

## AN ABSTRACT OF THE DISSERTATION OF

Stefan Seiter for the degree of Doctor of Philosophy in Horticulture presented on June 10, 1997. Title: Intercropping Trees in a Vegetable Production System: A Holistic Inquiry.

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Abstract approved: \_\_\_\_\_

Ray D. William

Red alder (*Alnus rubra*) and black locust (*Robina pseudoacacia*) trees were intercropped for green manure in a sweet corn (*Zea mays*) production system. We applied systemic and reductionist methodologies to explore biological, ecological, and social interactions in this cropping system. Field testing of potential planting arrangements showed that space available to trees and crops affected yield of both plant components. Compared to monocropping systems, corn yield reductions in alley cropping systems were proportionally less than space lost to trees. *A. rubra* and *R. pseudoacacia* green manure yields were low compared to tropical alley cropping species. *R. pseudoacacia*'s ability to produce green manure after frequent coppicing appeared to weaken. A nitrogen cycling study, using tree-injected  $^{15}\text{N}$ , revealed that tree root tissue turnover occurred earlier than turnover of prunings. Nine percent of the tree root  $^{15}\text{N}$  was recovered by corn plants next to the labeled trees during the first growing season. More than 30% of the  $^{15}\text{N}$  in prunings was recovered by corn plants. The turnover of alder green manure supplied only a small percentage of the N required by corn. Soil bacterial and fungal dynamics were measured using direct microscopy techniques. Active bacterial and fungal biomass were highest in tree rows and declined with distance from trees. The small amount of prunings had no detectable effect on microbial biomass at a distance of 150 cm from trees. Absence of tillage and additional substrate from tree roots likely contributed to higher fungal biomass in the tree rows. We explored the use of STELLA, a modeling tool, that uses a graphic-interactive simulation environment to develop a model that simulates light penetration into alley cropping canopies. STELLA represented a powerful modeling tool to create explicit diagrams that

show the structure and behavior of the system. Canopy light environment was simulated under a variety of management activities. Human activity systems research investigated the social components of tree-crop systems. We used participatory appraisal techniques to learn about farmers' decision-making and to improve farmers' ability to deal with complexity in their farming system. Farmers integrated trees to enhance natural resources and secure economically viable farming systems.

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**Intercropping Trees in a Vegetable Production System: A Holistic Inquiry**

by

**Stefan Seiter**

**A DISSERTATION**

submitted to

**Oregon State University**

**In partial fulfillment of  
the requirements for the  
degree of**

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Philosophy**

**Completed June 10, 1997  
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Doctor of Philosophy dissertation of Stefan Seiter presented on June 10, 1997

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Dean of Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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Stefan Seiter, Author

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## Contribution of Authors

Dr. Ray William was involved in the design, writing, and data analysis of chapters one, two, four, six and seven. Dr. Dave Hibbs assisted in the design and writing of chapter two and helped in data interpretation. Dr. William Horwath was involved in all aspects for the completion of chapter three, such as experimental design, technical assistance during the experiment data analysis and interpretation, and writing of the chapter. Dr. Elaine Ingham was involved in the design of chapter five and assisted in data interpretation. Soil samples were analyzed by her laboratory staff. Catherine Knott was involved in the design and writing of chapter seven and provided assistance in data interpretation.

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**Chapter 1**  
**Introduction: Systems thinking and practice for alley cropping research**

**Stefan Seiter and Ray D. William**

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## **Abstract**

We apply systemic and reductionist methodologies to explore alley cropping systems. Alder (*Alnus rubra*) and black locust (*Robinia pseudoacacia*) are grown as green manure in sweet corn production systems. Our research includes the study of biological, ecological and social interactions. The overarching approach follows the Hawkesbury systems agriculture model in which interactions are explored on four levels of research. On a basic science level, we study the soil food web composition and nitrogen cycling in the plant-soil system by using a new  $^{15}\text{N}$  method that involves direct injection of the tracer into xylem of the trees. Applied field research involves the response of trees and crops to various planting patterns and N equivalence trials. Optimized systems inquiry is a third level of inquiry involving modeling of alley cropping systems limited by light and nitrogen. Field data are compared to predicted tree and crop growth. Finally, human action inquiry investigates the social components of this cropping system. We use participatory appraisal techniques such as farmer-scientist focus sessions and participatory mapping to improve the farmers' ability to deal with complexity in their farming system and to learn about farmers' decision making.

**Keywords:** alley cropping, systems thinking, research methodology.

## **Systems approaches in agroforestry**

Agroforestry is a complex and dynamic land use system for integrated food and fiber production and ecosystem protection. The practice requires an intimate knowledge of trees, crops, soil and animals and an understanding of the interactions among these components. The ecology of an agroforestry system also involves human activities, decisions, and values that play a major role in its implementation.

Agroforesters have recognized that a systems approach would benefit research in complex cropping systems. For example, Kang and van Heide (1985) employ a systems approach to nitrogen management in tropical agroforestry. A systems approach to study the interacting soil, plant and management processes was suggested by Nair (1984). Systems approaches in agroforestry have been influenced especially by the farming systems research and extension (FSR/E) movement and have considered also the social constraints on agroforestry systems. For example, Jones and Price (1985) describe how a FSR/E approach can be used in the analysis of agroforestry systems and suggest that farmer motivation and priorities play a crucial role. These examples demonstrate the diversity of systems approaches in agroforestry research. Common to all is the use of general systems thinking ideas and practices.

Major concepts in systems thinking include: holism (i.e. a system is comprised of interacting components that function as a whole), communication and regulatory control between components (i.e. feedback loops), hierarchy (i.e. subsystems of lower complexity are nested in larger systems), and emergent properties on each level of complexity (Kaufman 1980; Checkland 1981). These concepts are used to explain and investigate agroforestry systems. For example, a feedback loop in an alley cropping system could consist of trees shading the crop, thereby reducing crop growth and residue which increases weediness, leading to reduced tree and crop yield. When these plant interactions cause farmers to change practices such as the coppicing regime, interactions involve the human management and the plant biology subsystems which illustrates the hierarchy concept.

### **Systems practice**

In agricultural and natural resource research, the scientific reductionist approach has been extremely effective to learn about basic biological and ecological processes.

However, in situations that require analysis of complex interactions between system components and the synthesis of knowledge from multiple perspectives, traditional reductionist research approaches often were not very successful. Furthermore, traditional science has not been able to adequately address people concerns and values. The ongoing worldwide debate about natural resource use clearly demonstrates that solving technical problems is only one part of the issue.

New methodologies such as Agroecosystem Analysis (Conway 1985) or various FSR/E approaches (Caldwell 1987) have been developed in the last decades to address complex agricultural and natural resource problems. Checkland and Scholes (1990) employ the soft systems methodology to resolve issues in human activity systems involving human values and decisions. This type of inquiry focuses on human management of agricultural resources and the expected consequences and interactions (Wilson and Morren 1990). The methodology may therefore be suited for alley cropping research.

Soft systems inquiry is one of four major approaches in agricultural science (Wilson and Morren 1990). The others are: hard systems inquiry, applied science, and basic science. Each approach handles a varying amount of complexity. Soft systems inquiry on one end and basic science on the other can be thought of being the poles of an axis that stretches from holistic integration to reductionist separation. The four research approaches form the basis for "Systems Agriculture", an overarching methodology developed by faculty of the Hawkesbury College in Australia. Their vision is to train agricultural scientists who are familiar with each of these approaches and depending on the situation, can choose a systemic, a reductionist or an integrated approach (Bawden 1991).

Regardless of the approach selected, a complete research or learning process involves at least four phases. Each phase requires different abilities from the learner (Kolb 1984). In the first phase, the learner observes and tries to obtain a complete picture of the situation (ability to diverge). Then the gathered information is assimilated and conceptualized to give the observations some meaning (ability to assimilate). This is followed by developing

a plan of action (ability to converge) and finally, the learner takes action and accommodates the outcome with the reality of the experience (ability to accommodate).

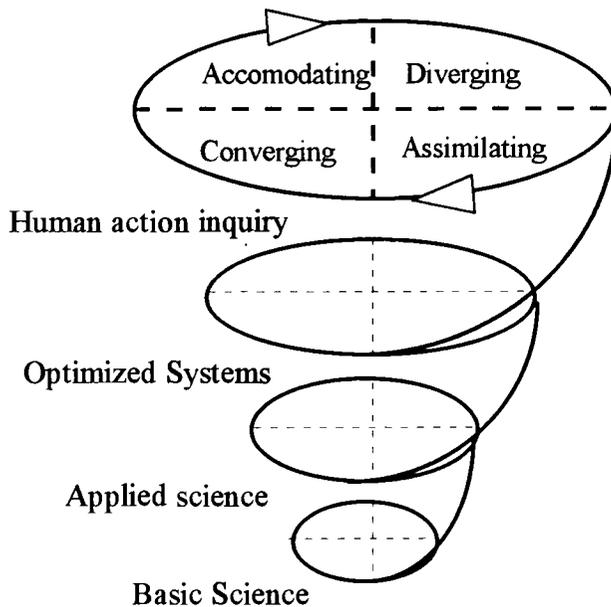


Figure 1.1 Spiral of interrelated research methodologies showing the cyclic learning process (Source: adapted from Bawden 1991).

