NITROGEN DYNAMICS AND OTHER INTERACTIONS IN TREE-CEREAL INTERCROPPING SYSTEMS IN SOUTHERN ONTARIO

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ABSTRACT

NITROGEN DYNAMICS AND OTHER INTERACTIONS IN TREE-CEREAL INTERCROPPING SYSTEMS IN SOUTHERN ONTARIO

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Main and interaction effects of three levels of soil moisture and three levels of soil N, on growth, development and yield of monocropped and intercropped poplar (*Populus* spp; clone DN 177) and monocropped and intercropped barley (*Hordeum vulgare*, var. OAC Kippen), were investigated in a potted greenhouse experiment. The evidence supported the hypothesis that co-plantings of poplar and barley can maximise resource utilization and reduce 'competitive' interactions. The total aboveground biomass produced per pot in the intercropped system was 14% higher than in the mono-cropped system, and there was no difference in the final grain yield between the two systems. Poplar leaf total N concentration was also high (> 2 %), indicating that addition poplar leaves in the field might positively influence soil N status.

Further investigations on interactions in a poplar-barley system were conducted in the field during the 1993, 1994 and 1995 growing seasons. Mean nitrate production rates, N availability and carbon content were higher in soils close to the poplar tree rows (2.5 m) compared to the corresponding values in the middle of the crop alley (4-11 m from the tree row). The results suggest that soil nitrate production rates, soil carbon content and plant N uptake adjacent to the poplar tree rows are influenced by poplar leaf biomass input in the preceding year. Preliminary N cycling models, developed for both tree-based intercropping and monocropping systems, indicate that nitrate leaching can be potentially reduced by more than 50% in intercropping systems.

The inhibitory effects of juglone (5-hydroxy-1,4-naphthoquinone) on soil N mineralization was also investigated, as black walnut (*Juglans nigra* L.) is also a recommended tree species for intercropping. Inhibition effect of juglone on nitrification in the field was not observed; laboratory incubation results confirmed the results of the field study.

These studies indicate that through proper design and management of tree-based intercropping systems, 'competitive' interactions can be reduced and 'complementary' interactions promoted, so that tree and crop components maximize sharing of resource pools. This can result in environmental and economic benefits to farming systems in southern Ontario.

DEDICATION

I dedicate this thesis to my late beloved father Mr. K. Thevathasan and to my loving brother Mr. Ajith Thevathasan, who has been missing since June 1990.

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1. Introduction

Since the beginning of the industrial revolution around 1700, the world population has been growing rapidly. Today's population growth rate of 1.7% per year is directly responsible for many of the problems encountered in almost all countries around the world related to food and energy supply and environmental health. Furthermore, it has been estimated that the annual increment to the world's population will continue to increase to a peak population of 6 billion by the year 2000 (Flavin, 1997). The vital issue of concern is not the large numbers of people, but how those numbers relate to the availability of limited resources such as land, food, energy supplies and other resources.

The food/population relationship between 1950 and 1985 is striking. World grain production almost tripled from 600 million MT in 1950 to 1700 million MT in 1985 (U.S.D.A., 1988). During the same period of time per capita grain production increased from 218 kg to 323 kg per year. This increase in food production was mainly achieved by augmenting productivity per unit land area through improved practices such as cultivation of high yielding varieties, and use of high inputs of fertilizers and pesticides and also by bringing more land area under agriculture at the expense of forested lands. This was largely seen as only a temporary solution to the world food crisis and was achieved at the cost of extensive environmental degradation and resource depletion. The overall extent of environmental damage suffered is well known. According to Brown (1991), for example, the world has lost about 480 billion MT of top soil, nearly 200 million ha of tree cover have disappeared, deserts have expanded by 120 million ha and thousands of valuable plant and animal species have vanished just in the past two decades alone. In the face of this, it is alarming that a number of competent authorities believe that there is a growing rate of species extinction and loss of biological diversity, caused mostly by deforestation in the tropics above and beyond natural rates of extinction (Raven, 1986; Abramovitz, 1997). By the end of this century thousands more plant and animal species are expected to be exterminated from the earth as a result of human activity (Wilson, 1988).

It is now evident that the degradation of the environment has become a serious worldwide problem and the world's growing population is putting even more pressure on natural resources, increasing the need for sound ecologically based land use techniques. Previous limited understanding of environmental balance has resulted in the injudicious management of land, leading to its impoverishment and severe degradation in many countries (Jarvis, 1991). Therefore, at present, sustainable development is widely perceived as the key to harmonizing economic growth and environmental sustainability (Kidd and

Pimental, 1992; Abramovitz, 1997; Suzuki, 1997), as it avoids maximizing any single outcome variable, (e.g. environmental quality, economic return or yield per ha), in order to achieve a long term balance among all variables. Sustainable agriculture also seeks a balance of environmental conservation, agricultural production, farm profit and community well-being (Flora, 1992). Current and future research must therefore be directed towards attempts to balance these multiple goals, constantly monitoring and adjusting the process to determine the impact of achieving one goal relative to the achievement of others.

Agroforestry, as a multiple land-use system, is an obvious means of fulfilling the sustainable developmental objectives mentioned above. Agroforestry refers to the land use system in which trees or shrubs are grown in association with either agricultural crops, pastures or livestock, or a combination of all three so as to obtain increased total productivity of system components in a sustainable manner from a unit of land (Nair, 1989). Conceptually, agroforestry systems are expected to fulfill both productive and service roles. The highest priorities for products from agroforestry systems include some combination of food (both from a tree and crop component), fuel, fodder and some timber. The highest priorities for services are soil fertility maintenance (through nutrient cycling, biological nitrogen (N) fixation, the input of soil organic matter and prevention of soil erosion) and microclimate amelioration. Although the service roles are common for both temperate and tropical agroforestry systems, the productive roles differ. In temperate agroforestry systems, trees are often expected to provide more service roles than productive roles (Gordon and Newman, 1997).

An underlying principle in effective food production systems is that soil productivity should not be undermined, but maintained, if not improved. Trees can have a benign or positive effect on soil, unlike agricultural crops which often tend to utilize the upper soil layers, finally exhausting most of the soil nutrients there. In contrast, an area left under forest cover tends to improve soil fertility (Young, 1997; Nair, 1993) and this is exactly what trees can do in agroforestry systems. In agroforestry systems, several experiments have been conducted in different climatic regions to test the effectiveness of different tree species to act as 'nutrient pumps' and to cycle leached nutrients which may then become available to the associated crop. In an experiment conducted in southern Ontario with black locust (*Robinia pseudoacacia* L.) intercropped with barley, application of black locust prunings contributed about 36 kg N ha^{-1} to the system (Ntayombya, 1993). Similar transfers of N from tropical legume tree species to associated crops have also been widely reported (Kang, 1988; Young, 1997; Ingram, 1990;

Nair, 1993). In China, the circulation rate of nutrients (N, P, K, Ca, Mg, Mn) in an ash (*Fraxinus* sp.) crop intercropping system was higher than in a monoculture system (Guangqin *et al.*, 1991). This nutrient cycling process needs to be understood and evaluated for tree species which are advocated for agroforestry systems in the temperate region.

Southern Ontario is beginning to experience land shortages as a result of unsuitable farming practices, inappropriate agricultural policies, conflicting land use priorities and population pressure from urban centers (Matthews *et al.*, 1993). Further, Gordon and Williams (1991) have indicated that in southern Ontario, agriculture production policies over the past 15 years have also relegated trees to small, over-utilized farm wood-lots and shelter belts, where soils are poor and sites marginal for agriculture. Agroforestry systems are highly applicable to such situations in the temperate region, where the ameliorative qualities of trees in farming systems can pose a solution to many problems caused by land degradation, soil erosion, destruction of wildlife habitat and other green spaces, water pollution and decreasing returns on agricultural investments (Matthews *et al.*, 1993). Therefore, practicing agroforestry in southern Ontario may be one manner in which farmers can bring both marginal lands now out of production and prime agricultural lands into sustainable agricultural production. Intercropping trees with cash crops in this region may be an appropriate agroforestry practice because of the flexibility of goals and a gradual change in land use which can prevent further environmental degradation (Gordon and Williams, 1991).

A decision to change any land management practice must take account of the objectives that the change is seeking to achieve. In southern Ontario, the ameliorative effects of trees in relation to soil fertility and productivity can be exploited, especially in the context of developing tree-based intercropping systems on marginal lands and on prime agricultural lands which are now out of production. The intercropping form of agroforestry infers the presence of both annual crops and perennial woody species on the same site under various types of spatial arrangements (Vergara, 1987). In recent years, intercropping has received considerable attention in terms of systematic research and development both in tropical (Kang *et al.*, 1990) and temperate situations (Gordon and Williams, 1991; Bandolin and Fisher, 1991; Gordon and Newman, 1997). In the past two decades, intercropping research in the tropics has identified several system components (different leguminous tree crop combinations) which can complementarily interact with each other resulting in positive service roles (Nair, 1993). However, studies of this nature are lacking for the temperate region in general and in southern Ontario in particular. Therefore, it is timely to design and evaluate a tree-based intercropping system in southern Ontario in order to foster the service roles from trees in a sustainable manner. This thesis attempts to evaluate some of these processes resulting from such a system.

The success of tree-based intercropping systems relies heavily on the exploitation of component (tree and crop) interactions, for limited resources such as land, light, nutrients and water. Although the importance of interaction between tree (woody) and crop (non-woody) components has been frequently recognized, the knowledge on this subject is rather limited (Nair, 1993). Component interactions refer to the influence of one system component on the performance of the other component as well as on the system as a whole (Muschler, 1991). The primary objective in designing tree-based intercropping systems is to promote more complementary biological interactions and to minimize competitive biological interactions among the components. Complementary biological interactions between system components are defined as those in which an increase in production of the tree component on a given land area automatically leads to a corresponding increase in crop production. Competitive biological interactions between system components are those in which an increase in the production of the tree component leads to a decrease in crop production (Hoekstra, 1990). In order for tree-based intercropping systems to be more profitable (biologically and economically) than monocropping systems, complementary interactions should outweigh competitive interactions. In fact, when complementary interactions are spread out over a long-term (e.g. 20-25 years), both biological and economical benefits are obtained from such systems. The latter scenario is normally referred to as a sustainable production system (Hoekstra, 1990).

Agroforestry research in the tropics has shown that the proper selection of components and the adoption of proper management techniques are the two most important steps that should be considered while designing agroforestry systems to promote complementary interactions among components (Wood, 1990). Willey (1979) also suggested that interactions between components in an intercropping scenario could be altered or modified by genotype (species) selection and through management techniques. He further suggested that complementary interactions will generally occur when components of an intercropping system are very different (e.g. woody and non-woody plants). Competitive interactions can be kept low, if not eliminated among the components as long as the demand for limited resources is staggered by space and time (Willey, 1979; Huxley, 1985; Nair, 1993).

A considerable amount of knowledge already exists on how to grow agricultural crop species, but much less is known about many tree species, especially when they are contemplated for use in temperate intercropping systems (Thevathasan and Gordon, 1995). Many publications contain long lists of tree species that are used for agroforestry practices in the temperate region (Bandolin and Fisher, 1991), but these are of little help when choosing tree species for specifically designed agroforestry interventions. The objectives of such interventions are to achieve beneficial changes in land use. The less information that is available on how a tree species will perform in an intercropping situation, the more important it is to evaluate that species against the criteria in which it is to be used. The production, service functions, and the biological and ecological interactions between the tree and the crop components are some of the parameters that could be evaluated during the establishment of a tree-crop intercropping experiment. Such information will be very useful for temperate agroforestry research programs.

The literature also suggests that if leaf N concentration exceeds 2%, and when they are added to the soil, net N mineralization can readily proceed in the soil (Palm and Sanchez, 1991). Optimum foliar nitrogen levels in poplar species are reported as being in the range of 2.4 to 2.8 % (Garbay 1980; Schoenfled 1975). It would therefore appear that there is a great potential for soil N enrichment under a poplar-based intercropping system.

At the same time there is a general belief that as the economical value for poplar wood is low, its suitability as a tree component in a tree-based intercropping system may not be profitable. However, in the past 10 to 15 years an abundance of research with hybrid poplars has shown many uses for and profitability in the cultivation of hybrid poplars in mono or mixed culture systems (Bernier, 1984; Newman and Wainwright, 1989; Zhanxue *et al.*, 1991; Newman *et al.*, 1991; Puri *et al.*, 1994; Gordon and Newman, 1997). On the other hand many potential environmental and crop yield benefits have also been shown to be associated with poplar-based intercropping systems (Zhanxue *et al.*, 1991; Gordon and Williams, 1991; Thevathasan and Gordon, 1995; 1997; Gordon and Newman, 1997). Increases in biodiversity, soil organic matter and soil invertebrate populations have also been documented under poplar-based intercropping (Park *et al.*, 1994; Gordon and Newman, 1997). Hybrid poplars have also shown promise in riparian buffer zones as nitrate and nutrient filters (O'Neill and Gordon, 1994). Therefore, it is evident that hybrid poplar may be a suitable tree component in a tree-based intercropping system if proper design and management strategies are adopted. Further, from a survey conducted in southern Ontario it became evident that farmers preferred quick economical returns from tree-based intercropping system (Matthews *et al.*, 1993). One way to achieve the above objective is to incorporate fast growing tree species such as hybrid poplars, into agroforestry systems.

Black walnut (*Juglans nigra* L.) is also one of the most commonly recommended tree species for tree-based intercropping systems in southern Ontario. Its high value, aesthetic qualities, capacity for nut production, rapid growth potential and adaptability to management deems the species very suitable to intercropping. However, black walnut is also well known for its allelopathic nature and it has long been observed that very few dicotyledonous plant species will grow beneath individuals or stands of walnut (Rice, 1984). Walnut produces an allelochemical named juglone (5-hydroxy-1-4-naphthoquinone), inhibiting the germination and growth of many other plant species (Kimmins, 1997). However, in the past twenty years studies have also shown that juglone is not only inhibitory to plant species but also inhibits the growth and existence of some beneficial soil microorganisms, especially *Frankia* spp. and *Rhizobium japonicum* (Dawson and Seymour, 1983; Rice, 1984). Nitrification in soils is also mediated by *Nitrosomonas* and *Nitrobactor* populations and if juglone inhibits the growth and development of these beneficial organisms, it might result in inhibition of nitrification under walnut-based intercropping systems. Therefore the inhibitory effect of juglone on nitrification, if any, was also tested in this study.

In this study, it is hypothesized that:

(a) The inherent characteristics of poplar (i.e. high leaf biomass production and leaf N content, drought tolerance, efficient nutrient acquisition and cycling (especially of N)), will promote more complementary interactions and reduce competitive interactions with the intercrop, in this case barley (*Hordeum vulgare* L.), resulting in beneficial effects on growth and yield of barley; and

(b) N released from decomposing poplar leaves shed each autumn will enrich soil N status and improve soil fertility in a poplar-based intercropping system, (c) in a black walnut-based intercropping system juglone released from walnut trees will inhibit nitrification in soils closer to the trees, causing a competitive interaction for N with the associated crop. With regard to the above, the following objectives were formulated and determined in this study:

1. to quantitatively evaluate the short-term effects of three levels of N fertilizer and three levels of soil moisture on the early growth of polar (monocropped and intercropped) and growth and yield of barley (monocropped and intercropped);

2. to determine the effects of poplar-leaf biomass distribution on N mineralization rates, soil respiration

rates, soil C, and N status of barley across the intercropped field;

3. to construct a preliminary N cycling model for poplar based intercropping system using the experimental data; and

4. to quantitatively evaluate the effects of juglone (5-hydroxy 1,4 napthoquinone) on soil N mineralization.

Agroforestry is in its infancy stage in this part of the world. Therefore, results from this investigation will certainly be of paramount importance to agroforestry research programs in the temperate region and also to the design of suitable, productive and efficient food production systems in southern Ontario in particular.

2. LITERATURE REVIEW

Agroforestry as a science is new to North America in general and to southern Ontario in particular. In the tropics, however, agroforestry is well advanced and has resulted in environmental, ecological and economic benefits in those regions. Some tropical agroforestry concepts can be adapted to southern Ontario farming systems in order to achieve the benefits mentioned above. Therefore, much of the information and many of the concepts presented in this chapter, even though they refer to tropical agroforestry systems, may be applicable in southern Ontario.

The material reviewed in this chapter is descriptive. The purpose of this review is to present all relevant materials pertaining to this study and to provide general information in agroforestry to the reader since this is one of the very first studies in southern Ontario.

2.1 Agroforestry

Agroforestry is not a new concept and historically throughout the world, trees, crops and animals have been grown together on small farms (Nair, 1993). It could be said that agroforestry is a new name for an old set of practices (Nair,

1989) and although there have been many efforts to define the art and science of agroforestry, the definition by Nair (1989) is perhaps the most appropriate. He defines agroforestry as a 'land use system that involves socially and ecologically acceptable integration of trees with agricultural crops and/or animals, simultaneously or sequentially, so as to obtain increased total productivity of system components in a sustainable manner from a unit of farm land, especially under conditions of low levels of technology input and on marginal lands'. Inherent features of developing countries such as limited capital, low soil fertility, small land holdings, ever increasing demand for food, low income, and antiquated technology have prompted indigenous farmers to develop integrated and sustainable approaches to agricultural production. These approaches have often brought together the disciplines of agriculture, forestry and animal husbandry. Such farming systems have been widely practised all over the world for many centuries (Nair, 1989).

In North America, using trees as an integral part of agriculture is not a new concept (Gordon and Newman, 1997). Prior to the European settlement of North America, Native Americans (First Nations) utilized agroforestry systems much like subsistence farmers in other parts of the world and were more active as land managers than is commonly acknowledged

(Anderson and Nabhan, 1991). Swidden systems (rotational or slash and burn) were common in many parts of North America and fire was used extensively to enhance forage for wildlife, encourage berry-producing shrubs and clear underbush to make it easier to hunt, travel and defend against enemies (Anderson, 1993; Boettler-Bye, 1995).

A review of the literature on temperate agroforestry indicates that, when agroforestry was first described in the late 1970's, certain practices common in North American agriculture were quickly identified as agroforestry or agroforestry-related practices. They are: forest range and farm woodlot management, maple syrup production, plantations on marginal or degraded land (e.g. forest or Christmas tree plantations; riparian forest plantings), and wind breaks, to name a few (Williams *et al.*, 1997).

Modern combinations of trees and agriculture have also been identified as agroforestry practices by Gold and Hanover (1987) who suggested that these systems have great potential in the temperate zone. Intercropping of black walnut (*Juglans nigra)* with cash crops (Garrett and Kurtz, 1983), forage production and silvopasture with pines in the southeastern United States (Lewis *et al.*, 1983) and the use of livestock to control weed competition in conifer plantations in the western

United States and in British Columbia (Ellen, 1991), and integrated riparian management systems (Williams *et al.*, 1997) are just a few that can be cited as new developments or modern applications of traditional agroforestry practices in North America. A detailed description of the above mentioned agroforestry systems in North America is not feasible here. Therefore, for an excellent treatise of the subject, the reader is referred to Gordon and Newman (1997).

The introduction of western technologies to developing nations during the middle of this century focused on increasing agricultural productivity by bringing a shift from integrated farming systems to monoculture farming (Bezkorowajnyj, 1990). This resulted in large scale deforestation leading to increased soil erosion rates, soil nutrient depletion, build up of atmospheric CO_2 and potential changes in global climate (Okigbo, 1990; Gholz, 1987). Agricultural productivity declined in many instances as a result of inappropriate technology and abusive land use, and aggregate outputs seemed unable to keep up with rapidly escalating populations (Nair, 1993). The literature suggests that the situation in North America was not that much different from that of developing nations. The farming community in North America has come under increasing criticism for past agricultural practices that have increased soil and wind erosion, degraded soil structure, lowered water quality and reduced wildlife habitat (Gordon and Newman, 1997). As a result of the latter, Williams *et al.*, (1997) indicate that conventional agriculture has become economically marginal for an increasing number of farming households and communities throughout North America. The authors further suggest that the land area under agriculture has also been reduced through incentive programs which promoted alternative agricultural practices. These observed adverse effects in the tropics as well as in the temperate regions raised an alarm around the world, and the need for further development of alternative sustainable systems became obvious.

The recent resurgence of agroforestry derives primarily from the recognized failure of large agriculture and forestry monocultures in the lesser developed world, primarily in the tropics (Gholz, 1987). However, a review of the literature indicates that agroforestry practices have also been recommended in North America for their ability to satisfy many needs, including 1) economic and agricultural diversification, 2) environmental impact mitigation, 3) land and water rehabilitation and restoration, 4) increased or decreased food production, 5) sustainable use, or retirement of marginal or fragile land, 6) natural habitat enhancement, and 7) profitability (Williams *et al.*, 1997).

Agroforestry is a low cost land use system which promotes soil conservation, productivity and sound environmental practices for farmers with meagre capital resources (Vergara, 1987). Several integrated systems are now being tested world-wide for long term productivity and sustainability in both the tropics and temperate regions of the world (Nair, 1989; Young, 1997; Bezkorowajnyj, 1990; Gordon and Newman, 1997). However, long term productivity and sustainability can only be achieved in any system (tropical or temperate) if the system is designed and managed to promote such beneficial ecological interactions.

Tree-based intercropped systems in the tropics are often cited as excellent land use systems due to their productivity, sustainability and adaptability (Nair, 1993). This is in part due to their multi-component nature and the interactions that occur between system components in relation to competition for water, light and soil nutrients. Agroforestry systems are always more ecologically complex with respect to structure and function than mono-crop systems, and in order to maximise the above characteristics, an understanding of the complex biological and ecological interactions that occur in intercropping is required. Many of these interactions have been researched for tropical systems (Tian, 1992;

Rao *et al.*, 1998) and a reasonable understanding has emerged (Ong and Huxley, 1996). Nevertheless, there is a lack of information concerning the latter in the temperate region. The need for understanding ecological interactions in North American tree-based intercropping systems has increased significantly in the past decade (Gordon and Newman, 1997). The latter authors have also indicated that many research programs across North America are currently underway to investigate the energy flow through trophic levels in multi-component systems with the aim of understanding component interactions and competition.

2.2 Interactions in agroforestry

There are two types of interaction in a population of plants: intraspecific and interspecific interactions (Begon *et al.*, 1990). Intraspecific interaction refers to interactions within a population of the same species, while interspecific interaction refers to interaction in populations comprised of different species (Harper, 1977). In agroforestry systems, it is interspecific interaction that is often of interest. For continued growth, plants require continuous and balanced access to the resource pools of light, water and nutrients (Connor, 1983; Borsa, 1990). In a tree-based intercropped system, these resource pools are shared between the tree and the agricultural crop components. The interactions that take place between the tree and the crop component can be either 'competitive', or 'complementary'. As outlined by Borsa (1990), 'competitive' resource utilization is characterized by the acquisition of growth resources by one species to the exclusion of the other. The term 'complementary' applies to cases where resource utilization by the components (trees and crops) is partitioned either in time or space as in different rooting depths, or different maturity patterns (Connor, 1983). Thus, when an interaction is complementary, in a tree-based intercropped system, stressful situations are often less. Trees need not compete with crops for water, given the relative distributions of the two root systems, and deciduous trees may allow the passage of enough light to support the seasonal growth of an understorey (Connor, 1983). Trenbath (1976) also reports that 'complementary' interactions in mixed plant communities may promote efficient resource utilization. Nevertheless, the complexity of agroforestry systems (Huxley, 1985; Buck, 1986; Leyton, 1983) often results in constant changes in spatial patterns, as the system grows in the horizontal and vertical dimensions (Borsa, 1990). As a result of these dimensional changes, interactions for resources between the species will also change over time (Begon *et al.*, 1990). Therefore, one can conclude that in a tree-based intercropped system the interaction between the tree and crop component is not always 'competitive' nor 'complementary' over time. As the temporal dimensions of the system keep changing, the pattern of interaction is also likely to change. However, as outlined by Buck (1986) and Trenbath (1976), through proper design and plant management, one can reduce 'competitive' interactions and promote more 'complementary' interactions, so that tree and crop components share the different resource pools in a way that minimizes mutual interference and maximizes resource sharing. The development of such a management system should be aided by an understanding of the biological potential and restraints of particular agroforestry combinations (or tree-crop combinations) (Borsa, 1990).

Even though the beneficial effects of tree-crop integration have been well documented, a number of negative effects have also been recognized, such as competition for moisture, excessive shading and allelopathy (Ong, 1996). The latter suggests that when the component interaction is complementary the outcome is generally beneficial but the reverse is true when the interaction is competitive. The evidence of such outcomes , beneficial or detrimental, can be direct or indirect. The main effects of tree-crop interactions and their evidence (direct or indirect) are summarized in Table 2.1 (Adapted from Ong and Huxley, 1996).

Table 2.1. The main effects of tree crop interactions. Positive effects are indicated by (+) and negative effects by (-): where evidence is not available it is indicated by (0). Only key or recent sources are quoted.

	Evidence		
Effects	Direct	Indirect	Source
Increased productivity	+	+	Ong, 1991
Improved soil fertility	+	+	Kang *et al.*, 1990
Nutrient cycling	+	+	Szott *et al.*, 1991
Soil conservation	+	+	Lal, 1989; Wiersum, 1984
Microclimate improvement	+	+	Monteith *et al.*, 1991
Competition	-	-	Ong *et al.*, 1991
Allelopathy	0	-	Rizvi,1991; Tian and Kang,1994
Weed control	0	+	Rizvi, 1991
Sustainability and stability	0	+	Sanchez, 1987; Young, 1997
Pests and diseases	0	-,+	Zhao, 1991

A detailed description for all of the tree-crop interaction effects listed in Table 1 is beyond the scope of this study and the reader is thereby referred to the sources. However, a few of the perceived beneficial and adverse effects of the tree component will be highlighted to justify the observed evidence in Table 1.

2.2.1 Increased productivity

A review of the literature indicates that when resources are not limiting, densely planted monocultures usually provide the most efficient resource utilization systems. However, where one (or more) resource is limiting, it may be possible to improve productivity by using species mixtures if the component species utilize more of the available resource or use them more efficiently for growth. In such instances, mixtures may have a greater productivity than the corresponding sole crop productivity (Ong and Huxley, 1996). Agroforestry systems are generally recommended for marginal lands where resources are often limited (Nair, 1993; Young, 1997). Therefore, under resource limiting conditions, agroforestry systems have generally resulted in higher overall (biomass) productivity over monocropped systems (Nair, 1984; Glover and Beer 1986; Kang and Wilson 1987; Vergara

1987). The basis for this higher productivity in tree-based intercropped systems is likely due to the utilization of more growth resources (Van Noordwijk, 1996; Ong *et al.*, 1996).

A proper understanding of the mechanism by which the components (tree and crop) utilize their growth resources is very important. The information derived from the latter will help to make proper selection and management of the components by which the demand for the growth resources can be staggered by space and time. Systems that have been established in accord with the above criteria are often productive and have widely been reported in the literature. Poschen (1986) reported that intercropping *Acacia albida* with maize in Ethiopia provided more than a 76% increase in maize grain yield, compared to maize grown in the open. Similarly, in Nigeria and other parts of west Africa, Kang (1988), and Kang and Vandenbeldt (1990) reported very high yield increases of maize alley-cropped with *Leucaena leucocephala*, compared with non-intercropped maize. Some studies have also indicated that alley-cropping can sustain yields of annual food crops at high levels, over several years of continous cropping, without additional N-fertilizer inputs (Kass, 1987; Kang, 1988; Kang and Vandenbeldt, 1990).

In other studies, authors have reported very high aggregate crop production from home gardens (i.e multistrata agroforestry systems), compared with perennial agricultural monocultures (Okigbo, 1990; Michon *et al,* 1986; and Nair, 1984). For example, although studies in multistrata perennial agroforestry systems in Central and Latin America have revealed that coffee (*Coffea arabica*) production obtained from unshaded and shaded coffee were not significantly different, the highest economic returns were generally obtained from multistrata agroforestry systems (Budowski, 1983; Beer, 1987; Glover and Beer, 1986). Another interesting attribute of agroforestry has been reported by Harwood (1979), who observed that the potential productivity of agroforestry systems is very high, yet requires low power and low chemical energy inputs, compared to agricultural monocultures.

2.2.2 Improved soil fertility and nutrient cycling

Literature on soil fertility improvements under agroforestry systems indicates that soil fertility improvements are based on traditional agroforestry systems that have been established for many years. However, the potential of microsite enrichment by some trees is an extremely important aspect of agroforestry which has received considerable attention (Nair, 1984; Young, 1997). Further, it is implied in the agroforestry literature that agroforestry systems improve soil physical properties, maintain soil organic matter and promote nutrient cycling, (Sanchez, 1987; Young, 1997; Prinsley and Swift, 1987). In addition, agroforestry systems are frequently presumed to require less 'purchased' inputs (Sanchez, 1987; Kang and Vandenbeldt, 1990; Vergara, 1987).

Underlying all considerations of the role of agroforestry in the maintenance of soil fertility is the fundamental proposition that trees improve soils (Young, 1997) and much has been written about soil improvement in agroforestry (see Nair, 1984; Sanchez, 1987; Sanchez *et al.*, 1985; Kang, 1988; Kang *et al.*, 1990; MacDicken and Vergara, 1990). It is accepted that improvements of soil by trees are mainly a consequence of (1) increases in organic matter inputs, (2) biological nitrogen fixation, (3) nutrient retrieval and nutrient recycling, and (4) protection of the soil from erosion. The processes by which trees improve soils are well known, and have been described by Young (1991), Sanchez *et al.*,(1985), Prinsley and Swift (1987), Nair (1984), and others.

Trees and shrubs feature prominently in traditional farming systems throughout the world (Nair, 1989). Under shifting cultivation, farmers have for generations exploited the potential of trees and shrubs for soil fertility regeneration and weed control (Kang *et al.*, 1990). Many studies have demonstrated the capacity of trees to restore soil fertility (e.g. Sanchez *et al.*, 1985; De las Salas, 1987; Nair, 1984; Vergara, 1987). The regenerative value of forest fallows is well recognized, and is linked to the regrowth of deep rooted trees and shrubs which recycle plant nutrients from considerable depth in the soil profile, and the build up of soil organic matter (Anderson, 1993). When fallow periods are long enough to permit full vegetative regeneration and soil fertility restoration, shifting cultivation systems are then believed to be sustainable (Raintree and Warner, 1986). However, the relentless pressure on the land caused by rising populations of humans and animals have made traditional and current shifting cultivation systems less productive and unsustainable (Swaminathan, 1987; Kang *et al.*, 1987), although a number of agroforestry approaches have led to improvements and intensification in shifting cultivation. These have been discussed by Raintree (1986), Raintree and Warner (1986), Vergara (1987), Kang *et al.*, (1990), Nair (1984), Lal (1989), and others. These improvements have enabled farmers to lengthen the cropping period, reduce the fallow period, and maintain or improve crop yields.

Similarly, trees and shrubs are widely grown in association with crops throughout the world. Nair (1984), Kang *et al.*, (1990), MacDicken and Vergara (1990), Beer (1987), and others have described a variety of intercropping systems currently employed. The intercropping form of agroforestry infers the presence of both annual and perennial woody crops on the same site under various types of spatial arrangement (Vergara, 1987); and the build-up of soil fertility under these various practices has been recently documented (cf. Beer, 1987; Poschen, 1986; Michon *et al.*, 1986; Nair, 1984; Okigbo, 1990; Glover and Beer, 1986; Kang *et al.*, 1990; and others). Vergara (1987) noted that the major advantage of intercropping is its ability (if properly implemented) to continuously yield food crops and tree crops from the same site without an intervening `idle' fallow period.

Deep-rooted tree species are usually selected because they function well from a soil conservation point of view by reducing soil erosion (Young, 1997), and also minimize the competition between trees and annual crops for nutrients and water in the surface soil (Vergara, 1987; Pickersgill, 1983). The concept of 'nutrient pumping' in agroforestry infers that tree roots extend into portions of the soil profile that may not be accessible to shallow-rooted herbaceous crops, thus enhancing access to nutrients and water that would normally be unavailable to herbaceous plants (MacDicken and Vergara, 1990). The extracted nutrients may be returned later to surface layers of the soil in leaf litter, and thus will become available to the associated herbaceous crops (Pickersgill, 1983; Stephenson and Raison, 1988; MacDicken and Vergara, 1990). Nutrients released through the decomposition of leaf litter and roots are perceived to be a major benefit of agroforestry systems.

As nitrogen is frequently limiting in many farming systems, multipurpose nitrogen fixing tree species are often selected for use in agroforestry systems (Burley, 1987). Nitrogen contributions of some of the better known tree legumes are well documented (e.g Dommergues, 1987; Moore et *al.*, 1990; Sprent and Sprent, 1990). For instance, it is estimated that *Leucaena leucocephala* may contribute up to about 600 kg N ha^{-1} y^{-1} (National Academy of Science, 1979). Even though the accuracy of this figure has been questioned (Dommergues, 1987), it is accepted that this species returns substantial amounts of nitrogen to the soil. Kang *et al.* (1990) has reported that fast growing nitrogen fixing tree species such as *Leucaena leucocephala* and *Gliricidia sepium* can substantially increase soil fertility in 2 to 3 years in the humid tropics.

