees within farms. These trees are mainly used to provide products for sale or for human consumption. Alley cropping is a new step because the trees are used primarily for soil improvement. Hedgerows of trees, often leguminous, are planted throughout farms, and crops are planted in the “alleys” between the hedgerows. Hedgerows ware spaced from four to eight meters apart and trees are spaced about every quarter meter within the hedgerows. By combining deep rooting trees with shallow rooting crops, alley cropping systems use resources more efficiently than monocropping systems. The trees are able to utilize nutrients in the subsoil, which are unavailable to crops. Many tropical soils are highly acidic and have low capacity to hold nutrients. Tree roots are able to capture nutrients that otherwise would leach out of the system. Many hedgerow species also add N to the system through symbiotic bacteria that fix atmospheric nitrogen in root nodules. The trees are pruned before planting season, and the leaves are used as green manure. In this way the nutrients recovered by the trees are made accessible to the crops. The stems of the hedgerows are used as firewood or as beanpoles. After pruning the trees re-sprout and grow back very quickly. Alley cropping also has a few drawbacks. Care must be taken in selecting the hedgerow species and locations to reduce competition between hedgerows and crops. If the hedgerows begin to shade out the crops in the alleys, the trees are pruned again and the leaves are used as mulch (Nair 1993).

Biophysical Effects of Alley Cropping

Initial studies of alley cropping were very promising. Hedgerows produced large amounts of biomass high in nutrient content. Green manure additions maintained soil fertility and increased crop yields (Kang and Wilson 1981, Chen et al. 1989, Juo 1989, Lal 1989, Kang et al. 1990, Szott et al. 1991). Other benefits were also associated with alley cropping. Soil physical properties were maintained or improved because of large additions of organic matter. Hedgerows planted along contour lines reduced erosion, a major cause of soil degradation in the tropics. Increased biodiversity in crop fields was predicted to reduce agricultural pests (Nair 1993). These initial studies were often short term, field station studies focusing on the establishment of leguminous hedgerows. The effectiveness of alley cropping may have been overestimated due to experimental design errors such as small plot sizes and controls without any nutrient inputs (Sanchez 1994, Cooper et al. 1996). Many of these problems were corrected in later studies. On-farm studies and adoption of techniques by farmers allowed analysis of alley cropping in real world situations.

Though later studies verified the beneficial effects of alley cropping, limits to its effectiveness were also discovered. Alley cropping was not a panacea for all farmers and all situations. Factors such as climate and soil quality determined the success of alley cropping at particular sites. Depending on the hedgerow species selected, alley cropping systems were able to maintain soil fertility and increase crop yields in areas with sufficient rainfall and moderate to high soil fertility (Dalland et al. 1993, Kang 1993, Salazar et al. 1993, Mureithi et al. 1994, Shannon and Vogel 1994, Alegre and Rao 1996, Shepherd et al. 1996, Mugendi et al. 1999, Tossah et al. 1999). Alley cropping helped to maintain soil fertility by increasing nutrient cycling and reducing leaching of nutrients (Kang 1997, Chamshama et al. 1998, Lehmann et al. 1999). When nitrogen-fixing trees were pruned, they shed their nodules providing additional subsoil nutrients. (Nygren and Ramírez 1994). During decomposition fine roots may have released nutrients faster than decomposing leaves (Jose et al. 2000b). While it was easy to quantify the amount of nutrients provided by the green manure, below ground interactions were much harder to describe. In a review article, Kass et al. (1997) suggested that below ground inputs were large. However Nygren and Ramírez (1995) found that roots of periodically pruned *Erythrina* contributed only a small amount of nitrogen compared to the contribution from the leaves. In some cases root die back after pruning may have lead to increased leaching of soil nutrients (Peter and Lehmann 2000). Timing hedgerow pruning to coincide with nutrient demands of the crop led to increased crop yields (Mafongoya and Nair 1997). In general, hedgerows were most successful at supplying N to the crop. Nutrient balances suggested that other nutrients, especially P, were being slowly drained from the soil over several years (Onim et al. 1990, Gachengo et al. 1999, Lupwayi and Haque 1999).

Though cuttings alone may not provide enough P for crops, estimating P availability solely from P inputs and outputs may be misleading. Only a portion of P added to soils becomes available to plants. In acidic soils, large amounts of plant available P in solution, PO_4, become unavailable to plants when P adsorbs to Al or Fe oxides. Adding organic sources of P may reduce the amount of P that becomes fixed and unavailable to plants. As high quality leaves decompose, organic acids are formed. These organic anions bind to Al and Fe oxides, competing with P for binding sites, reducing P adsorption, and making more P available to crops (Iyamureye and Dick 1996, Nziguhebe et al. 1998, Mäder 1999). Additions of organic matter and the binding of organic acids also leads to reductions in Al saturation and toxicity (Wong et al. 1995). Organic additions of P may be more available to plants over a season because P is mineralized gradually as the organic matter is decomposed.

If nutrient imbalances occur, it may be necessary to occasionally fallow farmland or to add minimal amounts of fertilizer or manure for maintenance of crop yields (Jabbar et al. 1994, Palm 1995, Cooper et al. 1996, Lupwayi et al. 1999, Samsuzzaman et al. 1999). In some cases, farmers have modify alley cropping systems to include a fallow period (Adesina et al. 2000). Fertilizer additions are also necessary for high crop yields such as the ones found in the developed world (Dallard et al. 1993, Danso and Morgan 1993, Shannon et al. 1994, Chamshama et al. 1998). If fertilizer is applied to alley cropping systems, interactions between the leaf litter and the fertilizer should be taken into account. Zaharah and Bach (1997) found that green manure from hedgerows increased solubility of less reactive phosphate rock and had no effect or a slight negative effect on the solubility of reactive phosphate rock. Addition of green manure from hedgerows also improves soil physical qualities such as bulk density (Alegre and Rao 1996, Samsussaman et al. 1999).

Alley cropping is seldom effective in extreme conditions because the hedgerows compete with the crops. Crop yields are suppressed in semi-arid areas and on infertile, acidic soils because of competition for water and nutrients (DePauw 1994, Sanchez 1995, Cooper et al. 1996, Rao et al. 1998). In resource-poor environments, hedgerow roots are more concentrated in upper soil layers, increasing competition with crops. Nitrogen fixation is limited when nutrients or soil moisture are low and the trees are severely stressed. Low yields of hedgerow prunings also contribute to low crop yields in infertile soils (Matthews et al. 1992b). One exception to growth on poor soils is on soils with an unusually fertile sub-soil although such soils are quite rare. If a degraded topsoil is above a relatively fertile sub-soil, alley cropping may lead to regeneration of the degraded top soil (Aihou et al. 1999). Alley cropping is successful on some acidic soils after organic matter accumulates for several years (Akyeamong and Hitimana 1996). High yields can also be found on acidic low fertility soils, if fertilizer or lime is added (Matthews et al. 1992a, Akeampong et al. 1995, Gachengo et al. 1999). In arid or semi-arid areas the trees compete with the crops for water, and crop yields are suppressed (Balasubramanian and Sekayange 1991, Kiepe and Rao 1994, Govindarajan at al. 1996, Korwar and Radder 1997, McIntyre et al. 1997, Lehmann et al. 1998, Mathuva et al. 1998, Odhiambo et al. 2001). Competition for water can be reduced however. Lehmann et al. (1998) found that root density of hedgerows decreased dramatically after pruning. They also found that hedgerows had more deep roots in the subsoil when intercropped with sorghum than when grown alone. In their opinion, alley cropping utilized soil resources more efficiently than a monoculture. In general alley cropping is not a suitable system in arid areas, but some success has been found with parkland agroforestry. Although alley cropping is generally less effective in harsh environments, modifications or species selection may allow alley cropping to be effective in areas where soils are dry, infertile, or acidic.

For alley cropping to be effective, the hedgerows must supply nutrients to the crop without competing for resources. Planting hedgerows with shallow rooted annual crops instead of deep-rooted perennial crops reduces competition. Hedgerow species with greater concentration of roots near the tree and in the sub-soil also reduce competition (Ruhigwa et al. 1992). Even when roots overlap spatially, there may be limited competition if hedgerow roots die off before crop roots grow (Odhiambo et al. 2001). Under fertile conditions competition is limited though evidence of minor competition has been seen in a few studies. Lupwayi et al. (1999) found that the maize growing closest to hedgerows did not respond to leaf inputs, inorganic fertilizer inputs, or manure additions. Presumably the hedgerows were out competing the maize for the nutrient additions. However the competition effects were easily offset by increased maize yields in the other rows. Trenches or root barriers can be effective at reducing competition for moisture and nutrients (Jose et al. 2000a). Peter and Lehmann (2000) found that pruning acacia hedgerows reduced root development and may have reduced below ground competition with the intercropped plants. The root dynamics of intercropping are still not understood though some studies have found increased yields when hedgerow roots were separated from crop roots (Schroth and Lehmann, 1995). Hedgerows and crops may also compete for light (Corlett et al. 1992, Friday and Fownes 2001), but light is often a less important interaction than competition for nutrients or water (Mugendi et al. 1999). Competition for light may be more important for ground creeping crops than for tall crops such as maize (Tonye and Titi-Nwel 1995). In some cases competition is beneficial. Akobundu et al. (1999) found weeds were better managed in an alley cropping system than in a traditional fallow system. Competition between hedgerows and crops is a problem when resources are severely limited.

Insect Effects of Alley Cropping

The natural enemies hypothesis suggests that vegetative diversity increases the population size of natural enemies which in turn regulate arthropod pests (Altieri 1990). According to this hypothesis, alley cropping systems (which have a diversity of microhabitats) should have reduced arthropod pest populations. Promoters of alley cropping often mention pest reduction as one of the benefits of alley cropping (Kang 1993). Few studies have tested this hypothesis in alley cropping systems. The studies that have been done present mixed results. One study in England found that hedgerows were correlated with higher natural enemy abundance and lower pest abundance (Peng et al. 1993). This study examined many natural enemies including generalist predators. Ogol et al. (1998) found the opposite results, but they examined specialist predators, parasitoids.

According to the resource concentration hypothesis, specialized insects will be less abundant in polycultures. The heterogeneity of the landscape may disrupt cues used by specialized parasitoids to find their hosts. These studies suggest that hedgerows provide shelter and alternate food sources for generalist predators, but not necessarily for specialist predators. Girma et al. (2000) found that arthropod abundance could not be generalized. Beanfly infestation was greater in hedgerows of one species, *Gliricidia*, but wasp activity was highest closer to hedgerows, and maize suffered from fewer stem borers in between hedgerows than in sole cropped plots.

Erosion Effects of Alley Cropping

Alley cropping is effective at conserving soil by reducing erosion (Kass et al. 1999). The erosion control effect is most pronounced in steeply sloping land with intense rainstorm events. When hedgerows are planted on contour bunds, they stabilize the bunds and significantly reduce erosion (Shepherd et al. 1997). Hedgerows aid in the formation of terraces, especially on the lower parts of slopes (Shepherd et al. 1997, Agus et al. 1999). After only one cropping season, slopes are reduced behind the contour bunds. Unlike other soil improvements made by alley cropping, hedgerow reduction of erosion occurs quickly and is easy for farmers to see and appreciate.

Alley cropping improves soil physical and chemical properties. The hedgerows help to recycle nutrients and help to maintain soil fertility in the topsoil. Biomass inputs also provide a constant replenishment of soil organic matter. However, alley cropping does not cause immediate and drastic changes in soil properties. Soil properties improve under alley cropping, but restoration of degraded soils happens very slowly. Alley cropping is most effective at maintaining soil fertility on continuously cropped land. In short, alley cropping is not a quick fix, but a slow and steady way to manage low input agriculture.

Economic and Social Factors

The appropriateness of alley cropping depends on other factors besides soil fertility and crop yields. Farmer adoption of alley cropping systems also depends on economic and social factors. Labor costs and opportunity costs need to be offset by benefits. Land tenure practices have a large influence on alley cropping adoption rates. The roles of men and women in a society help to determine interest in alley cropping. Some farmers hesitate to adopt alley cropping because they are risk adverse or because soil health and fertility are not there most immediate concerns. Both social and economic factors are important when farmers are deciding whether to adopt new farming techniques.

Alley cropping systems do not require expensive outside inputs, but there are non-monetary costs associated with alley cropping. Hedgerow establishment is labor intensive and occurs during planting, a period of peak labor demand. Labor inputs may be doubled the first cropping season of alley cropping (Ngambeki 1985). Tree establishment is lowered when labor costs are reduced by cutting corners, i.e. not weeding the seedlings (Swinkels and Franzel 1997). After hedgerow establishment, labor demands continue. Though maintenance tasks, such as pruning the hedgerows, are less labor intensive, they also occur during peak labor times (Nelson et al. 1997). If pruning is delayed, farmers may suffer serious crop yield losses (Versteeg et al. 1998). Maintenance tasks are necessary if farmers are to receive the full benefits of alley cropping. In some cases farmers reduce labor by not incorporating the hedgerow leaves into the soil when tilling and risk losing much of the soil fertility benefits (Fujisaka 1993). Over time, labor costs are reduced as farmers learn the new system (Swinkels and Franzel 1997).

Opportunity costs of land are also important. About 20% of farmland is no longer available for crop production when hedgerows are planted every 4 m (Ehui et al. 1990). For alley cropping to be cost effective, crop yields must increase on the 80% of farmland that is in production. Depending on rainfall and temperature, it takes three to four years before increases in crop yields due to improved soil fertility are obtained (Carter 1995). If labor costs are low and land is not severely limited, crop yields need to increase only a small amount to make up for establishment and opportunity costs (Swinkels and Franzel 1997). When there is little competition between hedgerows and crops, alley cropping may be the best option for farmers even in the first three years of alley cropping (Tonye and Titi-Nwell 1995). Cost benefit analyses are used to determine if the benefits that alley cropping produces over time out weigh competing investment opportunities (Nelson et al. 1997). Most cost benefit analyses do not include benefits related to nutrient cycling since nutrient dynamics are quite complicated. Instead they take into account the effects of erosion reduction. Studies comparing alley cropping to traditional systems show that traditional systems are more profitable in the short term, but alley cropping systems are more profitable in the long term (Ehui et al. 1990, Nelson et al. 1997).