The Hawkesbury group connected its research methodology with Kolb's learning theory. They visualized this connection as a spiral in which the levels of the spiral symbolize the different research methodologies (Figure 1.1). To complete a research process, the learner has to cycle through all learning phases. However, depending on the level of complexity of the problem, the learner can spiral up and down (i.e. select a certain method inquiry). The spiral also symbolizes close linkages in the hierarchy of interrelated methodologies. As Srikantharajah et al. (1991) describes: "Each level of inquiry provides a

perspective and a clearer focus on intent for the subsequent level and each lower level provides insights for the higher levels.”

### **The use of systems ideas in alley cropping**

We used the Hawkesbury systems agriculture model with some modifications to guide our alley cropping research program. Most agricultural researchers are familiar with the terms and concepts of basic science and applied science. However, the terms “hard systems” and “soft systems” continually cause misunderstandings. The soft systems approach also has been criticized to be exclusive and magnifying existing power differences between people (Flood and Jackson 1991). Therefore, we changed the terms of our systems approaches. Instead of hard systems we use optimized systems reflecting the goal of this approach. Soft systems is replaced by human action research. Ison (1994) defined action research as the linking of systems thinking to practice in a given context. Philosophically, our approach is close to participatory action research employing techniques such as participatory rural appraisal (Chambers 1992). Thus, human action research reflects our goal to move towards action and changes in resource management while integrating diverse perspectives.

Our alley cropping research is part of a long-term program exploring various vegetation management options that enhance profitable crop yield while protecting ecosystem integrity. Rows of the nitrogen fixing tree species *Alnus rubra*, *Robina pseudoacacia*, and *Alnus sinuta* were established in 1991 and intercropped with sweet corn since 1992. Corn and trees were planted in a variety of planting patterns to explore plant interactions. What follows is a summary of the key steps in each approach and a general description of the type of alley cropping research we initiated.

#### *Basic science inquiry*

In this methodology, the problem is reduced to small puzzles based on facts that are thought to be relevant. Hypotheses are proposed that may explain the perceived puzzles.

These hypotheses then are experimentally tested and after several replications, either confirmed or invalidated. In agricultural research, this often involves highly controlled experiments in the laboratory or small field plots to ascertain or quantify cause and effect relationships.

Many of the basic science questions remain to be answered in alley cropping research. In particular, basic plant physiological and soil ecological processes need to be explored to improve the cropping system. These processes include: quantification of biologically fixed N<sub>2</sub> by various woody species, role of mycorrhiza in nutrient uptake, and effect of trees on soil biota (Kang et al. 1990). In recent years, the number of alley cropping experiments conducted under highly controlled experimental conditions has increased, in particular, studies that have used stable isotopes to investigate nutrient fluxes (Xu et al. 1993; Haggar et al. 1993; Sanginga et al. 1990).

Our research also focuses on nutrient fluxes. While nitrogen may be effectively recycled in alley cropping systems, precise quantification of nitrogen fluxes through the soil and plant pools and particularly nitrogen transfer between trees and crops is sparse. Our experiments investigate these N-fluxes involving a novel method in which <sup>15</sup>N is directly injected into the tree xylem (Horwath et al. 1992). With a single <sup>15</sup>N application, we are able to follow nitrogen movement into the various plant and soil pools over several years. The experimental design allows us to differentiate between nitrogen entering the system from tree roots and from tree prunings. In this study, one of our hypotheses was that nitrogen released from trees by fine root turnover is transferred quickly to the corn and slower from soil incorporated tree prunings. Preliminary results validate this. A substantial amount of nitrogen was transferred from tree roots to the annual crop while nitrogen from tree prunings remained immobilized in the undecomposed plant tissue and the soil organic matter.

Alley cropping may improve soil quality through the addition of different forms of organic matter. One important indicator of soil quality is soil microbial activity (Visser and

Parkinson 1992). We are interested in quantitative and also qualitative changes in soil microbial activity resulting from alley cropping. For this reason we are studying multiple trophic levels of the soil foodweb including soil microbes and their predators using direct microscopy methods. We hypothesized that the addition of green manure will generally increase the microbial biomass and change the soil foodweb composition compared to monocropped corn. Because of tree root activity, we expected to find differences in the microbial biomass depending on sample location in the alley. We found that microbial activity was much higher in the tree rows. As the growing season progressed, we observed more microbial biomass in corn rows next to trees compared to corn rows in the middle of the alley.

In systems oriented research programs, linkages exist horizontally (i.e. same level of inquiry) and vertically (i.e. different levels of inquiry). The two studies described are closely linked horizontally since microbial biomass and type of soil microbes establish the balance between nitrogen mineralization and immobilization and thus determine the amount of nitrogen transferred from the trees to the other plant and soil pools. For us, the appropriate vertical linkage between basic science and applied science inquiry exists when the applied research seeks to demonstrate how relevant the basic processes studied are to production agriculture.

#### *Applied science inquiry*

In an applied science inquiry the problem is reduced to smaller units during the definition phase similar to the basic science approach. While basic science inquiry seeks to explain why something occurs, applied scientists ask what and how can it be done. Since most applied research is conducted in field plots where variable environmental conditions have to be integrated, applied science inquiry deals with a higher degree of complexity.

A review of research goals and needs shows the applied science focus in alley cropping research. The goal has been to contribute to the design of a cropping system that provides high crop yields while improving or maintaining soil resources. Reported research needs

deal with what has to be done to achieve this goal and to gather information from various fields to obtain a greater understanding of what is happening in applied agroforestry situations (Huxley 1986). Information sought is concerned with finding suitable tree species, optimum plant densities and field management practices (Seskabembe 1985).

Our research on this level of the spiral involves nitrogen equivalence field trials. We hypothesized that if green manure is decomposed fast enough, mineral nitrogen fertilizer could be substituted through alley cropping. To test this hypothesis, large field plots were planted with either monocropped or alley cropped sweet corn and fertilized at several nitrogen rates in a replicated design. We found that the green manure produced in the alley cropping system substituted some nitrogen but mineral nitrogen fertilizer always had to be added to obtain acceptable corn yield.

In another replicated field trial, trees and crops were planted in various densities. We compared potential tree species in several planting patterns. Under irrigated conditions, corn in rows next to the coppiced trees seemed to take advantage of higher levels of incoming radiation compared to corn in the middle of the alley. The increased corn yield almost compensated for the reduced corn growing area in the alley cropping systems compared to the monocropped corn. Very close spacing between trees and crops however, significantly reduced corn yield.

The planting patterns that we compared were feasible for farmer implementation. Using farmer feasibility as a design criterion demonstrates the close linkage between applied science and human action inquiry. Participatory on-farm research demonstrates how farmers in particular, but also other players in a human activity system such as extensionists, food processors or conservation groups are easily integrated in design, implementation and evaluation of an applied research program (Seiter et al 1994). Another vertical linkage exists by using data from applied research experiments to validate predicted results of modeling activities during the optimized systems inquiry.

### *Optimized systems inquiry*

In optimized systems inquiry, one attempts to deal with the system as if it is a whole with interactive parts. Research activities leads towards an agreed upon output or product (i.e. the optimization of a system). First, the problematic situation is described and the purpose of the inquiry defined. Synthesizing information from various perspectives, a systems model is designed next to study the interactions between system components. The model allows the systems analyst to test alternative strategies from which one is selected and validated in relation to the original problem. Model types range from diagrammatic representation of a system communicating component interactions to more elaborate models involving mathematical relationships to predict system behavior under certain environmental conditions.

Hard system models now exist for the biophysical and socioeconomic component interactions in alley cropping systems. For example, Young et al. (1987) developed a computerized program that predicts changes in soil properties under specified agroforestry systems within various environments. Other models deal with radiation and nitrogen supply in alley cropping systems (Nygren and Jimenez 1993). They use geographic and climatic parameters of one location and growth data from published values to predict optimum tree arrangement. Swift et al. (1991) compared changes in soil organic matter predicted by a simulation model with experimental data for maize monocropping and alley cropping. Mendora (1987) proposed a mathematical allocation model that generates feasible land use alternatives in Nigeria, including alley cropping.

We are currently developing a model of tree-crop competition for light and nitrogen (Figure 1.2). Observations from the applied and basic research experiments will be used to test the accuracy of the model. We used conceptual models at all stages and at all levels to clarify and communicate relationships between biotic and/or abiotic components of the cropping system. Frequently, these representations of agricultural systems or agroecosystem processes are diagrammed collaboratively by farmers, researchers and extensionists and used in the exploration of human activity systems.