The impact of intercropping nitrogen-fixing tree species on the improvement and sustainability of crop yields has also been demonstrated, especially in alley-cropping systems (Kang *et al.*, 1990; Kang, 1988; Moore *et al.*, 1990). Alleycropping (or hedge-row intercropping) refers to a cropping system where arable crops are grown in the alleys formed by hedgerows of trees or shrubs (preferably legumes), which are pruned periodically during the cropping season to prevent shading, and to provide green manure and/or mulch to the arable crop (Nair, 1984). The alley-cropping technique retains the basic features of traditional shifting cultivation. Its major advantage over shifting cultivation is that the cropping and fallow phases can take place concurrently on the same site, allowing the farmers to crop the land for extended periods without returning to fallow (Kang *et al.* 1990). The potential contribution of nutrients by some of the better known tree species used in alley-cropping systems has recently been documented (Nair, 1984; Kang, 1988; Kang *et al.*, 1990; Palada *et al.*, 1990), and the long-term effect of green mulch from hedgerows on soil fertility has been widely reported (e.g. Kang *et al.* (1990).

The latter reported that the organic matter and nitrogen content of soils under alley-cropping were much higher compared to soils without trees. They also reported that the addition of green mulch during the cropping period plays an important role in reducing soil erosion and runoff.

There is a paucity of literature on soil fertility improvement under agroforestry systems in North America. However, in recent years, trees have been introduced to overutilized agricultural and marginal lands in North America potentially to improve soil structure and fertility (Williams *et al.*, 1997). The latter further suggest that, the introduction of trees can also be used to rehabilitate degraded fields by reducing soil erosion, and improving soil organic matter and nutrient status.

Despite the general belief that agroforestry systems have played a positive role in improving and maintaining soil fertility, more research is needed to quantitatively demonstrate these effects, particularly in currently promoted agroforestry technologies.

2.2.3 Soil conservation

Humid tropical ecosystems are known to be fragile and prone to environmental degradation and loss of productive capacity when disturbed by human activities (Vergara, 1987). Abusive use of land coupled with climatic conditions of high temperature, humidity and precipitation in the humid tropics can very easily erode nutrient bearing soil and leach away soluble nutrients. In the tropics, descriptions of erosion damage date from the 1930's and 1940's (Young, 1997) and awareness of the need for soil conservation arose in the U.S.A. as early as the 1930's (Young, 1997).

In temperate North America, conventional agriculture has also resulted in excessive soil erosion and subsequent soil depletion, leaching of agrochemicals, reductions in ground water levels and their contamination, and the general degradation of natural ecosystems (Williams *et al.*, 1997). Severe wind erosion as a result of the absence of trees in southern Ontario has also been reported by Campbell (1991). A review of the literature in this area indicates that the above effects are, in part, a result of losses in number of woodlands, wetlands, windbreaks and hedgerows. Williams (1993) and Williams *et al.* (1997) suggest that agroforestry practices such as: 1) windbreak systems (shelterbelts), 2) silvopastoral systems, 3) intercropping/alleycropping systems, 4) integrated riparian management systems and 5) forest farming systems are a few potential land-use remedies for degraded lands in the temperate North America. A detailed description as to how these agroforestry practices can contribute towards soil conservation is found in Gordon and Newman (1997).

Soil erosion and subsequent nutrient losses can be reduced by either mechanical or vegetative means (Vergara, 1987). In terms of the former, terracing, contour ditching, and contoured banking to slow run-off and reduce erosion are excellent examples, but the high cost of labour requirements necessary to control run-off by such means is not practically feasible in less developed countries, due to the low capital resources of both farmers and government (Reij *et al.*, 1986; Vergara, 1987). The alternative here and for farmers with low capital resources in developed nations as well is to rely more upon vegetative means to control soil erosion and to maintain soil fertility.

All agroforestry systems consist of trees either with crop or pasture/livestock (Nair, 1993). A good understanding of the tree component and the role it plays in soil conservation is important. Trees reduce soil erosion by binding together the surface soil with their woody and interlocking root systems (O'Loughlin, 1974; Ziemer, 1981). Litter from the canopy, stems and surface roots impedes the velocity and erosive ability of surface run-off (Wiersum, 1984). Agricultural crops or pasture in conjunction with tree crops can provide a good ground cover against the direct impact of rain and displacement of soil particles (Nair, 1987; Young, 1997; Gordon and Williams, 1991).

Nair (1987) and Young (1991) have also outlined several beneficial soil changes that can occur with the incorporation of compatible and desirable species of woody prennials and agricultural crops: (1) an increase in organic matter content of soil by addition of leaf litter and other plant parts, (2) solubilization of relatively unavailable nutrients (e.g. phosphates) through the activity of mycorrhizae and phosphate-solubilizing bacteria, (3) an increase in the activity of favourable micro-organisms which produce growth-promoting substances through desirable interactions and cause commensalistic effects on the growth of plant species (4) an improvement in the physical condition of soil in the long run, with respect to permeability, water holding capacity, aggregate stability and soil temperature regimes.

2.2.4 Microclimate improvement

Some of the most important effects of combining woody and non-woody plants in mixtures result from changes in the microclimate which in turn influences the growth of all components of the system. A large number of changes can be identified when trees are introduced into a farm field. Those of particular importance include: changes in the radiation balance under trees, changes in the surface wind pattern, changes in air humidity, changes in temperature and the combined effect of the latter climatic parameters on evaporation (Brenner, 1996). Further, temperature and moisture extremes are modified under tree canopies (MacDicken and Vergara, 1990). Temperature extremes are mitigated by tree canopies and surface litter cover which protect the soil surface from solar radiation during the day, and reduce heat losses at night. Under agroforestry systems, lower temperature maxima and higher temperature minima are generally obtained (Budowski, 1982; Young, 1997). This may be particularly beneficial to plants and animals close to the ground surface (Budowski, 1982). Furthermore, experimental evidence has shown that tree canopies and the litter cover of agroforestry systems reduce ground surface temperatures much more than under agricultural monocultures, or bare soil (Young, 1997). Studies have also indicated that the air temperature within agroforestry system during cold spells was 1.5°C higher and soil temperatures were about 2°C higher than in the unprotected areas (Budowski, 1982; Young, 1997).

Reduction of wind speeds by trees used as shelterbelts in areas that experience high wind or sand movement is a well established fact (Wight, 1988; Horvath and Gordon, 1995; Williams *et al.*, 1997). Increases in crop yields as a result of improved microclimate have also been widely reported (Reifsnyder and Darnhofer, 1989; Brenner, 1996). For instance, Luo and Hu (1990) reported that a system of shelterbelts and windbreaks along the coastal plains of China reduced damage to crops caused by typhoons during the rainy seasons and cold spells in the early spring and late fall. These workers indicated that rice grain yields in the protected areas was more than 24% higher than in the unprotected areas, and the rotting rate of rice (*Oryza sativa*) seedlings during the cold spells declined by 30 to 40%.

The evidence of the beneficial effects of shade trees depends on the nature of the understorey crops. The clearest effect is reported for crops that require shading for normal growth, e.g. black pepper (*Piper nigrum*), turmeric (*Curcuma* *longa*), cacao (*Theobroma cacao*) (Nair, 1984). Analysis of *Paulownia* and tea in sub-tropical China suggest that tea production is slightly improved when shading is about 37%, but overall economic benefit was largely due to the additional timber from *Paulownia* (Shanqing *et al.*, 1991). Even though much has been understood on the ability of trees to modify microclimate, there is still a paucity of quantitative data and hence more research is needed.

2.2.5 Competition

Competition has long been recognized as an important agent of natural selection in agriculture and forestry (Grace and Tilman, 1990). Individual plants or communities that can successfully compete with their counterparts for the limited resources in any given habitat generally succeed in that given habitat, suppressing the rest (Harper, 1977). In this context it is generally believed that plants affect resources simply by their uptake of those resources. However, the literature also suggests that soil resources such as moisture and nutrients may be affected by non-uptake effects as well (Goldberg, 1990). For example, uptake can be influenced by the physiological activity of a plant, allocation of resources, and tissue production. But at the same time, non-uptake effects such as microbial mineralization, leaching, and nutrient addition in the form of throughfall and litter input can also influence available resource pools significantly (Chapin, 1980; Goldberg, 1990). Abiotic factors such as temperature, soil type and the evapotranspirative demand of the plant can also modify each of the above processes. For example, an increase in temperature can increase the rate at which soil microbes release nutrients tied up in the litter and can result in greater nutrient availability. Plant traits such as branching, leaf area, cuticle thickness, structural carbon concentrations and stomatal density may also have an effect on the composition and volume of throughfall and stemflow (Tukey, 1970; Goldberg, 1990).

Nutrient use efficiency or the mass of nutrients required to produce a given quantity of dry matter is another mechanism of importance to plant competitors. For example, Vitousek (1982) determined that tree species adapted to nutrient-poor substrates have higher nutrient use efficiencies than those adapted to fertile sites, despite the fact that plants from infertile habitats have greater concentrations of nutrients in contrast to those plants from fertile habitats. Two mechanisms were defined to describe these results, including a high carbon-fixing efficiency and re-absorption of nutrients from abscised tissues (Vitousek, 1982). The latter mechanism along with reduced leaching rates have also been suggested as processes responsible for increasing nutrient use efficiency and the competitiveness of a given species (Boerner, 1984). Boerner (1984) and Yoshioka *et al.* (1988) have found that a wide range of deciduous tree genera adapted to fertile sites could maintain productivity on infertile sites by decreasing leaching losses and/or allocating less nitrogen or phosphorus to a given mass of leaf or woody tissue.

Therefore, in an agroforestry scenario, if trees from different genera which can contribute these beneficial non-uptake effects are incorporated, competitive interactions with the associated crops may be reduced significantly. There are numerous examples in the literature citing such beneficial effects both in the tropics and in the temperate regions (Rao *et al.*, 1998; Young, 1997; Gordon and Newman, 1997 Ong and Huxley, 1996; Nair, 1993). There is also ample evidence to show that the overall (biomass) productivity of an agroforestry system is generally greater than that of an annual system although not necessarily greater than that of a forestry or grassland system (Ong and Huxley, 1996). The possible reason given in most of the literature for the increased productivity is either due to utilization of more growth resources or improved soil fertility (Ong and Huxley, 1996; Young, 1997).

However, competition for limited resources and negative impacts on the tree and/or crop components have also been reported in agroforestry systems. Competition between crops and trees for the same limiting growth resources is most obvious when they are grown in close proximity on poor sites (Young, 1997). In intercropped systems, studies have shown that this may usually have an adverse effect on crop yields as well as on tree growth. In an intercropped experiment in southern Ontario, Canada, Gordon and Williams (1991) found that certain tree species performed poorly when established in the presence of certain crops. The authors noted that black walnut established in barley (*Hordeum vulgare*) had less total height after two years than walnut established in corn (*Zea mays* L.). This observation was attributed to moisture stress in the barley treatment. In another study, Lawson and Kang (1990) reported that the grain yield of alley-cropped maize was reduced when *Leucaena* hedgerows were not pruned at frequent intervals to minimize the shading effect. Similarly, Eastham and Rose (1988) reported that water extraction from a sylvopastoral system was much higher than that from pasture alone. Budowski (1982) noted that the tree component competes with the associated crop for soil moisture, particularly in times of water stress, and even more so if the trees keep their leaves. Obviously, the problem of tree/crop competition for soil moisture is more critical in the arid and semi-arid regions. Some possible explanations given in the literature for such competitive effects are: improper selection of tree and crop components, poor design and management of the system and/or unsuitable technology (Ong and Huxley, 1996).

Therefore, in designing agroforestry systems, deep-rooted tree species are generally selected to minimize root competition between the tree component and shallow-rooted crops. Jackson (1989) and Wood (1990) discussed various aspects dealing with tree species selection and the management strategies necessary to enhance productivity of agroforestry systems by optimizing light utilization. The so-called `associative or non-competitive ideotypes' (Wood, 1990) are generally more desirable since they are likely to be less competitive with the associated crops, and may also be more effective in light interception (MacDicken and Vergara, 1990). Competition for soil moisture can also be minimized by carefully determining the most effective spatial arrangement of components for a given agroforestry design (Eastham and Rose, 1988). With respect to the latter, tree rows are widely spaced in North America, to facilitate the use of standard farm equipment and also to reduce competition for solar radiation. More research is needed to confirm this arrangement as the most appropriate management strategy which will minimize tree/crop competition in temperate North America.

However, from the array of literature currently available on tree/crop competition, it could be concluded that importance should be given to proper selection, design and management of the components in order to reduce competitive interactions and to promote complementary or synergistic interactions.

2.2.6 Allelopathy

Allelopathy has been defined as `any direct or indirect harmful effect by one plant on another through production of chemical compounds that escape into the environment' (Rice, 1974). These compounds (`allelochemicals') include tannins, alkaloids, phenols, organic acids, terpenoids, quinones and flavonoids (Rice, 1974). Evidence has shown that seed germination and plant growth may be inhibited by the release of naturally occurring compounds from roots and aerial tissues of other plants (Fisher, 1978; Rice, 1979). For example, black walnut is known to produce juglone (5-hydroxy-1-4-naphthoquinone), a phytotoxin that is effective against associated plants (Fisher, 1978; Rice, 1979).

Juglone, which occurs in a water-soluble non-toxic form (hydroxy-juglone) in leaves, fruits, roots and other tissues of walnut (Rice, 1984) is washed into the soil by rain, where it is oxidized to juglone, inhibiting the germination and growth of many other plant species (Kimmins, 1997). Similarly, some *Eucalyptus* species such as *E. globulus*, *E. microtheca*, and *E. camaldulensis* are also known to produce phytotoxins which can inhibit germination or growth of associated plants (Rice, 1979; Suresh and Rai, 1987). It has also been claimed that *L. leucocephala* possesses inhibitory proclavities, and mimosine has been identified as the possible phytotoxin in this species (Suresh and Rai, 1987). Other studies have indicated that certain allelopathic substances also inhibit nitrogen fixation and block the soil nitrification process (Fisher, 1978; Rice, 1979; Hollis *et al.*, 1982; MacDicken and Vergara, 1990). A review of the literature further indicates that numerous organic compounds (e.g. tannins, phenolic acids, phenolic glycosides) produced by important plants in the intermediate and climax stages of old field succession, are strongly inhibiting to autotrophic nitrifier organisms at low concentrations (10^{-6} to 10^{-8} M) in soils (Rice and Pancholy, 1973, 1974; Melillo, 1977; Baldwin et al., 1983; Olson and Reiners, 1983;). Despite this, there is no unequivocal evidence to date identifying any specific plant organic compound that could be directly linked to the allelopathic inhibition of nitrification, although many studies have reported possible sources of inhibition (Munro, 1966; Rice and Pancholy, 1973, 1974; Melillo, 1977; Haynes, 1986). Unless specific chemical compounds are identified and directly linked to allelopathic inhibition of nitrification in soils, no firm conclusions can be drawn with respect to the relationship between allelopathy and nitrification.

Even though there is still little evidence of allelopathy in agroforestry systems, these effects are a potential disadvantage in agroforestry development and adoption. More research is needed to provide a better understanding of the interactions between tree and crop combinations, and to identify the potential allelochemicals in particular agroforestry practices. Moreover, it has been suggested that accumulation of these chemical compounds under field conditions may be modified by factors such as soil moisture and soil microbial populations (Fisher, 1978; Rice, 1979). It is important that this aspect is investigated and well understood.

2.2.7 Sustainability and stability

In much of the agroforestry literature, it is generally presumed that agroforestry is both stable and sustainable (Nair, 1984; Sanchez *et al.*, 1985; Stepler and Nair, 1987; Prinsley and Swift, 1987; Young, 1997). Consequently, sustainability (i.e. sustainable land use) has become a major focus in agroforestry development. As a matter of fact, this may underline the current surge of interest in agroforestry. For the purpose of agroforestry, sustainable land use has been defined as `that which achieves production combined with conservation of the resources on which that production depends, thereby permitting the maintenance of productivity' (Young, 1997).

In temperate North America, agroforestry has been identified as an ecologically-based approach to land management that can contribute to ecosystem diversity and long term economic sustainability and profitability within the rural setting (Williams *et al.*, 1997). Therefore, from the preceding review on the effects of tree-crop interaction (Table 2.1) it can be concluded that, even though agroforestry should not be considered a panacea for all evils of land management, yet, for reasons of productivity, natural resource conservation and environmental protection it appears that agroforestry will remain a valuable alternative land use management system around the world.

2.3 Intercropping

Intercropping is a system where two or more crops are grown in close association with one another (Nair, 1984). In an agroforestry system, woody perennials (tree component) are intercropped with agricultural crops/pasture to obtain multiple uses from the same resources (Vergara, 1987; Nair, 1989; Gordon and Williams, 1991). Monoculture systems, due to extreme population pressure on the land base in developing countries, have not been able to meet the needs of farm families nor make optimal use of available land, labour and financial resources (MacDicken and Vergara, 1990). This has given rise to the origins of intercropping in developing countries, since this system met families' basic requirements and provided insurance against unfavourable environmental conditions (Rachie, 1983; Gordon and Williams, 1991).

Intercropping valuable hardwood trees with cash crops has also been practiced in temperate North America for some time (Williams and Gordon, 1992). In temperate systems, the trees are usually planted in widely-spaced rows leaving a strip or or 'alley' between the rows for crop production. This tree-row and alley arrangement allows the use of standard farm equipment and reduces the need for manual labour (Williams *et al.*, 1997). It is also believed that such wide spacing of tree rows will potentially reduce competition with the associated inter-crop for limited growth resources (Ong and Huxley, 1996).

Trees which are often included in this complex cropping system have a great potential to improve soil productivity and conservation. It is therefore interesting to examine tree-based intercropped systems as a land use system with an array of applications such as soil and water conservation (Thurman *et al.*, 1991), agricultural crop diversification (Gordon and Williams, 1991), rehabilitation of marginal or fragile lands (Gordon and Williams, 1991; Williams et al., 1997), and the improvement of soil productivity and fertility for sustainable land use (Young, 1997).

The economics of intercropping is also very encouraging as it has the potential to generate additional income from a unit of land (Gordon and Williams, 1991; Williams and Gordon, 1992; Garrett *et al.*, 1991). Williams *et al.* (1997) suggests that farmers in Ontario who alley crop fruit trees with numerous vegetables have documented a number of economic benefits from intercropping. These benefits include increased cash flow (improving financial viability), diversified production (which helped to market fruit crops), and improved growth and productivity of fruit trees. Such economical benefits have also been reported by Ontario peach (*Prunus persica*) producers, who routinely grow (intercrop) vegetables among peach trees during the early years of orchard development (Williams and Gordon, 1992).

The impact of intercropping with N_2-fixing trees on levels and sustainability of yields can be dramatic. For instance, Kang *et al*. (1984), and Nair (1984) have shown that alley cropping with *Leucaena* in Africa can maintain corn yield over time with less fertilizer input. Pacardo (1978) has noted that *Leucaena* contour hedges 5 m apart can supply sufficient nitrogen-rich green manure that can double corn yield. Borsa (1990) has also shown that *Leucaena* intercropped with maize in the coral rag soils of Zanzibar has a potential to improve soil fertility as well as maize yield. Some of the better known legume trees, for instance, from the genera *Acacia, Leucaena, Albizia* and *Mimosa*, can yield more than 100 kg of nitrogen per hectare per year (National Academy of Science, 1979). Black locust (*Robinia pseudoacacia*) has also been identified as a potential N-fixing tree in intercropped systems in North America (Dawson and Paschke, 1991; Ntayombya,

1993) and it has been estimated that it can fix 30-35 kg N per ha per year under North American growing conditions (Boring and Swank, 1984; Ntayombya, 1993).

It is important to note that the flow of benefits from food crops to trees has also been reported. For example, Jujuba (*Zizyphus jujuba*) a tree often intercropped with wheat, corn or soybeans, yields three times the dry fruit when intercropped than in monoculture (Tianchang *et al.*, 1991). In Papua New Guinea, growth of *Eucalyptus* in integral agroforestry farms has been noted to be about 10% higher than those of pure tree plantations (Vergara, 1987). It is not essential that a legume component be present to obtain beneficial effects from intercropping systems. In China, many non-legume tree crop combinations have been identified as successful intercropped systems (Tianchang *et al.*; 1991, Guangqin *et al.*, 1991; Zhanxue, 1991; Gordon and Newman, 1997).

Examples of various tree-crop combinations in intercropped systems throughout the world are numerous. Citing all types of combinations, however, is beyond the scope of this study. The reader is referred to Nair (1984; 1987; 1993), Huxley (1983)), Gholz (1987), Edwards *et al.* (1990), MacDicken and Vergara (1990), Gordon and Williams (1991), Garrett

(1991), Gordon and Newman (1997) and Young (1997) for detailed descriptions.

2.4 Soil moisture deficit stress

Stress describes a condition of the environment that causes a reduction in the growth of plants or damage to particularly sensitive meristematic activity that leads to a subsequent reduction in yield (Levitt, 1978). Moisture stress will arise in agroforestry associations whenever there is insufficient water available to the root system for any plant component to meet the evaporative demand placed upon its canopy. Among the resource pools in an intercropped system - light, nutrient and water - the most unpredictable is the level of available soil water (Connor, 1983). For light and nutrients, the predictability at any site is generally high (Leyton, 1983; Connor, 1983) although a problem with predicting available soil water exists because its availability depends upon climatic and edaphic factors such as rainfall, deep percolation losses, evaporation losses from the soil surface, interception losses, transpiration losses, and the physical nature of the soil. Irrigation also becomes a problem especially in arid, semi-arid and savanna regions as the availability of irrigation water depends on the rainfall

(Leyton, 1983). This situation often results in moisture deficit stress in an intercropped system since the demand for water is greater. It has been reported by Willey (1979) that in a planned intercropping system, light and nutrients appear to be more efficiently utilized, but this is not the case regarding soil moisture. Young (1991) reports that in semi-arid and dry savanna zones, moisture competition is possibly the most serious problem in agroforestry research and design. Competition for soil moisture in an intercropped systems in North America in general and Ontario in particular, also exists, especially when low rain fall is experienced (Gordon and Williams, 1991).

Generally, the crop component is more affected as a result of moisture stress than the tree component (Connor, 1983; Nair, 1984; 1987; Mittal and Singh, 1989). The reason for this is that the trees have more xeromorphic characteristics and by virtue of their greater root depth (Kimber, 1974) have access to soil water that is not usually available to the crop component. Further, from consideration of leaf reflectance (Sinclair and Thomas, 1970), photosynthetic capacity (Larcher, 1969), leaf diffusion characteristics (Korner *et al.*, 1979) and desiccation resistance tree leaves may show a greater ability to control water use, and hence, to persist actively under moisture stress conditions (Connor, 1983). However, the tree component, especially at a young age, can be affected by moisture stress as a result of crop competition as well (Gordon and Williams, 1991).

Reductions in crop yields as a result of moisture stress have been reported widely. Jonsson *et al.* (1988) reports on yield reduction in maize when intercropped with *Leucaena*, as a result of root competition for soil moisture. Similarly, alley cropping research conducted in the semiarid tropics of India, with a rainfall of 750 mm, reduced yield as a result of moisture stress on sorghum, cow pea *(Vigna sinensis)* and castor (*Ricinus communis*), when intercropped with *Leucaena* spp. (Singh *et al.*, 1989). Mittal and Singh (1989) also report yield reduction in maize, black gram (*Vigna mungo*), and cluster beans (*Cyamopsis tetragonoloba*), when intercropped with *Leucaena* spp. In Nigeria, Lal (1989a) noted that the seedling growth of maize was adversely affected by *Leucaena* and *Gliricidia* hedges due to competition for soil moisture. Gordon and Williams (1991) claim that seedling growth of certain hardwoods is retarded when intercropped with barley as a result of soil moisture competition. However, yield increases in agricultural crops intercropped with trees, have also been widely reported (Nair, 1984; 1987; Ssekabembe and Henderlong, 1991; Zhaomin and Ling, 1991; Young, 1997). In these instances, yield increase was due mainly to proper system design and management practices which reduced competition for soil moisture and nutrients.

2.5 Management of tree-based intercropped systems to minimize water stress

As a general rule selection of trees as well as crops that compete very little with each other is very important. Although trees possess several advantages when grown in association with crops, it should not be interpreted to mean that trees have only favourable effects on soil (Nair, 1987). A fast growing tree may place a heavy demand on soil moisture, and unless properly managed, this can lead to adverse effects, especially in drier environments (Nair, 1987). Crop selection can also have an effect on the tree component (Gordon and Williams, 1991).

Evaporation of water from the soil surface can be substantial. For example, from a wheat field in southern Australia or in the Great Plains of the U.S., as much as 50% of the total soil water can be lost as a result of soil evaporation (Fischer and Turner, 1978). Evaporation is driven by vapour pressure deficit of the air (VPD), wind speed and heat energy (Leyton, 1983). Development of shelterbelts and windbreaks through the adoption of tree-based intercropping systems has successfully reduced evaporation from soil surfaces by controlling these forces (Ong and Huxley, 1996). In China for example, Zhaomin and Ling (1991) reported an increase in soil moisture content of 1% due to the reduction of evaporation caused by shelterbelts. The associated crop yield was increased by 17.27 $g.m^{-2}$ and the average 1000 grain weight increased by 0.42 g. Similar observations have been reported by Zhaohua (1991), Nair (1989), Baldwin and Nanni (1991), Boysen (1991), and Green and Hutchings (1991).

Improved yields of annual crops in water deficit environments have been largely achieved by shortening the overall growing season and by sowing phenologically-adapted cultivars into moist fallows when the subsequent and predictable critical stages (moisture sensitive stages) in the development of yield are least affected (Huxley, 1983). This is likely to reduce moisture deficit stress in tree-based intercropped systems and sustain crop yield.

2.6 Nutrient competition between trees and crop

In general, trees are less demanding of nutrients than crops (Young, 1997). Competition for nutrients is most likely to be serious when trees have established root systems which can dominate that of newly planted annual crops. Therefore it is desirable that trees in agroforestry systems have rooting systems which penetrate deeply, but have limited lateral spread, so that crop roots dominate the surface soil. One of the objectives of agroforestry is that it should be able to capitalize upon the capacity of perennial plants to transfer nutrients from deep in the soil into the upper soil layers where they are accessible to the companion shallowly rooted crop plants (Connor, 1983). However, if nutrients are removed from the site by harvesting, (especially the perennial component) recycling of nutrients to the upper layer, to which the most intense root acitvity is restricted, is more likely to be limited (Nair, 1984; Young, 1997; Connor, 1983).

All nutrients are not equally mobile in soil. Among the major nutrients nitrate (NO_3^-) N is highly mobile and not strongly bound with the exchange surface, like P. Plants compete for nutrients whenever the zones of depletion of their roots overlap. Zones of depletion for mobile nutrients like nitrate are wide (Barber, 1984) and hence plant interaction can occur at relatively low rooting densities (Connor, 1983). Further, because of its high mobility as NO_3^- in soil, N is also lost as a result of leaching. Therefore, unless N is replenished to the nutrient pool, its availability, especially in the upper soil layer, is more likely to be restricted.

However, this may not be the case in an intercropped system with N_2-fixing trees since they are able to grow essentially independently of soil solution N, so that competition with non-legumes for this nutrient is not intensified by the symbiotic relationship (Connor, 1983; Nair, 1984; 1987; Vergara, 1987; Ssekabembe and Henderlong, 1991; Ntayombya, 1993; Young, 1997). In fact, legume-based intercropping systems are generally quite 'leaky', so that the associated non-legumes quickly benefit from the raised levels of N in the soil solution. Examples of agroforestry systems of this nature, and the contribution of N_2-fixing trees towards soil N, are numerous, although in the preceding review, few examples have been mentioned. Nevertheless detailed accounts can be found in Nair (1984; 1987), Gholz (1987), , Edwards *et al.* (1990), MacDicken and Vergara (1990), Ssekabembe and Henderlong (1991) and Ntayombya (1993), Young (1997).

The nitrogen fixing ability of a legume tree and the amount of N transferred to the non-legume component depends on species composition, initial soil N status, soil physical properties, climate, soil moisture and temperature and management practices utilized (Graham and Harris, 1982). Therefore, legume tree components can often only meet part of the N demand by associated crops. Unless complementary N is given, the crop component is likely to experience N stress (Ntayombya, 1993).

2.7 Nitrogen fertility and water stress

Little information is available on the combined effects of nitrogen fertility and water stress in tree-based intercropped systems. However, studies of this nature have been carried out on many cereals. Growth stages of all cereals are similar (Feeke's scale) and as such, results from experimental trials can be generalized for most cereals (Ontario Ministry of Agriculture, Food and Rural Affairs, Field Crop Recommendation, Publ.296, 1989-1990).

It has been shown that available soil water and N fertility are the primary factors in limiting cereal yields (Nielsen and Halvorson, 1991). These two factors are related in that, increased N fertility has stimulated deeper rooting in winter wheat (Brown, 1971) making a greater quantity of stored soil water available to the plant, thereby reducing potential water stress. However, Ritchie and Johnson (1990) have reported that high levels of N stimulated canopy growth and thereby produced larger above ground biomass, which resulted in greater transpiration demands. Therefore, if sufficient soil water reserve is not available, greater water loss at high N treatments can occur, possibly during later critical crop developmental stages, and can seriously reduce final grain yield and water use efficiency (Howell, 1990). Generally the heading, flowering and grain filling stages of cereals have been identified as the most critical stages with respect to water requirement, and water stress at these stages can reduce grain yield to a greater extent (Musick, 1963; Singh, 1981; Kirkham and Kanemasu, 1983). Contrary to the above findings, Hatfield *et al.* (1988) reported that evapotranspiration is not affected by N levels but an increase in grain yield, above ground biomass and water use efficiency were observed with increasing levels of N. An increase in water use efficiency as a result of increased levels of N has also been widely reported. Onken *et al.* (1990) found that water use efficiency based on final grain yield and cumulative growing season evapotranspiration, increased significantly with increased N fertility for winter wheat. Rhoades (1984) also reported that when N was limiting yield, water use efficiency was improved by as much as 41% under high N application rates. Water utilization efficiency in barley was also favoured by higher N rates (Stanberry and Lowrey, 1965). Brown (1971) also reported a 56% increment in water use efficiency as a result of increased levels of N. Similar trends have been observed by Olson *et al.* (1964), Hatfield *et* *al.* (1988), Warder *et al.* (1963) and Nielsen and Halvorson (1991).

The effect of increasing levels of N fertilizer on crop water use is more pronounced only if leaf area development is affected (Howell, 1990). Accordingly, Nielsen and Halvorson (1991) reported that when soil water content was moderately limiting, increasing levels of N decreased water stress because of a slight increase in rooting volume of winter wheat. However, when soil water content was low, an increase in the N rate increased water stress because the excessive transpirational demand of the resulting large leaf area and vegetative mass was not fully compensated by the increased rooting volume.

Increases in cereal grain yield at high N levels have been widely reported. The yield components are number of plants per unit area, number of heads per plant, number of grains per head, and individual weight of grains. In barley, increased N levels increased grain yield mainly by an increase in number of heads per plant and number of grains per head (Stanberry and Lowrey, 1965). Nielsen and Halvorson (1991) also reported an increase in winter wheat yield at high N rates as a result of an increase in LAI, above ground biomass and number of heads per hectare. Similar results were also reported by Warder *et al.* (1963), Olson *et al.* (1964), Brown (1971) and Hatfield *et al.* (1980), and Cooper (1980).

2.8 Poplar (*Populus* spp.)

Poplars are distributed throughout the northern hemisphere, chiefly in the temperate zone. About 40 species of poplar are recognized out of which six are native to Canada. Natural hybridization between species commonly occurs; in addition a number of cultivars derived from various species and their hybrids have frequently been planted throughout Canada (Farrar, 1995). Poplars also comprise more than one half of Canada's deciduous timber volume and 12% of it's total forest resources (Nielson, 1981).

Much interest has been raised in the past 10 to 15 years about intensively-cultivated plantations harvested in short rotations as a means to help meet the increased demand for wood products, or as a source of energy (Heilman *et al.*, 1994). In particular, attention has been focused on poplars because they grow rapidly, are easily propagated, respond well to cultural treatments and have been genetically-improved with potential for more improvement (Bernier, 1984). The literature suggests that growth, nutrients and nutrient cycling are important considerations in planning and managing poplar plantations in order to optimize yield while maintaining or improving site productivity (Switzer and Nelson, 1973; Switzer *et al.*, 1978).

Poplar stands are characterized by higher rates of nutrient acquisition, accumulation and return than most temperate forest species, either deciduous or coniferous (Bernier, 1984). Bernier also suggests that poplars are efficient in the cycling of nutrients and that a large portion of nutrients used in growth annually are periodically involved in cycling. Optimum foliar nitrogen levels in poplar species is reported as being in the range of 2.4 to 2.8 percent (Garbay, 1980; Schoenfeld, 1975). In China, it has been also reported that N content on three tested poplar clones (*Populus* I-69/55 CIJ, *Poplus* I-72/58 CIJ and *Poplus* I-69 CIN) ranged from 2.31 to 3.5% which was almost the same as that of alfalfa hay and the black locust leaves (Szekai *et al.*, 1991). It has been further documented that average litter production in a closed canopy hybrid poplar plantation is in the range of 5.5 to 6.0 Mg ha^{-1} yr^{-1} (Bernier, 1984). Cumulative overstory litter production in a widely spaced plantation of the euramerican hybrid I-476 reached 65.9 Mg ha^{-1} (97% leaves) over a period of 13 years (Rossi Marcelli *et al.*, 1980). Being a deciduous tree species, it appears that there is a great potential for soil N enrichment under poplar based intercropped systems (Thevathasan and Gordon, 1995). Studies conducted by Braatne *et al.* (1992) and Tschaplinski *et al.* (1993) suggest that hybrid poplars show a greater tolerance of drought stress than their parents, which is also a desirable characteristic to be considered in temperate agroforestry systems. Inherent characteristics such as fast growth rate, wide adaptability to less productive sites, deep root system and high production of above ground biomass allow poplar to be considered for inclusion in temperate agroforestry systems (Thevathasan and Gordon, 1997). Further, in temperate tree-based intercropping systems, crop alleys receive recommended levels of fertilizer. Often, a considerable amount of this applied fertilizer is leached below the crop rooting zone. Cycling of such nutrients in the presence of poplar may be more efficient than using other tree species, due to its efficient nutrient uptake and accumulation characteristics.