Land tenure and local financial structures also influence alley cropping adoption. In developing countries, there are a variety of land tenure systems. In southern Nigeria farmers may own land outright, share communal rights to land, have rights to land only until it is put into fallow, or use another farmer's land. Land and trees are often treated as separate entities (Lawry et al. 1994). Agrarian reform in the Philippines has been slow, and many cultivators are tenant farmers with no guarantee of long term use of farmland (Nelson and Cramb 1998). It makes little sense for tenant farmers risking eviction or farmers with no clear title to the land they farm to invest in long term improvements that they may never benefit from. Not surprisingly, adoption of alley cropping is positively correlated with long-term land tenure (Lawry et al. 1994). In many rural areas credit is nonexistent (Nelson and Cramb 1998). Without credit, farmers have to bear the initial cost of low yields themselves. Farmers with few resources may not be able to handle the initial financial burden. Many farmers do not adopt alley cropping because they are unwilling or unable to wait for a delayed payoff.

Though they are more difficult to quantify and measure, gender roles play an important part in the decision to adopt alley cropping. In much of Africa women are the main beneficiaries of alley cropping because they are the primary producers of food crops. However women may have social restrictions that make it hard for them to adopt alley cropping. In some cultures there are taboos against women using machetes or women cutting trees (Swinkels and Franzel 1997). Other cultures do not allow women to plant tress because it implies ownership of land. Digging along a contour is believed to cause miscarriages in the Northwest Province of Cameroon (personal observation). In that area women are initially slow to adopt alley cropping because they are hesitant to build contour bunds. Risk adverse farmers prefer a lower average income that is consistent than a higher more variable one (Pannell 1995). Because the food they raise is what will feed their families, many women are more risk adverse then men and less likely to adopt new technologies (Adesina 1996). In many cultures, women are less likely to own land than men. Gender issues need to be taken into account when introducing alley cropping to women.

Ability to take risks and cultural practices also affect farmers' interest in alley cropping. Farmers who have little surplus each year are likely to have short planning horizons and to be risk adverse. Long-term gains are not important if a farmer cannot remain solvent during the short term. Risk adverse farmers are hesitant to adopt any new technology unless it is heavily subsidized or risk-free. They are unlikely to adopt alley cropping, because it is not profitable in the short term. Farmers in areas with land shortages may lack extra land to experiment with a new technique (Adesina et al. 2000). Traditional agricultural practices help to determine whether farmers will be receptive to alley cropping. Cultures with traditions of planting trees and augmenting the soil produce farmers who are more open to alley cropping. Farmers with good access to markets and fertilizers are less likely to see soil fertility depletion as a problem. They are more likely to use fertilizers, especially to increase cash crop yields. Often these farmers are more interested in increasing revenue then in long term soil improvements. Since they do not see declining soil fertility as a problem, they are unlikely to adopt alley cropping (Nelson and Cramb 1998). Higher adoption rates of alley cropping occur when soil fertility decline is a concern of farmers (Shepherd et al. 1997). Cultural factors contribute to farmers' decisions to adopt new agricultural techniques.

Socioeconomic factors can determine whether farmers choose to adopt alley cropping. Land tenure determines whether farmers are interested in making long term improvements to the soil. The most important economic factor is the delayed payoff of increased yields. While labor and land shortages can prevent farmers from adopting alley cropping, the land and labor costs are less important when those costs are low. When farmers have cheaper or easier options, such as subsidized cheap fertilizers, they will be unlikely to adopt alley cropping. Cultural factors such as taboos and risk aversion also discourage adoption of alley cropping. Farmers most likely to adopt alley cropping are successful progressive farmers who are concerned about decreasing soil fertility and farmers who most benefit from secondary effects such as fuel wood production (Adesina et al. 2000).

Temperate Zone Alley Cropping

Five major types of agroforestry are practiced in North America: windbreaks, riparian buffers, forest farming, silvo-pastoral systems, and alley cropping. Windbreaks or shelterbelts have long been used in the United States. They are most common in the northern plain states where wind erosion is a serious problem. Riparian buffer systems are mixed vegetation corridors along streams and rivers. They are effective at reducing non-point source pollution of waterways in agricultural areas as well as areas with large amounts of new development. Forest farming is the creation of favorable microenvironments for non-timber forest products in a preexisting forest. This system is most popular in the Pacific Northwest, Appalachian states, and New England (Garrett and Buck 1997).

Alley cropping in temperate areas is quite different than alley cropping in the tropics. In most systems, high value trees are planted in widely spaced rows and are the main income generators in the system. Crops or forage are planted in between the trees to provide additional income. In some cases crops may be selected which will improve the growth and yield of the trees (Dupraz et al. 1999). The most common tree species used in this system is black walnut (*Juglans nigra* L.). Other trees used in this system include pecan, oak, white ash, silver maple, poplar and cottonwood. Companion crops planted within the alleys include row crops (corn, soybeans, winter wheat, barley) and forage crops (orchard grass, red clover, alfalfa, timothy) (Garrett and Harper 1999). Though these systems are more complicated to manage than traditional farming or forestry systems, they may be more favorable investments then monocultures (Benjamin et al. 2000). In some ways this system resembles the tangyua system more than alley cropping as it is practiced elsewhere.

Few studies have looked at temperate alley cropping systems in which the trees provide nutrients to the other crop through improved nutrient cycling or nitrogen fixation. Thevathasan and Gordan (1997) examined the effects of poplar leaves on corn and barley in southern Ontario, Canada. They found that the addition of poplar leaves through leaf fall may have increased nitrification rates and total soil organic carbon. An alley cropping system with leguminous hedgerows was established at the Rodale Institute in Pennsylvania (Matta-Machado 1992). Seiter et al. (1999) established several alley cropping plots in Oregon in 1991. They compared yields of sweet corn grown with two hedgerow species, black locust (*Robina pseudoacacia*) and red alder (*Alnus rubra*) in four cropping patterns. They found minor fertility improvements in alley cropping systems as compared to a monocropped system, but both systems had declines in soil organic matter. Yields were higher in monocropped systems because there was more area to plant corn. Hedgerows of mimosa (*Albizia julibrissin*) were planted with grain sorghum in the Piedmont of Georgia. In the first three years after hedgerow establishment, hedgerows affected nitrification rates though there was no difference in soil nitrogen (Matta-Machado et al. 1994). Hedgerows had significant effects on plant short term available nitrogen, and sorghum yields were higher in hedgerow plots than in plots with crimson clover (*Triticum aestivum* L.) as a winter cover crop (Rhoades et al. 1998). Though a few studies have been conducted on temperate alley cropping systems with leguminous hedgerows, none of these studies have examined the system after the hedgerows are mature and well established.

CHAPTER 3

MATERIALS AND METHODS

The main goal of this project was to determine the effectiveness of alley cropping at providing nutrients to a grain crop. Leguminous hedgerow intercropping was compared to two nutrient addition strategies currently practiced in the Piedmont of Georgia, winter cover cropping and inorganic fertilizer addition. Inorganic fertilizer addition was used as the control instead of a treatment without nutrient additions because Piedmont soils cannot support continuous cropping without additions. Nutrient inputs from the alley cropping and cover cropping treatments were determined by measuring biomass and nutrient concentration of the biomass. Total crop biomass and nutrient concentration of the crop biomass were used to estimate nutrient outputs of treatments. Crop grain yields indicated how well the crop utilized nutrients provided by each treatment. Factors that indicate the long term sustainability of nutrient addition treatments was also examined. Soil nutrient analyses were conducted to determine if nutrients were building up in or being drained from the soil. Physical properties indicative of soil health, bulk density and wet aggregate stability were measured. Because this study was conducted during a drought, water may have been a limiting factor to plant growth. Soil moisture was measured to determine if water availability differed between treatments. Finally, a simple economic analysis was performed. Any new farming system would be unlikely to be adopted if the costs of the system outweighed the benefits provided, or the costs of the system outweighed the costs of systems currently being practiced. During the 2000 cropping season, the costs of each nutrient addition system were compared.

Study Site and Treatments

This study was performed in northeastern Georgia, USA (33˚57' N latitude, 83˚19'W longitude). The soil was an Ultisol of the Madison series (clayey, kaolinitic, thermic, typic, hapludut.) and had a sandy loam texture, with 77% sand, 15% silt, and 8% clay (Matta-Machado and Jordan 1995). The climate is humid subtropical with average annual precipitation of 1260 mm and average annual temperature of 17˚C (Owenby and Ezell 1992). The data presented here was collected during the 1998-2000 cropping seasons. These years were the second and third years of a severe drought in Georgia, and local annual precipitation was only 73% of the long-term average (Figure 1).

Mimosa hedgerows had been established in January 1990 as part of a previous project. The hedgerows were planted 4 meters apart, and trees within the hedgerows were spaced 0.5 m apart. Each hedgerow plot consisted of three alleys. Beginning in June 1991, *Sorghum bicolor* (grain sorghum) was planted in the alleys between the hedgerows using a no-till planter. After sorghum seeding, the hedgerows were trimmed to a height of 60 cm and the branches and leaves were spread as mulch on the alleys. Planting was discontinued in the mid-1990s and the plots were left to fallow.

This project was begun in October 1998. The three treatments established included winter annual legume cover crop (CC) with *Trifolium incarnatum* (crimson clover), alley cropping (AC) with *Albizia julibrissin* (mimosa) as the perennial leguminous hedgerow, and inorganic fertilizer addition (IF) of 10-10-10 and dolomitic lime. Each treatment consisted of three 240 m^2 experimental plots established on a gentle slope. The experimental design was completely randomized design (Figure 2). In November 1998 crimson clover seeds were broadcast at a rate of 54 kg ha^{-1} in the CC treatment. In late May 1999, all plots were mowed and tilled using a rotary hoe. Roots were trimmed with a sub-soiler to a depth of 1 m in sub-plots of the AC treatment. Surface residue, including clover in the CC treatment, was tilled into the soil. Because of hardness of the dry soil, some patches were not tilled deeply. Sorghum was planted using a hand planter in rows approximately 40 cm apart. After sorghum planting, *A. julibrissin* hedgerows were pruned using a chain saw and machetes. Branches were removed from the site, and leaves were added to the alleys (Figure 3). Inorganic fertilizer (448 kg/ha of 10-10-10) and dolomitic limestone (4480 kg/ha) were added to the IF treatments. Sorghum yields were extremely low and patchy in 1999 making statistical analyses difficult.

The study design was altered during the second year to better test for the effect of competition between the hedgerows and the crop species. Plot maintenance and weeding had been a serious problem during the first field season, and as a result, plot sizes were reduced to a more manageable size of 120 m^2. Two paired treatments, root pruned hedgerows (RP) and root intact hedgerows (RI), replaced the AC treatment of the previous year (Figure 2). Root competition was reduced in the root pruned treatment by trimming *A. julibrissin* roots. In November 1999, crimson clover was broadcast in the CC treatment. Rows of *Triticale aestivum* (winter wheat) approximately 30 cm apart were planted in the other treatments. However, RI, RP, and IF treatments were dominated by *Lolium perenne multiflorum*, not winter wheat. In May 2000 all plots were mowed. Aboveground biomass in the RI, RP, and IF treatments was removed. Removal of nutrients stored in aboveground biomass stressed each system and forced sorghum to rely less on stored nutrients in each system and more on the nutrients provided by the treatments. Aboveground biomass was left on the soil in the CC treatment because the crimson clover residue was the nutrient addition for that treatment. As in 1999, inorganic fertilizer and limestone were added to the IF treatment. In the RI and RP treatments *A. julibrissin* hedgerows were pruned with machetes, and leaves were added to the alleys. Roots were trimmed with a sub-soiler in the RP treatment. In all treatments the nutrient additions were incorporated into the soil using a rotary hoe.

In late May 2000, sorghum was planted in rows approximately 40 cm apart using a no-till planter. Twelve rows of sorghum were planted in the RI and RP treatments and

20 rows of sorghum were planted in the IF and CC treatments. When hedgerow re-growth began to shade the sorghum, the hedgerows were trimmed back with a machete. The leaves and branches were left in the alleys as additional mulch. In September 2000, sorghum was harvested in all treatments. All weeding was done by hand and no pesticides, herbicides, or fungicides were used during the course of this study. No fertilizer was added to the hedgerow and clover treatments, since before 1990.

Plant Sampling and Analysis

In order to calculate the nutrient inputs and outputs of each system biomass and nutrient concentrations of biomass were determined. Nutrient inputs and outputs were estimated by multiplying nutrient concentrations by total biomass. Crimson clover biomass was determined by taking three 0.25 m^2 aboveground samples from each CC plot in May 1999 and May 2000. Alley cropping biomass addition was measured after the hedges were pruned. Mimosa leaves were spread in the alleys between the hedges and one 0.25 m^2 quadrat was collected in each alley. In order to reduce the amount of mimosa leaves removed for sampling, biomass additions of RI and RP treatments were combined and analyzed as one alley cropping treatment in 2000. Mimosa roots were pruned in the RP treatment after the sampling of mimosa leaves.

In September 1999 and 2000, sorghum grain, stover, and root biomass was determined by hand harvesting six 1 meter rows of sorghum in each plot. Sorghum plants were harvested in their entirety and separated into roots, stover, and grain. Further sampling was conducted during the second field season to determine the effects of root competition between sorghum and *A. julibrissin*. In the RI and RP treatments, half of the sorghum rows sampled bordered hedgerows on one side and half of the sorghum rows sampled bordered sorghum rows on both sides. In order to compare weed biomass, aboveground biomass was collected in three 1 m^2 quadrats per plot. The plant material was separated into weeds, sorghum stover, and sorghum grain. All biomass samples were dried in a drying oven for 48 hours, and the dry weight was recorded.

Nutrient analyses were performed to determine the nutrient concentration of the biomass samples. Grab sub-samples were dried at 60˚C and ground to pass through a 0.15 mm sieve. Total C and N were determined by Micro-Dumas combustion. Ground sub-samples were ashed at a temperature of 450˚C and digested in a double acid extractant (Jones 1990). Total P was analyzed using a colorimetric analyzer (Coakley 1981). Potassium, calcium, and magnesium were analyzed using a flame atomic absorption spectrophotometer (Baker and Shur 1982).