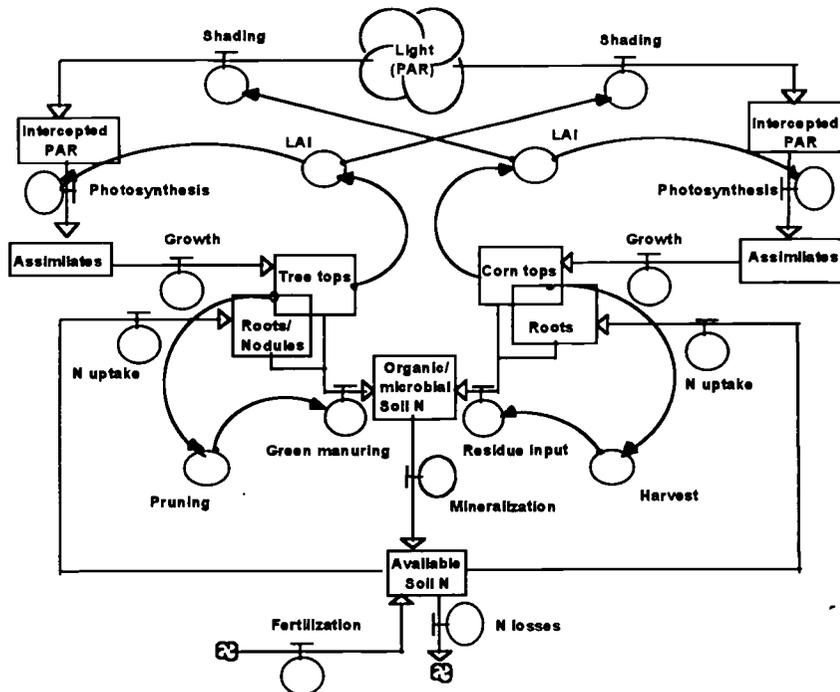


Figure 1.2 Model of an alley cropping system limited by light and nitrogen

### *Human action inquiry*

Human action research is the exploration into views, values and perceptions of various stakeholder groups. The research process begins by assembling a “rich picture” of problematic situations or opportunities (Checkland 1981). This includes not only a diverse collection of factual information but also an inquiry into the assumptions and worldviews or “*Weltanschauungen*” of the people who solicit, own or control the information. Next, common themes among the many problem descriptions are identified and action statements (transformations) that focus on an improved future state are defined. Before changes are implemented, pictures of the future are compared to reality; then feasibility and desirability of the proposed changes are debated from multiple perspectives. Postponing judgment until this final stage is a key to success of this approach (Flood and Jackson 1991). Human action research is participatory and interdisciplinary. Participants

agree to become co-learners who explore alternatives and discover the changes that would have to be made in the system to reach a common goal.

Participatory research has been an integral part of alley cropping research. The Diagnosis and Design methodology of the International Center for Research in Agroforestry (ICRAF), for example, allows farmers and extension agents to be actively involved in the research process (Scherr 1989). Sumberg and Okali (1988) note that in complex technologies such as alley cropping, farmers' role in the technology development is critical and cost-effective. Many alley cropping studies now employ FSR/E approaches to take advantage of farmers' knowledge and to develop a better understanding of the production system (Reynolds et al. 1991; Dvorak 1991; Heijer and Hombergh 1990). There is however, a critical difference between the systemic inquiry into human activity systems and the FSR/E perspective. FSR/E approaches are focused on the object of agricultural systems that exist in the world. Systems inquiry instead is focused on the process of people's perception of reality with the goal to create a learning system in which collaboration leads to desirable and feasible change (Bawden 1991).

Our efforts on the action inquiry level investigates human components of local farming systems. Agricultural production in Western Oregon/USA is dominated by high value vegetable crops. Traditionally, these are planted as large monocrops with high input of pesticides and chemical fertilizer. Many growers, vegetable processors, government agencies and the public are expressing concerns over potential detrimental effects to the environment caused by these practices. With them, social and agricultural science researchers explore the potential of alternative cropping systems, including alley cropping. To improve farmers' ability to deal with complexity in their farming system and to learn about farmers' decision making, we use participatory appraisal techniques such as participatory mapping, matrix scoring (Chambers 1992), and farmer-scientist focus sessions (Lev et al. 1993). Farmer-scientist focus sessions are specifically designed to share learning and improvements among the farmers, to investigate complex cropping system issues that require interdisciplinary examination and to explore diverse views,

values and beliefs. The goal of this type of systemic action research is to give ownership of both process and results to participating farmers.

### **Learning from systems practice**

As we explore alley cropping and other alternatives that enhance profitable crop production with environmental stewardship, we have found the Hawkesburry model a powerful and challenging tool. For us, the spiral provides the path along which we keep our research flexible, truly interdisciplinary and open to the changing demands and insights. Ideally, a research process begins with inquiry on the human activity system level to learn about the opportunities and problems. With the participation of all players involved, broad research goals and specific objectives are formulated and the appropriate level of inquiry to investigate the situation is identified.

I have described the systems agriculture approach as an overarching methodology for our research program. Initially however, the approach was developed as a way to improve student education (Bawden et al. 1984). By employing this approach, education shifts from a teaching to a learning paradigm. A learning environment is created where the boundaries between teachers and students blur. All participants in systems education become co-learners. If an institutional change goes hand in hand with the changes in the research and education programs, then conditions are provided in which learning can take place through experience, open and equal interactions, and personal exploration and experimentation (Pretty and Chambers 1994).

The nature of problems facing agricultural science is changing. The public asks farmers to produce food and fiber without harming the environment. Farmers in Oregon are looking for ways to meet this demand and to sustain agricultural productivity for future generations (Hatfield et al. 1994). The questions they raise often transcend disciplinary boundaries. To answer these questions, Jiggins (1994) suggests that future graduates in agricultural science will be required to integrate information from diverse perspectives and

disciplines and to have a strong conceptual, methodological and analytic understanding of how to introduce desired emergent properties in dynamic systems. By training scientists that are comfortable moving along the spiral through all phases of the learning cycle, we believe that we are able to better meet these challenges. At the same time, we feel that our action research approach contributes to collaborative learning among farmers and researchers and strengthens farmers' capability to experiment and manage the resource of their production system in harmony with their physical and social environment.

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**Chapter 2**  
**Planting arrangements and tree species for temperate**  
**climate alley cropping**

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## Abstract

Potential alley cropping planting arrangements involving *Alnus rubra* (red alder) and *Robinia pseudoacacia* (black locust) trees were tested in an irrigated sweet corn (*Zea mays*) production system in western Oregon. Space available to trees and crops affected yield of both plant components. High crop yield coincided with low woody plant yield, and vice versa. Compared to monocropping systems, corn yield reductions in alley cropping systems were proportionally less than space lost to trees. Yield reductions in traditional alley cropping designs with widely spaced, double tree rows ranged from 5 to 15%. *A. rubra* and *R. pseudoacacia* grew well when intercropped with corn. However, their green manure yield during the first four years of this trial were low compared to tree species widely used in alley cropping systems of tropical and subtropical regions. We observed that *A. rubra* yield continually increased during the trial, while the ability of *R. pseudoacacia* to produce green manure after frequent coppicing appeared to weaken.

## Introduction

Alley cropping received considerable interest from agricultural researchers in tropical countries when shortening fallow periods in shifting cultivation systems led to rapidly declining soil fertility (Kang et al., 1985). In alley cropping systems, annual crops are planted in the alleys between hedgerows of trees that are periodically coppiced to reduce competition with the annual crops. Prunings are incorporated into the top soil to function as green manure or left on the surface as mulch. Early experimental results promised high crop productivity while maintaining soil fertility, but a low level of adoption (due to technical and socioeconomic constraints) has replaced initial enthusiasm with a more conservative view on potential benefits and suitability (Ong, 1994; Carter, 1996). Nevertheless, recent focus on integrated and diverse farming systems that provide multiple benefits such as lowering fertilizer inputs, conserving soil resources, and providing habitat for wildlife and beneficial insects also has stimulated interest in

alley cropping and other tree-crop mixtures in developed countries in temperate climates (Gold and Hanover, 1987; Jahnke, 1989).

In the temperate climate of western Oregon, two tree species that are good candidates for use in alley cropping are *Robinia pseudoacacia* (black locust) and *Alnus rubra* (red alder). Both species are fast growing, fix atmospheric nitrogen, and tolerate repeated pruning (Dawson et al., 1983; Kurdali et al., 1990; Barrett and Hanover, 1991). Barrett and Hanover (1991) called *R. pseudoacacia* "the temperate zone counterpart of *Leuceana*" because of its similarity in growth characteristics. *A. rubra* is an early successional species of the Pacific Northwest characterized by rapid growth. It has the ability to accumulate significant amounts of nitrogen and increase soil organic matter content in forest stands (Binkley et al., 1994; Tarrant and Miller, 1963). Dawson, (1986) noted that farmers in Central America use *Alnus spp.* prunings to improve soil fertility in corn fields. In mixed tree stands both *A. rubra* and *R. pseudoacacia* have improved growth of timber and fruit trees by increasing soil nitrogen concentration (Friedrich and Dawson, 1984; Delver and Post, 1986).

The success of hedgerow intercropping systems depends on the selection of suitable plant arrangements. Different approaches are available to study planting arrangements of trees and crops. In one approach, individual components of the cropping system, such as crop row distance or tree spacing, are studied in isolation; information from these studies is later synthesized to suggest possible plant arrangements. Systematic experimental designs, such as fan designs (Nelder, 1962) or parallel row designs (Rao et al., 1990) are typical examples. The premise of these trials is that by fully understanding individual cropping system components it is possible to completely understand the whole system.