Poplars planted at a wide spacing among agricultural crops for wood production became a part of the agricultural system mostly in the 1980's in China (Farmer, 1992). In several parts of the world, agricultural crops are often intercropped with poplar trees (International Poplar Commission, 1980; Farmer, 1992). In China, poplar is a predominant tree component of agroforestry systems and has been used in windbreaks to increase crop yields (Zhanxue *et al.*, 1991; Farmer, 1992). In northern India, poplars (*Populus deltoides*) have assumed great importance in both regular plantation and social forestry programmes as the tree has a rapid growth rate and many varieties of it can be economically harvested in 8-10 years. It has also been stated in the literature that the suitability of poplars as agroforestry species has increased their planting in agricultural fields throughout the northern parts of India (Khosla and Puri, 1986; Puri *et al.*, 1994). In the United Kingdom, poplars are receiving increased interest from both foresters and farmers following the introduction of improved clones from Belgium (Potter et al.,1990). It has also been reported that in a silvoarable agroforestry system in the U.K., the introduction of poplar (P. *trichocarpa X deltoides*) positively influenced soil biological properties as a result of increased soil organic matter status (Park *et al.*, 1994). Poplar-based intercropping has widely been reported throughout Europe and the reader is referred to Dupraz and Newman (1997) for a concise review. However, it should also be emphasized that scientific knowledge on poplar-based intercropping in the temperate region is currently lacking (Thevathasan and Gordon, 1995).

2.9 The Decomposition of Soil Organic Matter (SOM)

The products of microbial decomposition of plant and animal remains and biological N fixation account for over 90% of the total organic N in most soils (Haynes 1986, Ntayombya, 1993). The importance of this organic N from the standpoint of soil fertility has long been recognized and knowledge concerning the nature and chemical composition of organic N is extensive (Stevenson, 1982). The literature also indicates that litter originating from both aboveground and belowground plant parts is the major pathway of supply of energy and N to the soil in most terrestrial ecosystems (Staaf and Berg, 1981). Decomposition constitutes the process by which N held in the structure of plant tissues is released into the soil for reuse by plants (Nair, 1984; Palm and Sanchez, 1991; Young, 1997). It has also been reported that litter decomposition represents a very important link in the N cycle of most natural ecosystems (Swift *et al.*, 1979) including many agricultural ecosystems (Floate, 1981).

According to Stevenson (1982), mineralization is the conversion of organic forms of N to NH_4^+ and NO_3^-. The initial conversion to NH_3 is referred as amminization and subsequent conversion to NH_4^+ is referred as ammonification, the oxidation of this compound to NO_3^- is referred to as nitrification. The utilization of NH_4^+ and NO_3^- by plants and microorganisms is referred to as assimilation and immobilization, respectively.

2.9.1 N mineralization and decomposer organisms

Mineralization of organic nitrogen in the soil is a biochemical reaction which is mediated by many soil organisms in which proteins, amino acids and nucleic acids are converted in the presence of oxygen to carbon dioxide, water and ammonia (Gordon, 1986). This biochemical process has been well elucidated and a number of reviews on the subject are available (cf. Jansson and Persson, 1982; and Paul and Juma, 1981). The release of organically-bound amino-N is termed `proteolysis', while its subsquent reduction to ammonium is termed `ammonification' (Carlyle, 1986).

A wide range of major groups of litter-decomposing organisms has been identified and documented in the literature. The major groups are: bacteria, actinomycetes, fungi, protozoa, nematodes, microarthropods, enchytraeid worms and lumbricid worms (Edwards, 1974; Harding and Stuttard, 1974; Lofty, 1974; Swift *et al.*, 1979). The microfloral population associated with dead plant and animal materials is extremely diverse (Swift, 1976; Swift *et al.*, 1979). Novack and Whittingham (1968), for example, found 161 species of fungi in deciduous leaf litter from a single forest. When bacteria and actinomycetes, as well as fungi, are included, a comprehensive list of the microflora of decaying detritus can give rise to many hundreds of species.

It is believed that the colonization of the decomposing organisms takes place on dead plant and animal material. However, there are studies to show that the microbial attack of plant parts begins long before senescence occurs. Bell (1974) and Jensen (1974), have shown in two separate studies that the surface of leaves become colonized by phylloplane bacteria and fungi as soon as they unfold or even before bud-burst. Roots are also invaded by bacteria and fungi well before they slough (Martin, 1977).

Even though different groups of decomposers have been identified, in most environments fungi constitute the bulk of the primary decomposer population of plant materials (Swift *et al.*, 1979). They consist of a filamentous, mycelial network that can permeate the relatively massive structure of recently deposited litter (Haynes, 1986). Bacteria occur as the secondary population and their unicellular nature is well adapted to the occupation of a particular detritus with a high surface to volume ratio (Haynes, 1986). Other decomposer groups mentioned above, with respect to number of organisms, succeed fungal and bacterial populations.

Small animals, particularly invertebrates, significantly influence the terrestrial decomposition process (Coleman *et al.*, 1977, Crossley, 1977; Anderson *et al.*, 1981; Hole 1981). Studies have generally indicated that when fauna are present, the loss of plant litter mass per annum is 25 to 80% greater than when fauna are excluded (Jensen, 1974). The four major groups of decomposer fauna found in the literature are: the annelids (earthworms belonging to the families *Lumbricidae* and *Enchytraeidae*), arthropods (collembolans, mites, insects, and ants), nematodes and protozoa (Stevenson, 1982; Haynes, 1986). Haynes (1986), suggests that soil fauna have three major effects on the decomposition process: (1) a physical effect of redistributing organic material, (2) a chemical effect of concentrating certain elements in their bodies and accelerating nutrient cycling, and (3) a biological effect of regulating microbial activity. Giving a detailed description of the latter processes is beyond the scope of this study and the reader is encouraged to refer to the above mentioned references for more information.

2.9.2 Decomposition and N Dynamics

A review of the literature indicates that N dynamics during the litter decomposition at the soil surface can be separated into three phases: leaching, accumulation and final release (Berg and Staaf, 1981; Haynes, 1986).

2.9.2.1 Leaching

Soon after litterfall, weight loss and nutrient release are caused, not by microbial action but rather by leaching of soluble substances from the litter (Hyanes, 1986 . Several field studies of litter decomposition have clearly illustrated the presence of a leaching phase of N release (Gosz *et al.*, 1973; Howard and Howard, 1974; Hodkinson, 1975; Staaf and Berg, 1977). The quantity of N leached is expected to be within 10% of the total available initial N content (Berg and Staaf, 1981). However, Haynes (1986) has reported that N leaching losses can be more than 10% and significant if the quantity of water percolating through the litter is high.

2.9.2.2 Accumulation

Several studies have reported on an increase in the relative amount of N (increasing N content relative to remaining litter weight) during the decomposition of litter (Aber and Melillo, 1980; Berg and Staaf 1981; Melillo *et al.*, 1982). N in organic debris is generally in short supply and therefore the decomposer organisms utilize and retain most of the N through incorporation into microbial cells. While most of the N retained, the amount of C is progressively reduced through the evolution of CO_2 (Haynes, 1986; Brady, 1990; Ladd and Jackson, 1982). Several other reasons have been reported in the literature for an absolute increase in the quantity of N in the litter (especially, forest litter decomposition) as it decomposes. Biological N_2-fixation, absorption of atmospheric NH_3, rainfall, throughfall, deposition of dust, insect frass, green litter and fungal translocation are a few to be mentioned (Gosz *et al.*, 1973; Staaf and Berg, 1977, Bormann and Likens, 1979).

2.9.2.3 Net release (N mineralization)

The C:N ratio of the litter is an important criterion which regulates the release (mineralization) or the retention (immobilization) of N during the decomposition process (Haynes, 1986; Brady, 1990). It is also reported that when the C:N ratio of the litter is high (> 25 to 30:1 ; N concentration < 1.4 to 1.8%) net immobilization takes place and mineralization proceeds when the C:N ratio < 25-30:1 and the N concentration > 1.4-1.8 (Kachaka *et al.*, 1993; Brady, 1990). During the decomposition process the C:N ratio progressively decreases and at one point N becomes no longer limiting to microbial growth and activity. At that critical point, there is a switch from net immobilization to net mineralization (Haynes, 1986). Other studies have also shown that the direction of the N mineralization process is dictated by the carbon/nitrogen ratio in the soil, and net mineralization will usually occur when N released from decomposing organic matter exceeds that required by the decomposer organisms (Carlyle, 1986; Rosswall, 1982; Franco and Munns, 1982). Therefore, carbon limitation will result in net-mineralization, while a nitrogen limitation will result in net immobilization of nitrogen. N immobilization here refers to the conversion of inorganic-N to organic forms by the microorganisms for synthesis of microbial tissue (Carlyle, 1986).

However, other studies have reported that substrate quality is a critical factor as well in determining the rate of litter decomposition and the release of mineral N. Polyphenolic compounds such as tannins and/or lignin content in the litter can significantly affect the release of N from decomposing litter (Vallis and Jones, 1973; Palm and Sanchez, 1991; Gutteridge, 1992; Kachaka et al., 1993). Generally, polyphenolics are reactive compounds and can form stable polymers with many forms of N found in the litter thereby preventing the release of N (Martin and Haider, 1980; Stevenson, 1982). Vallis and Jones (1973) reported that mineralization from the leaves of *Desmodium intotum,* which had a high concentration of tannins, was much less than that from *Macroptilium atropurpureum,* which contained only a small quantity of tannin. A high negative correlation between net N mineralization and polyphenolic concentration in leaf litter has also been documented by Palm and Sanchez (1991). Once the release phase has started, the pattern of N loss appears to follow that of weight loss (Wood, 1974). Staaf and Berg (1977) have reported that during the net N release phase, the release of N from Scots pine needles was linearly related to weight loss ($r = 0.93$).

Among the several physical factors which are known to affect soil N mineralization (net release), temperature and moisture content may be the most important. The effects of temperature and moisture on the process of N mineralization have been reviewed by Harmsen and Van Schreven (1955), Witkamp (1966), Savant and de Datta (1982), Gordon (1986), Grundmann *et al.* (1995), Zanner and Bloom (1995) and others. Since ammonification is primarily an enzymatic decomposition of organic-N, soil temperature is a very important factor controlling the kinetics and magnitude of ammonium production (Savant and de Datta, 1982). Microbial respiration increases with temperature and is directly related to N mineralization (Carlyle, 1986); it is generally therefore accepted that the higher the temperature, the faster the process of N mineralization. Q_{10} values, defined as the ratio of reaction rates at a temperature interval of 10°C, is widely used to describe N mineralization rates at varying temperature regimes (Vigil and Kissel, 1995). A Q_{10} of about 2.0 has been suggested as a good average for many soils (Marion and Miller, 1982; Kladivko and Keeney, 1987). Vigil and Kissel (1995) have also reported that values of Q_{10} for rate of N mineralization of native soil organic matter in the temperature range between 5 and 35°C were approximately 2. Campbell et al. (1984) reported that Q_{10} values may be higher in cool northern climates than in warmer tropical climates. They suggested that the increase in Q_{10} may be related to the relative resistance to degradation of the native soil organic matter in soils of different climatic zones. Thus, the lower the temperature, the greater the accumulation of organic matter in the soil. However, some studies have also demonstrated that even very low temperatures (0 to 5°C) permit active mineralization (Harmsen and Van Schreven, 1955). Nevertheless, many studies indicate that the optimum temperature for mineralization in many soils generally ranges between 25 and 35°C (Gordon, 1986; Zanner and Bloom, 1995; Vigil and Kissel, 1995).

Present concepts of N mineralization and temperature relations in the soil are based mainly on laboratory incubation studies conducted at constant temperatures (Keeney, 1980; ; Kachaka *et al.*, 1993). However, under field conditions, diurnal and seasonal temperature fluctuations are common, and some studies (e.g Campbell and Biederbeck, 1972; Stanford *et al.*, 1975; Franzluebbers *et al.*, 1995) have discussed this aspect. Campbell and Biederbeck (1972) reported that N mineralization under fluctuating temperatures differed from that observed when soils were incubated at constant mean temperature. In view of this, it has been suggested that comparison of the mean N mineralization under fluctuating temperatures with that occurring at the mean constant temperature may not be valid except within a very narrow temperature range of 10°C or less (Campbell and Biederbeck, 1972; Stanford *et al.*, 1975). This then raises questions regarding the validity of estimating field soil N mineralization under varying temperatures based on rate constants obtained from controlled laboratory incubations. Nevertheless, Stanford *et al.* (1975) suggest that ammonification may not be influenced differentially under fluctuating temperatures.

The effects of soil moisture regime on N mineralization are also well known and have been reviewed by Van Schreven (1955), Savant and de Datta (1982), Sahrawat (1983), Carlyle (1986), Harmsen and Gordon (1986), Zanner and Bloom, (1995) and Grundmann *et al.* (1995). It is also well known that the moisture regime of a soil is critical for mineralization of organic-N (Sahrawat, 1983). Gordon (1986) reported that nitrogen mineralization is linearly dependent upon moisture content within the available moisture range. Similar observations have also been reported by Skopp *et al.* (1990). Clarholm *et al.* (1981) reported a positive relationship between N-mineralization and moisture content over the range between 20 and 100% of water holding capacity. In other studies, Harmsen and Van Schreven (1955) reported unhampered ammonification in soils with very high water content, including soils nearly completely waterlogged. Nevertheless, Carlyle (1986) indicated that for a wide range of soils, the optimum moisture content for ammonification is between 50 and 75% of the water holding capacity. Other studies have indicated that ammonification is generally inhibited in excessively dry soils approaching wilting point (Carlyle, 1986; Franco and Munns, 1982).

The effects of changes in soil moisture regime on ammonification as a result of soil drying and re-wetting cycles are also well documented (Savant and de Datta, 1982; Sahrawat, 1983; Carlyle, 1986; Birch, 1964). Carlyle (1986) reported that the rate of ammonification is enhanced by cycles of soil drying and re-wetting, and generally, total inorganic-N released increases in the dry phase. This has been attributed to the physical disruption of the organic material, and to a partial sterilization effect on the biomass (Savant and de Datta, 1982; Carlyle, 1986). It has been suggested that killed cells of soil micro-organisms undergo rapid break-down by the remaining microbes, and this results in nutrient flux. This underlines the significant contribution of the soil organic matter derived from microbial cell wall constituents as an important source of the so-called easily mineralizeable nitrogen (labile N) in soils (Savant and de Datta, 1982). Carlyle (1986) pointed out that such fluxes generally occur after any soil disturbance such as freezing and thawing, grinding or cultivation which results in death of some fraction of the soil microbial biomass.

Combinations of temperature and moisture content fluctuations often cause maximum N mineralization (Gordon, 1986). Some studies have shown that temperature and moisture show considerable interaction, especially in their influence on microbial respiration (Bunnell *et al.*, 1975; MacDuff and White, 1985). The interaction is maximal at high temperatures and moisture contents, with the response to temperature declining at low soil moisture content and vice-versa (Carlyle, 1986). At a macro-climatic scale, studies have also shown that litter decomposition is also highly correlated with actual evapotranspiration, which is dependent upon both temperature and moisture (Haynes, 1986).

The effects of other soil factors such as pH, soil structure, cation-exchange capacity, and nutrient supply on N-mineralization are also well documented (cf. Savant and de Datta, 1982; Sahrawat, 1983; Keeney, 1980; Carlyle, 1986; Gordon, 1986; Jenkinson *et al.*, 1985). Ammonification is generally depressed by acid conditions, and a lowering of soil pH often brings about a decrease in N-mineralization (Carlyle, 1986). It is well recognized that application of lime to acid soils results in an increase in ammonification (Laune *et al.*, 1982; and Sahrawat, 1983). However, Gordon (1986) noted that, at times, the effect may either be non-existent, short-lived, or depressive. The pH range for ammonification appears to be between 3.5 and 7.0, but in general, nitrogen mineralization is said to be enhanced as pH is increased to near neutrality (Carlyle, 1986; Gordon, 1986). Studies have also indicated a positive relationship between production of ammonium ions and the cation exchange capacity (Savant and de Datta, 1982). Furthermore, these workers reported that ammonification was lower in clayey soils than in sandy soils.

The effect of added fertilizers on the ammonification of soil nitrogen is well known and has been documented by Keeney (1980), Savant and de Datta (1982), Jenkinson *et al.*(1985), Carlyle (1986), Gordon (1986) and others. The quantity of organic nitrogen released to the inorganic-N pool by application of fertilizer nitrogen and other salts is directly related to the concentration and type of salt solution, and the amount of organic-N originally present. Broadbent and Nakashima (1971) found positive results on nitrogen release by ammonium salts, and potassium, calcium, and aluminium chlorides. Similarly, Jenkinson *et al.*, (1985) reported that addition of low concentrations of non-fertilizer salts sometimes accelerated the release of inorganic-N from the soil. However, these workers noted that, of all salts tested, ammonium salts were by far the most effective in accelerating N-mineralization. The effect of added nitrogen fertilizers on the ammonification of soil nitrogen has been described as a `priming effect' (Jenkinson *et al.*, 1985). These workers indicated that the controversy over the cause and interpretation of the priming effect has not been settled. They pointed out, for example, that only in a few circumstances does the addition of inorganic-N to a soil accelerate the mineralization of soil organic-N. According to these workers, net mineralization may either remain the same, or found to be much lower in nitrogen amended soils than in the soil which had not been fertilized.

In contrast, there are also reports which indicate that additions of inorganic nitrogen can accelerate mineralization of soil organic nitrogen. For example, in wetland rice soils, Savant and de Datta (1982) reported accelerated NH_4^+ release following application of nitrogen fertilizers. Elsewhere, Luecken *et al.* (1962) and Jenkinson *et al.* (1985), reported that addition of inorganic nitrogen to soils containing substantial quantities of fresh organic matter such as straw, hay, and glucose of wide C/N ratio accelerated the release of NH_4^+ from the organic matter. Nonetheless, Jenkinson *et al.* (1985) suggested that such increases in N-mineralization from soil organic matter may only be temporary. In a recent study, Green *et al.* (1995) have also reported that the addition of N often only accelerates the initial stages of decomposition and N release.

2.9.3 N release from crop residues

Application of green manure remains an important source of nitrogen in many agricultural systems (Janzen and Radder, 1989; Costa *et al.*, 1990; and Kang *et al.*, 1990). Incorporation of green manure has been shown to be a very effective method of transferring N from legumes to other crops (Costa *et al.*, 1990). The overall contribution towards soil fertility improvement for subsequent crops largely depends on the N mineralization of the organic matter applied to the soil. Besides factors such as temperature, moisture content, and crop residue composition (discussed elsewhere) which are known to influence the process of N-mineralization, residue placement is another important factor known to have an effect on N-mineralization (Holland and Coleman, 1987; Janzen and Radder, 1989; Costa *et al.*, 1990; Ntayombya, 1993). Costa *et al.*, (1990) reported that incorporation of green manure in the soil resulted in higher inorganic-N accumulation in soil, compared to surface-placed green mulch. These workers reported that surface-placed mulch could only supply about 55% as much nitrogen as incorporated mulch. According to

Holland and Coleman (1987), surface placement of crop residues results in spatial separation of carbon-rich litter and mineralized soil nitrogen, whereas incorporation results in their intimate contact. Furthermore, the slower release of inorganic-N from surface placed plant material has been attributed to the less favourable moisture and temperature conditions for organic matter decomposition (Holland and Coleman, 1987), but N-volatilization of ammonia from the mulch has also been suspected (Costa *et al.*, 1990). Even though incorporation of green manure is widely considered to be an efficient method of transferring N from one crop to another crop, Costa *et al.* (1990) suggested that it may not always be an appropriate agricultural or agroforestry practice mainly because N mineralization may proceed faster than the requirement of the recipient crop. In this regard, since relatively less inorganic nitrogen tends to accumulate in the soil under surface mulched management, the practice of surface mulching may be more appropriate for transfer of nitrogen to agricultural crops.

Presently, there is a paucity of information regarding N-mineralization and N immobilization within agroforestry systems. However, some studies have shown that soil organic matter resulting from additions of pruning, crop residues, and litterfall often increases under various agroforestry practices (Duguma *et al.*, 1988; Glover and Beer, 1986; Kang *et al.*, 1990). For example, Glover and Beer (1986) reported that annual litterfall and pruning residues produced within multi-strata agroforestry systems were very high and were within the range of litter production reported in tropical forests. Elsewhere, O'Connell (1986), Hirschfeld *et al.* (1984), and Paschke *et al.* (1989) demonstrated the importance of including tree legumes and actinorhizal plants in agroforestry systems. These workers reported that nitrogen-fixing tree species enhanced the rate of litter decomposition. O'Connell (1986) reported that the presence of the legume, *Acacia pulchella,* had a marked effect on the chemical composition of decomposing *Eucalyptus marginata* leaf litter, and greater amounts of inorganic nitrogen were released compared to *Eucalyptus* leaf litter decomposing in the absence of the tree legume. Similarly, Hirschfeld *et al.*, (1984) reported increased nitrogen concentrations and lower C/N ratios from decomposing leaf litter collected from mixed hardwood stands containing black locust, compared to similar hardwood stands without any black locust. However, these workers also noted that black locust leaves decomposed more slowly than expected. This was attributed to the high lignin content. Actinorhizal plants interplanted with non-nitrogen fixing tree species generally showed similar effects on soil N-mineralization (Paschke *et al.*, 1989.).

For example, these workers reported that soil N-mineralization was accelerated in mixed plantations of black walnut and autumn olive *(Elaeagnus umbellatta)*, or black alder *(Alnus glutinosa)*, when compared to pure stands of black walnut. These studies showed that the presence of woody legumes or actinorhizal plants play an important role in influencing the process of N-mineralization, mainly because these species have relatively higher nitrogen concentrations in the leaf litter, which helps to lower the C:N ration of the soil organic matter. Although this ameliorative influence of trees is widely recognized (cf. Prinsley and Swift, 1987; Sanchez *et al.*, 1985; Young, 1997), the need for research to determine the patterns and rates of litter and soil organic matter decomposition and mineralization under agroforestry systems cannot be over-emphasized.

2.9.4 Nitrification

The end product of the decomposition of protein, nucleic acids, and other nitrogenous organic compounds in soils is the release of NH_3 which equilibrates to the ionic species, NH_4^+, in all but highly alkaline soils. Depending upon prevailing environmental conditions, NH_4^+ may either be the end-product, or in the presence of readily available carbonaceous materials, the NH_4^+ is assimilated rapidly into newly forming microbial biomass. However, under the more usual soil circumstances in which microbial development is limited by available C and energy, most of the NH_4^+ is oxidized to NO_3^- as rapidly as it is formed. This two-stage aerobic biochemical process in which NH_4^+ is first oxidized to NO_2^- and then NO_3^- is termed nitrification. Nitrification is an energy-producing process involving a net transfer of eight electrons causing a valance change from -3 to +5. The first stage is generally carried out by a group of autotrophic bacteria of the genera *Nitrosomonas, Nitrosococcus, Nitrosospira*, and *Nitrosolobus* (Focht and Verstraete, 1977). The second stage is generally carried out by the genus *Nitrobacter* (Carlyle, 1986). On a relative basis, *Nitrosomonas* and *Nitrobacter* are considered the primary autotrophic nitrifiers because they commonly occur in soils in large numbers (Sharma and Ahlert, 1977; Carlyle, 1986). The biochemical aspects of nitrification are well known and have been reviewed by Sharma and Ahlert (1977) and Focht and Verstraete (1977).

Nitrification by heterotrophic bacteria and actinomycetes has also been documented (e.g., Focht and Verstraete, 1977; Carlyle, 1986). Formation of NO_2^- from various nitrogenous substrates by *Arthrobacter, Pseudomonas,* and *Aspergillus* species has been reported by Focht and Verstraete (1977), Carlyle (1986). In addition, formation of NO_3^- from NH_4^+ or amino-nitrogen by some heterotrophs, especially fungi, has also been reported by Focht and Verstraete (1977). Heterotrophic nitrification is generally considered less important than autotrophic nitrification (Focht and Verstraete, 1977), except in acid soils where nitrification has been observed even in the absence of autotrophic nitrifiers (Stevenson, 1982). Focht and Verstraete (1977) reported that nitrification rates for heterotrophs is in the range of 10^3 to 10^4 times smaller than those of their autotrophic counterparts and that the biochemical pathway of heterotrophic nitrification may be either organic or inorganic, or a combination of both (Focht and Verstraete, 1977). In contrast, autotrophic nitrification proceeds strictly in inorganic pathways.

Nitrification is a key process which may determine the fate of nitrogen in both disturbed and undisturbed ecosystems. In agricultural soils, nitrification occurs readily, often maintaining NO_3^- as the dominant inorganic form of nitrogen. Nitrate is more mobile than NH_4^+, and hence lost more readily from the soil through leaching. It is also available for reduction to gaseous products such as nitrous oxide (N_2O) and dinitrogen (N_2) by denitrifying bacteria (Knowles, 1981; and Rosswall, 1982). Nitrification rates vary markedly, and factors which influence them have been studied and documented extensively mainly because of the potential for nitrogen loss that it creates (e.g. Focht and Verstraete, 1977; Sharma and Ahlert, 1977; Keeney, 1980; Verstraete, 1981; Rosswall, 1982; Carlyle, 1986).

Environmental factors that influence autotrophic nitrification are generally similar to those affecting N-mineralization. Nitrification reactions proceed better in warmer seasons or warm climates, and the optimum temperature for growth of autotrophic nitrifiers appears to be in the range 25 to 35^{o}C (Focht and Verstraete, 1977). However, higher temperatures (about 42^{o}C) have also been reported for *Nitrobacter* (Sharma and Ahlert, 1977). Generally, little or no growth of autotrophic nitrifiers occurs below 4^{o}C (Sharma and Ahlert, 1977), or above 40^{o}C (Focht and Verstraete, 1977). The maximum rate of autotrophic nitrification appears to be site-specific and is also a function of soil and climatic adaptation by populations of nitrifiers (Stevenson, 1982). Focht and Verstraete (1977) cited a number of examples which suggested that autotrophic nitrifiers become acclimated to the temperature regime of their habitat, and do not seem to vary in their adaptability to low temperatures. However, these workers indicated that it is uncertain which of the two groups of nitrifying bacteria (i.e. ammonium-oxidizers or nitrite-oxidizers), were more affected by temperature. Effects of fluctuating temperature on autotrophic nitrification have been reported by Focht and Verstraete (1977), and the pattern is generally similar to that of mineralization described earlier.

Soil pH is another important factor that often restricts nitrification (Donaldson and Henderson, 1990; Carlyle, 1986; Focht and Verstraete, 1977; Keeney, 1980). The pH optima for overall nitrification reactions appear to be slightly on the alkaline side (Sharma and Ahlert, 1977). Generally, the pH range for autotrophic nitrifiers is from 5.5 to 10 (Focht and Verstraete, 1977). However, nitrification has also been detected in acidic soils down to pH 4.5 (Carlyle, 1986), and in basic (pH 11.2) soils (Focht and Verstraete, 1977). The mechanism by which pH affects the rate of nitrification has been discussed by Sharma and Ahlert (1977), and Focht and Verstraete (1977). It has been observed that both free ammonia and free nitrous acid inhibit nitrifying organisms. At high pH, autotrophic nitrification is reportedly inhibited by free ammonia, while free nitrous acid is said to inhibit nitrification at low pH (Sharma and Ahlert, 1977).

The rate of ammonium and nitrate oxidation is also dependent on the substrate concentration (Focht and Verstraete, 1977). In general, NH_4^+ availability is a major limiting factor for nitrification, although substrate inhibition has also been observed at relatively high ammonium levels. Verstraete (1981) reported that autotrophic nitrifiers can be inhibited completely by ammonium availability exceeding 3 g kg^{-1} of soil. With respect to heterotrophic nitrifiers, even 10 μg of ammonium per g of soil could completely inhibit their nitrification activity (Haynes, 1986). Furthermore, Donaldson and Henderson (1990), and Carlyle (1986) indicated that autotrophic nitrifiers are generally poor competitors for NH_4^+ under conditions of low concentrations of NH_4^+ which may prevail on substrates of high C/N ratio. In contrast, heterotrophic microflora as well as mycorrhizae are known to be strongly competitive for NH_4^+ under such conditions, and the populations of autotrophic nitrifiers tend to be generally very low as a result. This inability to compete for low concentrations of NH_4^+ is considered to be the dominant controlling factor on nitrification in most ecosystems (Vitousek et al., 1982).

In agroecosystems, nitrification is also commonly influenced by nutrient availability, and P is particularly important (Rosswall, 1982). Purchase (1974) indicated that under P deficiency, NO_2^- may accumulate in some agro-ecosystems. This suggests that nitrite-oxidizers are affected much more by P deficiency than the nitrate-oxidizers. Furthermore, Donaldson and Henderson (1990) indicated that the type of nitrogen fertilizer applied may also influence nitrification through its effect on the populations of ammonium-oxidizers. These workers indicated that additions of urea or ammonium sulphate fertilizers were found to enhance nitrification more than a variety of other nitrogen fertilizer sources.

Positive influence on soil nitrification and release of nitrate-N from decomposing leaf prunings have been widely reported in the tropics (Sanchez *et al.*, 1985; Beer, 1987; Prinsley and Swift, 1987; Young, 1997). In the temperate region, Ntayombya and Gordon (1995) reported that surface application of black locust leaf prunings positively influenced soil nitrification. In a separate study in the same region Thevathasan and Gordon (1997) also reported an increase in soil nitrate levels closer to poplar tree rows possibly due to higher poplar leaf biomass input from the preceding fall season. Apart from these two studies there is a paucity of information on nitrification under temperate agroforestry systems suggesting that more work is needed.

3. Moisture and fertility interactions in a potted poplar-barley intercropping

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3.1 Introduction

Intercropping is a system where two or more crops are grown in close association with one another. In an agroforestry system, intercropping combines woody perennials (tree component) with agricultural crops/pasture to obtain multiple uses from the same resource base. In developing countries, monoculture systems, due to extreme population pressure on the land base, have not been able to meet the demands of farm families or make optimal use of available land, labour and financial resources. This gave rise to the origins of intercropping since this system met the basic requirements of families and provided insurance against unfavourable environmental conditions (Gordon and Williams, 1991; Rachie, 1983).

The above situation is not unique to developing countries. In North America, excessive land degradation has been the result of unsustainable farming practices, inappropriate agricultural policy, conflicting land use priorities and population pressure from urban centres (Mathews et al., 1993). Williams and Gordon (1992) suggest that intercropping of valuable tree species with cash crops could be a useful alternative to conventional agriculture and forestry practices because of the flexibility of goals and the gradual changes in land use that can result. However, when two crops are grown on the same piece of land, as in intercropping, competition for light, nutrients and moisture may limit the growth of one or more components of the system even though trees tend to be less demanding of nutrients than crops (Young, 1997).

Interactions between woody (tree) and non-woody (agricultural crops) components in an agroforestry intercropped system are complex (Huxely et al., 1989) and can be 'competitive', or 'complementary'. As outlined by Borsa (1991), 'competitive' resource utilization is characterized by the acquisition of growth resources by one species to the exclusion of the other. The term 'complementary' applies to cases where resource utilization by the components (tree and crops) is partitioned either in time or space as in different rooting depths, or different maturing patterns (Connor, 1983). Thus, when an interaction is complementary, in a tree-based intercropped system, stressful situations are often less. Nevertheless, the complexity of agroforestry systems often results in constant changes in spatial patterns, as components grow in the horizontal and vertical dimensions (Borsa, 1990). As a result of these dimensional changes, interactions for resources between the species will also change over time (Begon et al., 1990). Therefore, it can be concluded that in a tree-based intercropped system the interaction between tree and crop components is not always 'competitive' nor 'complementary' over time. However, through proper design and plant management, one can reduce 'competitive' interaction and promote more 'complementary' interactions, so that tree and crop components share the different resource pools in a way that minimizes mutual interference and maximizes resource sharing.

Based on the first hypothesis and objective outlined in this thesis (page 12), the main effects and interactions, if any, of three levels of soil moisture and N on the growth, development and crop yield of a selected tree (Hybrid Poplar DN177) and crop (Barley, OAC Kippen) was investigated in this study.

3.2 Materials and Methods

3.2.1 Main Experiment (Experiment 1)

The main study was a 3 x 3 factorial experiment arranged in a randomized complete block design, replicated 3 times, in a green house. The study was conducted in 1992 from May to August. Day and night temperature in the greenhouse was maintained at 25 and 20°C respectively. Sampling units consisted of a single hybrid poplar rooted cutting (2 months old) planted in the centre of a pot, which measured 36 cm in diameter and 35 cm in height and was filled with field sand (sandy loam). Poplar cuttings were rooted in small pots containing peat soil in the field. While transplanting, much care was taken to minimize root damage. Barley seeds were planted 1 to 2 cm below the surface of the soil. To maintain an even stand and to have the recommended plants per unit area (Field Crop Recommendations, Publ. 296, 1990/91 OMAFRA), barley seedlings were thinned to 30 plants per pot soon after germination. Measurements were not taken from barley plants in the 5 cm band around the outside edge of the pot. This was done to ensure that measurements were obtained from plants subject to even light distribution.