Soil Sampling and Analysis

Long-term effects of treatments were determined by examining soil chemical and physical properties. Soil nutrients were measured at the beginning and end of each growing season to determine if soil nutrients were increasing or decreasing in the soil over time. Soil physical properties such as bulk density and water stable aggregates were measured after the last cropping season. Low bulk density and high aggregate stability would indicate high nutrient and water holding capacity of soil. Soil moisture was measured to determine if hedgerows were competing with the crop for water.

Three composite soil samples 0-5 cm were collected from each plot in May 1999, October 1999, May 2000, and October 2000 and used for nutrient analyses. In the CC and IF treatments, the samples consisted of the upper, middle, and lower portion of each plot. In the hedgerow treatments the samples were collected from the hedgerows, one meter from the hedgerows, and the middle of the alleys. Each sample was taken at a depth of 0-5 cm.

Soil samples were oven dried at 60˚C. Available pH of the soil was measured with a pH meter using a 1:3 mixture of soil (10 g): dionized water (30 ml). Sub-samples were ground to pass through a 0.15 mm sieve and used in nutrient analyses. Total C and

N were determined by Micro-Dumas combustion. Nitrate was determined by extracting samples with 2M KCl and analyzing with continuous-flow colorimetry (Keeney and Nelson 1987). Samples to determine available phosphorus (PO_4-P) were extracted in Mehlich I solution and analyzed using a colorimetric analyzer. To determine K, Ca, and Mg, samples were extracted in Mehlich I solution and analyzed using a flame atomic absorption spectrophotometer (Baker and Shur 1982).

Soil physical properties were measured in October 2000. Six soil samples were taken from each plot at 0-5 depth using a 7.62 cm diameter tube. These samples were dried at 60˚C for 72 hours and weighed to determine bulk density. To determine aggregate stability, three samples from each plot were passed through a 2mm sieve. Ten grams of soil were measured and placed in a 0.25 mm sieve. In a tub of distilled water, each sample oscillated 1.5 cm at a rate of 30 oscillations per minute for 3 minutes. Samples were dried at 60˚C for 72 hours and weighed. Samples were immersed in a soap solution for five minutes and rinsed with distilled water until the stream was clear. Samples were dried at 60˚C for 72 hours and weighed. Percent water stable aggregates was calculated as [(weight of dry aggregates-sand)/(weight of dry soil-sand)]*100 (Angers and Mehuys 1993).

Soil moisture samples were collected bi-weekly from June to September 2000, the summer cropping season. Six cores were taken in each plot and the cores were divided into 0-5 cm and 5-10 cm. The samples were weighed immediately and then oven dried at 60˚C for 72 hours and re-weighed. The percent change in weight was determined as the percent moisture in the plots. Soil moisture was calculated as (wet weight - dry weight) ÷ dry weight.

Economic and Statistical Analyses

A simplified cost analysis was conducted during the second field season. Costs of external inputs such as fertilizer, clover seed, diesel fuel were recorded. The number of hours spent on each activity was recorded and converted to dollars using a standard wage of $7 / hour. Costs that were the same for each treatment, such as sorghum seed were not included. Also costs outside of the cropping season, such as land price, tractor, labor to plant the hedgerows, were not included. All costs were calculated as dollars per hectare per year.

Mean plot values were used for all statistical analyses. One-way Analysis of Variance and Tukey-Kramer HSD test were used to determine differences between treatment means of biomass measurements and nutrient analyses. Paired T-tests were used to compare yields and soil moisture of RI and RP treatments. Two-way Analysis of Variance and Tukey-Kramer HSD were used to analyze soil moisture data with treatment and date as the two regressor terms. All analyses were conducted using JMP 4.4 (JMP 2000).

CHAPTER 4

RESULTS

Plant Properties

Nutrient Additions

Nutrient inputs were calculated using two methods, alley-based and area-based. Alley-based inputs were the total additions per hectare ignoring the space taken up by hedgerows. Area-based inputs were the total additions per hectare taking into account the space occupied by hedgerows. Because there were no hedgerows in the CC and IF treatment, alley-based inputs and area-based inputs were the same for those treatments. The alley cropping (AC) treatment provided significantly more biomass addition than the cover crop (CC) treatment in 1999 and provided similar amounts of biomass in 2000 (Figure 4). A nutrient analysis was conducted on samples collected in 2000. The mimosa leaves were higher quality additions than the crimson clover residue. The AC additions had higher nitrogen and phosphorus concentrations while the CC additions had a higher C/N ratio (Table 1). Both nitrogen and phosphorus additions were greater in the AC treatment than in the CC treatment.

Sorghum Biomass

As with nutrient inputs, sorghum yields were analyzed by both alley-based and area-based methods. Yields for CC and IF treatments were the same using both methods because there were no hedgerows in those treatments. Sorghum yields were extremely low and patchy in 1999. There was a slight trend towards lower area-based yields in the AC treatment with an area-based comparison, but the overall low yields and high variance prevented this trend from being significant (Fig 5). There was no difference in alley-based yields between treatments. Sorghum yields were higher in 2000 though still lower than yields found in similar studies (Matta-Machado and Jordan 1995, Rhodes et al. 1998). Despite the low yields significant differences between treatments were found in 2000 (Figure 6). When using the area-based comparison, the sorghum grain yields in the IF treatment were higher than the yields in both the CC and RI treatments. When the space taken up by the hedgerows was not taken into account, alley-based yield, there were significantly lower yields in the CC treatment than in the IF treatment. In contrast, the yields in the both alley cropping treatments (RI and RP) were similar to the yields in the IF treatment. When analyzed with all treatments, grain yields in RI and RP treatments were not significantly different from each other. Since RI and RP plots were paired treatments, a paired t-test was used to compare the means of those two treatments. When grain yields were compared by plot and position within each plot, yields in RP treatments were higher (α=0.051). In both the RP and RI treatments, sorghum yields were higher in the middle rows than in rows bordering the hedgerows though the difference was statistically significant only in the RP treatment (Figure 7).

The sorghum stover and root biomass had similar trends to sorghum grain yields (Table 2). Sorghum root and stover biomass was extremely low in 1999. The only significant difference between treatments was found in stover biomass. Area-based stover biomass in IF treatment was almost four times greater than stover biomass in the AC treatment. More differences between treatments were measured in 2000. Area-based stover and root biomass was greater in the IF treatment than in all other treatments. With alley-based comparison, stover and root biomass in the IF treatment was statistically greater than stover and root biomass in only the CC treatment.

Nutrient concentration analyses were conducted on the sorghum harvested in 2000. For sorghum grains, only N differed between treatments (Table 3). Sorghum grain had a higher percentage of N in the RI and CC treatments than in the IF treatment. For sorghum stover and roots, only P differed between treatments. Stover in the IF treatment had a higher P concentration than stover in the RI and RP treatments. This trend was also found in the roots though the difference was not as strong. Roots in the IF treatment had more P than roots in the RI treatment.

Weed Biomass

Weed biomass was compared using an alley-based comparison. In 2000 cover crop and fertilizer treatments had more weeds than both of the alley cropping treatments (Figure 8) did. The cover crop treatment had significantly greater weed biomass than both of the alley cropping treatments while the IF treatment was greater than only the RI treatment at 0.05 level of significance and both alley cropping treatments at 0.1 level of significance.

Soil Properties

Soil Chemical Properties

Soil N was greatest in the alley cropping treatments. At the start of this study in October 1998, total soil nitrogen was greater in the alley cropping treatment than in the other treatments (Figure 9). There continued to be a trend of higher total N in the hedgerow treatment, though the difference was not significant during the first field season. In May 2000, soil total N in the RI (α=0.1) and RP (α=0.05) treatments was greater than total N in the IF treatment (Table 4). After harvesting of sorghum, that trend continued. However, only the RP treatment was significantly greater than the IF treatment in October 2000. The C/N ratios were consistently lower in the hedgerow treatments during all sample periods. Available phosphorus (PO_4–P) was similar between all treatments but increased during the second year of the study (Figure 10). Nitrate was analyzed in soil samples from the 2000 field season. Nitrate nitrogen was similar between treatments before planting (Table 4). Nitrate nitrogen was higher after harvest in all treatments, and alley cropping treatments had significantly higher levels of NO_3–N than the IF treatments. Soil pH was low in the RI, RP, and CC treatments for both the spring and fall of 2000. Soil pH was much higher in the IF treatment.

Physical Properties

Soil physical properties were also analyzed. While there was a trend towards lower bulk density in the AC treatment, the difference was not statistically significant with only three replicates (Table 5). There was also no significant differences in percent water stable aggregates between treatments though all treatments had low percentages of stable aggregates.

Moisture Analysis

Because soil moisture was heavily influenced by weather, the date sampled and the treatment were used in the analysis (Figures 11). Soil moisture values at 0-5 cm depth and 5-10 cm depth were averaged and soil moisture was analyzed at 0-10cm depth. Treatment and date sampled explained 94% of the soil moisture variation in samples. Treatment and date were both significant effects. Taking the date sampled into account, soil in the RP treatment was more moist than soil in the CC and IF treatments at a 0.05 level of significance.

There was no significant difference between RP and RI treatments when plots within treatments were pooled because of inter-plot variation within treatments. However when soil moisture was paired by plot and date, the soil moisture in the RP treatment was significantly greater than the soil moisture in the RI treatment (α=0.0002). It was only possible to compare RP and RI treatments using a paired t-test because those treatments had paired plots.

Cost Analysis

When total costs were compared, there were no significant differences between treatments (Table 6). Nutrient addition costs were highest in the AC treatment and lowest in the CC treatment. Weeding costs were highest in the IF treatment and lowest in the AC treatment. Human labor was the major cost in all treatments and labor trends were similar to cost trends (Table 7). This study was done in a labor-intensive fashion. In 1999 the removal of woody biomass from the three AC plots took over a week of intense effort involving multiple people, a chainsaw, a hatchet and three machetes. The labor was reduced the following year, but hedgerow trimming still took nearly a week. During both years fertilizer and lime were added by hand in the IF treatment. All weeding was done by hand and there was no use of herbicides.

CHAPTER 5

DISCUSSION AND CONCLUSION

Nutrient Addition Effectiveness

Mimosa hedgerows compared favorably with cover crops in amount and quality of annual biomass additions. Hedgerows produced more aboveground biomass than the clover in 1999, but the hedgerows had been untrimmed for several years and had large canopies (Figure 4). The biomass addition in 2000 better represented the additions provided by the hedgerows under continuous cropping because the trees only had one year's growth before they were pruned. Hedgerow biomass additions were higher in this study than in similar temperate zone studies (Matta-Machado et al. 1994, Rhodes et al. 1998, Addleston et al. 1999, Seiter et al. 1999). However those studies were conducted in areas with shorter growing seasons or with young hedgerows no more than three years after establishment. In 2000 the hedgerows produced similar biomass additions as the crimson clover winter cover crop (4680 kg ha^{-1} for clover and 3240 kg ha^{-1} for hedgerows). Hedgerows produced higher quality leaf litter and provided more N than the clover (Table 1). However the clover litter was of low quality in this study. The clover C/N ratio of 28.3 was high compared to other studies (Quemada et al. 1997, Teasdale and Abdul-Baki 1998). The drought in the winter and spring led to poor establishment of the cover crop, and many weeds grew among the clover. The mowing of clover at an advanced stage of maturity and the mixture of weeds in with the clover may have lea to the high C/N ratio (Matta-Machado et al. 1994). Winter growth of the mimosa hedgerows may have been less affected by the drought because the mature trees had deeper, more developed root systems than the clover. When compared to other cover crops, hedgerow biomass addition was also favorable. The biomass addition from the hedgerows was less than the highest biomass values for cover crops, but the N additions from the hedgerows were similar to other cover crops (Table 8).

Leguminous hedgerows provided far more N than the other two treatments (Table 1). Alley cropping N additions were high compared to similar temperate zone studies and in the middle when compared to tropical alley cropping systems (Matta-Machado et al., 1994, Kang 1997, Rhodes et al. 1998, Aihow et al. 1999, Nair et al. 1999). Though much more N was provided by the CC and AC treatments as compared to the IF treatment, reduced N recovery rates for organic N additions may have limited the amount of N available to the sorghum (Nair et al. 1999). Mimosa leaves decomposed quickly (Rhodes et al. 1998), but only a portion of the N provided by the hedgerows was available for uptake up by the sorghum. Studies using ^{15}N to estimate N recovery have found that maize varieties take up between 5% to 20% of the N provided by leguminous hedgerow leaves (Hagger et al. 1993, Jensen 1994, Vanlauwe et al. 1998, Mugendi et al. 2000). Using these studies as a guide and estimating 15% of N provided by the hedgerows was utilized, we estimated 30 kg N ha^{-1} were taken up by the sorghum. Using approximations for fertilizer and clover input uptakes, 50% and 35 % respectively (Crozier et al. 1998), we estimated approximate N uptakes of 22 kg N ha^{-1} for the IF treatment and 29 kg N ha^{-1} for the CC treatment. These rough approximations suggested that hedgerows provided similar amounts of N to sorghum despite lower N recovery rates from hedgerow leaves.

An input-output aboveground nutrient budget was calculated for the 2000 cropping season to determine if the nutrient addition treatments provided more N than was removed from the system (Table 9). Inputs included the nutrient additions as well as sorghum stover that was left on the soil at the end of the cropping season. Outputs included the sorghum grain that was harvested as well as the wheat and grass removed from the RI, RP, and IF treatments in May 2000. The CC, RI, and RP all had N surpluses. The N surplus for the RI and RP treatments was more than twice as large as the surplus from the CC treatment. The IF treatment had a slightly negative N balance when the weeds and biomass removed in the spring were included.