A contrasting approach to determine appropriate alley cropping planting arrangements is to compare potentially successful tree-crop combinations. Knowledge of ecological principles may eliminate many theoretical possibilities of species mixtures. This way research can be focused on the most promising ones. A similar approach was developed by Huxely and Mead (1988), who suggested Prototype System Trials to study "best-bet" treatments. These trials

were designed to study agroforestry in areas in which previous studies were lacking but where a general understanding of potential systems or systems functions exists. A wide diversity of alley cropping arrangements can be tested in an efficient manner when focusing on the most promising treatments. A comparison of treatments may reveal interactions between planting arrangement components. At the same time, it is possible to test the operational feasibility of several alley cropping designs. Including feasible planting arrangements in the research design allows farmers to participate actively in the research process by evaluating potential alley cropping systems. Sumberg and Okali (1988) noted that farmers' role in research becomes more critical and increasingly cost effective as proposed technologies become as complex as alley cropping.

Our objectives were to determine crop and tree yield in several alley cropping planting patterns, describe relationships between spatial factors and yield, and evaluate two potential tree species in a sweet corn production system. Farmers' objectives, such as maintaining adequate crop yield and creating practical tree-crop arrangements, guided our research. Space requirements limited the number of treatments and factor levels tested. However, we expected that the structure and control of proximity factors within these treatments would allow an assessment of their relative importance to the output of the systems. This study is one of several applied research projects in an alley cropping program that involved perspectives of basic and applied research, and optimized and human activity systems research (Seiter and William, 1995).

### **Materials and Methods**

The study was conducted at the Oregon State University Vegetable Research Farm near Corvallis in the Willamette Valley. The soil was a Chehalis clay loam soil. Low rainfall during the growing season between June and September requires irrigation of vegetable crops. Two corn monocrop and six alley cropping arrangements were established in plots measuring 9 by 4.5 m. Three alley cropping spatial arrangements were planted with either *R. pseudoacacia* or

*A. rubra* (Table 2.1). Corn and tree rows were planted in an east-west orientation. A guard row of sweet corn separated plots on the north and south sides.

Table 2.1 Alley cropping and monocropping planting arrangements. C represents corn rows; t represents tree rows.

	Plant Arrangement	Crop population Row Spacing	Tree Population / Arrangement	% Area <sup>1</sup> Crop - Tree
Alley cropping Systems	<u>CtCtCtCtC</u>	70000 plants ha <sup>-1</sup> 0.89 m x 0.16 m	350000 plants ha <sup>-1</sup> Alternate single rows	50 - 50
	<u>C C tt C C</u>	56000 plants ha <sup>-1</sup> 0.89 m x 0.16 m	140000 plants ha <sup>-1</sup> Center double tree rows	80 - 20
	<u>CCCtCCC</u>	70000 plants ha <sup>-1</sup> 0.635 m x 0.19 m	140000 plants ha <sup>-1</sup> Center double tree rows	86 - 14
Monocrop Systems	<u>C C C C C</u>	70000 plants ha <sup>-1</sup> 0.89 m x 0.16 m	0	100 - 0
	<u>CCCCCCC</u>	70000 plants ha <sup>-1</sup> 0.635 m x 0.19 m	0	100 - 0

<sup>1</sup> Denotes ratio of total area occupied by crops and trees

Scarified *R. pseudoacacia* seeds were sown directly into the experimental plots in May, 1991, and seedlings were thinned to the final density in August of the same year. Erratic *A. rubra* seed emergence in 1991 required transplanting of one-year-old seedlings in March, 1992.

During each growing season, we coppiced *A. rubra* and *R. pseudoacacia* trees twice to a vertical height of 30 cm. The first coppicing occurred during corn seedbed preparation in May. Prunings were shredded with a tractor-mounted tree shredder, distributed across the plot, and incorporated into the top 0.1 m of the seedbed with a rotary hoe. Four weeks after the corn planting, we coppiced a second time to reduce shading of the corn by the trees. The pruned material from that cut was left unshredded on the soil surface.

Sweet corn (var. Jubilee) was planted with a hand-pushed belt planter and hand thinned to final density. Plots were fertilized with 170 kg N, 130 kg P, 100 kg K ha<sup>-1</sup>. Each year nitrogen was split into two applications: the first was broadcast at planting in ammonium form; the second was side dressed as urea, six weeks after planting. No pesticides were applied. Weeds were controlled by hand and mechanical cultivation.

Sweet corn was hand-picked at a kernel moisture content of 72%. We harvested and measured yield of individual rows to determine possible row differences within each planting pattern. Yield of individual rows were combined to determine differences between planting patterns. The area harvested was 4.5 m (full plot width) by 4.5 m (half plot length). Corn yield in this paper represents yield of marketable ears. Measurements of both corn and tree yield per area refers to total cropping area (i.e., area occupied by trees and crops together). One meter row length in every tree row was hand clipped to determine pruning biomass. Prunings were oven-dried for one week at a temperature of 70° C and weighed.

Data were analyzed using General Linear Model (GLM) procedure of SAS (SAS Institute, 1987). The experimental layout involved a randomized block design replicated in three blocks, each with eight treatments (i.e., six alley cropping and two monocrop systems). Treatments were compared using multiple comparison procedures in SAS. Row sub-samples within treatments were analyzed as repeated measurements in space and contrasted using the contrast procedure (i.e., single degree of freedom comparison) of the GLM.

## Results and Discussion

### *Comparison of alley cropping systems*

Over the course of the experiment, an obvious pattern emerged when comparing crop yield of alley cropping systems: lowest yield of sweet corn was produced in the alternate tree-crop arrangement ( **CtCtCtCtC** ), intermediate yield in the widely spaced double tree row arrangement ( **C C tt C C** ), and highest yield in the narrowly spaced double tree row

arrangement ( CCCttCCC ) (Table 2.2). Yield in the latter two was statistically not different at a p-value of 0.05. The same yield pattern was observed each year, except in *A. rubra* arrangements of the first year. The absence of yield differences between planting arrangements suggested that newly planted *A. rubra* seedlings and corn did not interact, and corn grew as if trees were absent. Corn yield in the various treatments differed from year to year and declined substantially by the end of the 4-year study in 1995. In the narrowly spaced CCCttCCC of both tree species, for example, more than 18 t ha<sup>-1</sup> was produced in 1994 followed by 12 to 13 t ha<sup>-1</sup> in 1995.

Table 2.2 Sweet corn yield (t ha<sup>-1</sup>) in alley cropping and monocropping treatments. Values shown are mean values of three measurements. Different letters denote statistically significant differences between treatments within a year at a p-value of 0.05.

Treatment		Year <sup>1</sup>		
Plant Arrangement	Tree species	1992	1994	1995
<u>CtCtCtCtC</u>	Black locust	14.4 b	13.4 cd	8.06 b
	Red alder	16.9 ab	10.2 d	8.49 b
<u>C C tt C C</u>	Black locust	16.6 ab	15.3 bc	11.08 ab
	Red alder	16.5 ab	17.1 abc	11.78 ab
<u>CCCttCCC</u>	Black locust	18.4 a	18.6 ab	12.4 a
	Red alder	18.4 a	18.1 ab	12.9 a
<u>C C C C C</u>		17.0 ab	18.9 ab	12.56 a
<u>CCCCCCC</u>		18.7 a	19.4 a	14.2 a

<sup>1</sup> 1993 data is not presented due to uneven corn population and heavy weed infestation caused by unusually wet weather conditions.

The tree yield pattern was the reverse of corn: pruning biomass in the alternate CtCtCtCtC arrangement was highest, intermediate in the widely spaced C C tt C C, and lowest in the narrowly spaced CCCttCCC. Combined prunings from the two coppice cuts amounted to 4 to 5 t ha<sup>-1</sup> of dry matter in CtCtCtCtC (Table 2.3). Pruning biomass in C C tt C C and CCCttCCC did not differ significantly and ranged from 1 to 1.5 t ha<sup>-1</sup>. *A. rubra* accumulated

little biomass in the first year and no second cut was necessary in any of the plant arrangements.

Alley cropping treatments in this trial differed in tree species and proximity factors, such as corn and tree population, tree arrangement, crop row distance, and proportion of area occupied by trees and crops. Proximity factors affected crop and tree yield. For example, crop population was equal in CCctCCC and CtCtCtCtC, but 36% more space of the total area was available to corn in the former (86% and 50% occupied by corn, respectively). Relative corn yield responded proportionally. In 1995, corn yield in CCctCCC was between 35% and 36% higher compared to CtCtCtCtC (Table 2.4). In 1994, yield differences ranged from 28 to 44%. The area occupied by the crop was a reasonable parameter to predict corn yield in the three alley cropping arrangements. Linear regression showed that between 69 and 70% of crop yield variation was explained by this parameter (Figure 2.1).

Table 2.3 Pruning biomass ( $t\ ha^{-1}$ ) in alley cropping systems. BL and RA represent black locust and red alder trees, respectively. Values shown are mean values of 3 measurements. Different letters denote statistically significant differences between treatments within a year at a p-value of 0.05.