To determine experimental soil moisture regimes, soil samples (core samples) were collected from the pots and the moisture characteristic curve (desorption) was determined directly on the soil cores. Based on the desorption curve, three levels of soil moisture tension; 15 kPa (high moisture), 15 to 50 kPa (medium moisture), and 15 to 300 kPa (low moisture) were maintained on the basis of soil weight. The applied levels of N were: 35 (low), 70 (medium), and 140 (high) kg ha^{-1} N respectively. Both P and K were kept constant at a level of 75 kg ha^{-1} P and 75 kg ha^{-1} K in the applied fertilizer. In the high moisture treatment (15 kPa) the pots were watered twice daily to maintain the required weight (28.94 kg) in the respective pots. In treatments 15 to 50 kPa and 15 to 300 kPa, the soil was allowed to dry to the required weight (28.19 and 27.36 kg, respectively), and total pot weight was brought to 28.94 kg by adding water to the pots. Pot weights were monitored on a daily basis using a spring balance. At the time of potting, soil moisture was 14.5% and oven dry weight of the soil was 23.8 kg. The pots were lined with polyethylene sheets to prevent soil losses. The weight gain as a result of growth of crop and tree was not accounted for when determining watering schedule. (However, weight gain during the study period as a result of dry matter accumulation was negligible (less than 1%) relative to the total weight of the soil). The levels of moisture and nitrogen are identified as low, medium and high in the results and discussion.

Initial tree height and diameter were measured before treatments were imposed. The average initial height and diameter, at 5cm from the soil surface, of poplar seedlings were 84 cm and 0.66 cm respectively. Subsequent measurements were taken at 10 day intervals. At the time of harvest (120 days duration), the soil was taken out of the pot and the roots were separated carefully by washing with water. Once the samples were removed from the oven, the shoots and roots of barley were separated and weights determined using a Sartorius B310P electronic balance. Woody biomass (oven dry weight), leaf area (LI-3100 Area Meter, Li-Cor, Inc.) and leaf total N (micro kjeldhal method) were determined for poplar.

The number of barley grains per head was computed by averaging the number of grains from five randomly selected heads from each treatment. To calculate percentage filled grains, grains (filled + unfilled) were separated from the heads and total grain weight was obtained using an electronic balance. Grains were then floated in water and stirred. The floating unfilled grains were separated from the filled grains and the filled grains were then oven-dried at 75ºC for 48 hours. The percentage filled grain was then calculated. Weight of filled grain was taken as the final grain yield per pot.

3.2.2 Comparison between intercropped and monocropped systems

A separate experiment (Experiment 2) was carried out simultaneously in which poplar and barley were monocropped at three specific combinations of moisture and nitrogen (low moisture-low N, medium moisture-medium N and high moisture-high N), with 3 replications. This was done in order to compare the performance of monocropped poplar and barley with intercropped poplar and barley receiving the same treatment levels in the 3 x 3 factorial experiment mentioned above. Barley plant height (at 80 days after sowing), grain yield and total above ground biomass (shoot + grain dry weights) were compared between monocropped and intercropped barley. For poplar, diameter increment (at the final stage), leaf area, and leaf total N were compared between intercropped and monocropped conditions.

3.2.3 Statistical Analysis

Statistical analysis of the data was carried out using the ANOVA technique for RCBD. Treatment means were compared, using LSD values at $p < 0.05$. A simple \`t' test was performed (df=4) to compare the difference between the two independent means (monocropped vs. intercropped).

3.3 Results and Discussion

3.3.1 Barley (Experiment 1)

Barley plant height was significantly affected by the levels of N during early stages of growth (20 days after sowing), whereas moisture did not affect plant height until 30 days after sowing (DAS) (results not shown). The transpirational demand of the crop component may have been low during these early stages of growth as the canopy would not have developed enough to generate a high transpirational demand. However, at 30 days after sowing higher rates of transpiration may have caused moisture stress at the low moisture level thus causing a reduction in overall plant height.

Among the yield components tested percentage-filled grains and number of grains per head are reported here. These two yield components were significantly reduced at the lowest moisture level (Table 3.1). Plant height was significantly reduced at low moisture level at 40 DAS as well, (51.96 cm vs 46.79 cm at high and low moisture levels, respectively, LSD(p=0.05)= 1.95) as a result of moisture limitation. This period is very sensitive to moisture stress and hence it might have detrimentally affected the formation of fertile pollen, which in turn could have resulted in higher numbers of sterile spikelets per head at the lowest moisture level. The results obtained are in keeping with the observations of others as well (Briggs, 1978; Singh, 1981; Kirkham and Kanemasu, 1983).

Table 3.1. Effects of moisture and N levels on barley yield components.

Treatment main effects	% filled grains	grains per head
Low N	77.3^{a}	13.5^{a}
Medium N	74.5^{a}	17.9^{b}
High N	79.9^{a}	18.7^{b}
Low moisture	57.2^{a}	14.5^{a}
Medium moisture	88.5^{b}	17.5^{b}
High moisture	86.0^{b}	18.2^{b}

[a,b] Within a main effect, within column, values followed by the same letter are not significantly different at $p < 0.05$.

The fact that there was no significant difference in percentage-filled grain between high and medium moisture level, suggests there was little or no moisture stress at medium moisture level. This is expected as even the plant height was not affected between these levels of moisture at 40 DAS (51.96 vs 50.93 cm at high and medium moisture levels, respectively). Levels of N did not affect percentage filled grains, suggesting that the formation of fertile pollens is more sensitive to changes in moisture than nitrogen. However, number of grains per head was influenced when level of N was increased from low to medium but further increases in N did not influence this parameter.

Increasing levels of N responded differently over the levels of moisture tested due to significant interaction ($p < 0.05$) with respect to final grain yield. The response pattern with increasing levels of N was different with the lowest level of moisture than the other two moisture levels. Similarly the response pattern with the decreasing levels of moisture was different with the lowest level of nitrogen tested than the other two levels. The lowest yield was found in the low moisture low N treatment combination (6.10 g per pot). This was expected, as at the lowest moisture level yield components discussed above were detrimentally affected and grains per head was lowest at the lowest N level tested. Grain yield obtained at the highest moisture and high N treatment combination (32.6g per pot) did not significantly differ from grain yield obtained from the medium moisture and N treatment combination (28.1g per pot = 2.83 MT ha^{-1}). Therefore, under the tested conditions the results suggest that maintaining the soil moisture status at field capacity (15 kPa) or applying nitrogenous fertilizers above 70 kg ha^{-1} N in combination with poplar trees may not be useful.

3.3.2 Poplar (Experiment 1)

Levels of moisture and N tested did not significantly influence poplar height increment, diameter increment, total leaf N, or leaf area (Table 3.2). At the time of harvest, visual observation of the barley and poplar roots indicated that barley roots were mostly confined to the top 10 to 12 cm layer of the soil and poplar roots were found curled at the bottom of the pot. It is possible that poplar may not have experienced moisture stress even at the lowest moisture level tested because it may have utilized moisture present in the lower zones of the soil in the pot. The duration of stress at the bottom of the pot would be short since soil moisture was brought up to field capacity at each watering session.

Table 3.2. Effects of moisture and N levels on poplar growth parameters.

Treatment main effects	Height increment (cm)	Diameter increment (cm)	Leaf N (%)	Leaf area (cm^2)
Low N	26.0	0.59	1.8	41.1
Medium N	35.3	0.78	2.0	47.4
High N	34.5	0.70	2.5	48.9
Low moisture	35.7	0.71	2.3	46.4
Medium moisture	32.0	0.72	2.2	48.5
High moisture	28.1	0.64	1.8	42.5

Within a main effect, within column, none of the above values were significantly different at $p < 0.05$.

The short duration of stress did not appear to affect the perennial tree component (poplar). However, with respect to barley, the surface soil tended to lose moisture at a faster rate than the soil at lower levels due to the evaporation and active absorption by barley roots, and as such, occurrence of moisture stress at the lowest moisture level treatment is quite possible in the upper layer of soil. The duration of the stress will also be longer in the upper soil layer than in the soil at the bottom of the pot. Other studies have shown that generally, the crop component is more sensitive to moisture stress than the tree component (Connor, 1983; Nair, 1987; Mittal and Singh, 1989). This is because trees have more xeromorphic characteristics than food crops and, by virtue of their greater root depth (Kimber, 1974), have access to soil water that is not usually available to the crop component.

Levels of N also did not influence any parameter measured in poplar. In this study, poplar was grown in the field for a period of two months in peat soil before transplanting. Therefore, part of the N requirement of poplar might have been met in the field itself. As trees tend to be less demanding of nutrients than crops (Young, 1997), poplar likely had enough N even at the lowest level tested. The fact that the poplar leaf N was 1.8% at the lowest level of N tested supports the above argument. (There were no interactions effects found in the ANOVA analyses of the data in Tables 3.3 and 3.4).

3.3.3 Poplar-Barley interactions (Experiment 2)

Intercropped barley did not significantly differ from monocropped barley with respect to final plant height , above ground biomass and final grain yield (Table 3.3). This suggests that under the tested conditions, poplar did not

Table 3.3. Comparison between monocropped and intercropped barley under specific treatment combinations.

	Monocrop			Intercrop		
Treatment Combination	Plant height (cm)	Biomass ($g\ pot^{-1}$)	Grain yield ($g\ pot^{-1}$)	Plant height (cm)	Biomass ($g\ pot^{-1}$)	Grain yield ($g\ pot^{-1}$)
Low N-Low moisture	61.6[1]	57.9	5.4	59.9[1]	49.1	6.1
Medium N-Medium moisture	68.6	93.1	31.8	67.6	81.6	28.1
High N-High moisture	72.3	87.9	34.4	67.2	91.8	32.6

[1] None of the values in the monocropped and in the intercropped barley were significantly different at $p < 0.05$, within measured variables.

Table 3.4. Comparison between monocropped and intercropped poplar under specific treatment combinations.

	Monocrop			Intercrop		
Treatment Combination	Diameter increment (cm)	Leaf area (cm^2)	Leaf total N (%)	Diameter increment (cm)	Leaf area (cm^2)	Total leaf N (%)
Low N-Low moisture	0.60[1]	41.1	2.3	0.59[1]	40.8	1.9
Medium N-Medium moisture	1.10	50.3	2.3	0.70	46.5	2.2
High N-High moisture	0.62	47.2	2.8	0.62	42.4	2.0

[1] None of the values in the monocropped and in the intercropped poplar were significantly different at $p < 0.05$, within measured variables.

compete severely for moisture or N with intercropped barley. As mentioned above, the observed spatial arrangement of the two root systems suggests that they may have not interacted with each other thus, reducing competition for moisture and N between the crop and tree component.

Intercropped poplar did not significantly differ from monocropped poplar with respect to diameter increment, leaf area and total leaf N, under any of the tested treatment levels (Table 3.4). This is expected because in the presence of barley, neither N levels nor moisture levels significantly affected poplar growth and other parameters tested, suggesting N and moisture were not limiting factors for poplar growth under the intercropped system.

There were no N losses to leaching from either system tested as the soil moisture was not increased above field capacity and the bottom of the pots were lined with a polyethylene sheet to prevent soil losses during the weighing process. The trees used in this study were small, and as such, there was no shading effect by the tree component on the crop component. Therefore, competition for light did not exist in this study. The above mentioned experimental conditions may have contributed towards reducing competition for moisture and N between tree and crop components. Therefore, under these conditions, one could expect intercropped barley to behave the same as monocropped barley as competition for moisture and N would have been less. The same argument applies to intercropped poplar and monocropped poplar as well.

As there was no significant difference in the above ground biomass of intercropped and monocropped barley (Table 3.3) in this study, the presence of the tree component in the intercropped scenario will obviously add to the above ground biomass when compared with monocropped scenarios. Under the tested N levels (low, medium and high), poplar leaf N content was 1.8%, 2.0% and 2.5%, respectively (Table 3.2). As poplar is deciduous, addition of leaf biomass may significantly affect the N nutrient status in soil in an intercropped system.

3.4 Conclusions

In a tree-based intercropping system, moisture and nitrogen fertilization effects seem to be more pronounced on the crop component than on the tree component. In this short term study, the fact that barley growth and yield were affected by levels of moisture and N, whereas growth of poplar was not, supports the above statement. Therefore, when designing such a system attention should be given to meeting the crop requirements to optimize yield. The results from this study, under the conditions tested, indicate that in a poplar-barley intercropped system, demand for N nutrient is high during the early stages of barley growth, followed by a greater moisture requirement, especially during tillering, heading and flowering stages of barley. Low levels of N (less than 70 kg ha^{-1} N) during the establishment of the crop and moisture stress during the tillering, heading and flowering stages can reduce grain yield by adversly affecting the yield components. Increasing the level of N beyond 70 kg ha^{-1} N and maintaining the soil moisture at field capacity, is not likely to significantly influence grain yield. However, under field conditions, optimum moisture and N requirements would vary from those observed in this study, but the critical stages for moisture and nitrogen requirement identified are more likely to remain the same even under field conditions.

Poplar seems to compete less for moisture and N with the crop component, as there was no difference in above ground biomass and final grain yield of intercropped and monocropped barley. Therefore, poplar is less likely to compete with the crop component for limited resources. One of the objectives in agroforestry is to select tree and crop components which result in more complementary interactions and less competitive ones. In this study, poplar was not competitive with the crop component, and therefore shows promise in agroforestry. Further research should investigate the effects of poplar leaf input and N transformation on soil in intercropped systems.

As the grain yield of the crop component was not affected by the presence of the tree component, poplar-barley intercropping system has an advantage over monocropped systems, in terms of resource utilization, and economic return from a unit land area.

4. Poplar leaf biomass distribution and nitrogen dynamics in a poplar-barley intercropped system in southern Ontario, Canada

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4.1 Introduction

An underlying principle in effective food production systems is that soil productivity should not be undermined, but rather should be maintained, if not improved. It is generally accepted that the improvement in fertility by trees is mainly a consequence of increased organic matter inputs (litter and root decay) and biological N_2-fixation by leguminous trees (Nair, 1993; Young, 1997).

There are very few studies in the temperate region that have investigated complementary interactions in tree-crop systems. Studies conducted by Thevathasan and Gordon (1995), (chapter 3), found that poplar (*Populus* sp. Clone DN 177) promoted complementary interactions with intercropped barley (OAC Kippen) and hence it was suggested that trees from this genus might be a suitable tree component in temperate tree-based intercropping systems. Poplars are widely distributed throughout North America and are well-adapted to differing soil and climatic conditions. They also comprise more than one half of Canada's deciduous timber volume and 12% of its total forest resources (Nielson, 1981). Poplar stands are characterized by higher rates of nutrient acquisition, accumulation and return than most temperate forest species, either deciduous or coniferous (Bernier, 1984). Bernier (1984) also suggested that poplars are efficient in the cycling of nutrients and that a large portion of nutrients utilized for annual growth are periodically involved in cycling.

Although poplar is currently being used in some tree-based intercropping systems in southern Ontario, there are no studies to date that have investigated the pattern of poplar leaf biomass distribution in the field over the course of the growing season and its subsequent impact on nitrate production. Release of N by the decomposing poplar leaves will also help in budgeting inorganic N fertilizer additions to tree-based intercropping systems, as N may get efficiently recycled in the presence of a tree component. This study was therefore designed to investigate the effects of poplar leaf-biomass distribution on soil nitrate production patterns under a 7 to 9 year-old poplar plantation intercropped with barley. The results will help to describe ecological relationships present in intercropping systems and will be useful in designing more productive and efficient food production systems.

4.2 Materials and Methods

4.2.1 Field Procedures

Two experiments were carried out during the 1993, 1994 and 1995 growing seasons under 7 to 9 year old poplar trees intercropped with barley in Wellington county, southern Ontario, Canada (43° 32' 28" N, 80° 12' 32" W). In the second experiment, barley was replaced by corn (*cv*. Pioneer 3917) during the 1994 and 1995 growing seasons, due to field operational protocols beyond the researcher's control. The experiment was a stratified randomized complete block design in which treatments (distance from the tree row) were pre-determined and replicated three times (Snedecor and Cochran, 1989). Soil type was sandy loam (order-Luvisolic, great group-grey brown luvisols, Can. Soil classification; in American soil classification, Order-Alfisol, group- Typic Hapludalf). Sampling areas were located where the tree rows were spaced 15 m apart. Each replication comprised a centre row of poplar (5 to 7 trees 6 m apart) and two adjacent rows of trees, each 15 m from the poplar row. Trees found in the adjacent rows were red oak (*Quercus rubra* L.) and white pine (*Pinus strobus* L.); because of their poor growth and size, they did not contribute any substantial amount of leaf biomass to the adjacent field. Soil nitrate production was measured at the poplar row (0) and at 1, 2, 3, 4, 7.5, 11, 13, 14 and 15 m (next tree row) from the poplar tree row on either side. All cultural practices (land preparation, seed rate, weed control and fertilizer application) were the same for all three growing seasons. The land was zero-tilled and barley was drilled at the rate of 200 plants m^{-2}. During the establishment phase (1988 to 1992) of this intercropped research site the field was disc ploughed for the first four years to reduce the density of tree lateral roots in the first 15 to 20 cm of soil depth. During the study period (1993-1995) the field was fertilized at the rate of 45 kg N ha^{-1} during the last week of April. There was no major difference in weather parameters (temperature and rain fall) between the years during the study period.

4.2.2 Nitrate Production

In situ field incubations using the buried polyethylene bag (bag thickness = 0.02 mm) method (Eno, 1960; Gordon *et al.*, 1987) were used to estimate nitrate production. In order to ensure adequate moisture for incubation, soil sampling was done two days after rain. The experiment therefore did not commence on the same date in June each year, which was the first sampling month of the growing season.

At the beginning of each field season (June), soil was collected from 0 to 15 cm depth using a soil auger at the specified sampling site. Soil was mixed well and cleared free of any woody debris. Poplar leaves collected by the soil auger, if any, were placed in the bag. The same soil sampling procedure was adopted in experiment 2 as well. Following this procedure, four sub-samples (100 to 150 g of field moist soil), were prepared (e.g. two sub-samples for each distance on each side and therefore four sub-samples in total for each distance) in polyethylene bags and the bags sealed with twist-ties. Two sub-samples were then buried at 15 cm below the soil surface at the specified distance from the poplar tree row (one each on either side) to incubate in the field as mentioned above and the other two sub-samples were placed in a cooler box with ice, transferred to the lab and kept frozen (2 to 4 months) at -20°C until extraction.

Sampling dates were on a monthly basis starting from June each year and ending in September with the exception of 1995. In 1995, the experiment was carried out only from June to August. However, in this paper only peak summer (June to July) results are presented as most of the poplar leaves decomposed within two months. Incubation period varied from 30 to 40 days, depending on the rainfall event. In order to keep the soil moisture constant soil sampling was done on the second day after a rainfall event.

4.2.3 Biomass estimation - Barley and Poplar

Total above ground biomass of barley was estimated at the end of the cropping season (end of August) in experiment No. 1 only. At the same locations where nitrate production was assessed, 1 m^2 plots were established and the crop manually harvested and dried at 75°C for 48 to 72 hours in a conventional forced air oven for dry weight. Grain was analyzed for total N.

In order to estimate the total leaf biomass produced by poplar trees on the research site, six trees were randomly selected for each year 1993 and 1994 (7, 8 year-old). At the beginning of the fall season, the trees were covered with cherry nets (mesh size = 2 cm X 2 cm) to trap the leaves. The nets stayed on the trees until late fall ensuring that all shed leaves were collected. Leaf biomass was estimated by collecting the trapped leaves from the net and weighing them.

Poplar leaf biomass distribution on the experimental site was also estimated. In the fall of 1993, 30 m long *Chick nets* were placed vertically but parallel to the poplar row (like a fence) on either side at distances of 2.5 and 6.0 m away from the poplar tree row. Visual observations made on site revealed that most of the leaves fell very close to the poplar row, and therefore the *Chick nets* were placed at these distances in order to estimate the poplar leaf biomass distribution in the field. At the end of September, poplar leaves were collected from the above mentioned areas (0 to 2.5 m and 2.5 to 6.0 m corridors) using a `Mad-Vac' machine. In 1994, *Chick nets* were not placed on the field since observations made during the 1993 fall season revealed that when the poplar leaves landed on the ground they became entangled among the barley stubble and remained there (5 to 10 days). Therefore, as the barley stubble prevented the poplar leaves from being blown from the field, the poplar leaves were collected in the absence of *Chick nets* in the same surface area (0 to 2.5 m and 2.5 to 6.0 m) in 1994. Some barley stubble was picked up by the `Mad-Vac' machine but was removed by hand before poplar leaf biomass was calculated.

4.2.4 Experiment No. 2

On the same site, a second experiment was carried out along with the first experiment in all years, using a similar design. In this experiment, poplar leaves were not removed from the field during the 1993 and 1994 fall seasons. Nitrate production measurements and soil organic C measurements were taken at the same distances from the poplar row and at the same sampling dates as in the first experiment. However, in 1994 and 1995, the crop in the second experiment was corn instead of barley.

4.2.5 Laboratory procedures

Samples were allowed to thaw in order to re-incorporate the moisture inside the bags before extraction with 2 M KCl (Keeney and Nelson, 1982). The extracts were analysed on a Technicon Autoanalyzer II system. Nitrate production rates were determined by subtracting the un-incubated sample values from the incubated sample values, and dividing by the number of days incubated. Total N concentration (%) in plant materials (barley grains and poplar leaves) was determined according to Tel and Rao (1982).

Total soil organic C at specific locations from the poplar row was measured at the beginning of the growing season for all years. Air dried, ground soil was analyzed in a Leco CR12 Carbon Analyser for total soil organic carbon.

4.2.6 Statistical analysis

The data were analysed using the Statistical Analysis System (SAS) package. Analysis of variance (ANOVA) was used to determine if there were any significant differences in treatment (the distance from tree) based on F test statistics. In the presence of significant differences ($p < 0.05$), pair wise comparisons were made between means using Bonferoni `t' tests at $p < 0.05$.

4.3 Results and Discussion

The biomass distribution of poplar leaves in the field for the 1993 and 1994 growing seasons is shown in Table 4.1.

Table 4.1. Poplar leaf-biomass distribution in the field for the 1993 and 1994 growing seasons.

Distance from the poplar tree row (m)	leaf biomass (Mg ha^{-1}) 1993[a]	leaf biomass (Mg ha^{-1}) 1994[b]
0-2.5	2.67 ± 0.04	2.76 ± 0.14
2.5-6.0	0.52 ± 0.05	0.61 ± 0.06

[a] 84% of leaf biomass found in the 0-2.5 m zone
[b] 82% of leaf biomass found in the 0-2.5 m zone

Leaf biomass collected in both years within 2.5 m of the tree row accounted for more than 80% of the total poplar leaf biomass collected from the field with the rest being collected in the 2.5 to 6.0 m region. Based on a leaf moisture content of 8 to 10% and a leaf N concentration of 2%, almost 50 kg ha^{-1} N was present for potential release by the decomposing leaves within 2.5 m of the tree row. This can be compared to the recommended rate of inorganic N fertilizer for barley in southern Ontario which is 40 to 45 kg ha^{-1} N (OMAFRA Publication No. 296, 1996).

Mean peak summer soil nitrate production rates in experiment No. 1 within 2.5 m from the tree row were 102, 27 and 22 μg N 100 g^{-1} dry soil day^{-1} in 1993, 1994 and 1995 respectively (Figure 4.1(a)). In experiment No. 2, the corresponding nitrate production values within 2.5 m from the tree row for all years were 105, 100 and 128 μg N 100 g^{-1} dry soil day^{-1} (Figure 4.1(b))[Mean values for all 3 years were calculated by averaging mean nitrate production rates, 0, 1 and 2 m from the poplar tree row]. A further comparison of Figures 4.2 (a),(b) and (c) clearly depicts the change in the magnitude of nitrate production rates as affected by the absence or presence of poplar leaf biomass, especially within 2.5 m of the poplar tree row. In the middle of the crop alley, (4 to 11 m from tree row) in experiment No.1, mean nitrate production rates for 1993 , 1994 and 1995 were only 62, -33 and -12 μg. N 100 g^{-1} dry soil day^{-1} respectively. In experiment No. 2, for the same period, mean nitrate production rates in the middle of the crop alley, were 60.8, -2 and 12 μg N 100 g^{-1} dry soil day^{-1} respectively. In both experiments, nitrate production rates within 2.5 m from the tree row were significantly ($p < 0.05$) higher than the middle of the crop alley nitrate production rates. These results suggest that soil nitrate production rates in a poplar tree-based intercropped system will largely depend upon the quantity of leaves shed during the preceding fall.

There will obviously be differences between poplar clones with respect to root biomass (Bernier, 1984), but generally, poplars are likely to have fewer roots distributed in the crop rooting zone (0 to 20 cm) when compared to other tree species recommended for temperate agroforestry systems (R.C. Schultz, 1996; pers. comm.) Belowground root biomass contribution was not assessed in this study but results from experiment 1 and 2 suggest that contributions to nitrate production from poplar roots were not important. If belowground poplar roots had significantly contributed to nitrate production, then removal of aboveground poplar leaf biomass in the fall of 1993 and 1994 should have had less impact on N turnover close to the poplar tree row in 1994 and 1995. However, the results suggest that the opposite occurred (Figures 4.2 (b) and (c)).

Elevated soil nitrate production rates in the middle of the row crop were observed during the summer (June to July) of 1993 for both experiments (Figure 4.1 (a), (b)). In 1992, both fields were cultivated with soybeans. The high rates in 1993 may have resulted from decomposing root nodules and the N released by soybeans in 1992 or it is also possible that less residue input from soybean crop can result in a flux of nitrate production during peak summer in the following year

(Beauchamp, 1998 pers. comm.). However, this effect was prominent only during the first month of incubation (June to July). During the second month of incubation, mean nitrate production rates close to the poplar tree row (< 2.5 m) were 44.3 μg N 100 g^{-1} dry soil day^{-1} in the first experiment and 53 μg N 100 g^{-1} dry soil day^{-1} in the second experiment. Soil nitrate production values in the middle of the row crop (4 to 11 m) were 11.96 μg N 100 g^{-1} dry soil day^{-1} and 12 μg N 100 g^{-1} dry soil day^{-1} respectively.

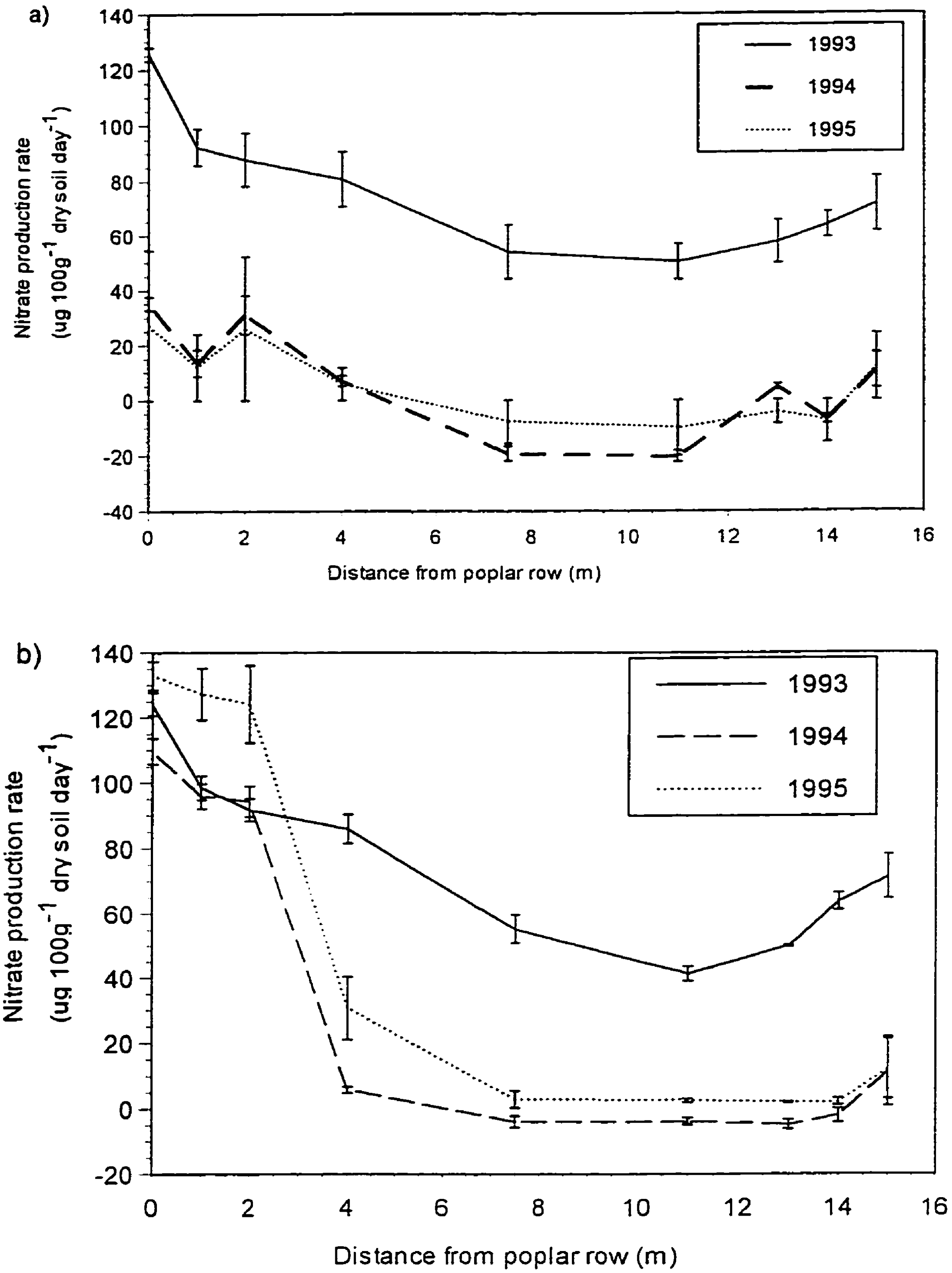

Figure 4.1. Effect of poplar leaf removal on nitrate production rate across the intercropped field during the 1993, 1994 and 1995 growing seasons. (a) Poplar leaves removed. (b) Poplar leaves not removed (Error bars that overlap indicate that associated values are not significant at $p < 0.05$).

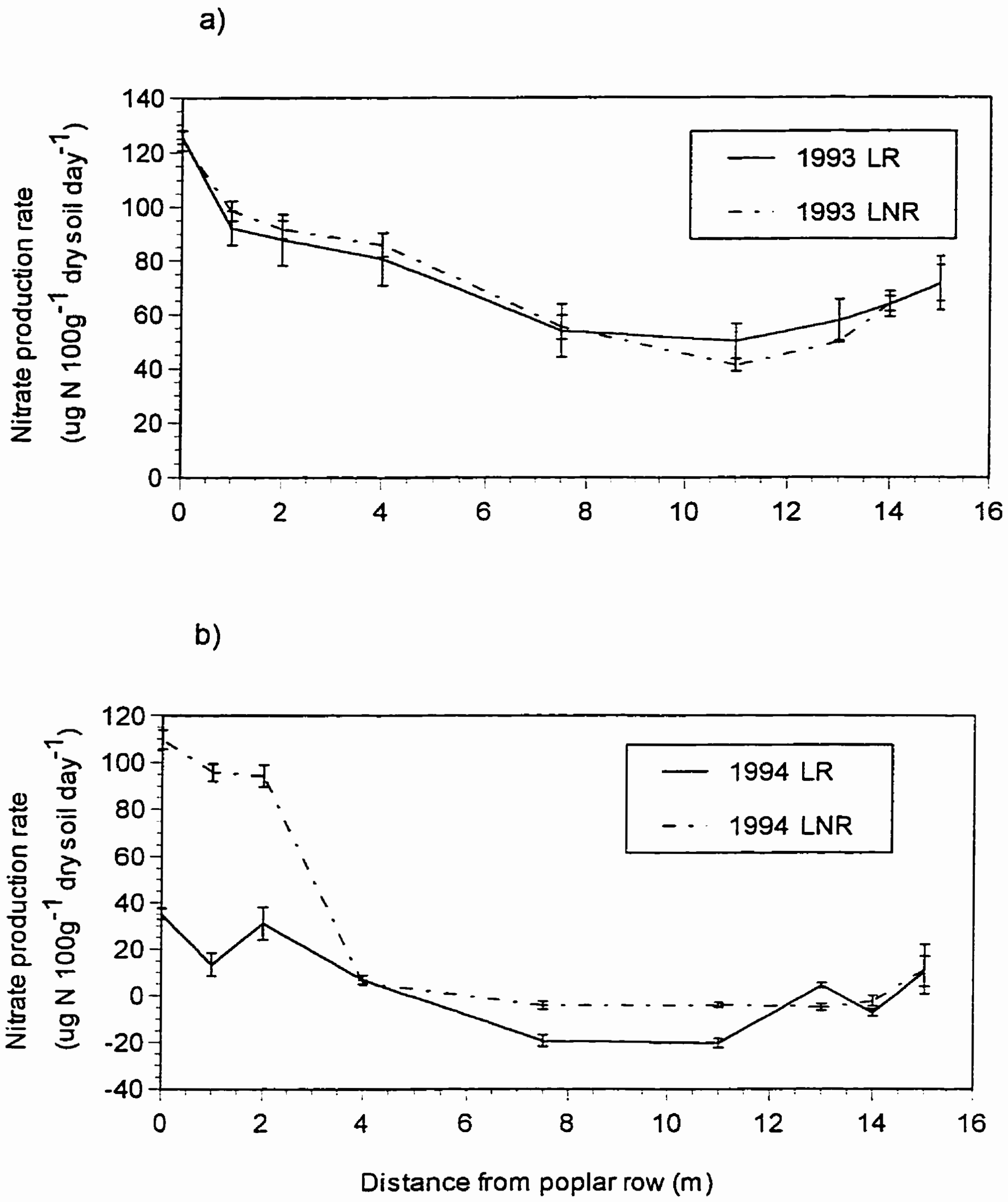

Figure 4.2. Effect of poplar leaves removed (LR) or leaves not removed (LNR) on nitrate production rate across the intercropped field during the 1993 (a) and 1994 (b) growing seasons. (Error bars that overlap indicate that associated values are not significant at $p < 0.05$).