As with N, P concentrations were higher in mimosa leaves than in clover residue (Table 1). However, total P inputs were low in both CC and AC treatments. The IF treatment provided over twice as much P as the CC and AC treatments. All P input-output budgets were positive, but the IF treatment had a significantly higher P balance than the other treatments (Table 9). Despite the positive P balance in the CC and AC treatments, mimosa leaves and crimson clover residue may not have provided enough P for the sorghum. Only a proportion of the P added could be utilized by the sorghum. Fixation of P to Al and Fe oxides, the uptake of P by soil organisms, and leaching reduced the amount of P available to the sorghum. Low P addition has been a problem in other alley cropping systems. In some cases applications of external P inputs has been needed to insure long term sustainability (Onim et al. 1990, Sanchez 1995, Gachengo et al. 1999, Lupwaje et al. 1999). Matta-Machado and Jordan (1995), in an earlier study at this site, found that mimosa hedgerows alone did not provide enough P for continuous grain production. They suggested that hedgerow inputs combined with a winter cover crop could provide sufficient P. Comparing the P inputs in this study suggested that mimosa hedgerows were unable to supply sufficient levels of P for the long term continuous cropping. However, adding P in organic matter, as opposed in inorganic fertilizer, may have increased the amount of P available to the sorghum. As high quality litter decomposed, organic acids may have chelated with Fe and Al, making P more available (Iyamureye and Dick 1996, Nziguhebe et al. 1998). This effect was not measured directly, but soil available P (PO_4-P) levels in the alleys were similar to available P levels in the other treatments throughout the study (Figure 10). Despite the greater addition of P in the IF treatment, there was no corresponding increase in soil

PO_4–P as compared to other treatments. Most likely excess P provided by the IF treatment was fixed by Al and Fe oxides or leached from the system.

The ability of sorghum to access nutrients and other resources determined sorghum biomass and grain yield. In 2000, sorghum yields in the RI and RP treatments were similar to yields in the IF treatment, but yields in the CC treatment were significantly less than in the IF treatment (Figure 6). Matta-Machado and Jordan (1994) found the opposite relationship between alley cropping and cover cropping during the first three years hedgerow establishment at this site. The greater maturity of the mimosa hedgerows, and poor crimson clover production in this study may have led to the reversal in results. Yields in the alley cropping treatments were lower than the yields in the IF treatment only with the area-based comparison where the reduction in sorghum yield due to the space taken up by hedgerows was taken into account. The slightly lower yields in the AC treatments may have been due to P limitations. Sorghum stover in the IF treatment had significantly higher P concentrations than stover in both the RI and RP treatments. The large difference between area-based and alley-based yields would have been reduced if more sorghum rows were planted in the alleys between the hedgerows. In this study the rows were widely spaced with only four rows per four-meter alley. Sorghum grain, stover, and root biomass was significantly lower in the CC treatment than in the IF treatment. The lower yields in crimson clover suggested that clover was unable to provide sufficient nutrients, especially P, in a drought year. Sorghum grain yields were low in all treatments. Other alley cropping studies in the tropical and temperate zone had sorghum grain yields ranging from 2300 kg ha^{-1} to 6300 kg ha^{-1} (Matta-Machado and Jordan 1994, Lehmann 1999). A severe summer drought at the rain-fed only site reduced growth and a wide row spacing lead to low yields per hectare. Sorghum biomass data from 1999 was not used in the analysis because of extremely low yields and because of external effects, such as widely spaced planting dates, which may have influenced sorghum growth.

Competition Between Hedgerows and Sorghum

For alley cropping to be an effective system, the benefits of nutrient addition must outweigh losses due to competition for resources. In low fertility soils, trees and crops may compete for soil nutrients, while in arid areas they compete for water. For a study of competition, roots were pruned in the RP treatments and yields and soil properties were compared with those of the RI treatment. This study found evidence of root competition between the hedgerows and the sorghum. Sorghum grain yields in the RP treatment, where root competition was reduced, were higher than yields in the RI treatments when compared using a paired t-test. In the RI treatment there was no significant difference between sorghum grain yields in rows that bordered mimosa hedgerows and rows in the middle of alleys (Figure 7). The undamaged roots of the RI treatment reached into the middle of the alleys and competed with sorghum in all rows. The difference in sorghum yields between edge and middle rows was significant in the RP treatment. Competition in rows bordering hedgerows may have increased as trimmed roots began to grow back into the alleys. While the large N additions suggest that N was not a limiting factor, there may have been competition for P between hedgerows and sorghum.

Though previous studies suggested hedgerows and crops compete for water under arid conditions, there was only limited evidence of competition in this study. (Sanchez 1995, Agus et al. 1997, Korwar and Radder 1997, Mathuva et al. 1998, Rao et al. 1998, Odhiambo et al. 2001). Despite the drought conditions, little competition for water was observed. The RP treatment had greater soil moisture than the CC and IF treatments while the RI treatment had similar soil moisture to all other treatments (Figure 11). The hedgerows may have created a micro-climate that reduced water loss from the soil. Shading may have reduced evaporation and mimosa mulch may have increased water retention during the few summer rain storms. Also mimosa may have used deep roots to access water reducing the competition for water in upper soil depths. There was evidence for some root competition for water because the RP treatment had higher soil moisture content than the RI treatment when compared using a paired t-test. However this competitive effect did not seem severe because the difference between the RI and RP treatments was not significant when all treatments were compared together. In general the hedgerows had a positive or neutral effect on soil moisture.

It is unlikely that competition for light affected yields. Mimosa hedges were trimmed back when they started to shade the sorghum. Sorghum height was similar across all treatments suggesting that light was not a limiting factor within the alleys (Figure 12). Competition between mimosa and sorghum did occur in this study. Most likely competition was for water and nutrients, especially P. Root pruning the hedgerow roots reduced competition but did not eliminate it completely.

Long Term Sustainability

Leguminous hedgerows had a positive effect on soil properties. There was a trend towards higher soil total N levels in the alley cropping treatments (Figure 9). At the beginning of this study soil total N was higher in the alley cropping plots than in the other treatments. All treatments had lain fallow for several years. During that time, the alley cropping treatments received nutrient inputs from the mimosa hedges through leaf fall that may have lead to a build up of soil total N within alleys. The trend of higher N in hedgerow treatments continued through 1999 though the differences between treatments were not significant. In 2000, total N levels were significantly higher in both alley cropping treatments than in the fertilizer treatment. Available nitrogen (NO_3–N) was lower in the IF treatment than in the RP treatment in October 2000. Over the course of this study, N levels remained relatively stable in the treatments with organic nutrient inputs, CC, RP, RI. However, total N levels had a downward trend in the IF treatment. Organic inputs of N may have been incorporated into the active pools of soil organic matter because C in the clover residue and mimosa leaves was an energy source for microbial immobilization (Palm 1995). In this way excess N not used by sorghum could help maintain or build up N levels in the soil. Nitrogen values may have been decreasing in the IF treatment because N applied without a carbon source tends to have higher rates of loss due to leaching and denitrification (Sanchez 1995). Soil available phosphorus (PO_4-P) levels in alley cropping treatments were comparable to levels in the fertilizer treatment even though less P was added by nutrient addition (Figure 10). An exception to the positive effect of hedgerows was soil acidity. Piedmont soils tend to be acidic, and the soils in this study were no exception. Soils in both the hedgerow treatments and the clover treatments were highly acidic. Soils in fertilizer treatments had significantly higher pHs. Addition of lime to the IF treatment and H^+ excretion during biological nitrogen fixation in the organic input treatments may have contributed to the differences in pH (Kang et al. 1999). Differences in physical properties were not statistically significant though some positive trends were suggested. Studies have shown that alley cropping systems tend to have lower bulk densities than other continuous cropping systems (Alegre and Cassel 1996, Samsuzzaman et al. 1999). While there was a trend towards lower bulk density in alley cropping treatments and higher bulk density in IF treatments, the differences were too small to be significant with only three replicates (Table 5). A previous study at this site reported higher bulk density than were found in this study. The bulk densities of all treatments were more similar than was found in this study suggesting that the difference in bulk densities may be increasing over time (Figure 13). Soil wet aggregate stability was similar between treatments and was low for all treatments. Use of a rotary hoe my have led to decreased aggregate stability and may have reduced the positive effects of organic matter addition on aggregate stability.

Cost Effectiveness of Alley Cropping

In developing countries, one of the deterrents of alley cropping adoption is the high labor costs. To determine the adoption potential of alley cropping in Georgia, costs of production and labor costs were compared for each treatment. Surprisingly, all treatments had similar total labor and total costs (Tables 6 and 7). However the small scale of this study caused the production costs to be inflated for the IF treatment. Inputs such as fertilizer were purchased in only small amounts and were more expensive than they would be if purchased in bulk. Fertilizer and lime were applied by hand in a labor intensive manner in order to ensure evenness of application. The highest single cost associated with the IF treatment was the labor used in weeding. However, a conventional farmer would most likely use herbicides to control weeds which would greatly reduce the costs of maintenance and weeding. Total costs for the CC treatment and the AC treatment were similar. As expected, the costs of nutrient addition were highest in the AC treatment because of the large amount of manual labor used to trim the hedges (Table 7). However, this high initial cost was partially offset by the reduced weeding in the AC treatment. Both alley cropping treatments had significantly lower weed biomass than the other treatments (Figure 8). Planting costs were less in the alley cropping plots because fewer sorghum rows were planted and fewer passes were made with the tractor.

Alley cropping may be appealing to farmers who weed by hand and do not have land limitations. One of the biggest barriers to adoption would be the high labor costs associated with nutrient addition. However it may be possible to reduce those costs and make alley cropping more appealing to farmers. For this study, mimosa branches were cut with a machete, the leaves were removed from the branch, and the leaves were added evenly over the alleys. Other methods of nutrient addition are less labor intensive. Using a mechanized trimmer and a woodchipper to blend branches and leaves together would reduce the costs and provide more nutrient inputs. Though the costs of alley cropping are relatively high, the costs are similar to other organic options such as use of a winter cover crop.

Conclusion

Alley cropping with *A. julibrissin* hedgerows provided sufficient N for a summer grain crop. However, P additions were low, and outside P inputs may be needed over the long term for continuous cropping. During a drought year, alley cropping supplied greater N and P additions than an annual leguminous cover crop. Sorghum yields were comparable to yields using other nutrient inputs. Root pruning of *A. julibrissin* hedgerows reduced root competition between hedges and sorghum and increased grain yields. Root competition may have been for nutrients and water. However soil moisture was higher in alley cropping treatments than in the other treatments. Because of reduced weeding, costs for the alley cropping system were similar to costs of other treatments. Further studies should be conducted to refine alley cropping techniques and reduce competition between hedgerows and crops, reduce labor costs, and improve P availability. Alley cropping with mimosa hedgerows has potential as an organic farming technique in Georgia.

Table 1: Nutrient inputs for 2000 from three addition treatments: *Albizia julibrissin* leaves in the alley cropping treatment, *Trifolium incarnatum* in the cover cropping treatment, and 10-10-10 with dolomitic limestone in the inorganic fertilizer treatment. Inputs are calculated by two methods. Area-based calculations account for the reduction in inputs due to the space taken up by the hedgerows. Alley-based calculations make no reduction for that space.

Treatment	Total Nitrogen			Total Phosphorus			C/N Ratio
	N (g kg^{-1})	N (kg ha^{-1}) Area-Based	N (kg ha^{-1}) Alley-Based	P (g kg^{-1})	P (kg ha^{-1}) Area-Based	P (kg ha^{-1}) Alley-Based	
Alley Cropping	46 a	149 a	198 a	2.4 a	7.8	10.4	10.6 a
Cover Cropping	19 b	84 b	84 b	1.2 b	5.8	5.8	28.3 b
Inorganic Fertilizer	100	45	45	4.36	20	20	—

Letters denote differences between Alley Cropping and Cover Cropping treatments at the 0.05 level of significance.

Table 2: Sorghum biomass. Area-based calculations account for reduced sorghum biomass due to space taken up by mimosa hedgerows, and alley-based calculations estimate sorghum biomass without adjusting for space occupied by the hedgerows.

Year	Treatment	Grain Biomass		Stover Biomass		Roots Biomass	
		(kg ha^{-1}) Area-Based	(kg ha^{-1}) Alley-Based	(kg ha^{-1}) Area-Based	(kg ha^{-1}) Alley-Based	(kg ha^{-1}) Area-Based	(kg ha^{-1}) Alley-Based
1999	Hedgerows	75	125	125 b	208	48	80
	Cover Crop	137	137	282 ab	282	86	86
	Fertilizer	122	122	485 a	485	147	147
2000	Root Pruned	380 ab*	1630 ab	890 b*	1490 ab	175 b*	292 ab
	Root Intact	700 b*	1160 ab	750 b*	1250 ab	147 b*	246 ab
	Cover Crop	790 b*	790 b	950 b*	950 b	198 b*	198 b
	Fertilizer	2030 a*	2030 a	2270 a*	2270 a	520 a*	520 a

Letters denote differences between treatments at 0.1 level of significance.

Letters with * denote differences between treatments at 0.05 level of significance.

Table 3: Nutrient concentration in the dry matter of sorghum in 2000.

	Treatment	N (g kg^{-1})	P (g kg^{-1})	C/N
Grain	Root Pruned	16.3 ab	2.5	26.8
	Root Intact	17.0 a	2.4	33.0
	Cover Crop	17.1 a	2.6	28.3
	Inorganic Fertilizer	14.1 b	2.6	29.3
Stover	Root Pruned	15.6	2.6 b*	26.4
	Root Intact	16.5	2.6 b*	28.7
	Cover Crop	15.1	2.8 ab*	28.1
	Inorganic Fertilizer	13.9	3.3 a*	26.2
Roots	Root Pruned	9.5	3.1 ab	32.5 a*
	Root Intact	9.8	2.8 b	25.6 b*
	Cover Crop	8.5	2.9 ab	31.7 a*
	Inorganic Fertilizer	6.6	3.4 a	32.5 a*

Letters denote differences at 0.1 level of significance. Letters with * denote differences at 0.05 level of significance.

Table 4: Soil Chemical Properties in 2000. All soil was collected in composite samples at 0-5 cm depth.

Treatment	pH		Total N ($g\ kg^{-1}$)		C/N Ratio		NO_3-N ($mg\ kg^{-1}$)		PO_4-P ($mg\ kg^{-1}$)	
	May	October	May	October	May	October	May	October	May	October
Root Pruned	5.08 b*	5.33 b*	2.39 ab*	2.36 a	13.5 b*	13.5 ab*	3.35	30.9 a*	6.09	7.03
Root Intact	5.01 b*	5.22 b*	2.36 a*	2.16 ab	13.4 b*	13.0 b*	4.86	30 ab*	10.93	7.63
Cover Crop	4.90 b*	5.23 b*	1.89 ab*	1.91 ab	13.7 ab*	14.0 ab*	2.57	26.5 ab*	11.92	8.71
Fertilizer	6.81 a*	5.98 a*	1.69 b*	1.64 b	15.0 a*	14.4 a*	1.86	20.2 b*	6.48	6.32

Letters denote differences between treatments at 0.1 level of significance.