Treatment		1992			1993			1994			1995		
Arrangement	Species	1st <sup>1</sup>	2nd <sup>1</sup>	total	1st	2nd	total	1st	2nd	total	1st	2nd	total
<u>CtCtCtCt</u>	BL	2.5	2.0	4.5a	1.6	1.1	2.6a	3.8	1.2	5.0a	2.2	1.7	3.9a
	RA	0.2		0.2d	1.2	0.6	1.8b	3.0	1.0	4.0a	3.7	1.1	4.7a
<u>C C tt C C</u>	BL	1.2	0.5	1.7b	1.0	0.47	1.3bc	1.1	0.5	1.6b	0.9	0.7	1.6b
	RA	0.1		0.1d	1.0	0.3	1.4bc	1.2	0.2	1.4b	1.1	0.3	1.5b
<u>CCctCCC</u>	BL	0.9	0.2	1.1c	0.6	0.3	0.9c	0.9	0.4	1.3b	0.5	0.4	0.9bc
	RA	0.1		0.1d	0.7	0.3	1.0c	0.8	0.2	1.0b	0.9	0.4	1.4bc

<sup>1</sup> Represent 1st and 2nd pruning cut, immediately before and 4 weeks after corn planting, respectively.

Table 2.4 Relative sweet corn yield (%) in 1994 and 1995. Values shown were determined by assigning alley cropping systems with highest mean yield a value of 100% and calculating reduction in other planting arrangements.

Tree Species	Treatment		Year	
	Plant Arrangement	% Area Crop - Trees	1994	1995
Black locust	<u>CtCtCtCtC</u>	50 - 50	72.0	65.1
	<u>C C tt C C</u>	80 - 20	82.1	89.3
	<u>CCCttCCC</u>	86 - 14	100	100
Red alder	<u>CtCtCtCtC</u>	50 - 50	56.3	65.8
	<u>C C tt C C</u>	80 - 20	94.5	91.3
	<u>CCCttCCC</u>	86 - 14	100	100

Available space also may have played a role in treatment differences of pruning biomass. For example, equal tree populations in C C tt C C and CCCttCCC resulted in slightly greater yields in the former arrangement, where more light might have penetrated due to greater distance between trees and corn. Rao et al. (1990) also found an increase of tree biomass when distance between the first crop row and trees increased. Highest pruning biomass accumulation was measured in CtCtCtCtC, compared to the other planting arrangements, and was probably due to the combined effects of increased available space and tree population.

The fact that both crops and trees took advantage of increased space illustrates that sharing of environmental resources depends on space available to each component (Buck, 1986; Karim and Savill, 1991). Greater tree biomass production coinciding with lower crop yield is a commonly reported response pattern (Lawson and Kang, 1990). The actual crop yield response to tree growth depends on nutrient input levels and environmental conditions. When green manure is the only form of fertilizer or when soil erosion is a major factor affecting crop yield, higher tree density may produce more mulch and green manure biomass and increase crop yield (Yamoah and Burleigh, 1990; Jama et al., 1991). However, when soil fertility is high, general trends are the same as those observed in the present study: crop yield decreases

with greater tree densities and biomass production, illustrating the trade-off between potential soil improving effects of high green manure production and crop yield.

#### *Alley cropping versus Monocropping*

Because of the presence of trees in alley cropping, the area crops can use to exploit resources is always reduced. One might expect that reduced cropping area leads to a proportionally reduced crop yield. However, we found that corn yield reductions were less than expected as more of the total area was occupied by trees (Figure 2.2). When yield is calculated on the basis of the whole area, including area occupied by trees, crop yield in alley cropping often is lower than in monocropping systems (Sseskabembe, 1985). Alley crops yield similar to monocrops only under adverse growing conditions, such as low fertilizer regimes (Yamoah and Burleigh, 1990). However, our results show that proximity factors, such as row distance and plant density, can be changed within certain limits without greatly influencing corn yield. Similarly, Huxely and Maingu (1978) reported that the manipulation of plant rectangularity (i.e., inter-row spacing times intra-row spacing) to retain a crop population comparable to that in sole cropping may minimize yield losses.

When crop yield is similar in alley cropping and monocropping systems, greater yield must be produced in the cropping area of the alley cropping systems. In the first year, we observed that yield compensation in alley cropping systems that featured double tree rows occurred in the corn rows next to the trees (Figure 2.3). Timely coppicing might have improved light interception and resulted in beneficial edge effects similar to strip cropping systems where strips of grains or corn are intercropped with strips of legumes (Trenbath, 1977). However, analysis of individual rows within alley cropping treatments did not reveal any significant trends in 1994 and 1995. Measurements of corn biomass production might have been more sensitive to potential row differences than cob yield.

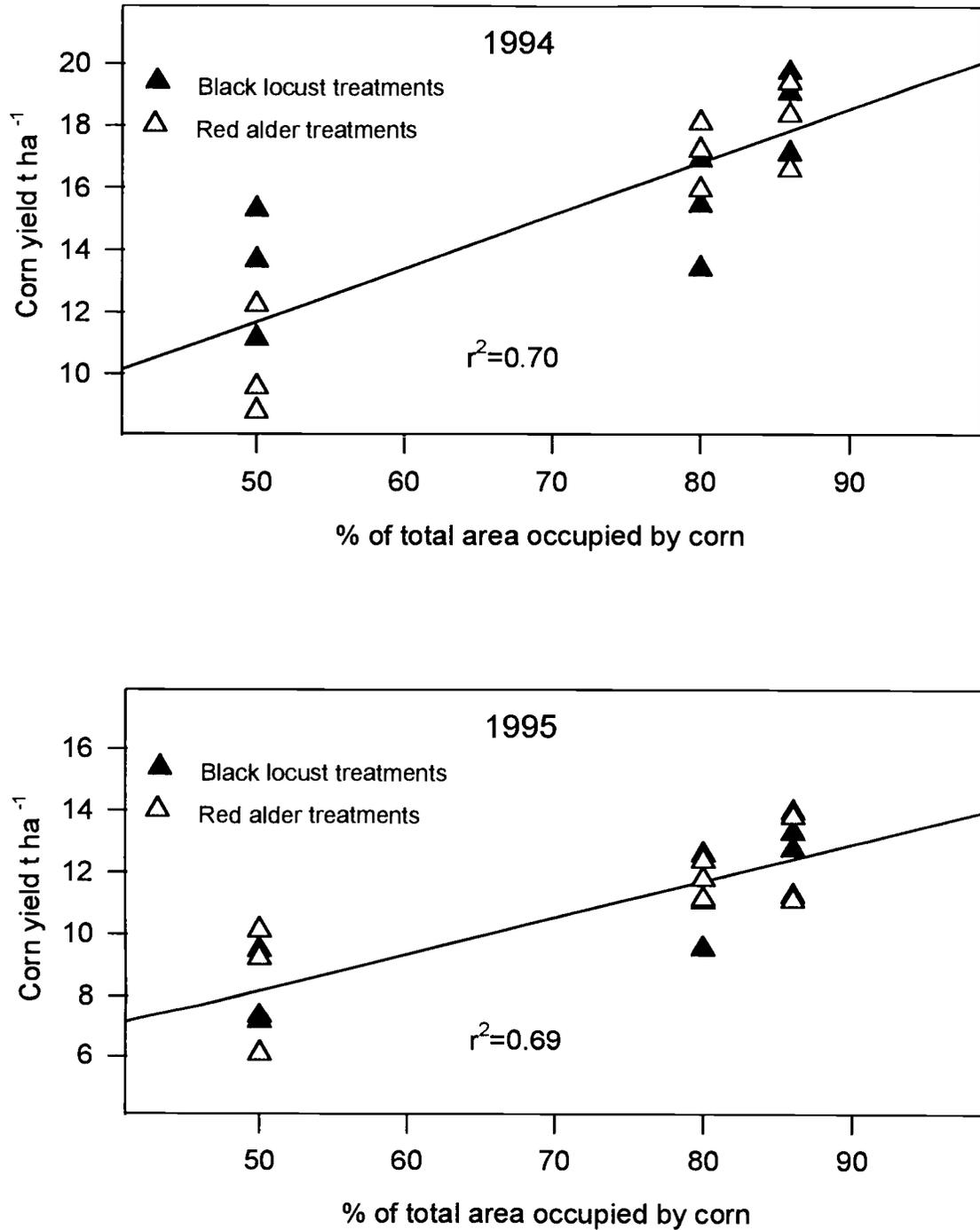


Figure 2.1 Corn yield relative to corn cropping area; 50, 80, and 86 percent of total area occupied by corn represent planting arrangements CtCtCtCtC, C C tt C C, and CCCttCCC, respectively.