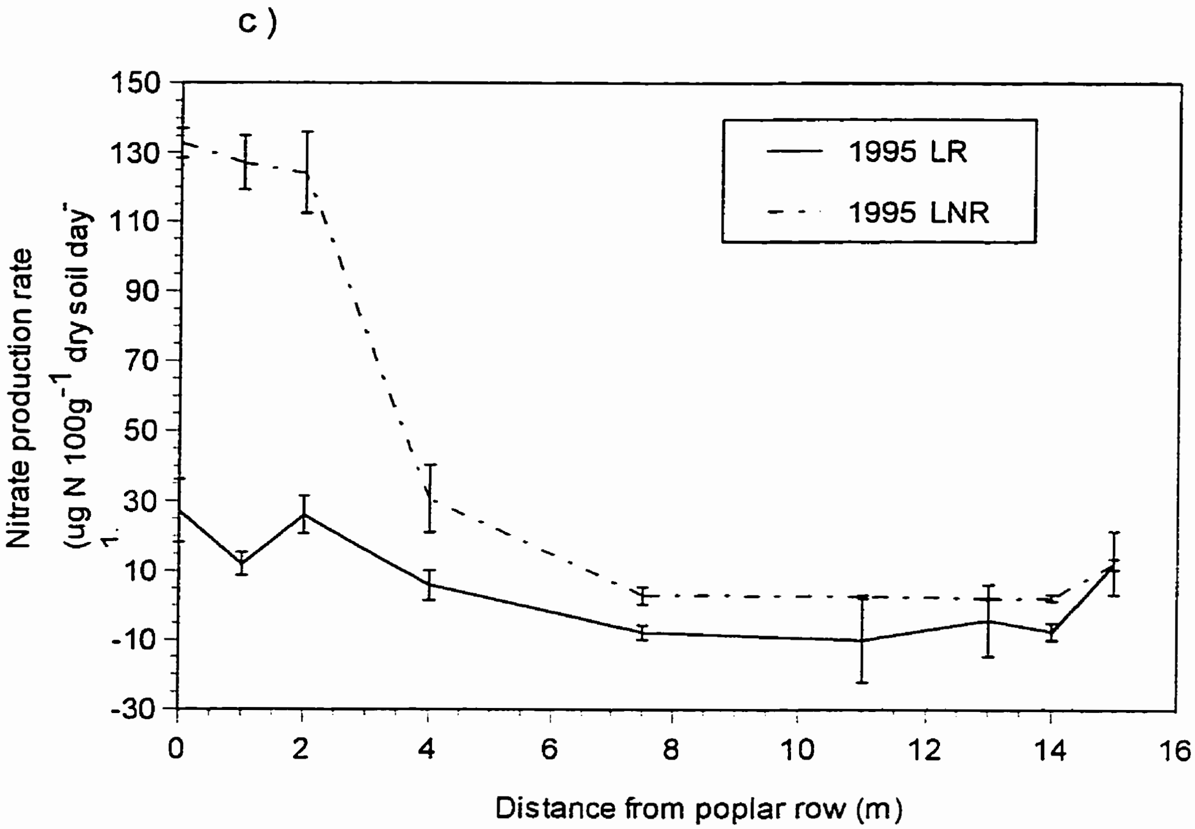

Figure 4.2. Effect of poplar leaves removed (LR) or leaves not removed (LNR) on nitrate production rate across the intercropped field during the 1995 (c) growing seasons. (Error bars that overlap indicate that associated values are not significant at $p < 0.05$).

As the season progressed in 1993 (August to October) nitrogen immobilization (Appendix 3) across the field might have contributed to lower nitrate production values. Therefore, it is likely that the effect of the legume crop on nitrate production persisted only until the end of the first incubation period.

The variation in soil organic carbon observed across the field is shown for experiment No. 1 (Figure 4.3 (a)) and experiment No. 2 (Figure 4.3 (b)) for all three years. Soil organic carbon close to the poplar tree row (< 2.5 m) was about 1 percentage point higher than SOC values observed in the middle of the row crop (4 to 11 m) in both experiments. The collected poplar leaves had approximately 40% carbon, and from the poplar leaf biomass data presented in Table 4.1, ~1000 kg of C ha^{-1} is added to the soil within 2.5 m of the poplar tree row annually. The build up of soil organic matter under tree canopies and the positive influence of agroforestry tree species in improving soil fertility has been well reported (Kang *et al.*, 1990; Nair, 1993). A gradual build up of soil organic carbon over a period of seven years under a black locust agroforestry system has also been reported in the Azad Kashmir region in Pakistan (Ahmed *et al.*, 1996). The removal of poplar leaf biomass in experiment No. 1 during the

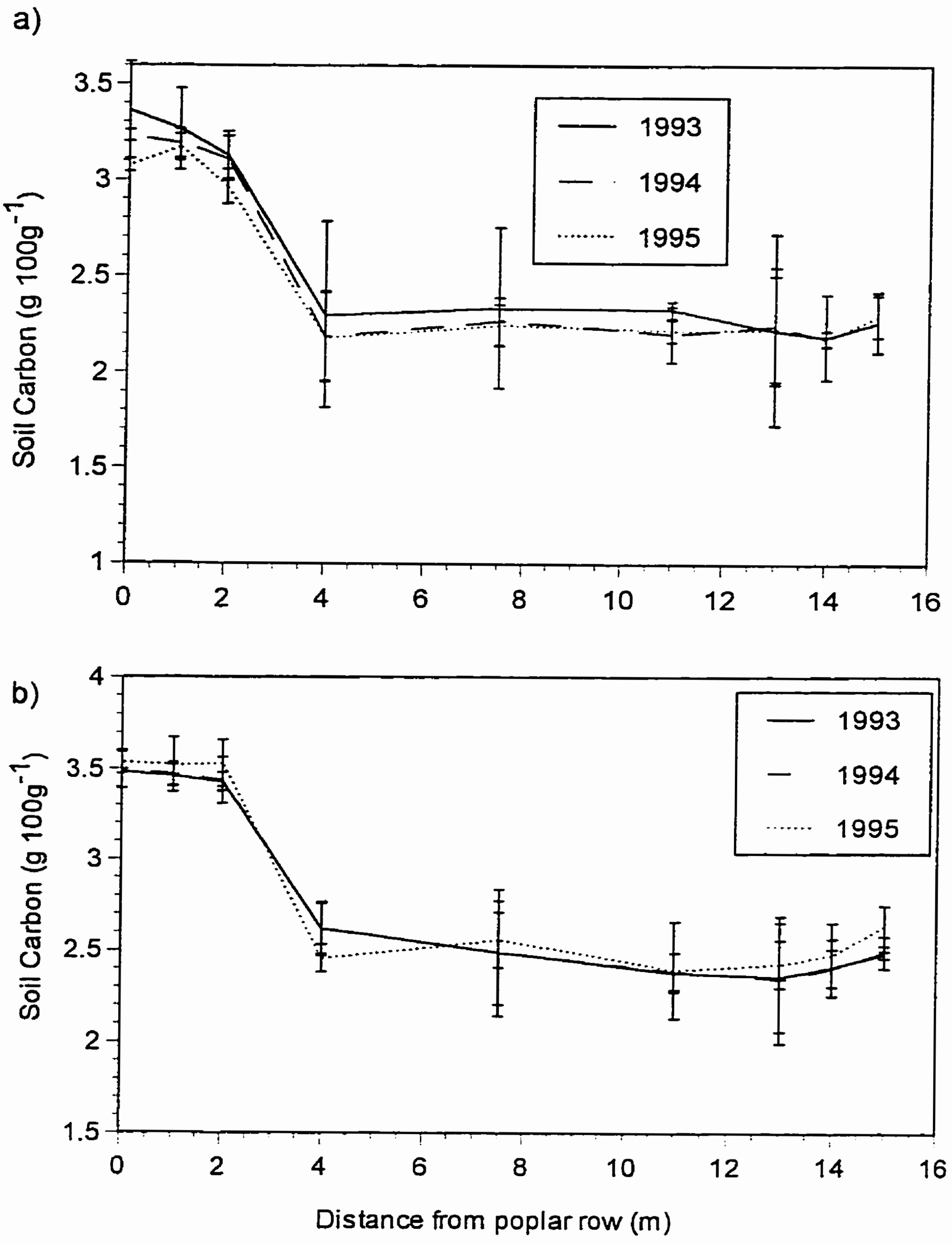

Figure 4.3. Variation in soil organic carbon across the intercropped field in 1993, 1994 and 1995. (a) Poplar leaves removed. (b) Poplar leaves not removed (Error bars that overlap indicate that associated values are not significant at $p < 0.05$).

1993 and 1994 fall seasons or the addition of poplar leaf biomass during the same period of time in experiment No. 2, did not significantly alter the total SOC pool close to the tree row ($p < 0.05$) over the period tested (Figures 4.3 (a),(b)). This is to expected as only 15 to 35 % of the added organic residue is actually incorporated into the permanent organic pool (humus)(Brady, 1990). Hence, two years of addition or removal unlikely affected the total SOC pool close to the poplar tree row.

Total aboveground biomass (AGB) of barley [grains + straw] for all three years is given in Figure 4.4 for experiment No. 1. Mean barley AGB close to the poplar tree row (< 2.5 m) was 517, 500 and 450 g m^{-2} in 1993, 1994 and 1995 respectively, compared to 491, 484 and 464 g m^{-2} in the middle of the row crop. Grain yield will be 35 to 40 % of the barley AGB (D. Falk, 1996; pers. comm.), for the cultivar used in this study (OAC Kippen). Barley AGB yields in 1993 and 1994 were significantly ($p < 0.05$) higher close to the poplar tree row when compared with the middle of the row crop yield (Figure 4.4). In 1995, no significant difference in barley AGB yields across the field was noted (Figure 4.3). The yield reduction in 1995, especially close to the poplar row, follow roughly those predicted by Van Noordwijk (1996). The latter is likely a result of decreased nitrate production and N availability. Further, it is recommended to rotate cereal crops. However in this study barley was cultivate consecutively for three years. This also could have contributed to low yields in 1995.

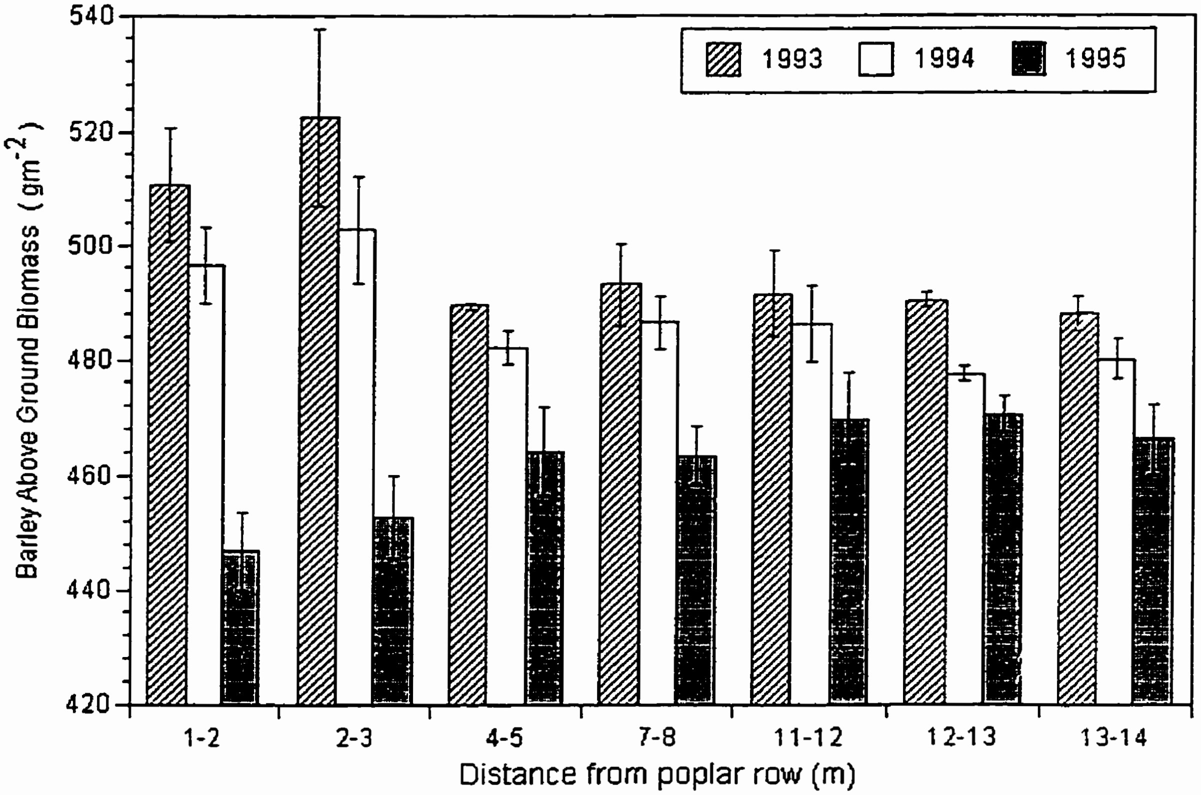

Figure 4.4. Above ground biomass of barley across the intercropped field during the three seasons (Error bars that overlap indicate that associated values within a year are not significant at $p < 0.05$).

The distance between tree rows in this study was 15 m. The adjacent tree rows (on either side of the poplar row) did not have any large trees (average height: 1 to 1.5 m compared to poplar trees (~7 m)). Poplar trees were 6 m apart in the row and due to the inherent cone shape of the poplar canopy there was no complete closure of the canopy, and shading therefore was not a large concern in this study. Even during the peak growing season, only a partial shading effect was experienced as there was considerable amount of light penetration through the poplar canopy (visual observation). Compared to other temperate tree species, poplar has a relatively low root density in the 0 to 20 cm horizon (R.C. Schultz, 1996; pers. comm.). During the establishment phase of this experimental site, the field was disc ploughed to reduce lateral root density in the cropping zone. Therefore, tree root interference adjacent to the tree row in the first 20 cm soil layer was likely minimal. Puri *et al.* (1994), working with *Populus deltoides* in India, have also recommended lateral root pruning in poplar-based intercropped system to reduce competition. In China, wider spacing of *Populus tomentosa* (4 X 6 m and 6 X 8 m) barely affected crop yield, but increased stand timber volume (Zhanxue et al., 1991). A reduction in grain yield or AGB yield close to a tree row could occur if there is significant amount of shading by the tree row and/or if trees compete for moisture and nutrients with the adjacent crop in the same rooting zone. However, such negative interactions did not occur in this study as a result of proper selection of the components and management of the system.

Nitrogen concentration in barley grains within 2.5 m of the poplar row declined (Figure 4.5) from 1993 to 1995. The mean N concentration in the grain was 2.5% in 1993 compared to 1.7% in 1995. A significant reduction ($p < 0.05$) in the grain N concentration from 1993 to 1995 is possibly related to the significant ($p < 0.05$) reduction in nitrate production rates (Figure 4.1 (a)) in the same region. Low N availability could also have led to less uptake by the crop as the barley AGB was also significantly reduced in the same region from 1993 to 1995. If each year is considered individually, N concentration in the barley grains harvested across the field showed a trend similar to that observed for barley AGB yield (Figure 4.4). Barley grains harvested from the same field but in the absence of poplar trees had an N concentration of 1.6% (control plot). This was similar to that observed for grain N from the middle of the row crop region. The latter suggests that the middle of the row crop area was not influenced by poplar leaf biomass input.

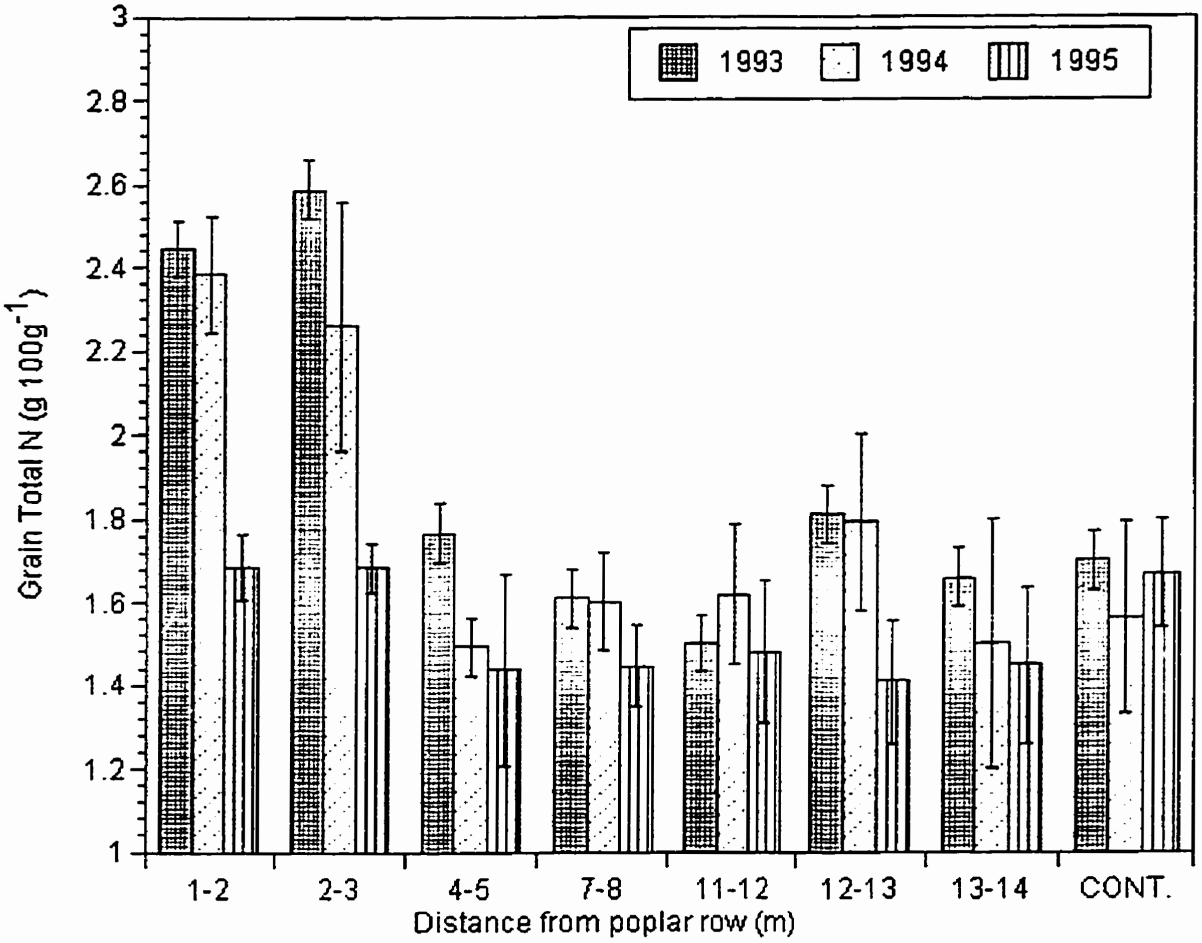

Figure 4.5. Variation in barley grain nitrogen concentration in a poplar-based intercropping system, during the 1993, 1994 and 1995 growing seasons. CONT= N concentrations from barley in a non-intercropped field (Error bars that overlap indicate that associated values within a year are not significant at $p < 0.05$).

Seasonal changes in foliar N concentration were also assessed in poplar from 1993 to 1995 (Appendix 1). Foliar N concentration was found to be in the range of 0.1 % to 4.4 % N, with a peak in the spring, a decline in the summer and a subsequent rise in the fall. This follows documented patterns (Giulimondi and Durianti, 1974; Baker and Blackmon, 1977; McColl, 1980). For the purpose of this study, it should be noted that N concentration in poplar leaves is high when they are shed (~ 2.3 to 2.5 % N).

Soil respiration was also measured in 1993 (Figure 4.6). No firm conclusions can be drawn from the data as root respiration was not separated from microbial respiration. Higher root volumes on the tree rows (0 and 15 m) and closer to the tree rows (1 and 14 m) appears to have contributed to higher root respiration which masked the microbial respiration that would have taken place during the decomposition process. Higher microbial activity closer to the tree row and transfer of N from Alder (*Alnus rubra* Bong.) to sweet corn closer to the tree row has been reported (Seiter *et al.*, 1996). Root density on the tree row or closer to the tree row was not measured in this study. However, it is obvious that the root density at the tree-crop interface will be higher compared to the root density at the middle of the row crop region. Towards the end of the season, all physiological activities in plants tend to decline and this might have contributed to the decline in CO_2 emission during the month of September.

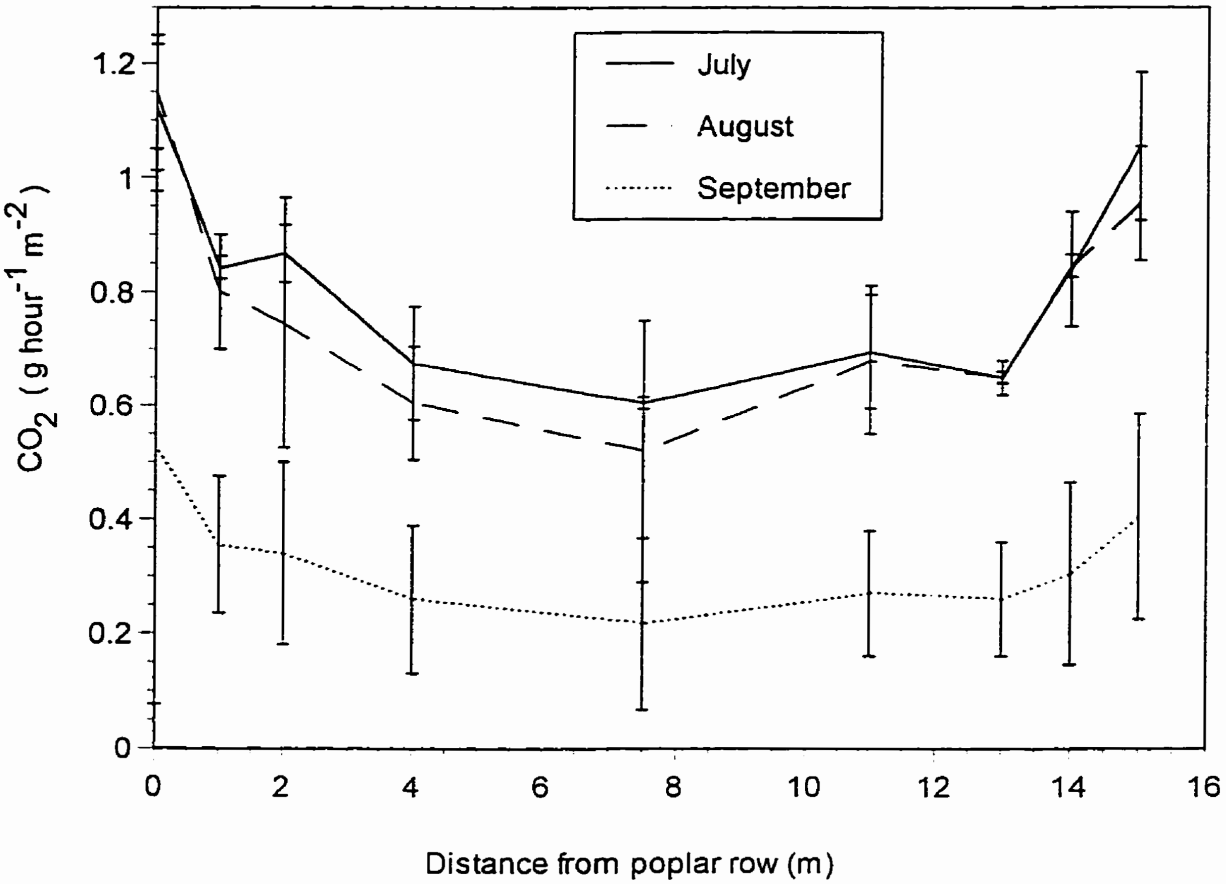

Figure 4.6. Soil respiration estimates (soda-lime absorption) at nitrate production locations during the 1993 growing season (Error bars that overlap indicate that associated values are not significant at $p < 0.05$).

The results from this study suggest that poplar leaf biomass distribution in the crop alley had a distinct pattern and this in turn also affected nitrate accumulation, soil organic carbon and possible nitrogen uptake by barley across the crop alley in a fixed manner. This type of behaviour is known as 'monotonic behaviour' (Ponnrajah, 1997; personal communication), and when experimental data suggest such behaviour, the utilization of piecewise linear-quadratic functions and a linear least squares fitting criterion may be a recommended approach to capture the behaviour of the experimental data. Using the above approach, 3D models were developed for poplar leaf biomass distribution and soil organic C build-up across the crop alley with tree age (see Appendix 2).

4.4 Conclusions

An increase in nitrate production rate and higher total soil organic carbon close to the tree row as a possible result of poplar leaf biomass input was observed in this study. This most likely contributed to an increase in barley above ground biomass and grain N concentration close to the tree row. As the trees were young in this study, the beneficial effects were restricted to the area closest to the tree row. As the tree canopy develops this `area of beneficial effect' could be expected to extend further into the intercropped field. Another management strategy that could be adopted in this region is the planting of fast growing tree species like poplar in concert with more valuable, but slow growing hardwood tree species in alternative rows in order to maximize the beneficial effects by poplar as observed in this study.

As there is a limited number of leguminous and other N fixing species of trees that will grow in temperate North America, poplar may prove to be a suitable alternative. Current research indicates that poplar can provide many of the benefits observed with leguminous species while also being very tolerant of a wide range of site and climatic conditions found in the temperate zone.

5. N flow through a poplar-barley intercropping system and a barley monocropping system in Wellington county, southern Ontario

5.1 Introduction

In the past 20 years or so, N outputs in subsurface or overland runoff have been identified as an important source of nonpoint pollution in agricultural watersheds (Lowrance, 1992a). Some studies during the early 1970's concluded that increased use of nitrogenous fertilizers did not cause significant increase in NO_3-N concentrations in surface waters (Tomlinson, 1970; Thomas and Crutchfield, 1974). However, recent research has clearly identified that increased use of N fertilizers in agricultural fields has been the prime factor contributing to the above problem (Duda, 1982; O'Neill and Gordon, 1994).

Many studies in Ontario have shown increased NO_3-N in streams draining fertilized agricultural fields. Miller (1979), for example, reported that certain mineral soils in Ontario, fertilized at rates greater than recommended, exhibited NO_3-N concentrations in drainage water between 11.3 and 20.4 mg L^{-1}. In another study, Whiteley *et al.* (1983), while investigating small agricultural watersheds in Ontario, found NO_3-N concentrations in well samples from abandoned fields to be less than 2 mg L^{-1}, whereas samples from cultivated fields had a mean NO_3-N concentration of 6.7 mg L^{-1}. The above results support the conclusions of a study by Neilson *et al.* (1982), who estimated that agricultural activity was responsible for up to 98% of the NO_3 loading to the Grand River in southern Ontario.

As indicated in the literature review (chapter 2), poplars are considered efficient tree species to cycle nutrients, especially N. Poplars have also been shown to have an affinity to absorb NO_3-N efficiently (O'Neill and Gordon, 1994). In chapter 4, nitrate production rates, poplar leaf biomass, barley above ground biomass and barley grain N were assessed in a poplar-barley intercropping system. Data collected on the above parameters can be used to construct a N flow model for a poplar-barley intercropping system in southern Ontario. There are no N flow models currently available for poplar-based intercropping systems in this region. Hence, the potential ability of poplar to absorb leached nitrate and efficiently cycle the same is not yet quantitatively assessed. A quantitative assessment of N flow through a poplar-barley intercropping system and through a barley monocropping system will provide useful information on the ability of poplar to reduce nitrate leaching. Understanding nitrogen flow in these systems may lead to reduced nitrate loading to nearby waterways, and may also be useful for future fertilizer management programs.

Therefore, since no studies to date have modelled N flow through poplar-based intercropping systems in southern Ontario, an attempt was made to construct a N flow model for this type of system. However, it should be cautioned at this point that the model depicted here is of a preliminary nature and more research is needed to verify the assumptions of the model. This type of work, simulation modelling, is much needed in temperate agroforestry systems in general.

5.2 Assumptions and related calculations associated with the N flow models

1. A N flow model for a poplar-barley intercropping system (Figure 5.1) was constructed using the 1993 field season data (chapter 4). Even though nitrate production was measured during the summer months, adjustments were made to accommodate nitrate production for the entire frost free period, which is 136 days for Wellington County, southern Ontario.

2. Assuming a soil bulk density of 1.33 g cm^{-3}, the weight of soil at plough depth (15 cm) was taken as 2×10^6 kg ha^{-1}. Soil N content was 0.13% and it was assumed that 2% of organic N was mineralized. Atmospheric N input was taken as 18 kg ha^{-1} out of which 10 kg ha^{-1} was in the form of NH_4-N and 8 kg ha^{-1} was NO_3-N. Denitrification was

taken as 10 kg ha^{-1}. (Professors E. Beauchamp and P. Voroney (1998), Department of Land Resource Science, University of Guelph, personal communication).

3. A tree spacing of 15m x 6m results in 111 poplar trees per hectare. Average leaf litter production from this tree density was calculated to be 1100 kg ha^{-1} in 1993. Poplar leaf N content was taken as 2% (C = 40 %) and it was assumed that 30% of the total leaf litter input is mineralized (Brady, 1990), yielding about 7 kg N ha^{-1}. It should be noted that below ground litter input from poplar was not assessed. Therefore, the total N input from poplar may be slightly higher than 7 kg N ha^{-1} (see chapter 4). It was also assumed, out of annual leaf N, about 5% comes from the permanent structure (stems) of poplar trees and 95% from current year N uptake. An additional 10% of leaf total N was added to the current year total tree uptake to account for N stored in stems (cf. Van Cleve, 1983). As poplars are early successional species, it was assumed that the major form of N uptake would be in the form of NO_3-N (Kimmins, 1997).

4. Nitrate production close to the poplar tree row (< 2 m) during 1993 was calculated to be 0.5 mg kg^{-1} day^{-1} and in the middle of the crop alley was 0.2 mg kg^{-1} day^{-1}, which yielded 136 and 54 kg ha^{-1} of nitrate-N, respectively, in those regions (chapter 4). Therefore the average nitrate

production was taken as 95 kg N ha^{-1} $year^{-1}$ for the poplar-barley intercropped field.

5. Pool sizes for NH_4 and NO_3 were calculated from time zero values obtained from this study and were estimated for the entire frost free period.

6. Pool sizes for poplar trees (except for leaf pool size) were estimated from values reported for quaking aspen (*Populus tremuloides* Michx.) found in taiga forest types in interior Alaska (Van Cleve *et al.*, 1983). Estimated branch biomass was 6250 kg ha^{-1} (N = 0.3%) and trunk biomass was 36,667 kg ha^{-1} (N = 0.0015%).

7. Average barley grain yield was 2000 kg ha^{-1}, average grain N was taken as 2%, average straw yield was 3131 kg ha^{-1}, harvest index (HI) was 0.38, and N concentration in the straw and in the roots was assumed as 0.57%. It was also assumed that the barley root weight was 20% of the total plant weight (Professors E. Beauchamp and P. Voroney (1998), Department of Land Resource Science, University of Guelph, personal communication).

8. N flow in a barley monocropped system (Figure 5.2) was constructed using the same assumptions mentioned above with the exception that the barley grain yield was taken as 2300 kg ha^{-1} accounting for the greater availability

of land area. HI was maintained at 0.38. The grain yield reported here is close to the mean yield recorded for this site.

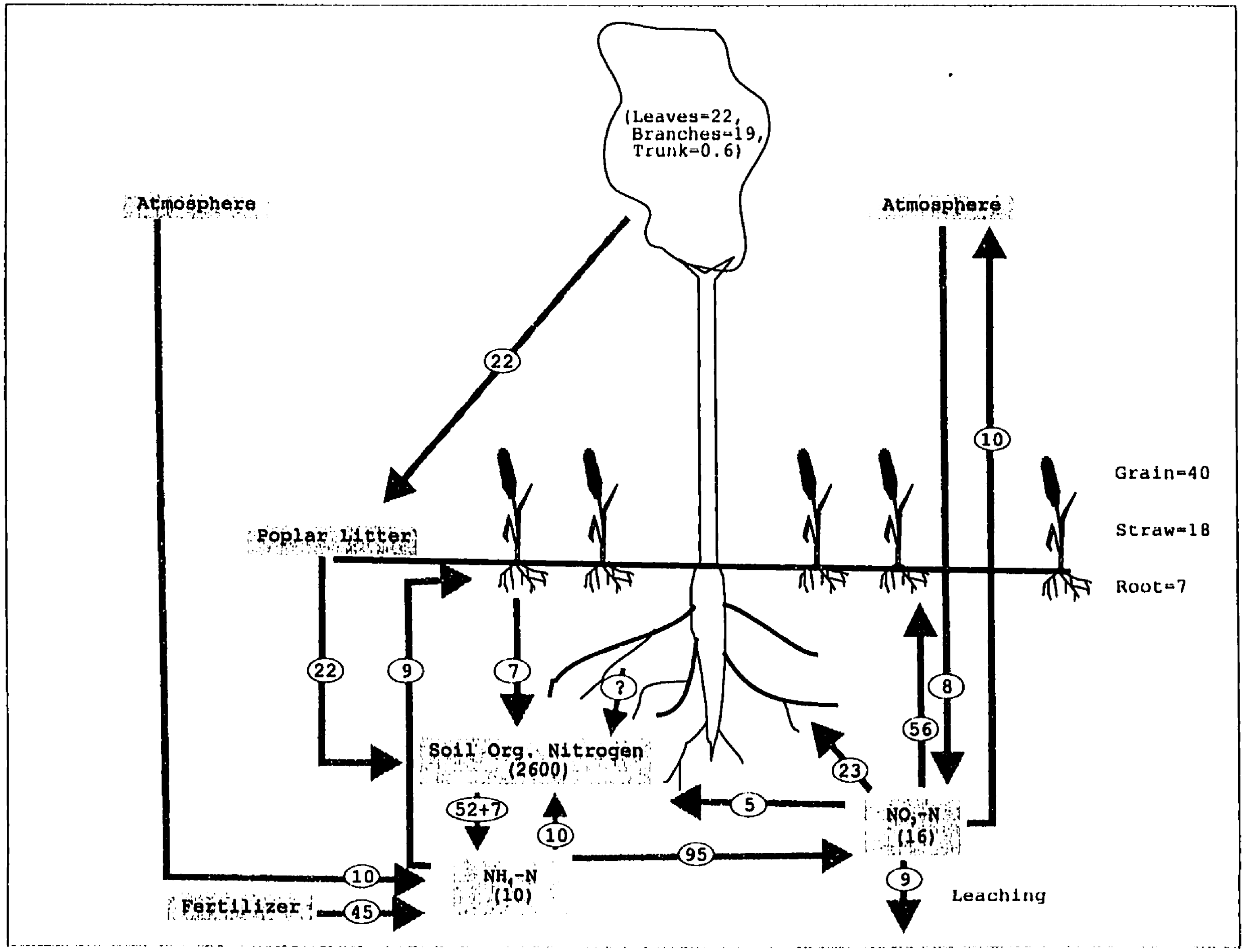

Figure 5.1. N flow in a poplar-barley intercropping system. Fluxes are reported in kg ha^{-1} yr^{-1} and pool sizes are given within parentheses in kg ha^{-1}.