Letters with * denote differences between treatments at 0.05 level of significance.

Table 5: Soil Physical Properties in October 2000. All samples were 0-5 cm depth.

Treatment	Bulk Density ($Mg\ m^{-3}$)	Water Stable Aggregates (Percent stable aggregates)
Root Pruned	1.06	54
Root Intact	1.09	49
Cover Crop	1.18	52
Fertilizer	1.23	50

No significant differences between treatments.

Table 6: Yearly costs on a per plot basis. Each plot was 120 m^2. Cost analysis were based on labor costs (\$7.00 hr^{-1}), and costs of external inputs (fertilizer, lime, clover seed, diesel fuel). Costs identical in each treatment, such as sorghum seed were not included. Costs sustained before the study period were not include (land price, equipment purchase). Harvesting costs were not included because entire sorghum plants were harvested for study purposes resulting in labor intensive harvesting techniques.

Treatment	Nutrient Addition (dollars $plot^{-1}$)	Planting (dollars $plot^{-1}$)	Weeding and Hedge Trimming (dollars $plot^{-1}$)	Total Costs (dollars $plot^{-1}$)
Alley Cropping	46.10 a	1.90	25.10 b	73.10
Cover Crop	10.10 b	3.90	47.10 ab	61.00
Fertilizer	21.00 b	3.90	62.40 a	87.30

Letters denote differences at 0.05 level of significance.

Table 7: Comparison of labor between treatments in 2000. All measurements were man hours plot^{-1}. Each plot was 120m^{-2}.

Treatment	Nutrient Addition (hours plot^{-1})	Planting (hours plot^{-1})	Weeding and Trimming (hours plot^{-1})	Total Labor (hours plot^{-1})
Alley Cropping	6.6 a	0.3	3.6 b	10.4
Cover Cropping	1.3 b	0.5	6.7 ab	8.6
Inorganic Fertilizer	2.2 b	0.5	9.4 a	12.0

Letters denote differences between treatments at 0.05 level of significance

Table 8: Comparison of biomass and nitrogen addition of temperate cover crops.

Cover Crop	Above Ground Biomass (kg ha^{-1})	Total Nitrogen (kg N ha^{-1})
Crimson clover[a]	7200	170
Crimson clover[b]	6100	145
Crimson clover[c]	6520	149
Crimson clover[d]	2444	78
Subterranean clover[a]	4000	114
Common vetch[a]	4300	134
Hairy vetch[a]	4300	153
Hairy vetch[c]	5263	171
Hairy vetch[d]	1753	72
Lupin[d]	946	32
Rye[b]	3450	42
Rye[c]	5740	55
Rye[d]	3048	74
Wheat[d]	2425	56
Crimson clover + rye[c]	8775	150
Hairy vetch + rye[c]	7606	176
Hairy vetch + rye[d]	2600	65
Hairy vetch + crimson clover + rye[c]	8423	166
Hairy vetch + rye + barley + clover[e]	11930	290
Fallow[b]	950	17

a: Hoyt and Hargrave 1986. b: Torbert et al. 1996. c: Teasdale and Abdul-Baki 1998. d: Daniel et al. 1999. e: Creamer et al. 1996.

Table 9: Nutrient budget (kg ha^{-1} yr^{-1}) for four treatments from January through December 2000. Input = Crimson clover, mimosa leaves, fertilizer addition, and sorghum stover. Output = Sorghum grain harvested and grass removed. Budget = Input - Output

		Root Pruned (kg ha^{-1} yr^{-1})	Root Intact (kg ha^{-1} yr^{-1})	Cover Crop (kg ha^{-1} yr^{-1})	Inorganic Fertilizer (kg ha^{-1} yr^{-1})
C	Input	2810 a	2730 a	2710 a	1030 b
	Output	1890 b	1770 b	360 b	3530 a
	Budget	910 a	960 a	2350 a	-2500 b
N	Input	243 a	238 a	99 b	76 b
	Output	47 ab	43 ab	14 b	82 a
	Budget	196 a	195 a	85 b	-5 c
P	Input	12.9 b	12.7 b	7.3 b	25.4 a
	Output	4.9 b	4.6 b	2.4 b	11.3 a
	Budget	7.9 b	8.1 b	5.0 b	14.1 a

Letters denote differences between treatments at 0.05 level of significance.

Figure 1: Precipitation in Athens-Clarke County, Georgia.

The mean bars represent average monthly precipitation in Athens-Clarke County, GA from 1961-1990 (Owenby and Ezell, 1992). The study bars represent monthly precipitation in Athens-Clarke County from October 1998 to September 2000, the time period of this study (NOAA, 1998, 1999, 2000).

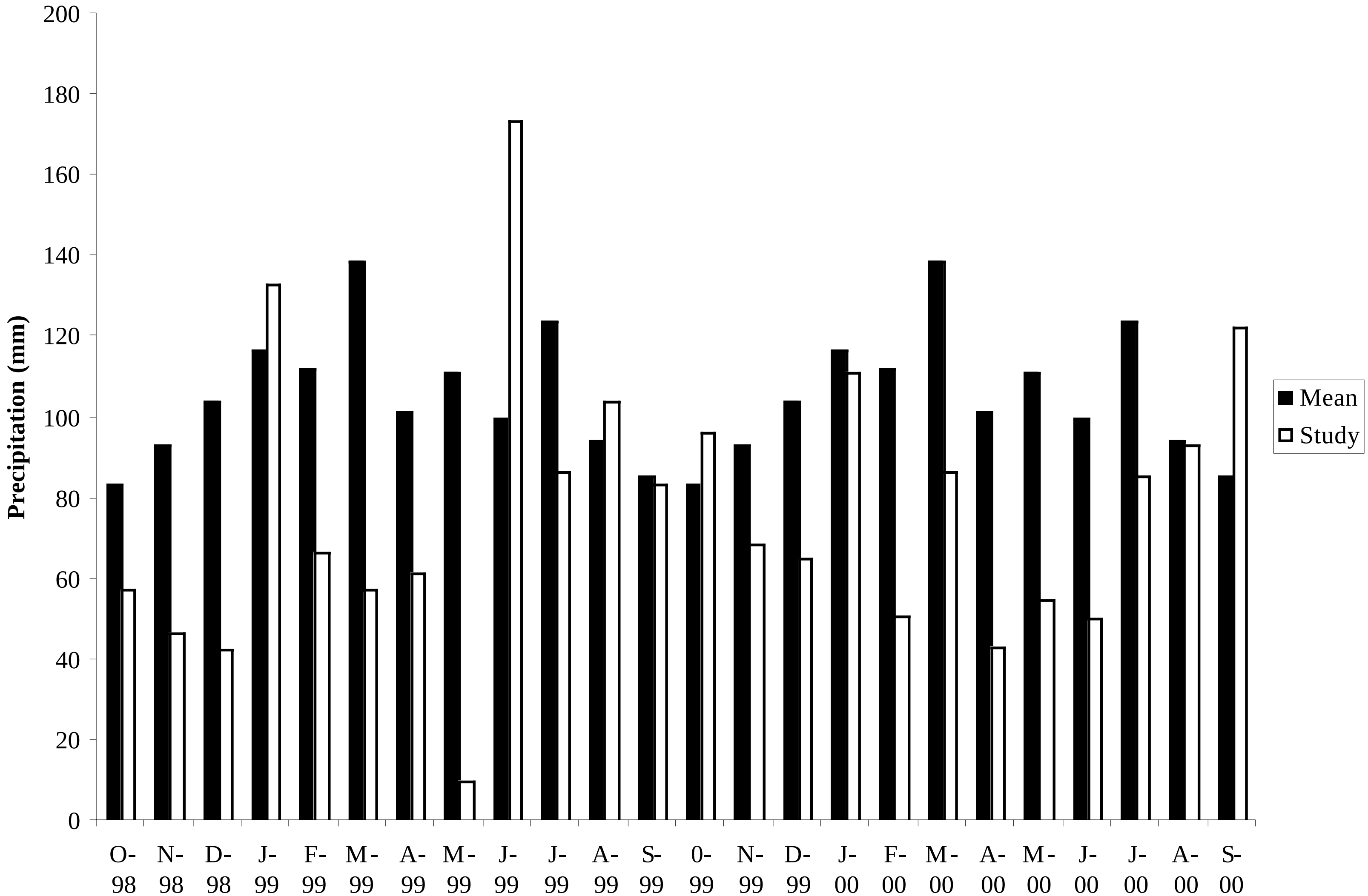

Precipitation (mm)
200
180
160
140
120
100
80
60
40
20
0
O-98
N-98
D-98
J-99
F-99
M-99
A-99
M-99
J-99
J-99
A-99
S-99
0-99
N-99
D-99
J-00
F-00
M-00
A-00
M-00
J-00
J-00
A-00
S-00
Mean
Study

Figure 2: Diagram of study site in 2000.

Site was on a slight slope, and *Albizia julibrissin* hedgerows were planted along elevation contours. Hedgerows were spaced 4 meters apart. Hedgerows that had sustained deer damage were not used in the study. In 1999, all plots were 20 m by 12 m. In 2000, each alley cropping plot was divided into a root pruned (RP) and a root intact (RI) plot. *Albizia* roots were trimmed with a sub-soiler to a depth of one meter before planting in the root pruned (RP) treatment. Plots in cover crop (CC) and inorganic fertilizer (IF) treatments were reduced in size and all plots in all treatments were 10 m by 12 m in 2000.

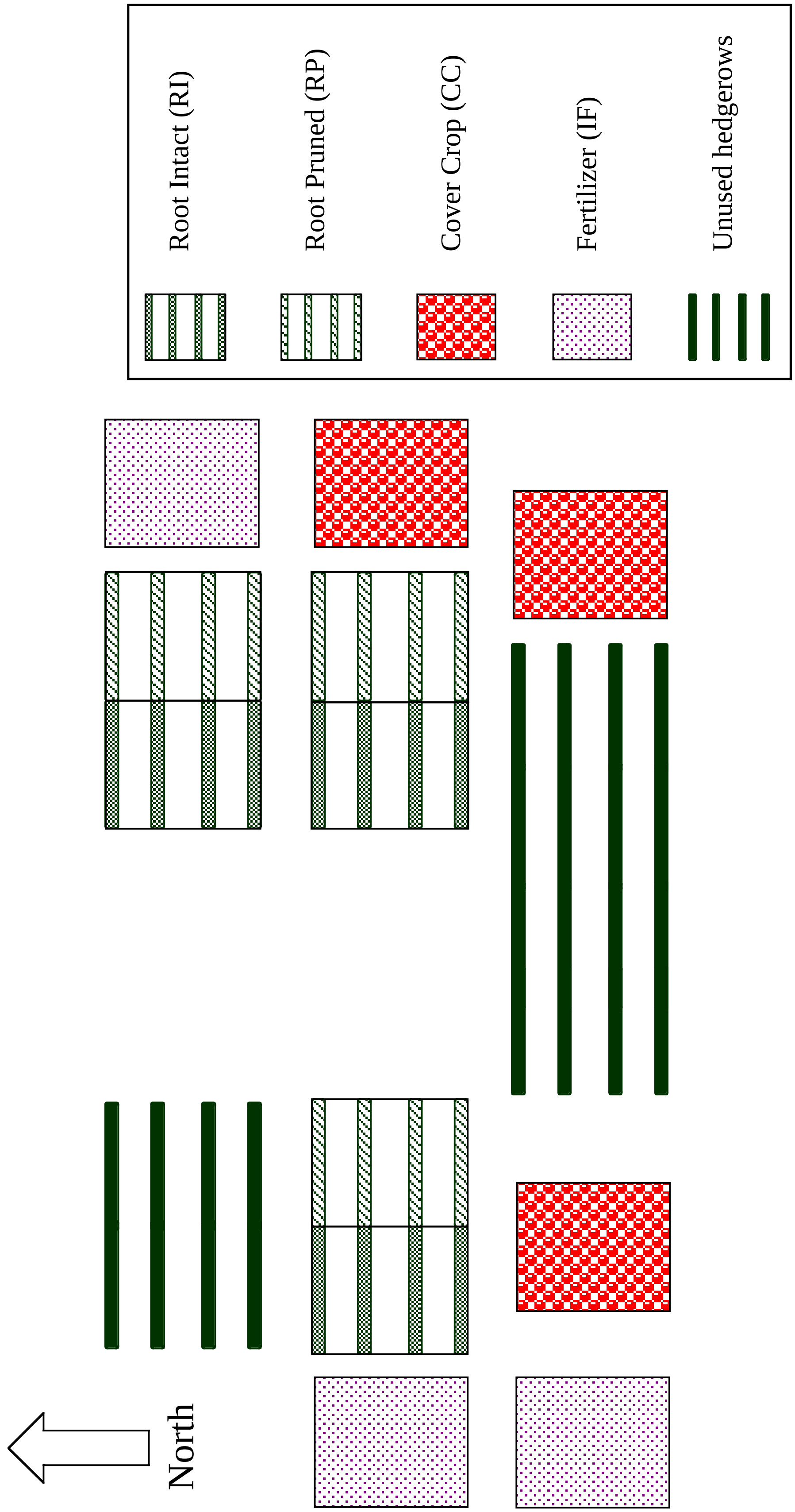

Root Intact (RI)
Root Pruned (RP)
Cover Crop (CC)
Fertilizer (IF)
Unused hedgerows
North

Figure 3: *Albizia julbrissin* hedgerows.

Before planting sorghum, hedgerows were coppiced. The leaves were removed from the branches using machetes and tilled into the soil with a rotary hoe.

Figure 4: Comparison of biomass additions between treatments.

Albizia julibrissin leaves were added to the alley cropping (AC) treatments, and *Trifolium incarnatum* was added to the cover crop (CC) treatments. Biomass was compared using area-based (reduction in yields due to space taken up by hedgerows) and alley-based (no reduction in yields due to hedgerows) analyses. The inorganic fertilizer (IF) treatment was not included in the statistical analyses because there was no recorded variation in nutrient additions for the IF treatment. Letters denote a significant difference in biomass between treatments at 0.05 level of significance.