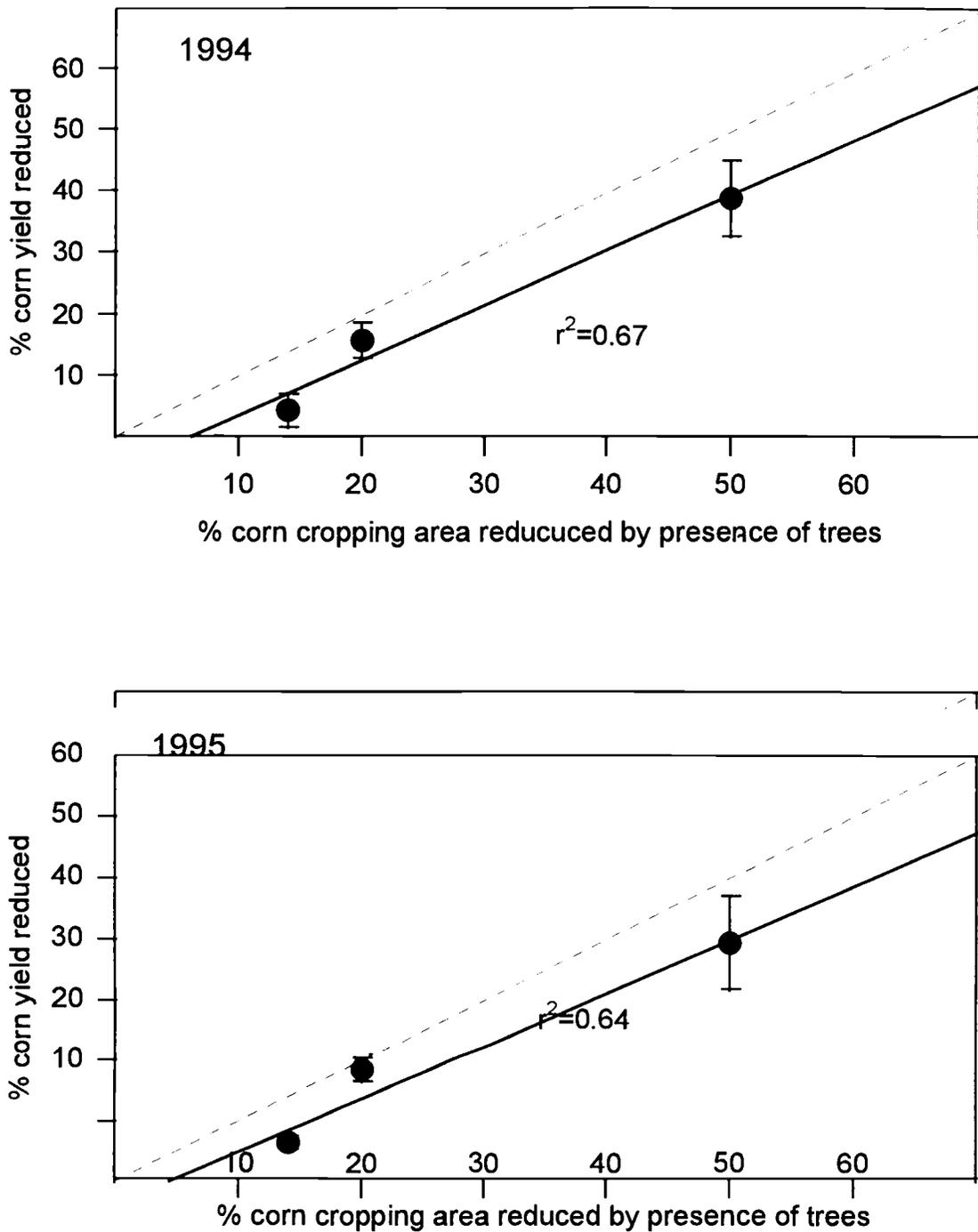


Figure 2.2 Corn yield reduction in alley cropping arrangements relative to cropping area reduction. Percent corn yield reduced represents yield reduction relative to monocropping; 14, 20, and 50 percent area reduced represent planting arrangements CCCttCCC, C C tt C C, and CtCtCtCtC, respectively. Dotted line indicates where corn yield reduction is proportional to cropping area reduction. Values shown represent mean values of 6 observations (vertical bars = standard error of the mean).

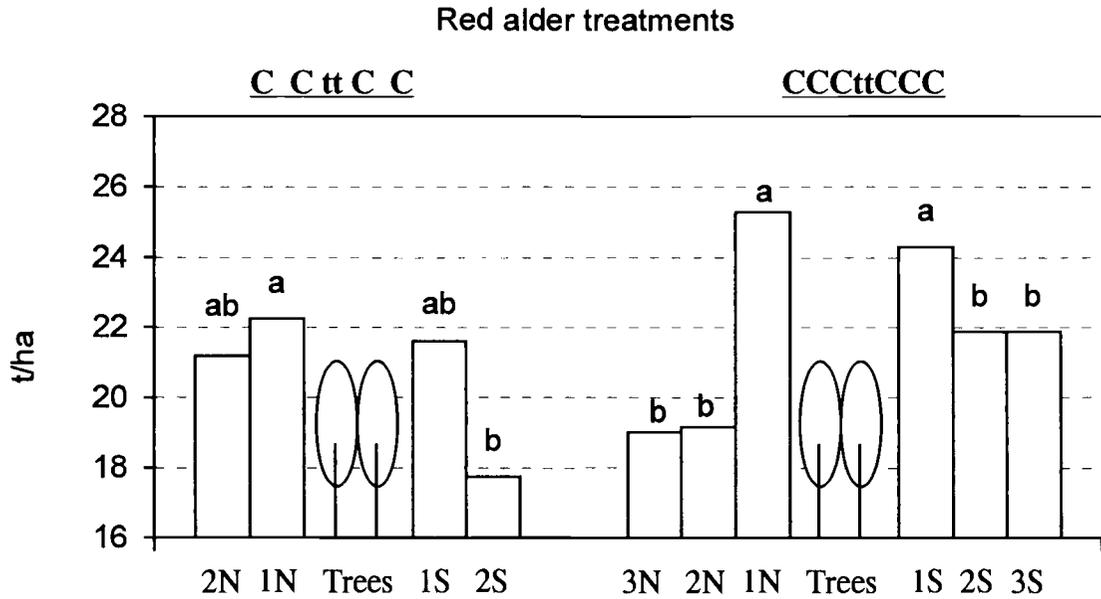


Figure 2.3 Corn yield in alley cropping arrangements C C tt C C and CCCttCCC in 1992. Row numbers indicate 1st, 2nd and 3rd rows next to trees. N and S represent location of rows north or south of trees, respectively. Columns show mean values of 3 measurements. Different letters above columns denote statistically significant differences at a p-value of 0.05.

Similar to our study, Sseskabembe and Henderlong (1991) found increased yield of corn next to the trees during the establishment year of an alley cropping system. However, yield reduction in crop rows adjacent to trees due to competition for soil moisture and/or light are more common observations (Salazar and Palm, 1987; Gichuru and Kang, 1989; Rosecrane et al., 1992). In semi-arid regions the major limiting factor is soil moisture (Singh et al., 1989); in the moist tropics shading associated with fast tree growth is the major limiting factor. Local soil and environmental conditions appear to determine the yield response. Yamoah et al. (1986) reported decreasing yield close to the trees when plots were fertilized. However, they observed increasing corn yield next to *Gliricidia*, *Fleminga*, and *Cassia* tree rows in plots where no nitrogen was added and prunings were removed. They concluded that this was due to litter accumulation near the hedgerow.

### *Evaluation of tree species*

We did not observe an advantage of one tree species over the other when considering corn yield as a measure of performance. Table 2.2 shows that crop yield was similar in the same *A. rubra* and *R. pseudoacacia* planting arrangements. The controlled field management in this experiment might have not allowed any differences between tree species to materialize. High rates of fertilizer applications, for example, prevented us from evaluating effects of nitrogen transfer between *Alnus* and corn that we have observed in *Alnus* alley cropping systems without nitrogen fertilization (Seiter et al., 1995). Timely tillage and coppicing controlling root and above-ground competition also might have eliminated differences in detrimental effects that would have emerged under less optimal field management.

*A. rubra* yields increased continually throughout the study while *R. pseudoacacia* yield fluctuated (Table 2.3). *R. pseudoacacia* yield in 1993 was reduced compared to the previous year. We observed that in the unusually wet and cold growing season of 1993, *R. pseudoacacia* leaves expanded much later in the spring and thus accumulated less biomass before coppicing compared to a typically warmer and drier year. The yield decline in 1995 compared to the previous year, however, could not be attributed to climate conditions. Rather, it appeared that regrowth of *R. pseudoacacia* was weakening after frequent coppicing. Hanover (1991) reported on *R. pseudoacacias*' rapid growth and its ability to resprout readily after repeated pruning. Our data and field observations of tree vigor and viability, however, support Sennerby-Forsse et al. (1992) who noted that *R. pseudoacacia* coppice yield tend to decline after a few coppice treatments. Longer establishment phases before first coppicing might have prevented the decline.

For both tree species the bulk of the total biomass was derived from the coppicing that occurred before planting the crop. Fifty-six to 87 % of the total dry matter production came from the first coppice cut. The two tree species, however, differed in the speed of regrowth. Second coppicing yield of *A. rubra* always was lower than that of *R. pseudoacacia* even when the first coppicing yield of *A. rubra* was greater. Yamoah et al. (1986) also found that tree

species differed widely in uniformity of dry matter accumulation during multiple prunings. In their study, *Gliricidia* yielded similarly over the course of several prunings while *Cassia* yield fluctuated.