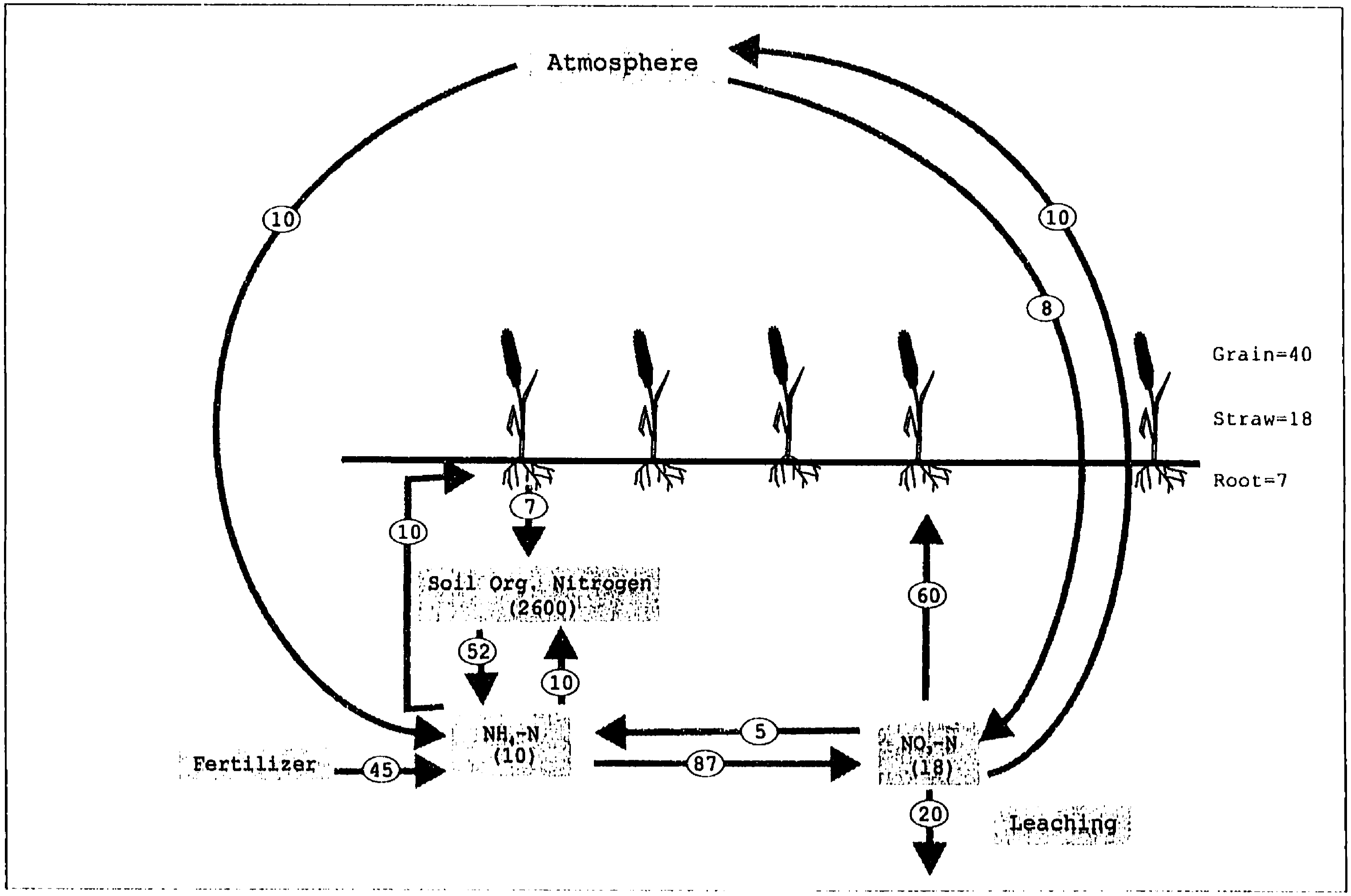

Figure 5.2. N flow in a barley monocropping system (adapted from Beauchamp, 1998; pers.comm.). Fluxes are reported in kg ha^{-1} yr^{-1} and pool sizes are given within parentheses in kg ha^{-1}.

5.3 Conclusions

The ability of poplar to absorb NO_3 (O'Neill and Gordon, 1994; Kimmins, 1997) is advantageous, especially in a field crop production scenario where most of the NO_3 leached below the crop rooting zone will be absorbed by poplar roots.

Furthermore, barley is harvested early in August and therefore there is a relatively long period for NO_3 accumulation and possibly high leaching potential (even much more than that represented in the model, Figure 5.2). It should also be noted that the soil depth was taken as 15 cm (plough depth) and nitrate production was calculated based on the above depth. Nevertheless, nitrification can proceed in deep soil (15-30 cm) as well but at a lower rate (Gordon, 1986). Therefore, the estimated amount of nitrate leaching from both systems may have been underestimated in this model and, thus, more data are needed on nitrate production below 15 cm soil layer. However, since the magnitude of the latter is generally considered insignificant compared to nitrate production in the first 15 cm soil profile due to low soil temperature, low oxygen availability and low substrate availability (Brady, 1990), for the purpose of this study nitrate leaching estimates indicated in the models could be taken as a close approximation of reality.

The nitrogen flow model for poplar-barley intercropping indicates that NO_3 leaching losses are potentially reduced by more than 50% compared to monocropped barley (Figure 5.2). Therefore, introducing poplars (at a tree density of 111 trees ha^{-1}) in agricultural fields, especially in fields where high nitrogenous fertilizers are used, may substantially reduce NO_3 loading to nearby watersheds.

6. Effects of Juglone (5-hydroxy-1,4 napthoquinone) on soil ammonification and nitrification

(This chapter has been submitted to the Agroforestry Systems journal)

6.1 Introduction

In recent years, the farming community in North America has come under increasing criticism for past agricultural practices that have increased water and wind erosion of soil, degraded soil structure, lowered water quality and reduced wildlife habitat. An increased reliance on fertilizers and herbicides has developed, causing agriculture to become a possible contributor of pollutants to lakes and streams (Sotomayor and Rice, 1996). Increased levels of nitrate in agricultural streams, for example, have been linked to excess fertilizer use and improper disposal of livestock wastes. In addition, nitrate in ground water poses serious health hazards to humans and farm animals (Sotomayor and Rice, 1996) and has led to excessive algae growth in both streams and lakes (Jacobs and Gilliam, 1985). Tree-based intercropping, or the growing of perennial trees amongst agricultural crops, is a common form of agroforestry employed in the tropics and shows promise as an environmentally-friendly yet profitable farming system in temperate regions (Gordon and Williams, 1991).

Intercropping has the potential to reduce nutrient inputs to watercourses from adjacent farm fields in a variety of ways. Trees can reduce run-off losses, soil erosion and can act as 'nutrient pumps' (Young, 1997): nutrients which are leached from upper soil horizons may be recycled from deeper soil horizons by tree roots (Nair, 1993; Ntayombya and Gordon, 1995), a function not performed by most agricultural crops, since they are generally shallow-rooted. Litterfall from trees also adds organic matter to the soil, which upon decomposition, releases nutrients that can be utilized by adjacent agronomic crops. The role of trees in performing the above nutrient transfer mechanism, which includes enhanced nitrification close to tree rows, has been well documented in both tropical (Young, 1997; Nair, 1993) and temperate regions (Thevathasan and Gordon, 1997; Gordon and Newman, 1997). The combination of trees and annual crops creates a dynamic agroecosystem that, when properly designed, can increase and diversify farm income, enhance wildlife habitat, abate soil erosion and nutrient loadings to waterways and protect watersheds from erosion (Gordon and Newman, 1997).

Black walnut (*Juglans nigra* L.) is one of the most commonly recommended tree species for tree-based intercropping in the temperate region. Its high value, aesthetic qualities, capacity for nut production, rapid growth potential and adaptability to management deems the species very suitable for this purpose (Gordon and Newman, 1997; Williams *et al.*, 1997). At the same time, black walnut is also well known for its allelopathic nature and it has long been observed that very few dicotyledonous plant species will grow beneath individuals or stands of walnut (Rice, 1984). Walnut produces the allelochemical juglone (5-hydroxy-1-4-naphthoquinone), which occurs in a water-soluble non-toxic form (hydroxy-juglone) in leaves, fruits, roots and other tissues (Rice, 1984). Hydroxy-juglone is washed into the soil by rain, where it is oxidized to juglone, inhibiting the germination and growth of many other plant species (Rice, 1984; Kimmins, 1997). It is also believed that juglone can inhibit the growth and activity of some beneficial soil microorganisms such as *Rhizobium japonicum* and *Frankia* spp. Isolate Ar 13 (Dawson *et al*. 1981; Dawson and Seymour, 1983; Rice, 1984).

Nitrification in soil is mainly mediated by autotrophic bacteria from two common genera *Nitrosomonas* and *Nitrobactor*. Even though reports exist on allelochemical inhibitory effects on *Nitrosomonas* and *Nitrobactor* populations in soils and in pure culture medium (Rice, 1964; Boughey et al., 1964; Munro, 1966 a,b; Boquel et al., 1970; Moore and Vaid, 1971), no studies to date have reported on the effects of juglone, specifically, on soil nitrification. Under field conditions, the fate and concentration of juglone in soil depends upon several factors such as soil moisture content, aeration, and the type of organism present (Schmidt, 1990). Schmidt (1990) suggested that certain soil bacteria could degrade juglone by using juglone as a sole source of carbon and energy, thereby keeping juglone concentrations in soil at low levels. Fisher (1978) also suggests that juglone persists in soils under wet moisture regimes and disappears with time as soils become drier or have drier moisture regimes.

In order to test the effect of juglone on soil nitrification, a field and a laboratory study were conducted in 1994 and 1995, respectively.

6.2 Materials and Methods

6.2.1 Field Procedures

Soil nitrate accumulation was measured in two separate experiments during the 1994 growing season within and outside of an 8-year-old poplar (*Populus* spp. clone DN 177) and a 60-year-old black walnut plantations in southern Ontario, Canada. The experimental site was in McGillvray Township, Middlesex County. The soil type was Huron sandy loam soil with good drainage properties. The site receives an average rainfall of 83 cm a year.

The experiment was a stratified randomized complete block design in which treatments (distance from the selected tree) were predetermined and replicated 3 times (Snedecor and Cochran, 1989). The poplar and black walnut plantations were 600 m apart (Figure 6.1). The spacing between trees in both plantations (ie., walnut: 12m; poplar: 6m) is common in tree-based intercropping systems in this region. In each plantation, three blocks (2m X 25m) were established and within each block, a 60-year-old walnut tree was selected in the walnut plantation and an 8-year-old poplar tree in the poplar plantation. Nitrate accumulation was measured in each block at 2, 6, 12 and 24 m from the selected trees (There was no tree, other than the selected ones, within the above distances). The first two distances (2 and 6 m) were located within the respective plantations whereas the other two were located outside (Figure 6.1). The area outside the respective plantations has not been under any type of agricultural cultivation for many years.

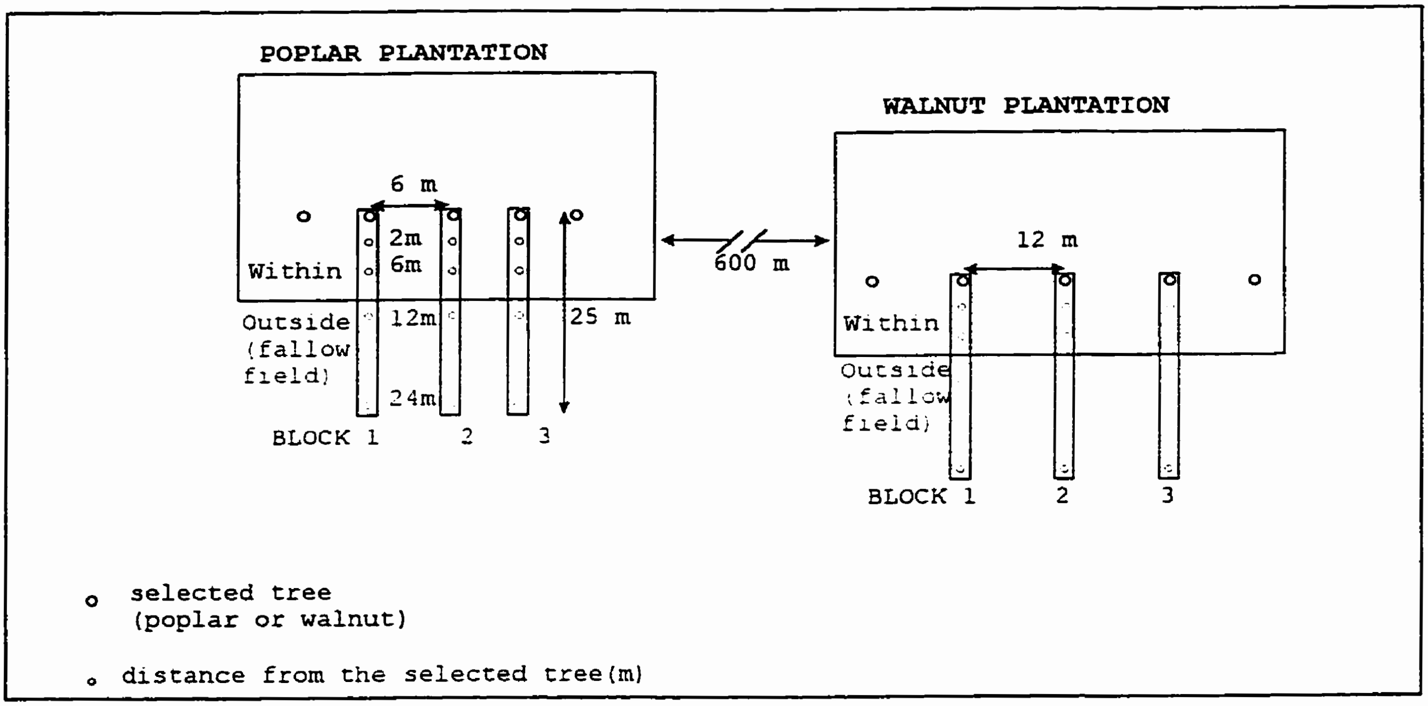

Figure 6.1. Diagrammatic representation of the field lay-out

6.2.2 Statistical analysis

The data was analysed using the Statistical Analysis System (SAS) package. Analysis of variance (ANOVA) was used to determine if there were any significant differences in treatments (tree species and distance from tree) based on F test statistics. In the presence of significant differences ($p < 0.05$), pair wise comparisons were made between means using Bonferoni t test at $p < 0.05$.

6.2.3 Nitrification

In situ field incubations using the buried polyethylene bag (bag thickness = 0.02 mm) method (Eno, 1960; Gordon *et al.*, 1987) were used to estimate nitrification. The method prevents leaching and plant uptake of mineral N but allows for the effects of natural diurnal temperature fluctuations since polyethylene of this thickness is permeable to CO_2 and O_2 but not to water; aerobic conditions are therefore maintained (Gordon *et al.*, 1987). In order to ensure adequate moisture for incubation, soil sampling was done two days after a rainfall event. The bags were incubated in the field for 70 days from 6 June to 18 August, 1994.

Soil was collected in both plantations using a soil auger from 0 to 15 cm depth at the above-mentioned distances. Soil was mixed well to ensure that it was free of woody debris. Following this procedure, 4 sub-samples (about 100 to 150 g of moist field soil), were prepared in polyethylene bags and the bags sealed with twist-ties. Two sub-samples were then buried at 15 cm below the soil surface at the specified distance for incubation and the other two sub-samples were placed in a cooler box with ice, transferred to the lab and kept frozen (2 to 4 months) at - 20^{o}C until extraction. Before freezing the sub-samples 50g of soil was removed from each sub-sample in the lab for standard carbon and nitrogen analysis. Replicates numbered three.

6.2.4 Laboratory procedures

Samples were allowed to thaw in order to re-incorporate the moisture inside the bags before extraction with 2 M KCl. Soil (20 g) was extracted with 60 ml of 2 M KCl in a 100 ml clear snap vial by shaking on a mechanical shaker for one hour (Keeney and Nelson, 1982). In order to determine the moisture content of the samples, another sub-sample of soil was taken from each sample and oven-dried at 105^{o}C for 48 to 72 hours. The calculated moisture contents were then used to convert mg L^{-1} nitrate concentration value to an oven dry soil weight basis (µg/100g soil). Extracts were analysed on a Technicon Autoanalyzer II system. Nitrate accumulation rates were determined by subtracting the unincubated sample values from the incubated sample values, and dividing by the number of days of incubation.

6.2.5 Laboratory Incubation and Methodology

A laboratory incubation experiment was also carried out in conjunction with field incubations. Stock juglone solution (10^{-3} M) was prepared by dissolving 0.174 g of juglone powder (98%, Aldrich Chemical Co., Milwaukee, Wisconsin) in 1L of distilled water, constantly stirring the solution at 25°C for 72 hours. This temperature was maintained throughout to prevent juglone precipitation. Juglone concentrations in soil were maintained at 0 (control),1, 2, 4, and 8 $\mu g\ g^{-1}$ dry soil (only at the beginning of the experiment) to bracket reported juglone levels in the soil under field conditions (e.g. De Scisciolo et al., 1990; Dawson and Seymour, 1983)

The soil for incubation was collected in the absence of any walnut trees although the same type of soil (sandy loam) was utilized. A soil moisture characteristic curve (desorption) was developed for the collected soil. Based on the desorption curve, soil moisture content at field capacity (15 kPa) was 17%. Soil was air-dried to a moisture content of 2.4% and then re-wetted with the prepared juglone solution (treatment application) and water on a weight basis to 17% moisture content, as described below. About 25 g of air dried soil (moisture content 2.4 %) was weighed into 100 mL clear snap vials. The soil was saturated with stock juglone solution diluted to specific volumes so that each treatment received the appropriate juglone concentration. Distilled water was then added to the inoculated soil on a weight basis to bring the soil to 17% moisture content, which was maintained throughout the incubation period. Incubation temperature was maintained at 25°C. Soil samples, inoculated with juglone, were placed in the incubation chamber on a weekly interval in order to obtain data from soils incubated for different lengths of time. All soil samples were then extracted with 2 M KCl solution for ammonium and nitrate determinations.

6.2.6 Statistical analysis (laboratory study)

The experiment was a randomized design with 3 replications. The data were analysed using the Statistical Analysis System (SAS) package. Analysis of variance (ANOVA) was used for each incubation period separately to determine if there were any significant differences in treatments (juglone levels: 0, 1, 2, 4 and 8 μg g^{-1} dry soil) based on F test statistics. Since there were no treatment differences, further analysis was performed with pre-planned contrast, between groups (e.g. juglone concentrations, 0 vs 1, 2, 4, 8 μg g^{-1} dry soil) were combined and compared for significance for each incubation period. However, the latter statistical procedure also suggested to reject the null hypothesis.

6.3 Results and Discussion

6.3.1 Field

Mean peak summer soil nitrate accumulation rates at 2, 6, 12 and 24 m from the selected walnut trees were 193, 133, 106 and 102 µg $100g^{-1}$ dry soil day^{-1}, respectively (Figure 6.2).

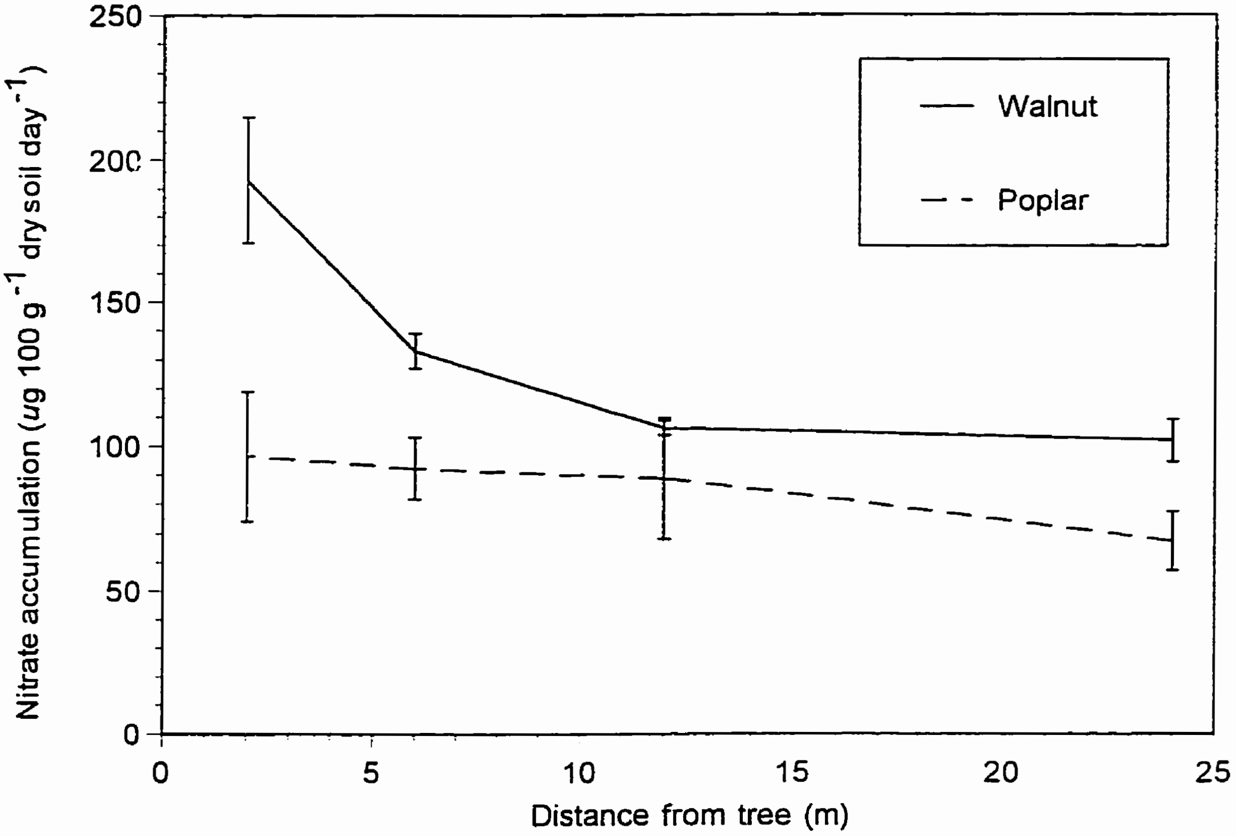

Figure 6.2. Nitrate accumulation rates within (2 and 6 m) and outside (12 and 24 m) walnut and poplar plantations during the summer of 1994 (Error bars that overlap indicate that associated values are not significant at $p < 0.05$).

The calculated mean nitrate accumulation rate within the plantation (163 μg $100g^{-1}$ dry soil day^{-1}) was significantly higher ($p < 0.05$) than that observed outside (104 μg $100g^{-1}$ dry soil day^{-1}). In the literature it has been suggested that juglone concentrations are always high close to mature walnut trees and decline with distance away from the tree (Rice, 1984; Kimmins, 1997). In this study, if juglone had any inhibitory effects on nitrification, nitrate accumulation within the plantation should have been much lower than that outside. However, the opposite was observed. Further, nitrate accumulation rates within the walnut plantation also appear to be equivalent to those reported for other temperate undisturbed forests (Gordon, 1986), suggesting no possible inhibitory effects of juglone on nitrification at the tree density investigated.

The presence of high soil organic matter content (carbon), soil total N and soil moisture within the plantation (Table 6.1) may have contributed to the higher nitrate accumulation rates found there compared to those found outside. The literature further suggests that when nitrification is inhibited by an allelochemical, it generally results in ammonium ion accumulation (Rice, 1984; Rice and Pancholy, 1973; 1974). From Table 6.2 and Figure 6.3, it is evident that

Table 6.1. Variation in soil organic carbon, total nitrogen and moisture concentration (MC) under walnut and poplar plantations.

	Location					
	Within Plantation			Outside Plantation		
	Organic C (%)	Total N (%)	MC (%)	Organic C (%)	Total N (%)	MC (%)
Walnut	7.33^a	0.63^a	23^a	3.12^b	0.22^b	18^c
Poplar	4.52^b	0.42^b	16^b	2.51^a	0.21^b	15^b

[a,b,c] Values for similar soil parameters followed by the same letter are not significantly different at $p < 0.05$, within column or row.

Table 6.2. Accumulated ammonium and nitrate from incubated samples[1].

	Location			
	Within Plantation		Outside Plantation	
	NH_4^+ ($\mu g\ 100g^{-1}$ dry soil)	NO_3^- ($\mu g\ 100g^{-1}$ dry soil)	NH_4^+ ($\mu g\ 100g^{-1}$ dry soil)	NO_3^- ($\mu g\ 100g^{-1}$ dry soil)
Walnut	708^a	15659^a	513^a	15032^a
Poplar	478^b	10988^b	466^{ab}	9173^b

[a,b,] Values for similar soil parameters followed by the same letter are not significantly different at $p < 0.05$, within column or row.

[1] Note: Figure 6.2 denotes rate of accumulation - the above values are averages of accumulated inorganic nitrogen.

such a condition did not exist in this study. This precludes the possibility of any nitrification inhibition by juglone in the walnut plantation. Figure 6.3 also suggests that for walnut, at 12 and 24 m from the tree (outside the plantation) ammonium accumulation rates were -1.53 and 1.19 µg $100g^{-1}$ dry soil day^{-1} respectively, which were higher than that observed within the walnut plantation at 2 and 6 m. The low rate of nitrate accumulation outside the walnut plantation (Figure 6.2) might have resulted in a higher rate of ammonium accumulation outside the walnut plantation. However, it should be noted that there was no absolute increase in ammonium concentration or accumulation outside the walnut plantation (Table 6.2).

Nitrate accumulation rates during the same period of time and at the same distances from the selected poplar trees were 97, 92, 89 and 67 µg $100g^{-1}$ dry soil day^{-1} (Figure 6.2).

The calculated mean nitrification rates within and outside the poplar plantation were only 95 and 78 µg $100g^{-1}$ dry soil day^{-1} respectively. These are substantially lower ($p < 0.05$) than those reported under walnut (Figure 6.2). This is possibly due to increased soil organic matter (carbon) and soil moisture, which were significantly higher ($p < 0.05$) within and outside the walnut plantation when compared with values (within and outside) from the poplar plantation (Table 6.1). Within the plantations, soil total N was also greater in soils in the walnut plantation compared to soils in the poplar plantation. Collectively the data presented in Figure 6.2 tend to indicate that inhibition of nitrification by juglone is highly unlikely.

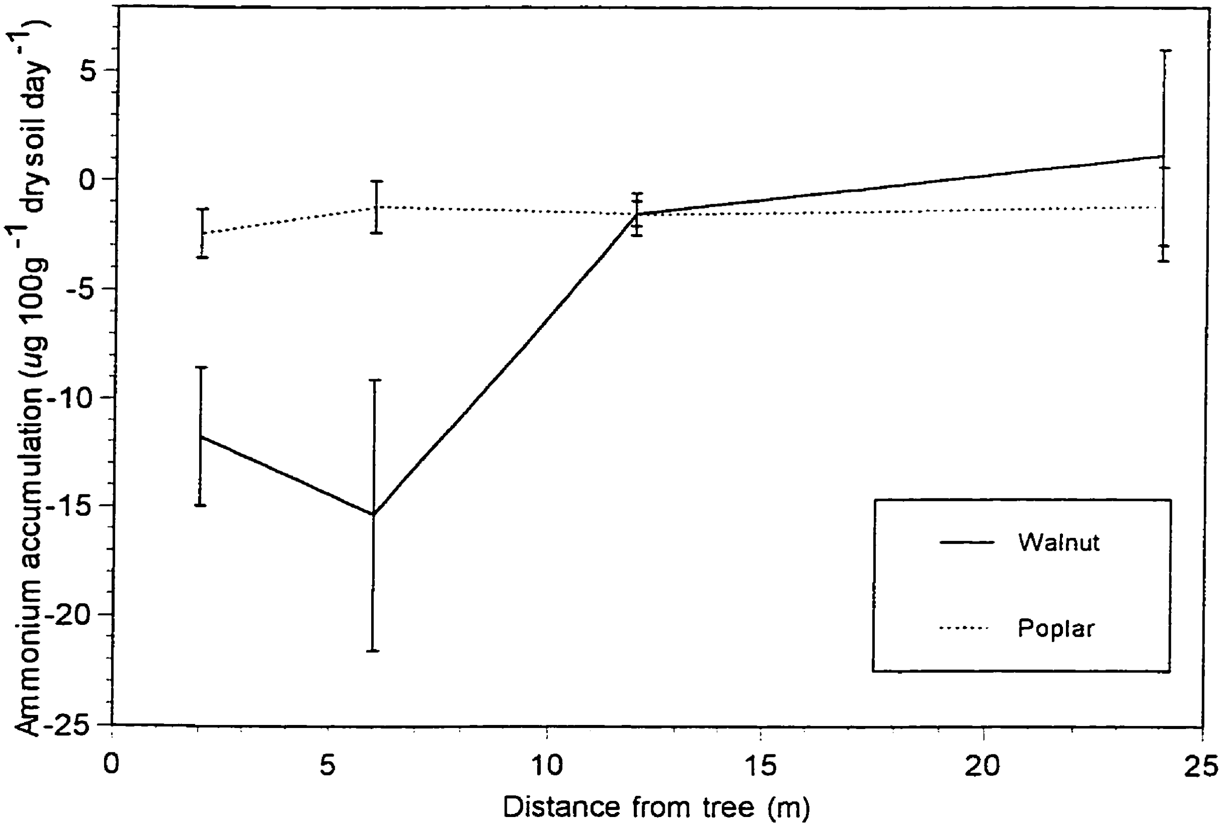

Figure 6.3. Ammonium accumulation rates within (2 and 6 m) and outside (12 and 24 m) walnut and poplar plantations during the summer of 1994 (Error bars that overlap indicate that associated values are not significant at $p < 0.05$).

The concentration of juglone in soil depends upon several biotic and abiotic soil factors (i.e. soil moisture, soil pH, texture, soil organic matter, types of juglone degrading soil bacteria present, time of the year and tree age) (Marking, 1970; Rietveld, 1981; Dalton *et al.*,1983; Rettenmaier *et al.*, 1983; Rice, 1984; Ponder, 1987; Schmidt, 1988; De Scisciolo *et al.*, 1990). In this study juglone was not extracted from the field soil. A common method used for the extraction of juglone is chloroform-extraction (De Scisciolo *et al.*, 1990). A review of the literature indicated that chloroform-extractable juglone concentrations under 14-year-old walnut plantation varied from 1.88 µg/g dry soil to 3.95 µg/g dry soil(Ponder and Tadros, 1985; De scisciolo *et al.*, 1990). However, it has also been established that under field conditions the concentration of water extractable juglone is the determining factor in the inhibition of microbial growth or plant growth. Water extractable juglone accounts for less than 1% of chloroform-extractable juglone concentration (De Scisciolo *et al.*, 1990). Therefore, extraction of juglone from soil using chloroform does not provide any information on the levels of juglone available to microbes or for plants under field conditions.

However, inhibitory effects of water extractable juglone on microbial populations (i.e. *Rhizobium japonicum strain 71* and *Frankia* spp. ArI3) may be seen at juglone concentrations greater than 10^{-6} M (Dawson *et al.*, 1981). For example, Dawson and Seymour (1983) reported that a concentration of 10^{-3} M juglone absolutely inhibited the growth *in vitro* of a *Frankia* isolate from root nodules of red alder (*Alnus rubra* L.) and of *Rhizobium japonicum* strain 71. Given the annual precipitation and coarse nature of the soil under study, it is unlikely that water soluble juglone is responsible for the patterns of field nitrification observed.