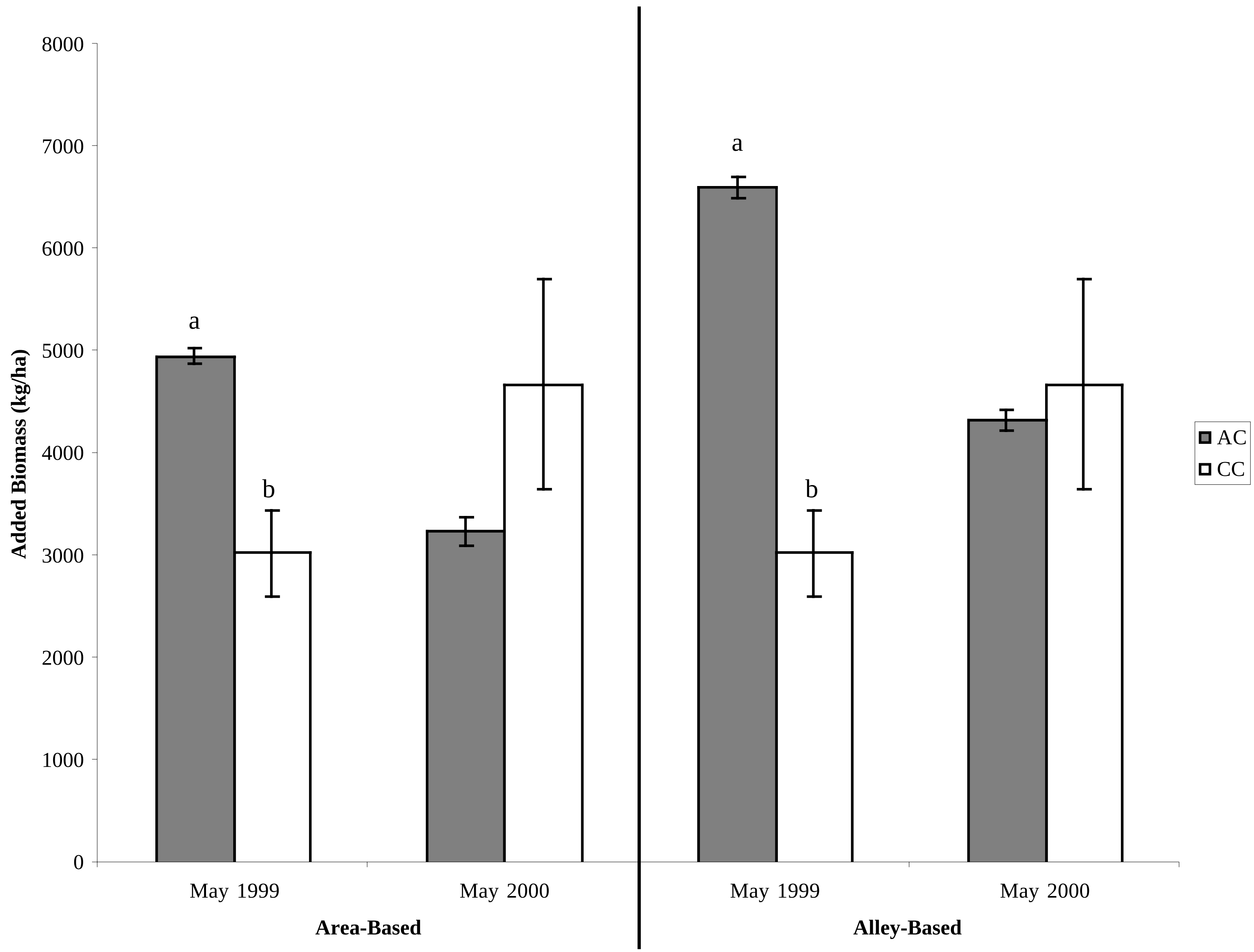

Added Biomass (kg/ha)
8000
7000
6000
5000
4000
3000
2000
1000
0
a
b
a
b
May 1999
May 2000
May 1999
May 2000
Area-Based
Alley-Based
AC
CC

Figure 5: Sorghum grain yields summer 1999.

Yields were compared using area-based (reduction in yields due to space taken up by hedgerows) and alley-based (no reduction in yields due to hedgerows) analyses. There was no significant difference between treatments. AC=ally cropping treatment, CC=cover crop treatment, IF=inorganic fertilizer treatment.

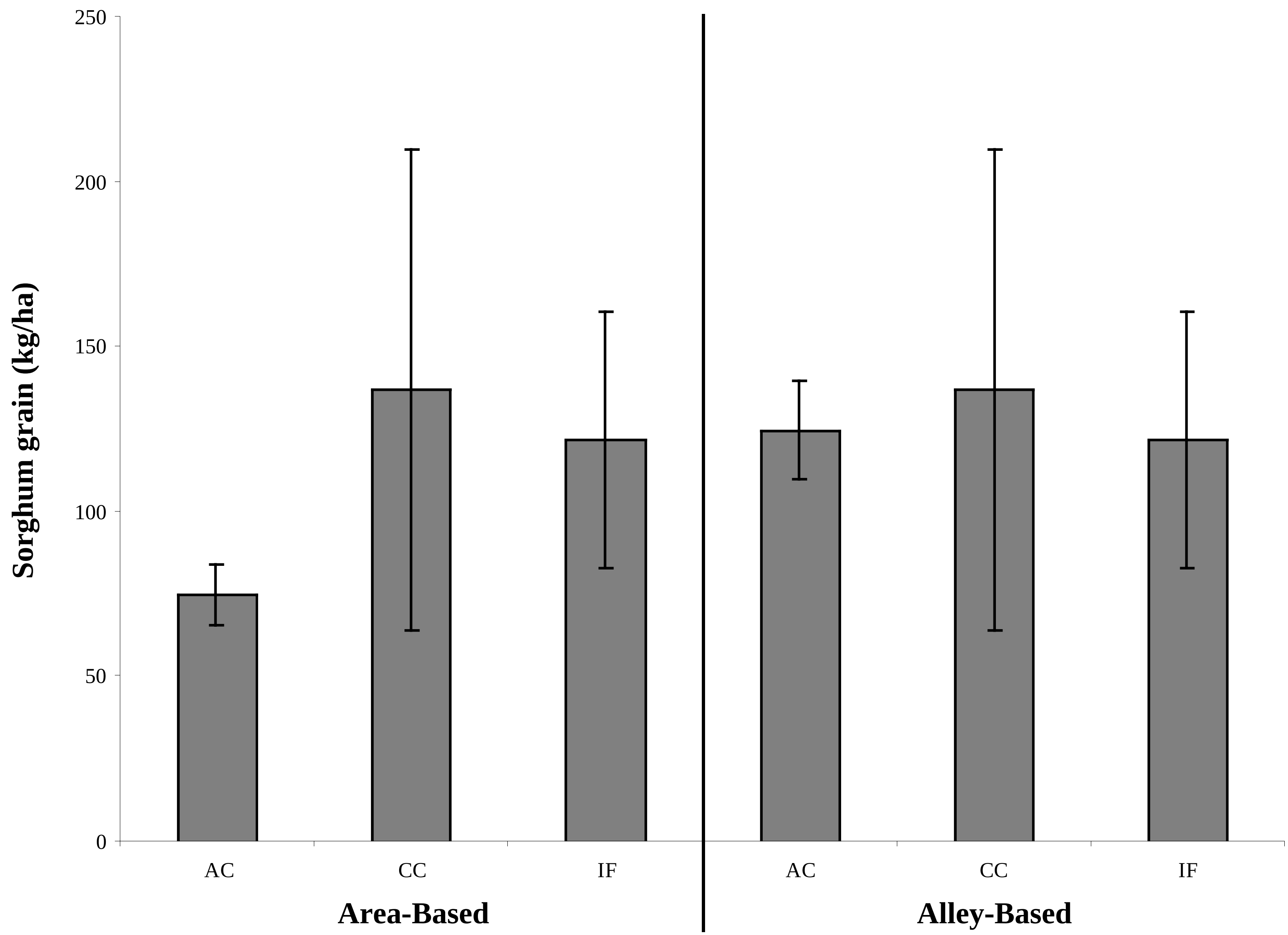

Sorghum grain (kg/ha)
250
200
150
100
50
0
AC
CC
IF
AC
CC
IF
Area-Based
Alley-Based

Figure 6: Sorghum grain yields for summer 2000.

Yields were compared using area-based (reduction in yields due to space taken up by hedgerows) and alley-based (no reduction in yields due to hedgerows) analyses. Letters denote significant differences at 0.1 level of significance. RP=root pruned treatment, RI=root intact treatment, CC=cover crop treatment, IF=inorganic fertilizer treatment.

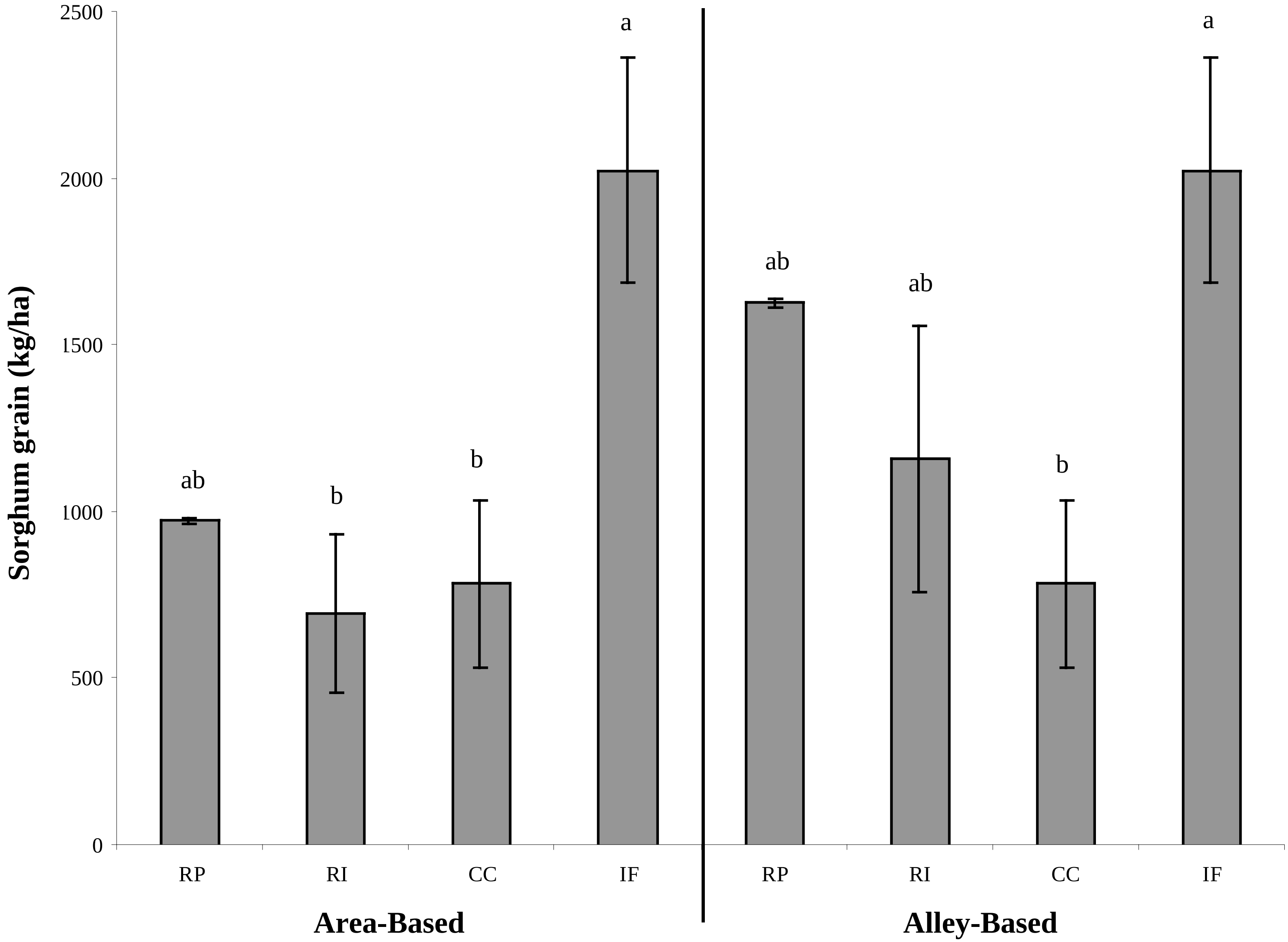

Sorghum grain (kg/ha)
2500
2000
1500
1000
500
0
a
ab
b
b
a
ab
ab
b
a
RP
RI
CC
IF
RP
RI
CC
IF
Area-Based
Alley-Based

Figure 7: Sorghum grain yields comparing yields in rows bordering hedgerows on one side, edge, and in rows bordering sorghum on both sides, middle.

Roots Pruned = mimosa roots were pruned with sub-soiler in May 2000. Roots Intact = mimosa roots were left intact. Letters denote significant difference at 0.01 level of significance.