Pruning yield in the present study was low compared to typical alley cropping systems in tropical and subtropical regions (Wilson et al., 1986; Brewbaker and Glover, 1988). Potential soil improving effects may not materialize when low quantities of green manure are added to the soil. We found that after 4 years of alley cropping with *A. rubra*, soil organic matter was slightly higher in the top soil of the alley cropping compared to monocropping system (Table 2.5). However, lower levels of soil organic matter in both alley cropping and monocropping systems in 1995 compared to 1991 suggested that green manure additions were too small to maintain original levels.

Table 2.5 Soil organic matter content (%) in two red alder alley cropping and one monocropping planting patterns at the onset and before the last growing season of the experiment. Values are the means of 3 measurements each composed of 15 sub-samples. Different letters denote statistically significant differences between planting pattern within the indicated soil depth at a p-value of 0.05.

Year	Planting patterns/ Location in plot	depth			
		0-45 cm avg.	0-15 cm	15-30 cm	30-45 cm
1991	All <sup>1</sup>	2.55	2.57	2.52	2.54
1995	<u>CCctCCC</u> / 0.3 m from trees	2.26 a	2.41 a	2.15 b	2.22 a
	<u>CCctCCC</u> / 1.5 m from trees	2.19 ab	2.37 a	2.13 b	2.07 a
	<u>CtCtCtCt</u> / 0.3 m from trees	2.30 a	2.34 ab	2.35 a	2.20 a
	<u>CCCCCCC</u> / 0.3 m from corn	2.11 b	2.25 b	2.05 b	2.04 a

<sup>1</sup> Random plot locations - before tree establishment

*Feasibility of alley cropping planting arrangements*

Evaluating the feasibility of a particular planting pattern or cropping system is a subjective process that depends on individual farmer's resources and world views (Wilson and Moren, 1990). Crop yield and management inputs are likely factors that farmers consider when debating the feasibility of alternative planting patterns. When maximizing food crop yield is the main interest of the farmer, yield reduction of 36 %, as we have observed in some planting arrangements, may be unacceptable regardless of how much green manure is produced. In fact, narrow profit margins in row crops may render any yield reduction in alley cropping systems unacceptable to many farmers unless other benefits such as lower pesticide or fertilizer inputs can benefit the whole farming system significantly.

Manageability of a planting pattern is another important consideration for farmers. In the alternate tree-crop arrangement CtCtCtCtC, use of commonly available machinery for seedbed preparation, pest control, and harvest is severely limited because of closely spaced tree and crop rows. In the double tree row arrangements C C tt C C and CCCttCCC, regular farm size equipment can be used. Our experience showed that the risk of plant damage during operation of farming equipment is lowest in C C tt C C where the distance between trees and the crop is widest.

Another management aspect involves coppicing. Timely coppicing is extremely important in alley cropping systems (Chavangi, 1986), especially where light sensitive crops such as corn are grown in association with trees. The present study was conducted in the field of a research station. In the "real world," yield differences between monocrop and alley cropping systems may be more pronounced if coppicing doesn't occur at optimal times. Labor cost and the availability of appropriate coppicing and shredding equipment poses a major challenge to farmers who are interested in implementing alley cropping systems. While farmers from diverse backgrounds and farming systems were intrigued by and contributed to this study, most interest in Oregon comes from farmers who intensively manage small acreage (Seiter et al., 1996).

## Conclusion

The experimental approach of comparing potential tree-crop combinations helped us to identify points of leverage in temperate climate alley cropping. Space occupied by crops and trees determined the yield of each plant component where water and nutrients were not limited. Other alley cropping components such as tree species or crop population within the tested range had little effect on cropping system outputs.

*A. rubra* might be a suitable alley cropping tree species. Its biomass yield continually increased during the four years of this study. *R. pseudoacacia* produced well initially. However, its ability to produce green manure after frequent coppicing appeared to weaken. Green manure yield of both tree species during the first 4 years of this trial were low compared to prominent alley cropping tree species grown in tropical and subtropical regions.

Our study showed that sweet corn may be produced in alley cropping systems with only small (5 to 15%) yield reductions compared to monocrops when trees and crops are arranged in appropriate planting patterns. Alley cropping with less light sensitive crops may result in smaller yield reductions when water and nutrients are non-limiting. In addition to crop yield reduction, availability of management inputs such as time, labor, and machinery present socio-economic constraints to the implementation of alley cropping systems. Farmers' objectives may determine whether alley cropping benefits in the form of green manure and other effects not investigated in this study offset trade-offs in the form of yield reduction or changing management input structure.

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**Chapter 3**  
**The fate of tree root and pruning nitrogen in a temperate climate alley  
cropping system determined by tree-injected  $^{15}\text{N}$**

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## Summary

Nitrogen fluxes through the major plant pools of an alder (*Alnus sinuta*)-sweet corn (*Zea mays*) alley cropping system were determined over the course of two cropping seasons. Alder trees were injected with  $^{15}\text{N}$  to study N cycling. The contribution of the above- and below-ground tree N to corn was determined by exchanging the labeled above-ground prunings with those from unlabeled plots. During the first growing season after coppicing of the injected alders, 18% of the alder  $^{15}\text{N}$  was taken up by the corn with 12% coming from the above-ground prunings. Nine percent of the  $^{15}\text{N}$  that was present initially in tree root/stump tissues was recovered by corn plants within the rows next to the labeled trees during the first growing season, showing the spatial dependency of the below-ground alder N availability to the corn. Tree root tissue turnover occurred earlier than turnover of above-ground prunings during the first year. By the end of the first and second growing seasons, 34 and 38% of the  $^{15}\text{N}$  initially present in prunings was recovered in corn plants, respectively. Approximately 80% of the total injected  $^{15}\text{N}$  was found in the soil during the second growing season. The turnover of above- and below-ground alder components during the year of green manure application supplied only 3 to 4% of the N required by corn. Thus, most of the corn N demand was met by mineralization of residual soil N. The synchronization between N mineralization from the hedgerow green manure components and nutrient uptake of the alley crop remains a major challenge in alley cropping and other green manure systems.

**Keywords:** Alley cropping -  $^{15}\text{N}$  injection - Nitrogen recovery - Nitrogen transfer - *Alnus sinuta* - *Zea mays* - Green manure

## Introduction

In alley cropping systems, trees growing in parallel rows are coppiced periodically to provide green manure in the form of soil-incorporated prunings for crops planted in between the alley hedgerows. The recycling of nitrogen is a primary objective of alley cropping systems (Nair 1984). A detailed understanding of green manure N recycling requires quantitative analysis of inter-specific plant N transfer and nitrogen fluxes through the plant-soil system. Nitrogen recovery estimates from hedgerow prunings by associated alleycrops range from 2 to 38% in tropical cropping systems (Haggar et al. 1993; Xu et al. 1993; Handayanto et al. 1995). The potential recovery of green manure N in alley cropping systems is dictated largely by the quality of prunings and the ratio of leafy and woody components, which differs among tree species and management (Yamoah et al. 1986; Handayanto et al. 1992; Haggar et al. 1993; Handayanto et al. 1995). The recovery of green manure N by associated alley crops is also dependent on the timing of N release from decomposition activity (Sseskabembe 1985). Fernandes (1991) noted that asynchrony of nutrient release from alley cropping prunings and nutrient demand from the crops are often the main causes for low crop N use efficiency, and yield.

Alder trees (*Alnus* spp.) are used as potential alley cropping species because they grow fast, fix atmospheric nitrogen, and coppice readily. Alder prunings are used by South American farmers to fertilize annual crops (Dawson 1986). Various alder species are also used in agroforestry systems in Asia, Africa, and Central America (Peden et al. 1993; Johnson 1997). In forest ecosystems of North America, alder trees have been found to increase the level of inorganic N (Brozek 1990; Kurdali et al. 1990). Several species have received considerable attention in interplanting systems with timber producing trees species. For example, alder has been grown with Douglas fir, black walnut, and hybrid poplar to improve timber yield (Binkley and Greene 1982; Friedrich and Dawson 1984; Kurdali et al. 1990).

Alley cropping systems have received widespread research interest emphasizing the contribution of prunings to soil fertility. However, research on the contribution of root residue has been noticeably absent (Huxely 1986). Sanginga et al. (1990) found 60% of the total plant N in roots of frequently coppiced *Leuceana leucocephala*. They concluded that management of root N release may be a more important strategy in achieving N translocation to associated crops than manuring with above-ground plant components.