6.3.2 Laboratory

Laboratory incubation results are presented in Figures 4 and 5. These results suggest that juglone did not inhibit soil nitrification during the six-week incubation period (Figure 6.4). Any inhibitory effect of juglone on soil nitrification would have resulted in ammonium ion accumulation during the incubation period. However, from Figure 6.5, it is evident that this did not happen. There was no statistical difference ($p > 0.05$) in nitrate or ammonium concentration between any treatments at any stage of the incubation period.

Recorded soil juglone chloroform extracted concentrations in the literature range from 1.88 to 3.95 µg/g dry soil (Ponder and Tadros, 1985; Dawson and Seymour, 1983; De Scisciolo et al., 1990), likely indicating very low levels of water-extractable juglone. Under normal field conditions juglone accumulation above 3.95 µg/g dry soil is very unlikely (De Scisciolo et al., 1990). In this laboratory incubation study the highest concentration of juglone used was 8 µg g^{-1} dry soil. Even at this high concentration no significant inhibition of nitrification was observed (Figure 6.4).

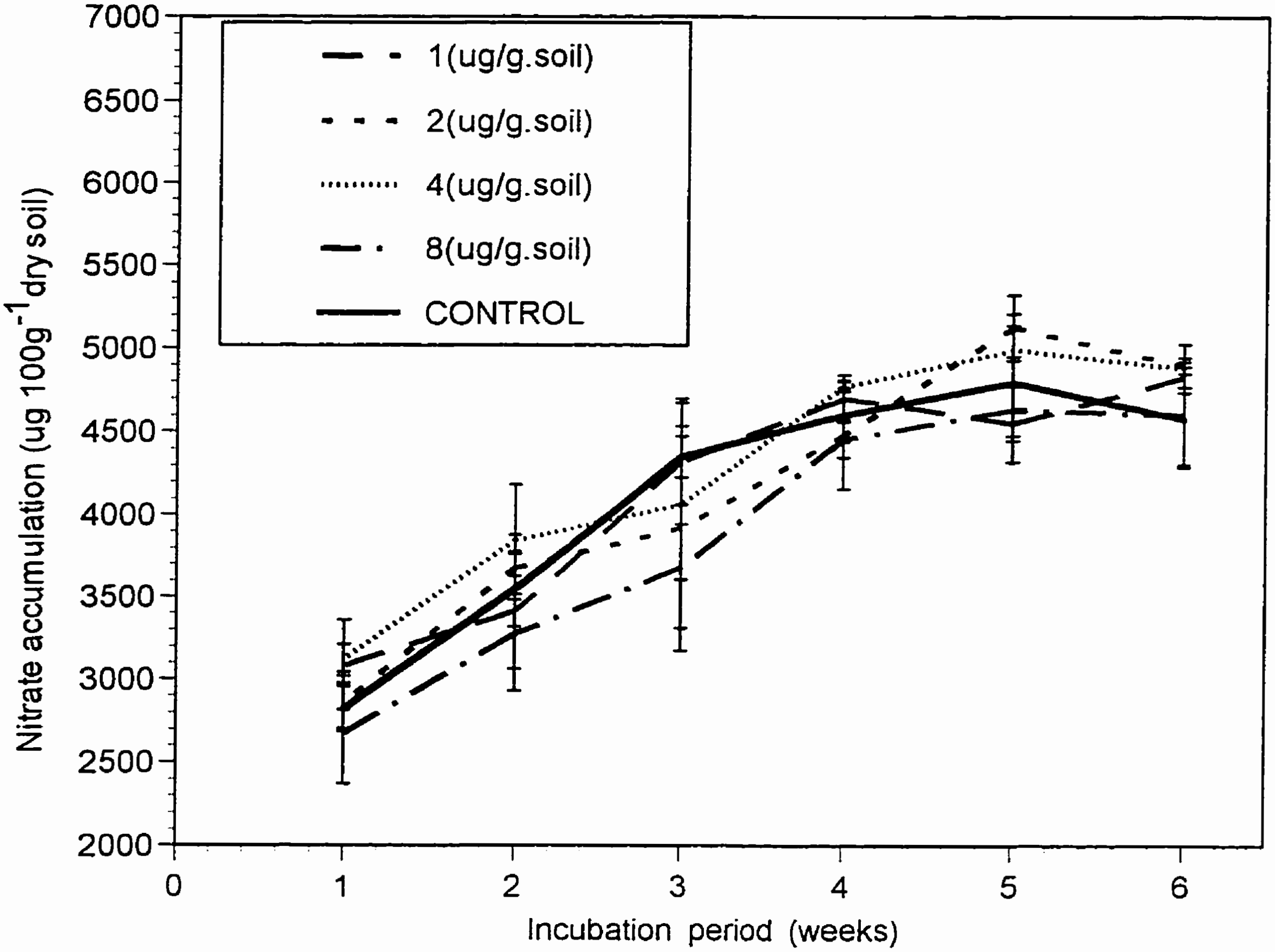

Figure 6.4. Nitrate accumulation in soil incubated in the presence of different concentrations of juglone for six weeks (Error bars that overlap indicate that associated values are not significant at $p < 0.05$).

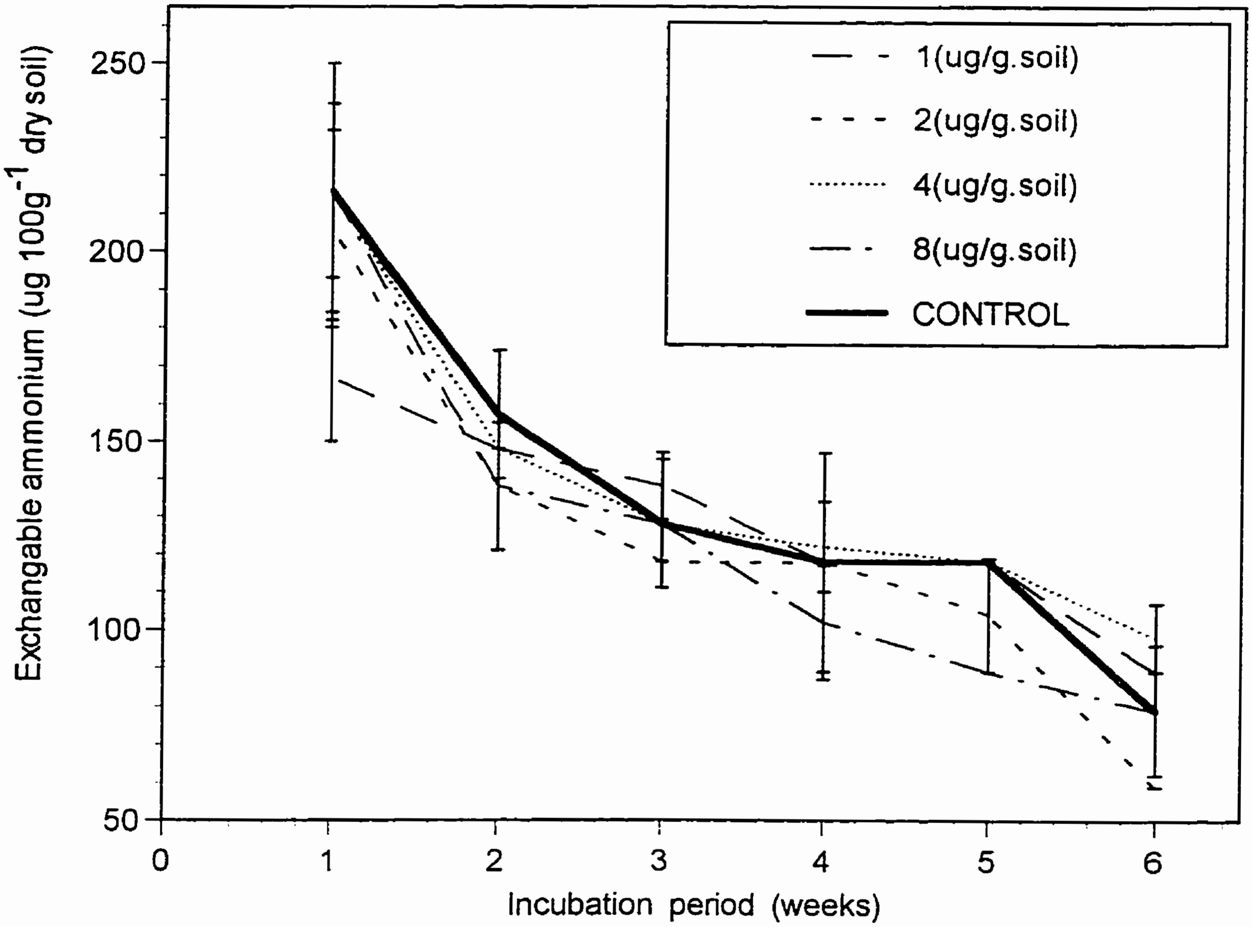

Figure 6.5. Ammonium accumulation in soil incubated in the presence of different concentrations of juglone for six weeks (Error bars that overlap indicate that associated values are not significant at $p < 0.05$).

6.4. Conclusion

If juglone inhibits nitrification in soils, nitrate availability would be limited under walnut-based intercropping systems. However, both the field and laboratory incubation results from this study indicate that juglone does not inhibit ammonification or nitrification in soils. Similar type of investigation should be further extended to test and identify other suspected allelochemicals, under different types of vegetation, which are often described as soil nitrification inhibitors. Such studies will certainly help in the long term design and development of viable tree-based intercropping systems in North America.

7. General Discussion and Conclusions

Among the various alternative agricultural practices currently under consideration in southern Ontario capable of curbing further environmental degradation resulting from traditional practices, tree-based intercropping systems are considered to be a viable option (Gordon and Williams, 1991; Gordon and Newman, 1997). The ameliorative effects of trees in relation to soil fertility, productivity and nutrient cycling, their filtering ability and ability to modify microclimate can be exploited, especially in the context of developing tree-based intercropping systems on both marginal and prime agricultural lands.

The success of intercropping depends mainly on the ability of the system components to maximize resource utilization while at the same time maintaining 'complementary' interactions between them. When this occurs, productivity per unit land area is often enhanced resulting in higher economic returns (Ong and Huxley, 1996; Young, 1997). When components of an intercropping system are very different (e.g. woody and non-woody), the demand for limited resources is staggered in space and time (Willey, 1979; Huxley, 1985; Nair, 1993), and resource capture and productivity per unit land area may be maximized. However, before any recommendations can be made to the southern Ontario farming community, extensive research is required to understand the benefits and the shortfalls of tree-based intercropping systems in this region. Therefore, the objectives of this study were to 1) quantitatively evaluate a poplar-barley intercropping system in relation to utilization of the limited resources; 2) identify and quantitatively evaluate 'complementary' interactions between the tree and the crop component, if any; 3) construct a preliminary N flow model for a poplar-barley intercropping system 4) quantitatively evaluate the effects of juglone (5-hydroxy 1,4 napthoquinone) on soil N mineralization. The last is also important since, although this thesis concentrated on poplar as a potential intercropping species, walnut has also often been suggested as a viable intercropping species.

In a pot experiment of 120 days duration, within the three levels of moisture and nitrogen tested, barley intercropped with young poplar plants did not significantly differ from monocropped barley with respect to final plant height, above ground biomass and final grain yield. This suggests that under the tested conditions, poplar did not compete severely for moisture or N with intercropped barley. The observed spatial arrangement of the two root systems in this study suggests that they did not interact with each other and may have utilized resources from two different layers in the pot thus reducing competition for moisture and N between the crop and tree component. Intercropped young poplar also did not significantly differ from monocropped poplar with respect to diameter increment, leaf area and total leaf N. Therefore, the hypothesis examined in this study is corroborated, in that the inherent characteristics of hybrid poplar such as deep rooting ability and drought tolerance can result in 'complementary' interactions with the crop component and reduce 'competitive' interactions. When recommendations are made towards the selection of tree species for tree-based intercropping systems in southern Ontario, importance should be given to the inherent characteristics of the tree species. Characters or traits such as shallow or lateral rooting ability and wide crown structure should be avoided. Selection of components to maximize resource capture is therefore an important management strategy that should be considered for this region or for any regions in the temperate zone.

Poplar leaf total N concentration in the intercropped treatment was above 2 % and the C:N ratio was in the vicinity of 20:1 or less. The above leaf N concentration is comparable with leaf N concentrations found in tropical legume tree species. As poplar is deciduous, addition of leaf biomass may significantly affect the N nutrient status in soil in an poplar-based intercropped system. This aspect was further investigated and tested in the field.

In field experiment 1, poplar leaves were removed during the 1993 and 1994 fall seasons and in experiment 2 leaves were not removed. The results suggest that poplar leaf biomass distribution in the field had a distinct pattern (Table 4.1). It also appears that different poplar leaf biomass inputs across the field created three distinct regions with respect to soil nitrate accumulation and soil organic C. Based on the abundance of these resource pools, the intercropped field can be divided into three regions: the area close to the poplar tree row (0-2.5 m on either side), middle of the crop alley (2.5-8.0 m from the tree row), and away from the middle of the crop alley (8.0-15.0 m). Observed mean soil nitrate production in the above regions during 1993 (June to August) was 73.1, 41.0 and 34.0 $\mu g\ 100g^{-1}$ dry soil day^{-1} respectively. In 1995, as a result of the removal of poplar leaves from the field for two consecutive years (1993 and 1994), nitrate production values were decreased to 17.6, -2.8 and -1.7 $\mu g\ 100g^{-1}$ dry soil day^{-1} in the same regions, respectively. However, in experiment 2 (June to August 1995) mean nitrate production in the same regions was 109.4, 15.4 and 5.7 $\mu g\ 100g^{-1}$ dry soil day^{-1} respectively. It appears that the addition of poplar leaves significantly ($p < 0.05$) affected nitrate production rates, especially in regions close to the tree row and middle of the crop alley. It also appears that the major portion of nitrate was released from the labile organic pool (recently added poplar leaf biomass) rather than from the recalcitrant organic pool, since the removal of poplar leaves from the field did not significantly change the soil organic carbon pool over the three-year period. Rapid decomposition of recently added poplar leaf mulch and possible release of N was also reported by Kotey (1996) for the same site (different experiment) during the same period of time.

Soil organic carbon (SOC) did not significantly ($p > 0.05$) change in these regions over a period of three years in experiment 1 or 2. The mean SOC in the above regions was 3.25, 2.32 and 2.50% respectively in experiment 1 and 3.46, 2.56 and 2.38% respectively in experiment 2. However, it should be emphasized that the higher rate of poplar leaf biomass addition close to the tree row (1000kg C $ha^{-1}year^{-1}$) over a period of 5 to 6 years has resulted in about 1 % higher SOC close to the tree row. Such build-up of SOC in the cropping area may reduce soil erosion and help maintain soil fertility and stability. In a separate experiment on the same site, Price and Gordon (1997) have also reported an increase in earthworm populations close to the poplar tree row. They concluded that the availability of higher soil organic matter, higher soil moisture and cooler temperatures close to the tree row provided a conducive environment for earthworm population development. It can also be speculated that a higher number of earthworms close to the tree row could have aided in the rapid breakdown of poplar leaves and release of nitrate as observed in this study.

It also appears that the difference in resource pools across the crop alley affected barley growth and development. Final mean barley above ground biomass (AGB) in the above regions were 517, 491 and 490 $g.m^{-2}$ in 1993 and 450, 464 and 468 $g.m^{-2}$ in 1995 respectively. Barley AGB closer to the tree region in 1993 was significantly higher ($p < 0.05$) than the recorded AGB in the other regions. However, there was no significant difference ($p > 0.05$) in barley AGB recorded in 1995. A similar trend was noted with respect to barley grain total N concentration. In 1993, grain N concentrations in these regions were 2.52, 1.69 and 1.65 %, respectively, and in 1995 the recorded values were 1.69, 1.44 and 1.44 %, respectively. Removal of poplar leaves from the field for two years resulted in a significant reduction in nitrate accumulation across the crop alley and this may have affected nitrate uptake by barley, causing a reduction in barley AGB and grain total N concentration. Barley yield (grain) was not measured directly but the yield should be about 37 % of the recorded barley AGB for this variety of barley. Therefore, it is likely that a similar trend exists with respect to barley grain yield across the crop alley.

It has been suggested in the literature that some of the non-uptake effects such as microbial mineralization, leaching, nutrient addition in the form of throughfall and litter input, can also influence available resource pool significantly (Chapin, 1980; Goldberg, 1990). Competitive interactions with associated crops may be reduced significantly if these non-uptake effects are maintained in any production system (Ong and Huxley, 1996). In a tree-based intercropping system, leaching losses are often less as trees have the ability to utilize nitrates and other nutrients leached below the cropping rooting zone (Young, 1997). Therefore, as long as nutrient additions from the tree in the form of throughfall, stemflow and litter input are maintained, microbial mineralization should proceed unchecked resulting in more nutrient availability for associated intercrops. This scenario can ideally reduce competition for limited nutrients (Ong and Huxley, 1996; Young, 1997)(see chapter 5).

The transfer of nutrients from trees to crops generally takes place through above-and below-ground litter inputs (Young, 1997). Results from the 1995 field season suggest that two consecutive years of poplar leaf removal from the field may have resulted in some form of N competition with a subsequent negative impact on barley AGB and grain N concentration. The above hypothesis could have been quantitatively assessed if poplar trees had been injected or fertilized with labeled N in 1992. The amount of N transfer from decomposing leaves (fall 1992 leaves) to barley during 1993 summer could also have been calculated. However, it should be emphasized that the ameliorative effects of trees in a tree-based intercropping system need to be maintained, if not improved, through proper design and management practices. This may help to delay competitive interactions that may develop when trees grow larger.

A linear-quadratic function was developed to understand how some of the dependent variables such as poplar leaf biomass distribution and soil organic carbon build-up would vary across the crop alley with tree age. In this study, within the experimental period (3 years), the above approach was successful in generating numbers which did not deviate more than 10% from the measured experimental data (Appendix 2). However, it is cautioned here that the only biological variable that was taken into consideration in building the 3D model in this study was tree age. As the tree canopy becomes larger it will likely affect soil temperature and moisture in the regions considered in this study. This in turn can significantly alter soil organic carbon build-up. Soil temperature and soil moisture also have to be included as variables along with tree age in the model for long term predictive capability and understanding of these complementary interactions.

Nevertheless, poplar leaf biomass distribution will depend mainly on tree height and this variable was linearly correlated ($r^2 = 0.99$, data not reported in this thesis) with age. Therefore, the model developed for poplar leaf biomass distribution in this study may hold forth for a long period of time, assuming no major changes in weather or wind patterns. This can be validated in the field during the coming years. It must be recognized that the model developed in this study is only a preliminary approach to describe a very complex system. However, in young tree-based intercropping systems, interactions similar to those observed in this study may be experienced. Under those circumstances building models using piece-wise linear-quadratic functions and a linear least squares fitting criterion, as adopted in this study, may be useful to understand and predict short-term tree-crop interactions.

Another tree species recommended for tree-based intercropping systems in southern Ontario is black walnut (Williams *et al.*, 1997). Juglone (5-hydroxy-1,4 napthoquinone) is the allelochemical produced by black walnut trees and it is believed that this chemical can inhibit the growth and activity of some beneficial soil microorganisms (Dawson *et al.* 1981; Dawson and Seymour, 1983). Nitrification in soil is mainly mediated by autotrophic bacteria from two common genera *Nitrosomonas* and *Nitrobactor*. Even though reports exist on allelochemical inhibitory effects on *Nitrosomonas* and *Nitrobactor* populations in soils and in pure culture medium (Boquel *et al.*, 1970; Moore and Vaid, 1971), no studies to date have reported on the effects of juglone, specifically, on soil nitrification. One of the main objectives of this study was to quantitatively measure nitrate accumulation across the crop alley as influenced by the tree component. Therefore, as walnut is also a recommended tree species for this region, a series of experiments was conducted in the field and in the laboratory to test the effects of juglone on ammonification and nitrification. These studies were considered important because if juglone inhibits nitrification in soils, nitrate availability may be limited under walnut based intercropping systems. However, neither the field nor the laboratory incubation results suggest that juglone inhibits ammonification or nitrification in soils. This information is important for the promotion of black walnut-based intercropping systems in southern Ontario, which may result in economic benefits to farmers. Similar type of investigation should be extended to test and identify other suspected allelochemicals, under different types of vegetation, which are often described as soil nitrification inhibitors.

The complexity of agroforestry systems (Leyton, 1983; Huxley, 1985; Buck, 1986) often results in constant changes in spatial patterns, as tree growth proceeds in both horizontal and vertical dimensions (Borsa, 1991). As the temporal dimensions of the system keep changing, the patterns of interactions are also likely to be changed. Therefore, the beneficial interactions observed in this study may also change over time as tree canopies becomes larger and/or when lateral tree roots are further extended into the rooting zone of the cropping alley. This may result in many competitive interactions with respect to light, moisture and nutrients. The ameliorative effects of poplar may also get masked as a result of these possible competitive interactions. However, when competitive interactions are observed, alternative management strategies may be considered so that competitive interactions between components are delayed, reduced or completely eliminated from the system. Agroforestry research in the tropics has shown that the proper selection of system components and the adoption of proper management techniques are the two most important processes that should be considered while designing agroforestry systems to reduce or avoid competitive interactions among components (Wood, 1990). Willey (1979) also suggests that interactions between components in an intercropping scenario could be altered or modified by variety or species selection and through additional management techniques.

Several alternative management strategies could be considered for poplar-based intercropping systems in southern Ontario to maintain the viability and sustainability of these systems. However, the effectiveness of any alternative management strategy requires testing in the field on a long term basis and to be scientifically proven before any recommendations are made. The following alternative management strategies are suggested as worthy of future research:

1. A strategy that could be adopted in this region is the planting of fast growing tree species like poplar in concert with more valuable, but slow growing hardwood tree species in alternate rows in order to maximize the beneficial effects by poplar as observed in this study. This will also reduce shading effects and delay crown closure. However, more research is needed in these areas. More knowledge is also needed on the effects of shading on crop productivity. Closure of stomata during noon or early afternoon hours is an adaptive mechanism plants often exhibit to overcome temporary water stress (Sallisbarry and Ross, 1992). Therefore, shading effects by poplar trees or any other tree species for this matter, might not detrimentally affect the crop productivity if root competition is kept low, especially in C4 plants. This area needs more research.
2. Root competition can be significantly reduced if tree roots and crop roots utilize nutrients and water from two different distinct layers of the soil

profile. This could be achieved by pruning tree lateral roots (if any) in the first 20 to 30 cm of the soil profile. The effects of tree lateral root pruning could be tested by comparing the effectiveness of different root pruning strategies with permanently placed root barriers (e.g. galvanized tin sheets), using intercrop growth performance and yield as indicators. The above experimental design will also be helpful to assess the degree of competition brought about by tree shading versus tree root competition.

3. Tree root distribution, not only for poplar but also for all other tree species that are recommended for this region for intercropping, needs to be mapped on a continuous basis. This will also give a better understanding with respect to tree root pruning practices.
4. Short term as well as long term economic cost and benefits need to be evaluated for these agroforestry practices in southern Ontario. As the trees become larger, a shift from field crops to more shade tolerant intercrops needs to be considered. These types of planning strategies will help to maintain economically profitable as well as environmentally sound agricultural systems in southern Ontario.

As we step into the next millennium, a change is warranted in current agricultural practices and land use options so that priority is given to the stewardship of soil and water resources. The results from this study with poplar have shown much promise in this regard. However, the long term viability and sustainability of tree-based intercropping systems needs to be examined before recommendations on the use of these systems can be made to the farmers of southern Ontario. Results from this study, in combination with the above suggested areas where further research is warranted, will therefore be useful in the design and development of such systems.

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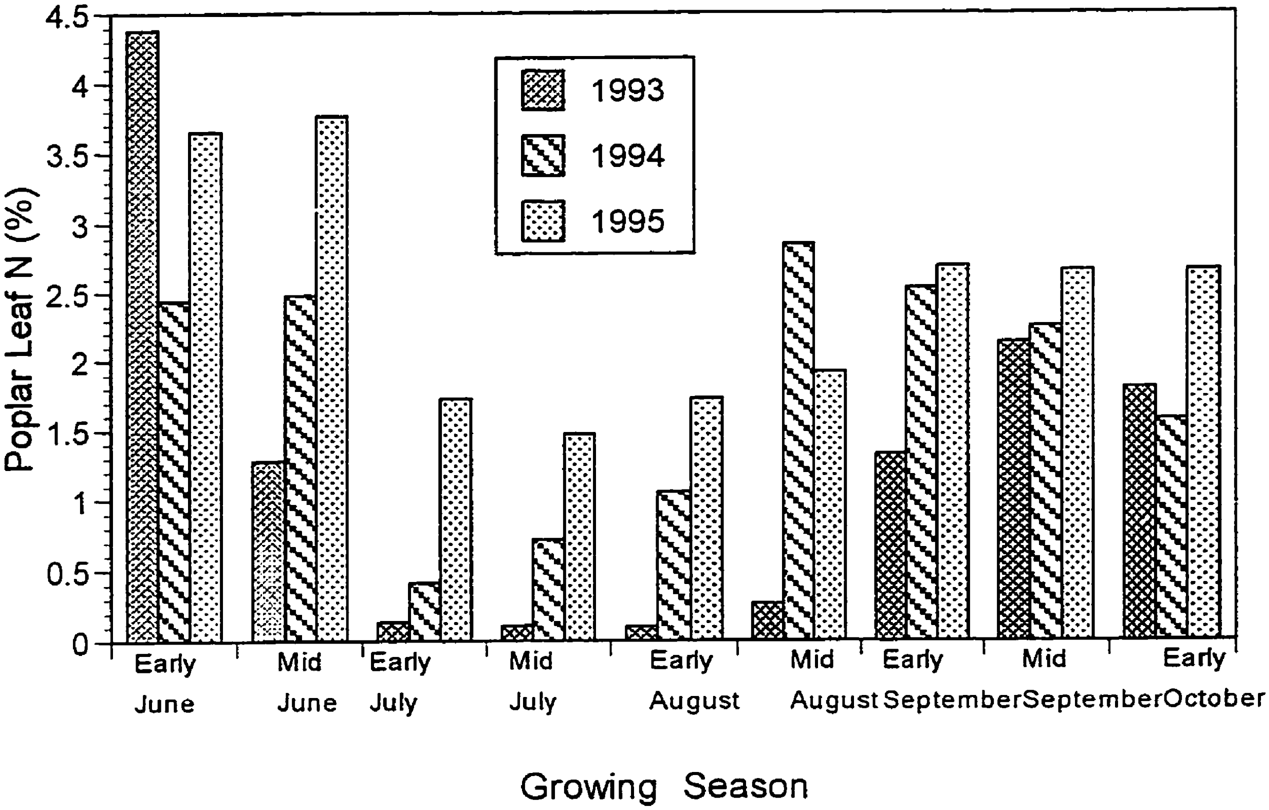
Appendix 1.

Seasonal changes in poplar foliar N concentration during the study period 1993 to 1995.



Appendix 2.

Three Dimensional Models of poplar leaf biomass distribution and soil carbon variation.

2D Model Development

A 2D model was initially developed for the experimental data by identifying regions showing similar behavior, utilizing piece-wise linear-quadratic functions and a linear least squares fitting criteria. It is generally futile to attempt to determine a single polynomial to approximate the complete variation in the experimental data, although, if such a function does exist, it would greatly simplify the whole process of building a 3D model. It is important to recognize that piecewise linear-quadratic functions are able to capture the behavior of experimental data with fair degree of accuracy.

3D Model Development - Methodology

A form for the 3D model was assumed. In this thesis, a 3D model of the following form (from Golub and Van Loan, 1983; Paige, 1994) was found to give satisfactory

Appendix 2. Continued.

results:

$$z = a_0 + a_1 x \; y^{k1} + a_2 x^2 y^{k2}$$

where,

x = Independent variable 1 (the distance from trees or the selected band of interest, for example, the intercropped field was divided into 3 bands: closer to the tree, middle of the crop alley and further away from the middle of the crop alley)

y = Independent variable 2 (age of trees)

z = The dependent variables (poplar leaf biomass percentage or soil organic carbon variation)

a_0, a_1, a_2 = coefficients to be determined

k1,k2 = Pre determined parameters (constants)

Note that when y is constant, z, varies quadratically with respect to x. Therefore, for a given age (y), if distance (x), is increased in small distinct quantity

Appendix 2. Continued.

uniformly it will result in a series of values for z (dependent variable). Once the above process was completed for the first year (1993), it was repeated for the other two years (1994 and 1995). This method was adopted to generate sufficient amount of model data for each region of interest (specific regions across the intercropped field, as indicated above in independent variable 1), over a period of time (age), to build the 3D models. The resulting data was then arranged in a matrix form to solve a least squares problem so that the solution yields values for a_0, a_1, and a_2 coefficients. These coefficients were calculated for each region of interest separately because the experimental data suggested a similar type of behaviour in those regions (see Table). Parameters k1 and k2, were in the range of 0 to 2. For an explicit mathematical workout or methodology the reader is referred to Golub and Van Loan(1983) and Paige (1994).

Appendix 2. Continued.

Parameters and coefficients for the respective 3D models developed for poplar leaf biomass distribution and soil organic carbon distribution.

Dependent variable	Region of interest (Band No.)	Range of Band (m)	a_0	a_1	a_2	k1	k2
Poplar leaf	1	0.0-2.5	1.1319	0.2024	-2.4408	-1.5	-0.5
leaf biomass	2	2.5-6.0	0.6680	0.0959	-0.9401	-1.5	-0.5
distribution	3	6.0-15.0	0.3691	0.0498	-0.3714	-1.5	-0.5
(%)							
Soil	1	0.0-4.0	0.9588	0.6409	-5.4387	1.0	0.0
organic	2	4.0-11.0	0.6758	0.1280	-0.1485	1.0	0.0
carbon (%)	3	11.0-15.0	0.5566	0.1109	0.0409	1.0	0.0

Appendix 2. Continued.

Descriptions on the 3D models and a few individually worked out examples.

Scaling:

In order to enhance the accuracy of the least squares solution, it is important that the coefficient matrix be well conditioned, i.e., the numerical values should preferably be close to one. This is normally accomplished through scaling, and in this thesis the following scaling factors are utilized; namely,

Age Offset:

This is a quantity, which must be subtracted from the actual age of trees.

Scaling Factors:

The experimental data, distance (or band representing distance), and the actual age minus the age offset are divided by the corresponding scaling factors in order to condition the coefficient matrix. It is important to remember to supply data to the 3D model in scaled down form and scale up the results derived from the 3D model. This process will be demonstrated in an example.

Appendix 2. Continued.

Experimental Data showing percentage poplar leaf biomass distribution for 1993, 1994 and 1995.

Band	Distance (m)	Year 1993	Year 1994	Year 1995
1	0.0-2.5	82	80	73.6
2	2.5-6.0	16	18	23.2
3	6.0-15.0	2.6	2.0	3.3

Scaling factors for age, band number and measurement used in developing a 3D model for poplar leaf biomass distribution.

Offset for Age	Scaling factors Age	Scaling factors Band	Scaling factors Measurement
1992	3.0	3.0	82.0

Appendix 2. Continued.

Worked Numerical Examples:

The sections to follow will demonstrate two examples to calculate the leaf biomass distribution. These examples, along with the appropriate coefficients and parameters, indicated in the above table must be used to determine other experimental quantities.

Example-1:

Determining the leaf mass distribution on band-1 (0.0-2.5 m) for 1994, and compare the results of the 3D model with that of experimental data.

Scaled age of trees: (1994-1992)/3.0 = 0.667

Scaled band: 1/3 = 0.333

Leaf biomass distribution is computed from the following equation:

$$z = a_0 + a_1 x \ y^{k1} + a_2 x^2 y^{k2}$$

a_0, a_1, a_2, k1 and k2 are obtained from Table 7 for the dependent variable poplar leaf biomass distribution, therefore;

Appendix 2. Continued.

$$z = [\,1.1319 + 0.2024 \;{}^{*}0.333 \;{}^{*}0.667^{-1.5} + (-2.4408) \;{}^{*}0.333^{2}{}^{*}0.667^{-0.5})]{}^{*}82.0$$

$$= 75.8 \text{ units}$$

Experimental Measurement = 80.0 units

% Error = (75.8 - 80.0)/80.0 = -5.2%

Example-2:

Project the leaf biomass distribution in the year 1998, on band 3 (6.0-15.0 m).

Scaled age of trees: (1998-1992)/3.0 = 2.0

Scaled band: 3.0/3.0 = 1.0

Leaf biomass distribution is computed from the following equation:

$$z = [\,0.3691 + 0.0498 \;{}^{*}1.0 \;{}^{*}2.0^{-1.5} + (-0.3714) \;{}^{*}1.0^{2}{}^{*}2.0^{-0.5})]{}^{*}82.0$$

$$= 10.2 \text{ units}$$

Assuming an error bandwidth of ±5%, the leaf mass distribution can be anywhere from 10.7 to 9.7 units.

Scaling factors used in developing 3D models for soil carbon distribution (leaf not removed experiment).