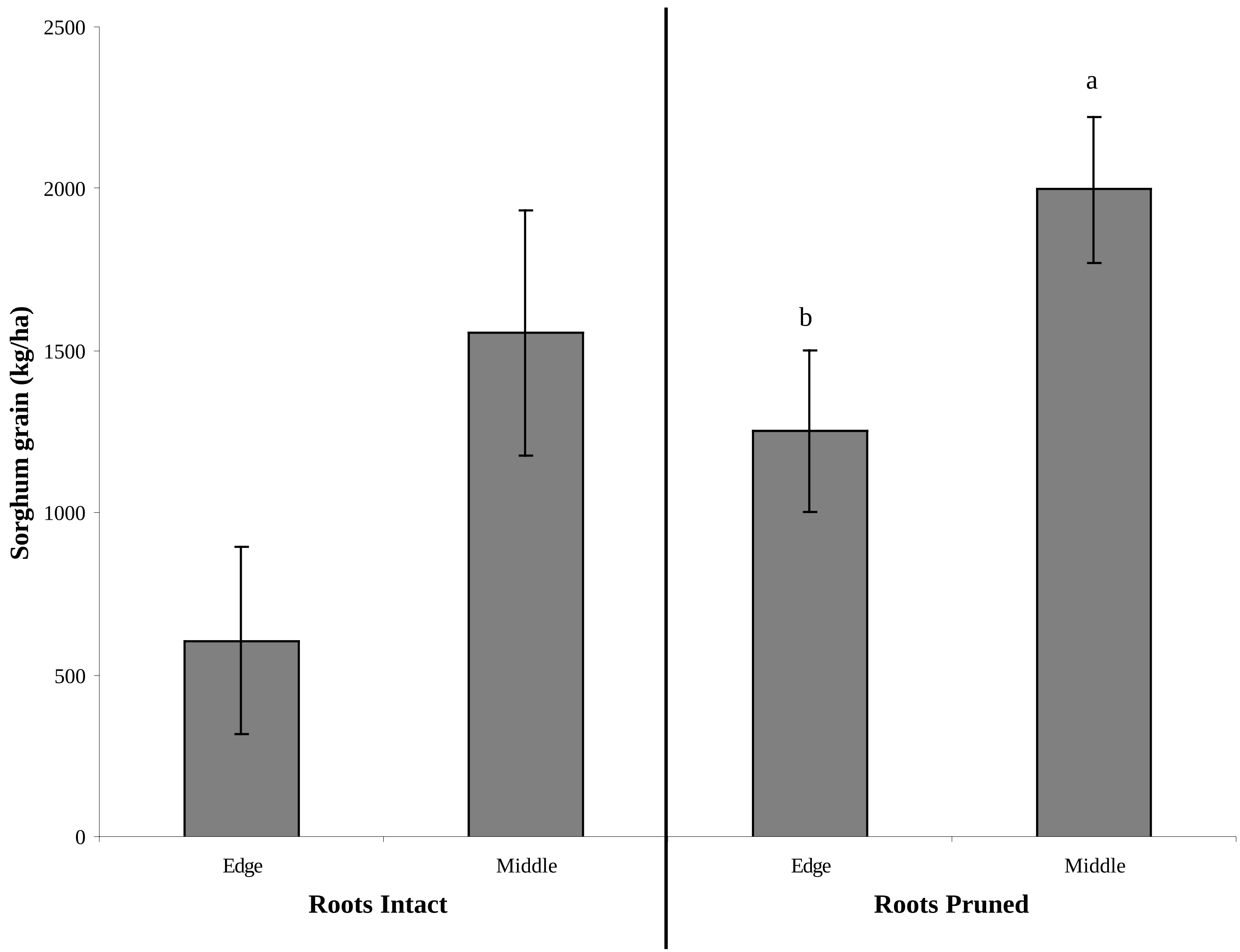

Sorghum grain (kg/ha)
0
500
1000
1500
2000
2500
a
b
Edge
Middle
Edge
Middle
Roots Intact
Roots Pruned

Figure 8: Weed biomass between treatments.

Measurements were based on 1 m^2 quadrat samples. Letters denote significant differences at 0.05 level of significance. RP=root pruned treatment, RI=root intact treatment, CC=cover crop treatment, IF=inorganic fertilizer treatment

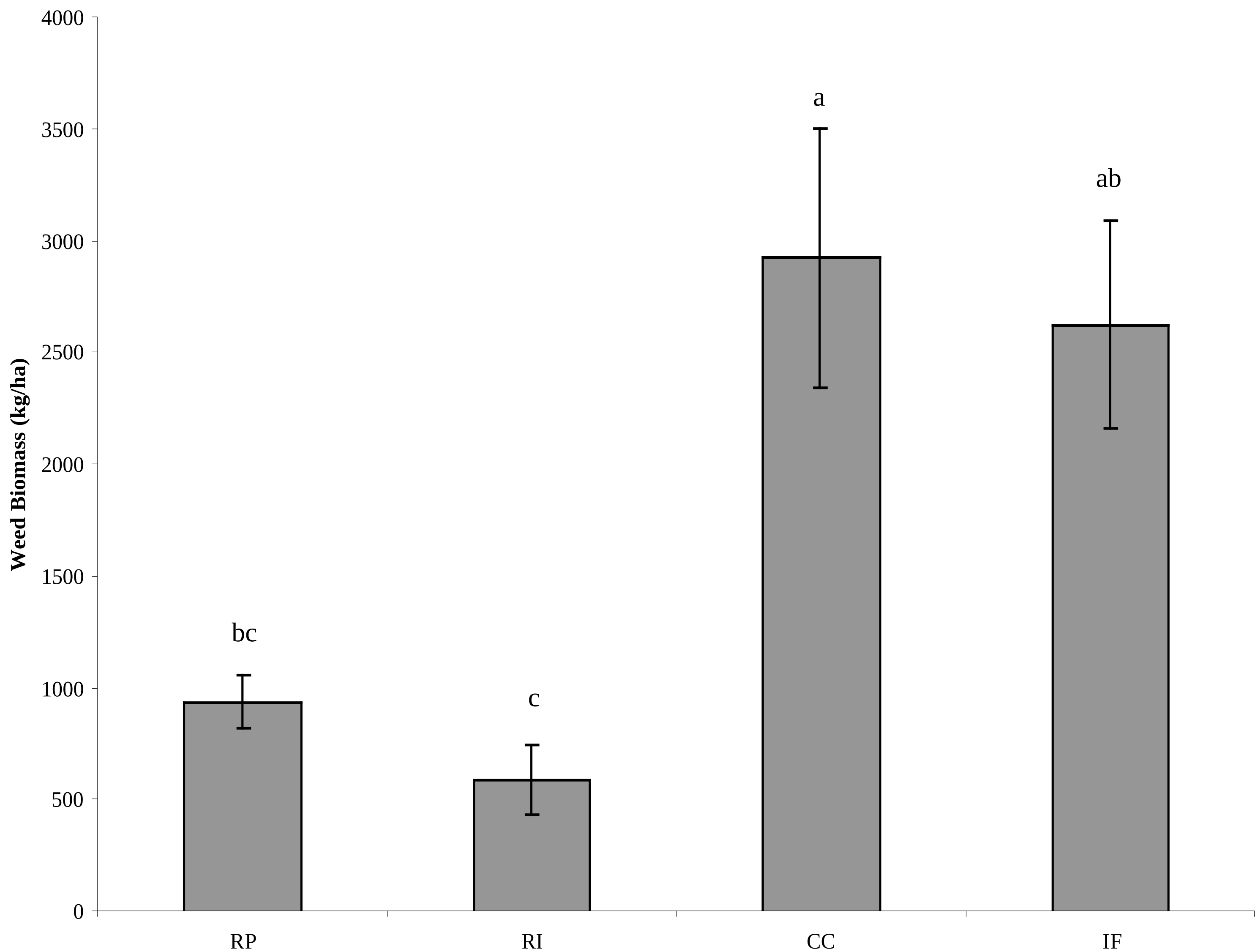

Weed Biomass (kg/ha)
4000
3500
3000
2500
2000
1500
1000
500
0
a
ab
bc
c
RP
RI
CC
IF

Figure 9: Soil total nitrogen levels at 0-5 cm depth.

In October 1998-October 1999, no distinction was made between root pruned and root intact treatments, and they were both included in the AC treatment. In October 1998, the cover crop treatment and the inorganic fertilizer treatment were grouped together as non-AC. In May 2000-October 2000 alley cropping plots were subdivided into root pruned and root intact treatments. AC=alley cropping treatment, RP=root pruned treatment, RI=root intact treatment, CC=cover crop treatment, IF=inorganic fertilizer treatment. Letters denote significant differences at 0.1 level of significance.

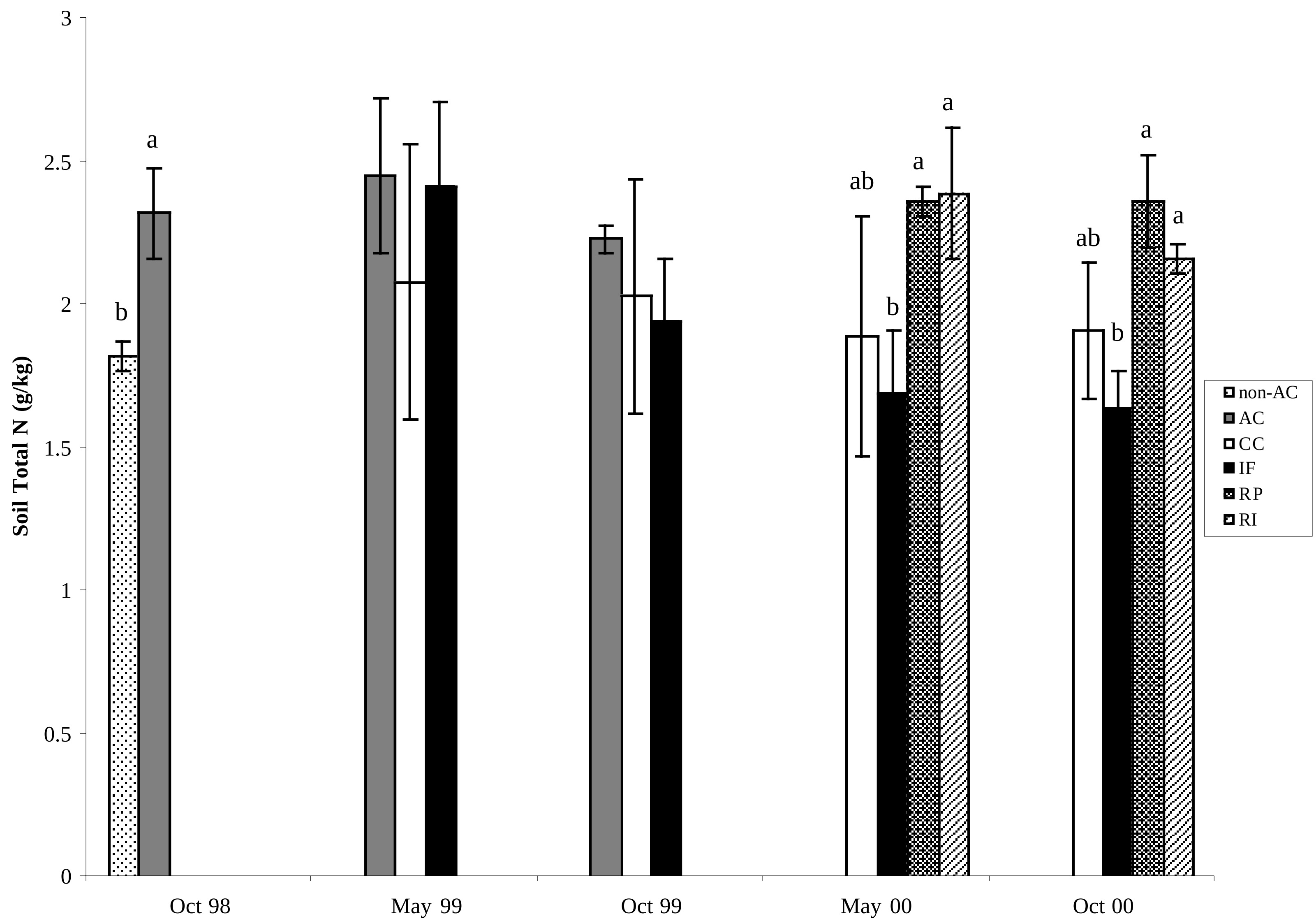
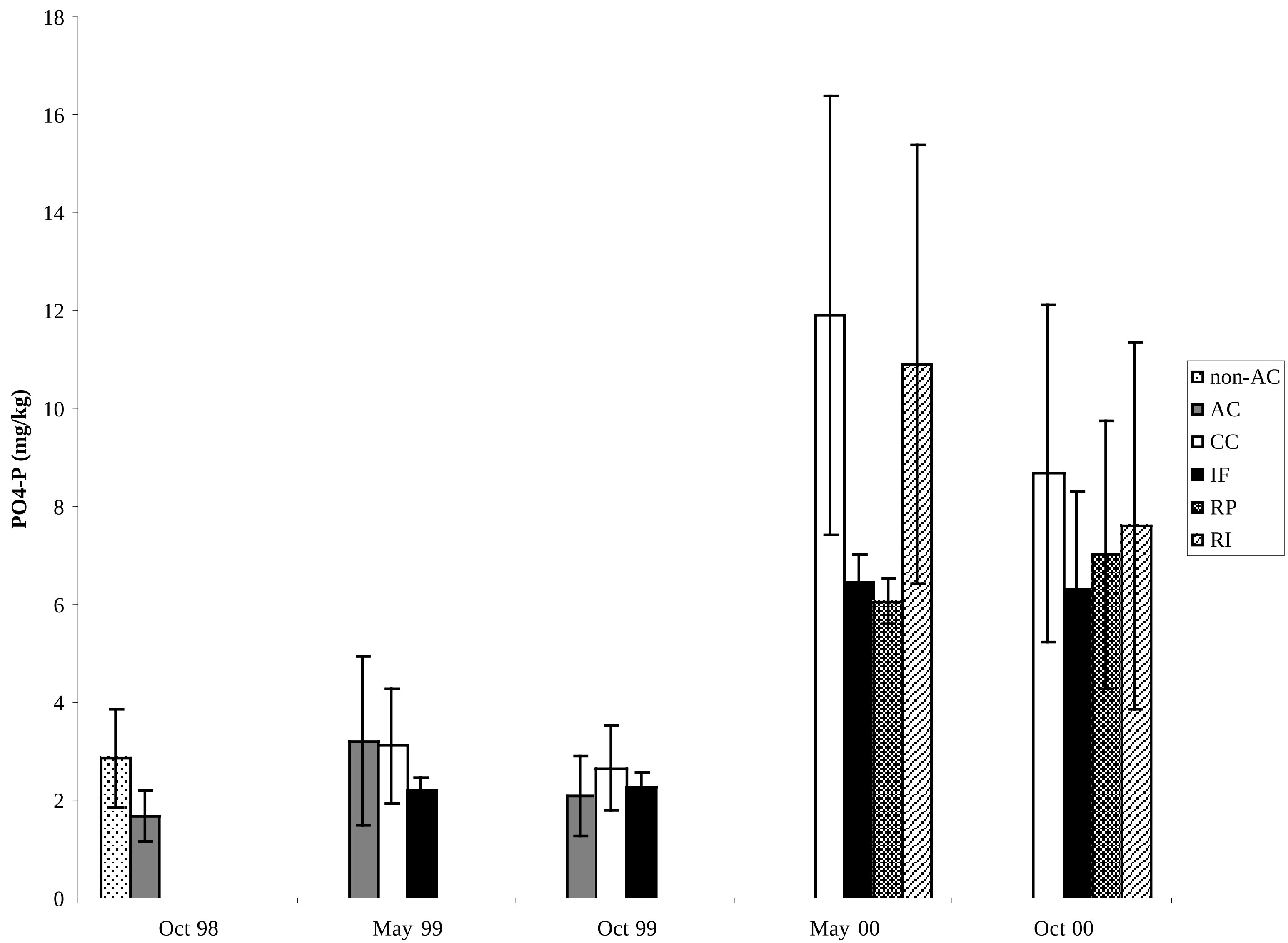

Soil Total N (g/kg)
3
2.5
2
1.5
1
0.5
0
Oct 98
May 99
Oct 99
May 00
Oct 00
a
b
ab
non-AC
AC
CC
IF
RP
RI

Figure 10: Total available phosphorus levels at 0-5 cm depth.