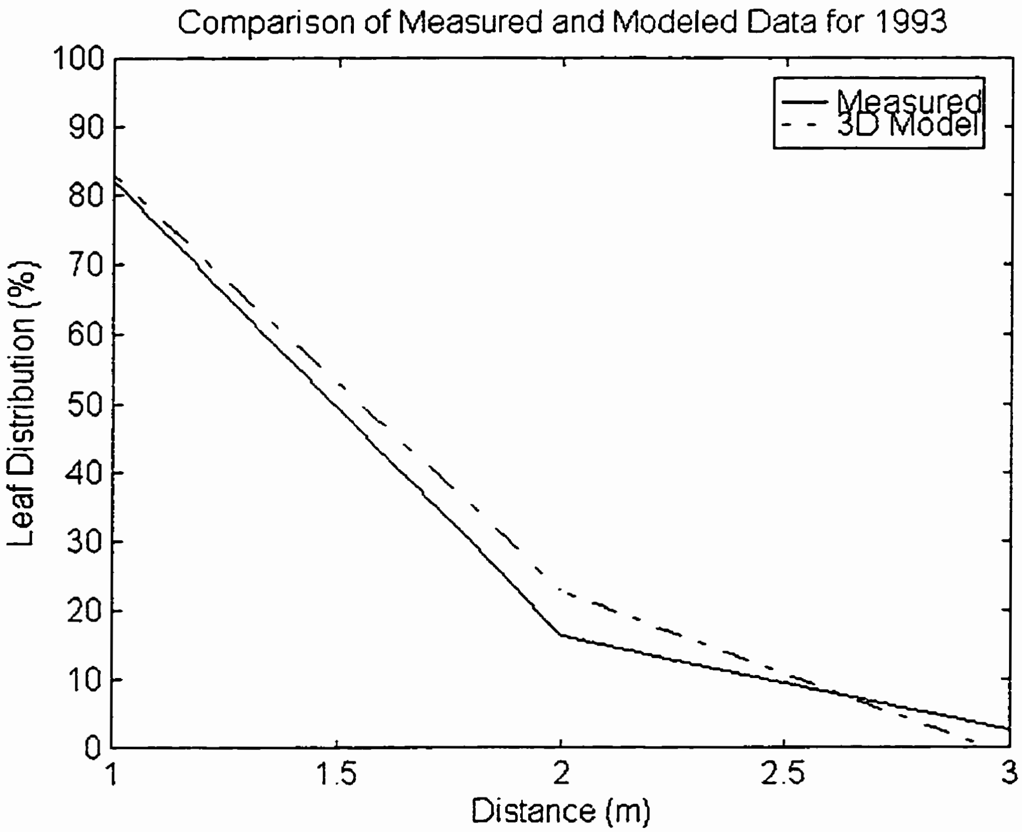
Dependent variable	off set for age	Age	Distance	Measurements
Soil carbon variation	1992	3.0	15.0	3.6066

Appendix 2. Continued.

Modelled and Experimental Plots for the selected dependent variables

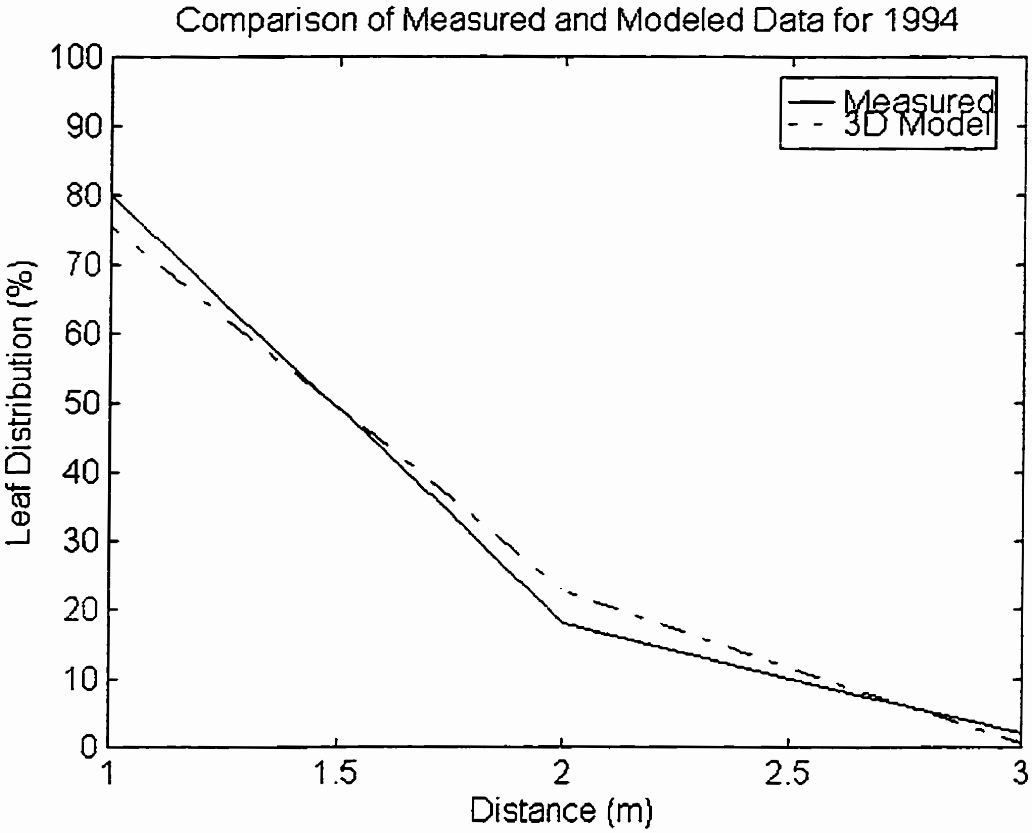
Poplar leaf biomass distribution (%)

Poplar leaf biomass distribution percentage in the field during fall 1993. Modelled and experimental data are plotted.



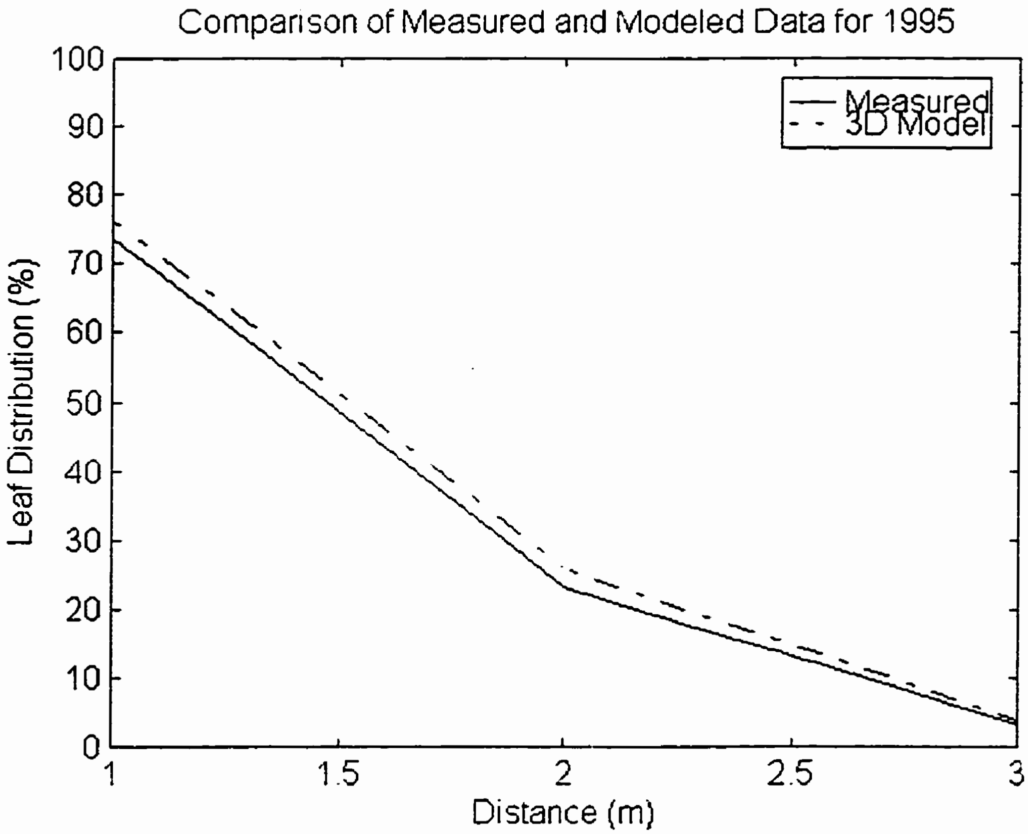
Appendix 2. Continued.

Poplar leaf biomass distribution percentage in the field during fall 1994. Modelled and experimental data are plotted.



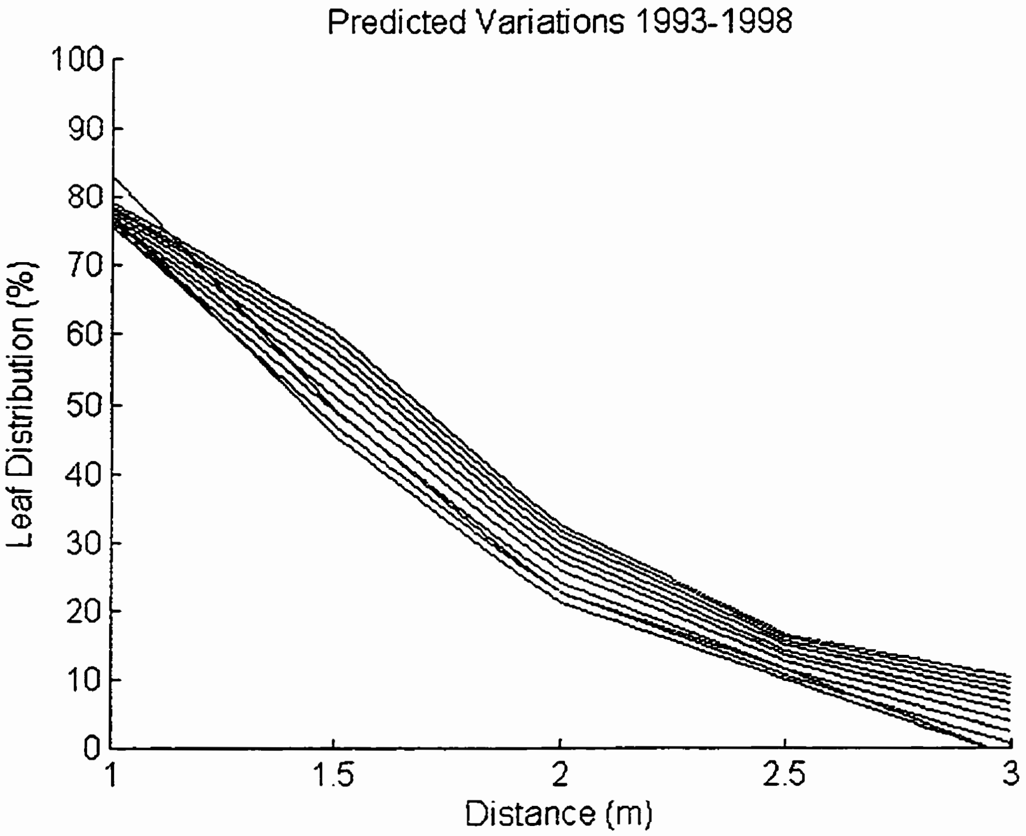
Appendix 2. Continued.

Poplar leaf biomass distribution percentage in the field during fall 1995. Modelled and experimental data are ploted.



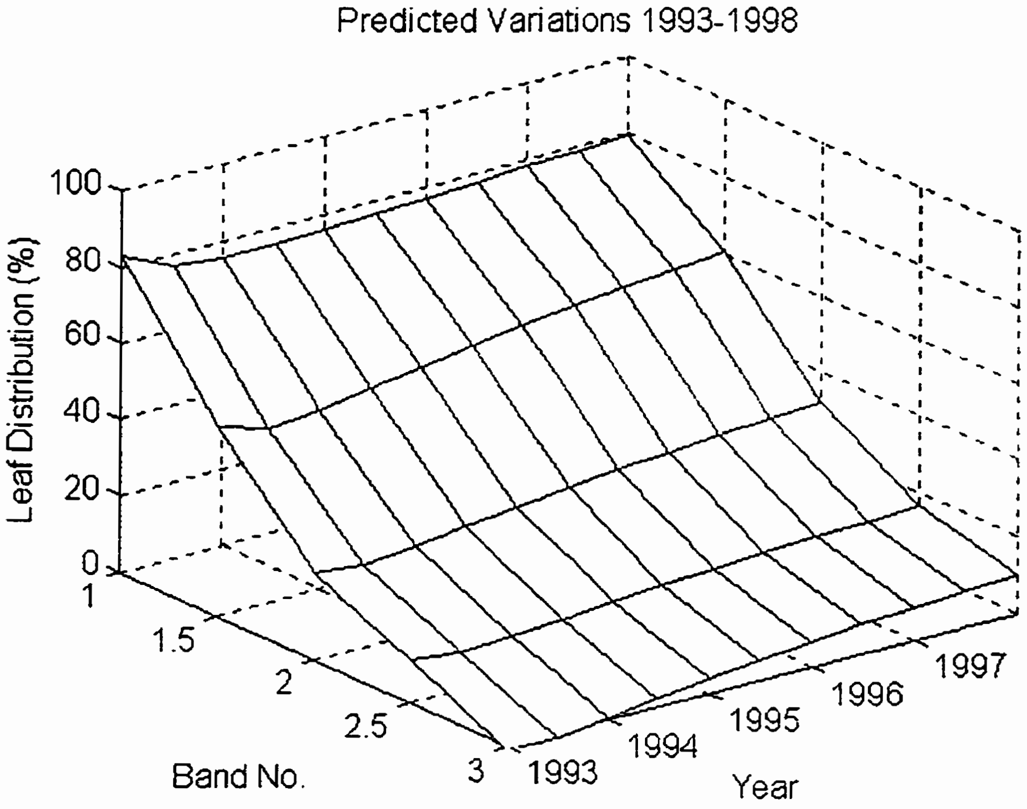
Appendix 2. Continued.

Modelled poplar leaf biomass distribution percentage in the field from 1993 to 1998.



Appendix 2. Continued.

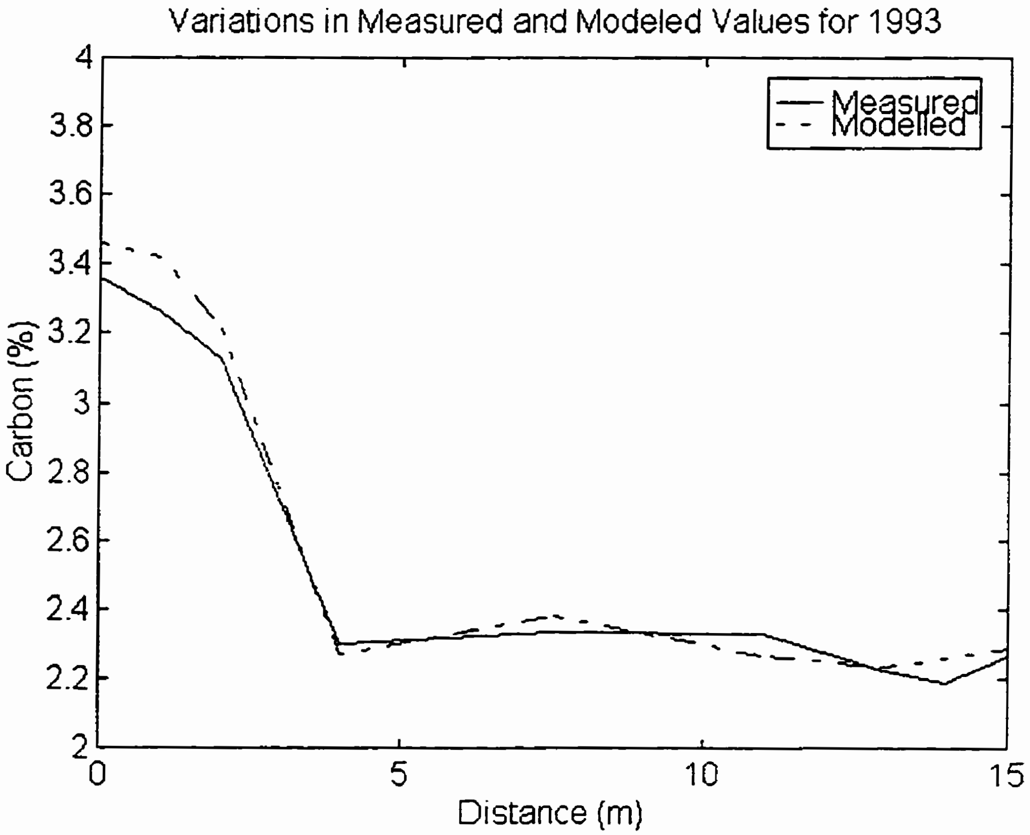
Constructed 3D model for poplar leaf biomass percentage distribution from 1993 to 1998.



Appendix 2. Continued.

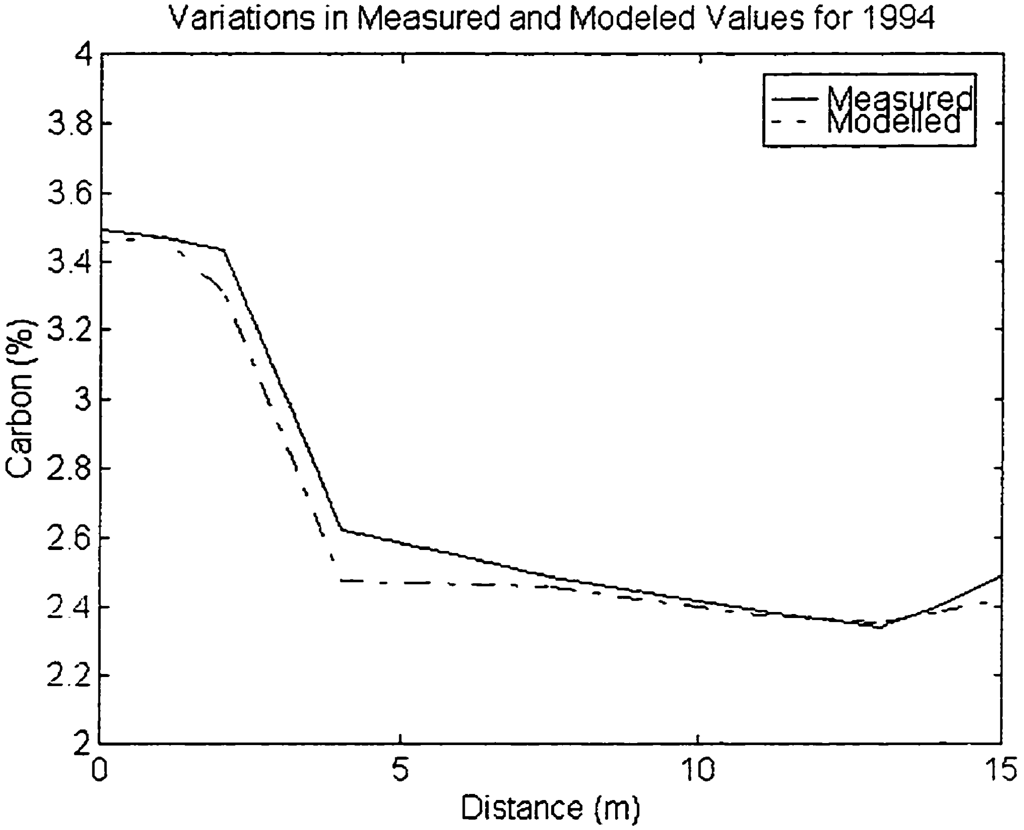
Soil Carbon Distribution (%)

Soil carbon variation at specific distances from the tree row (1993), in leaf not removed experiment. Modelled and experimental data are ploted.



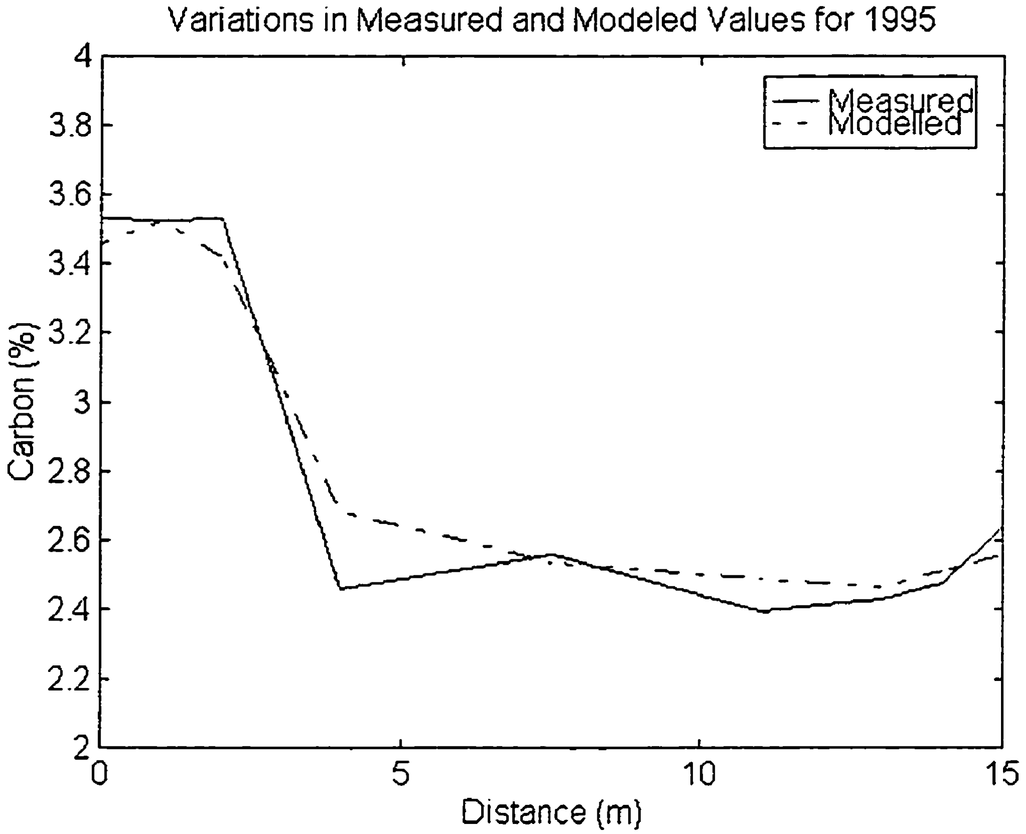
Appendix 2. Continued.

Soil carbon variation at specific distances from the tree row (1994), in leaf not removed experiment. Modelled and experimental data are ploted.



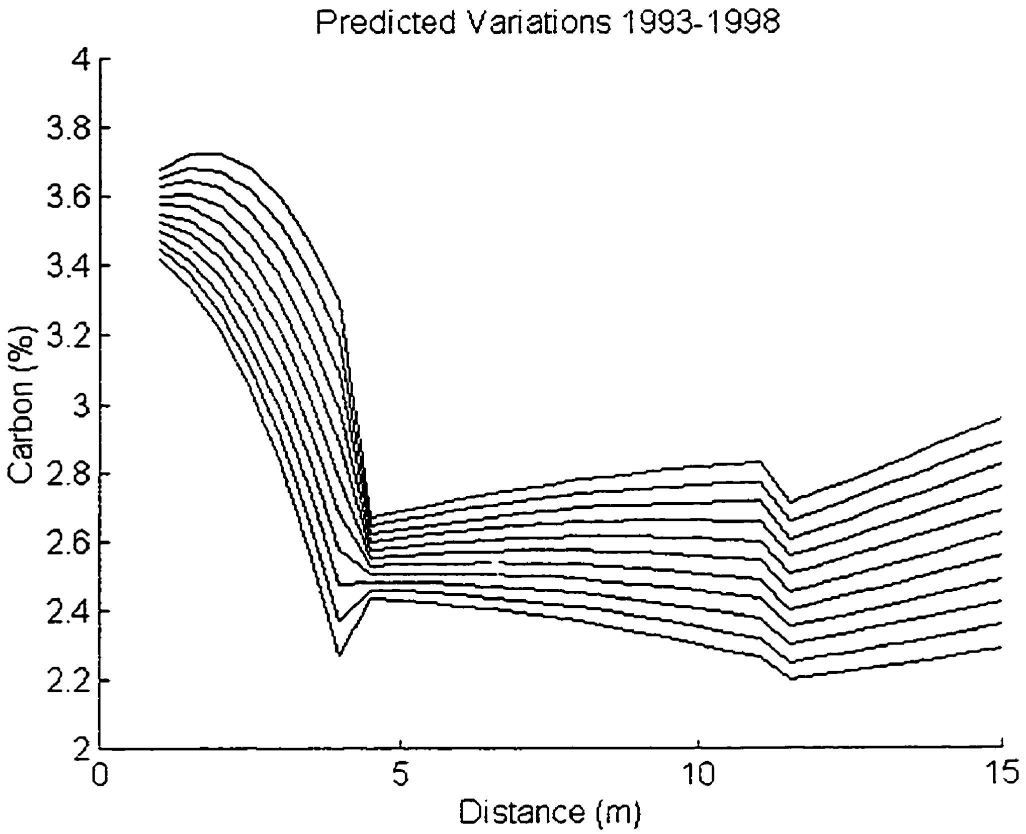
Appendix 2. Continued.

Soil carbon variation at specific distances from the tree row (1995), in leaf not removed experiment. Modelled and experimental data are ploted.



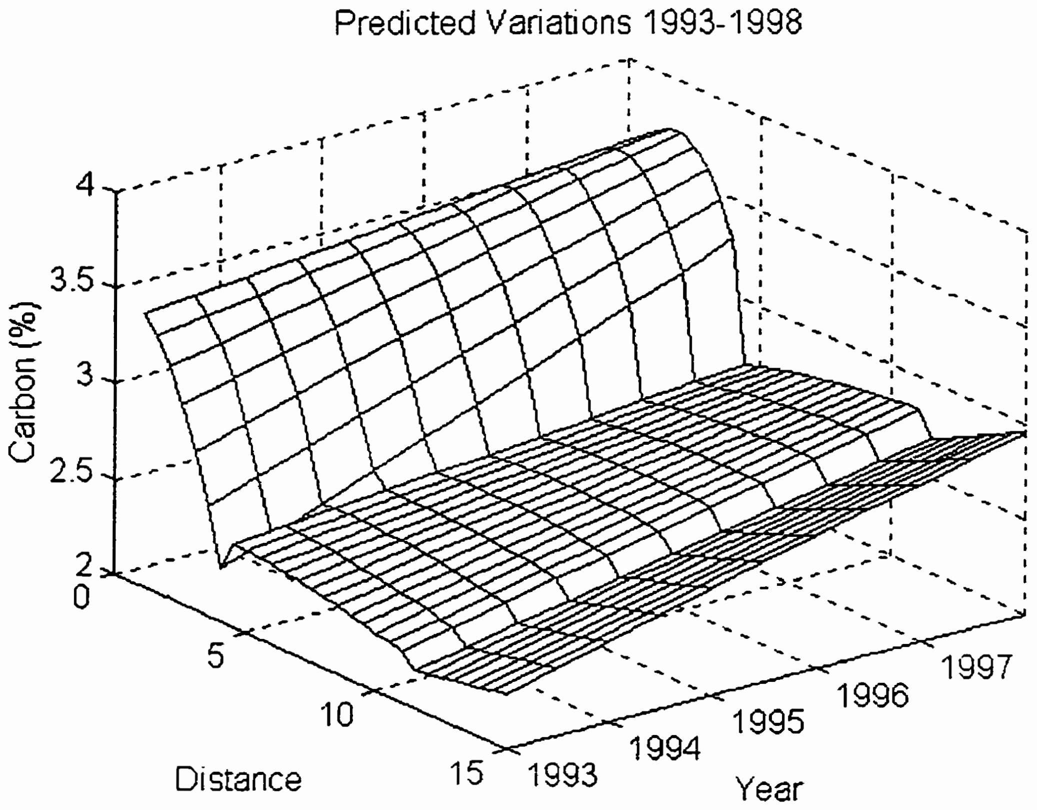
Appendix 2. Continued.

Predicted variation in soil carbon at specific distances from the tree row from 1993 to 1998 , in leaf not removed experiment.



Appendix 2. Continued.

Constructed 3D model for soil carbon variation at specific distances from the tree row (1993 to 1998), in leaf not removed experiment.



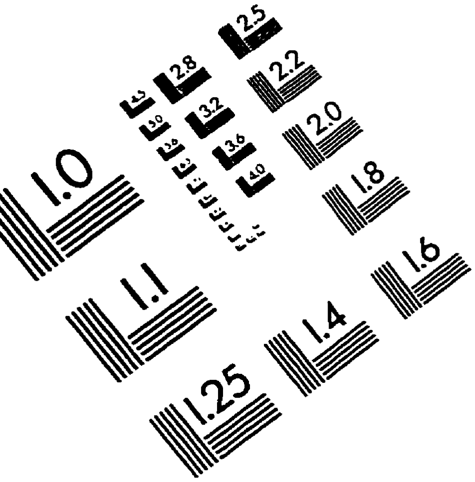
Appendix 3.

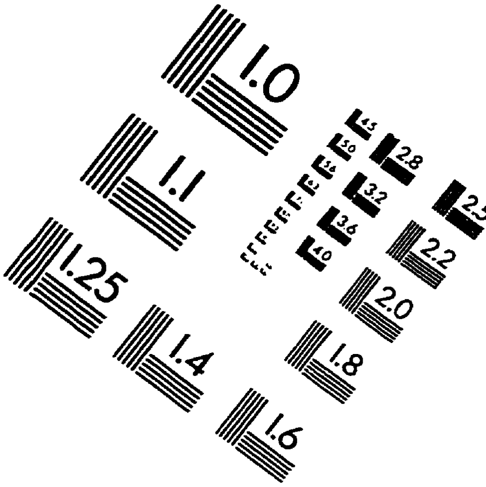
Nitrate Production Rate ($\mu g.100g^{-1}$ dry soil.day^{-1}), off-peak summer values (Mean values ($S_{\bar{x}}$))

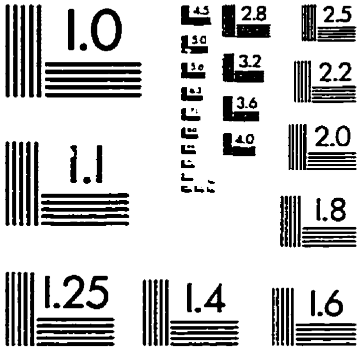
Year	Distance from tree row (m)	July-August	August-September
1993	0	82.1 (0.4)	7.2 (0.5)
	1	23.3 (2.6)	12 (1.8)
	2	27.4 (3.3)	8.2 (2.0)
	4	16.7 (1.2)	-7.8 (1.8)
	7.5	12.7 (1.4)	-15.0(4.6)
	11	6.5 (0.6)	-6.3 (1.1)
	13	12.8 (0.9)	-4.7 (2.8)
	14	3.3 (0.6)	-0.4 (2.1)
	15	6.5 (2.0)	8.3 (1.1)
1994	0	24.7 (7.1)	11.9(1.0)
	1	13.4 (2.6)	7.5 (0.6)
	2	4.1 (1.1)	-1.6 (1.0)
	4	-6.4 (1.6)	-1.0 (0.6)
	7.5	-17.3 (3.4)	-6.0 (1.0)
	11	-23.6 (5.2)	-10.1(0.5)
	13	1.2 (0.2)	-14.4(4.6)
	14	4.8 (1.0)	-5.5 (2.7)
	15	6.3 (1.3)	-12.6(7.1)
1995	0	16.2 (1.0)	data[1] not collected
	1	11.4 (1.1)	
	2	12.4 (0.6)	
	4	-4.7 (0.1)	
	7.5	-4.5 (0.1)	
	11	-8.4 (0.6)	
	13	-4.2 (0.3)	
	14	-2.8 (0.1)	
	15	11.6 (0.2)	

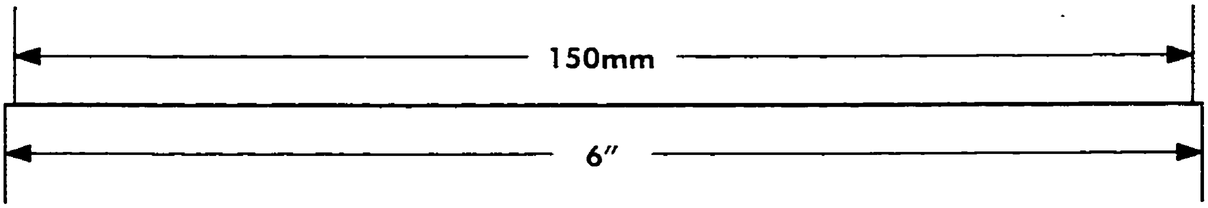
[1] Experiment was concluded in August.

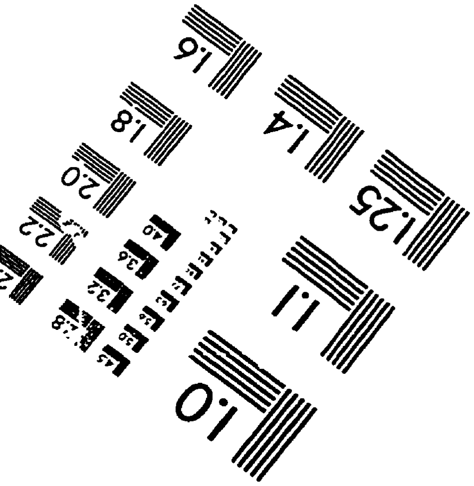
IMAGE EVALUATION TEST TARGET (QA-3)

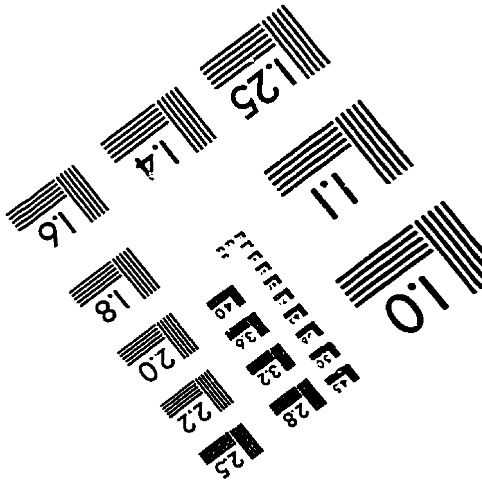












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