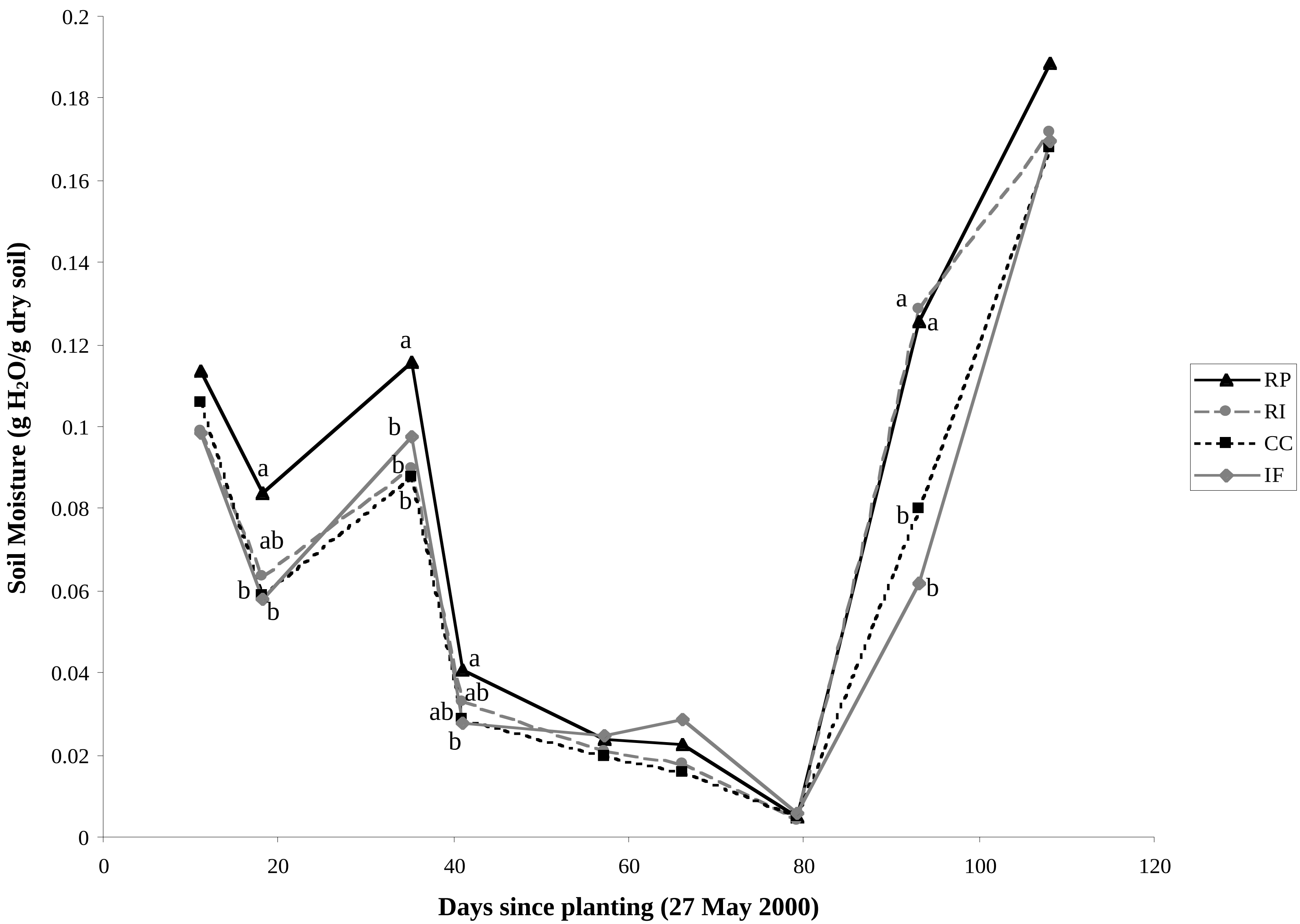
In October 1998-October 1999, no distinction was made between root pruned and root intact treatments and they were both included in the AC treatment. In October 1998, the cover crop treatment and the inorganic fertilizer treatment were grouped together as non-AC. In May 2000-October 2000 alley cropping plots were subdivided into root pruned and root intact treatments. AC=alley cropping treatment, RP=root pruned treatment, RI=root intact treatment, CC=cover crop treatment, IF=inorganic fertilizer treatment. There were no significant differences between treatments although phosphorus levels in all treatments rose during the second field season.



PO4-P (mg/kg)
18
16
14
12
10
8
6
4
2
0
Oct 98
May 99
Oct 99
May 00
Oct 00
non-AC
AC
CC
IF
RP
RI

Figure 11: Gravemetric soil moisture for all treatments at 0-10 cm, 2000.

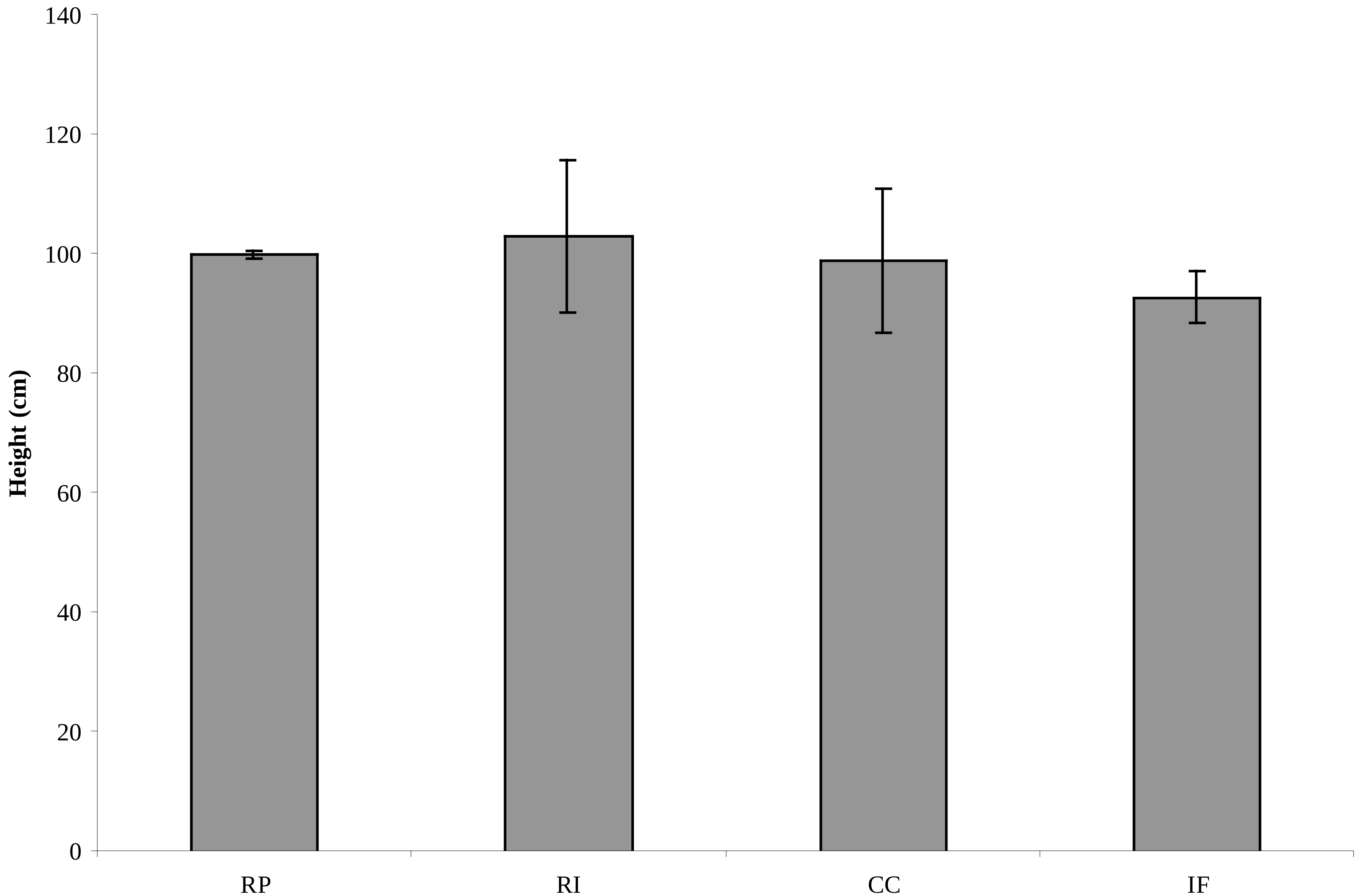
Day 0 is the day sorghum was planted in each plot, 27 May 2000. RP=root pruned treatment, RI=root intact treatment, CC=cover crop treatment, IF=inorganic fertilizer treatment. At each date samples were analyzed using One-way ANOVA and Tukey-Kramer HSD test to determine differences between treatments. Letters denote significant differences between treatments at 0.1 level of significance.



Soil Moisture (g H_2O/g dry soil)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
100
120
Days since planting (27 May 2000)
RP
RI
CC
IF
a
ab
b

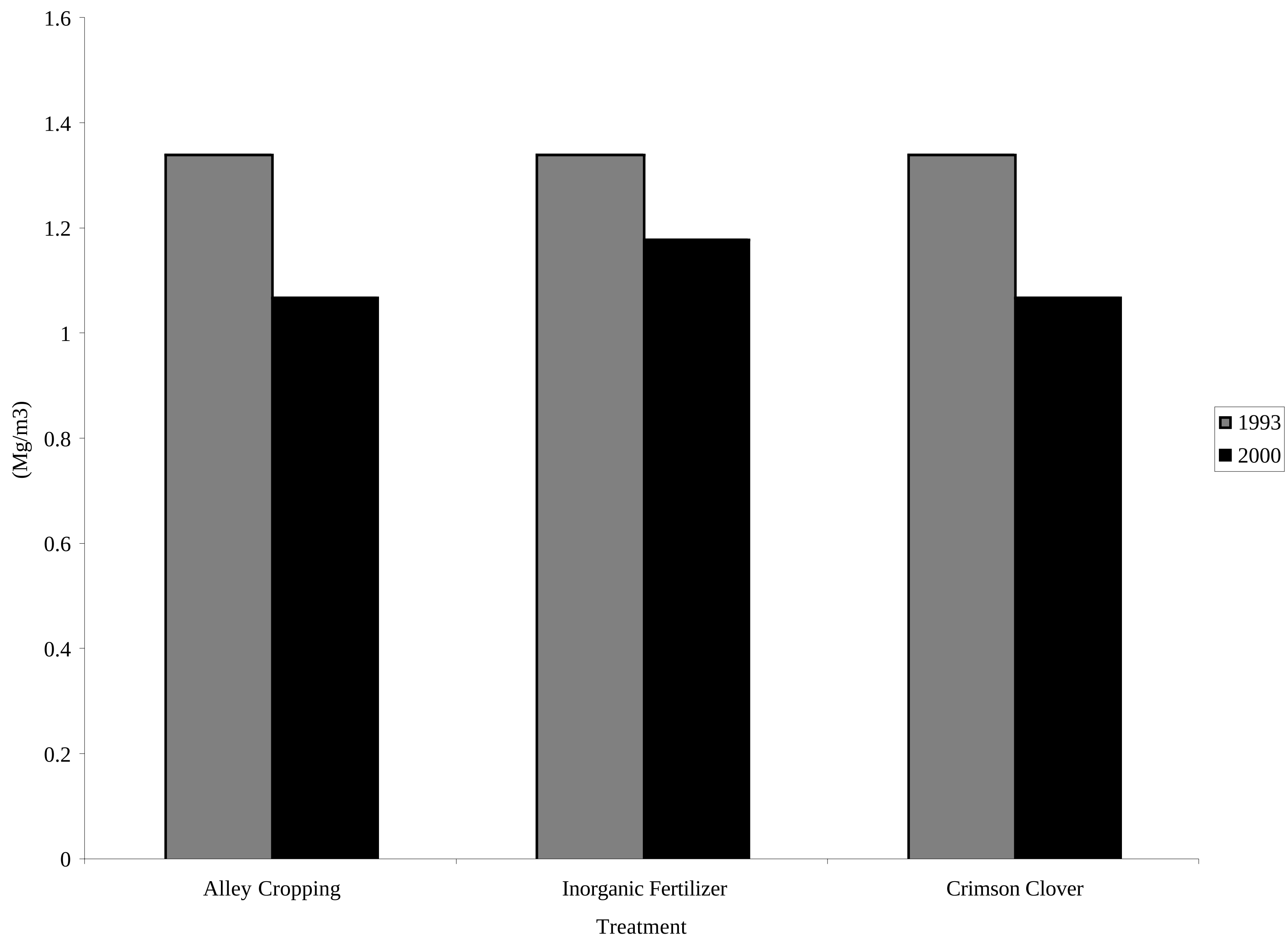
Figure 12: Average sorghum heights, 2000.

RP=root pruned treatment, RI=root intact treatment, CC=cover crop treatment, IF=inorganic fertilizer treatment. There was no significant difference between treatments.



Height (cm)
140
120
100
80
60
40
20
0
RP
RI
CC
IF

Figure 13: A comparison of soil bulk density between treatments, 1993 and 2000. Soil was sampled at a depth 0-5 cm in 1993 (Rhodes et al. 1998) and October 2000. AC=alley cropping treatment, CC=cover crop treatment, IF=inorganic fertilizer treatment.


1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
(Mg/m3)
Alley Cropping
Inorganic Fertilizer
Crimson Clover
Treatment
1993
2000

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