A common method of quantifying N fluxes in plant-soil systems involves the application of  $^{15}\text{N}$  enriched or diluted fertilizer to soil that can be traced through the various N pools (Patra et al. 1986; Brophy and Heichel 1989; Futjita et al. 1992; Tobita et al. 1994). Alternatively,  $^{15}\text{N}$  label has been applied directly to roots and above-ground tissues of growing plants. For example, Martin et al. (1990) applied  $^{15}\text{N}$  to petioles of soybeans, which resulted in significant enrichment of adjacent corn plants. However, this effect was not repeatable with application of the label to the roots. Exposure of various plant organs to  $^{15}\text{N}_2$  gas is another direct labeling method, but it requires extensive technical preparation and is not suitable for field studies (Ta et al. 1989). In plant mixtures containing at least one woody component such as alley cropping systems, injection of  $^{15}\text{N}$  into the vessels of the trees offers an alternative direct labeling method (Horwath et al. 1992). The injection method eliminates the need for repeated labeling and allows the study of N fluxes over several growing seasons. The study of N recovery over multiple seasons is critical since the first crop after introduction of the  $^{15}\text{N}$  may only recover a small fraction of the labeled N (Ladd et al. 1983; Seligman et al. 1986; Sisworo et al. 1990).

The objective of this study was to quantify nitrogen fluxes through major plant pools of an alder (*Alnus sinuta*)-sweet corn (*Zea maize*) alley cropping system over the course of two cropping seasons. We were particularly interested in the contribution of the alder's above- and below-ground production in supplying N for crop uptake. The contribution of N from the alders was assessed by  $^{15}\text{N}$  injection technique. Following coppicing of the trees, the fate of labeled N in the plant-soil system and crop N uptake efficiency was determined.

## Materials and Methods

### *Study site and field procedures*

The study was conducted at the Oregon State University Horticultural Research Farm in Corvallis, Oregon, on an alley cropping site established in 1991. Main plots were 9 x 9 m containing two parallel rows of Sitka alder (*Alnus sinuta*) trees (Figure 3.1). Trees were spaced 0.3 m in the row and 4.45 m between rows. For this study, three plots with trees of uniform height and diameter were selected. On May 14, 1994, alternate trees in one plot were injected with 1.2 g of 99.9%  $^{15}\text{N}$  enriched  $\text{NaNO}_3$  following the method of Horwath et al. (1992). Three weeks after injection, the trees were coppiced 0.3m above ground level. Labeled prunings were exchanged with unlabeled prunings from a second field plot to distinguish nitrogen derived from above-ground prunings (referred to as ‘pruning plot’) and below-ground (referred to as ‘root plot’). A third field plot without labeled plant material was used as a control. Representative trees of approximately the same diameter and height as those of the labeled trees were sampled from outside the plots to determine total biomass and N content.

Prunings from the labeled, exchange, and control plots were shredded with a tractor mounted chipper and incorporated into the top soil to a depth of 0.2 m with a rotary hoe during corn seedbed preparation. Sweet corn (*Zea mays* var. Jubilee) was planted at a spacing of 0.63 m between rows and 0.19 m in the rows resulting in a density of 70,000 plants hectare<sup>-1</sup>. No nitrogen fertilizer was applied. During the corn growing season, the study area was kept weed-free by hand weeding. After manually harvesting corn cobs, standing stalks were flailed and left on the soil surface as a mulch. Tree prunings were not exchanged nor were trees labeled in the second year.

### *Plant tissue and soil sampling procedures*

Corn plants, above- and below-ground tree components, and soil were sampled frequently in all plots over the course of two growing seasons. Plant samples were dried (80 °C, 24

hrs), ball milled, and analyzed for  $^{15}\text{N}$  Atom % enrichment (A%) on an isotope ratio mass spectrometer (Europa Scientific, Crewe, England). Differences in nitrogen transfer to corn as a function of distance from the trees was determined by sampling all corn rows between the two parallel tree rows representing distances of 0.63, 1.27, and 1.90 m from the trees (Figure 3.1). Five grams (fresh wt.) were collected with a paper hole punch from the blades of randomly selected corn leaves. In the beginning of the second growing season, replicate samples of corn residue in each corn row were collected by carefully removing the residue from the soil surface. Four residue samples from an area of 1 x 0.3 m were analyzed for biomass and  $^{15}\text{N}$  abundance.

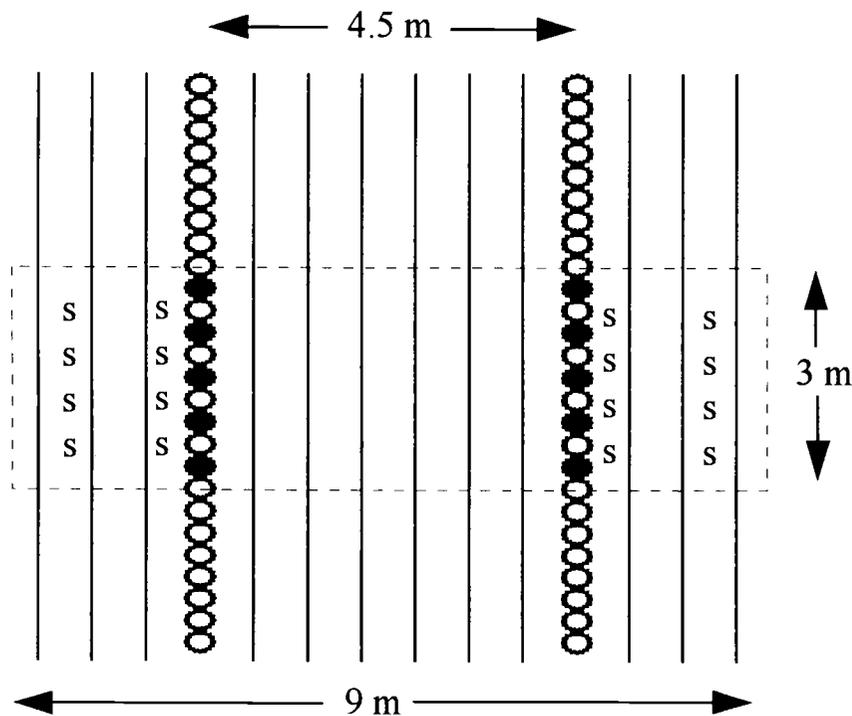


Figure 3.1 Field plot design and sampling location of root plot. Corn rows are represented by solid lines; labeled trees within the 3 x 9 m subplot are represented by solid star symbols; unlabeled trees are represented by open star symbols. "s" represents the location of soil samples. Samples next to trees were taken at a distance of 0.5 m. Samples further away were taken at a distance of 1.5 m. Corn tissue was sampled from all corn rows between the two tree rows, representing distances of 0.63, 1.27, and 1.90 m from trees to corn plants.

In the root plot both labeled and unlabeled trees were sampled to estimate potential nitrogen transfer among trees. At the end of the first growing season, we also determined N pool size of the leaf fall. After corn harvest, four trees per plot were encased in commercial bird netting to trap falling leaves. The leaves collected in the netting were used to estimate the total and labeled N content of the tree leaf litter. At the time of tissue sampling, representative whole trees and corn plants outside the 3 m subplot were excavated to estimate biomass and nitrogen content of above- and below-ground components of corn plants and trees.

Soil cores, measuring 15 cm in length and 5 cm in diameter, were taken three times during each growing season from 0-15 cm and 15-30 cm soil depths. Four soil samples were taken on the outside of both tree rows at a distance of 0.5 m (i.e. inside alley) and 1.5 m (i.e. outside alley) from the trees to avoid disturbing corn inside the alley (Figure 1). Soil from the root and control plots was collected during both growing seasons. Soil in the pruning plot was collected only in the second growing season. Soil was passed through a 2 mm sieve and roots were separated and analyzed separately for  $^{15}\text{N}$ . Soils were dried at 80°C, ball milled, and analyzed for  $^{15}\text{N}$  A%.

#### *Expression of results*

Enrichment of plant tissues is expressed as atom percent  $^{15}\text{N}$  in excess (A% ex) of the  $^{15}\text{N}$  level in control plots. The recovery of labeled nitrogen in the plant and soil pools was calculated by multiplying measured A% ex with N pool size. The data were analyzed using SAS software (SAS 1987). Analysis of variance was performed for  $^{15}\text{N}$  enrichment. When a significant treatment effect was found, the least significant difference was calculated to compare treatment means. Standard errors were calculated for  $^{15}\text{N}$  recovery in the various N pools. All values for plant and soil are expressed on an oven dry basis.

## Results

### *Size of plant N pools*

Prior to coppicing, trees in the selected plots reached an average height of 1.5 m and whole tree excavation outside the subplot area revealed an average 0.9 m horizontal spread of tree roots into the alley. The trees contained an average of 79 kg ha<sup>-1</sup> N (7 g tree<sup>-1</sup>). The coppiced prunings contained 27 kg ha<sup>-1</sup> N and stump and root tissues contained the remaining 52 kg ha<sup>-1</sup> N. At the end of the first growing season, alder leaf litter contained 5.4 kg N ha<sup>-1</sup>. In the second year, leaf litter contributed 6.3 kg ha<sup>-1</sup> N to soil N pools. Total nitrogen uptake in corn plants was similar in the root and pruning plots.

During the first weeks of growth, corn plants closest to the trees accumulated less biomass and as a result had lower total N uptake compared to corn plants in the middle of the alley (Table 3.1). By the end of the first growing season, corn plants close to the trees still yielded less biomass but contained higher N concentration than plants in the middle of the alley. Corn stalks within the various rows contained between 178 to 186 kg ha<sup>-1</sup> N at the end of the first growing season and between 175 to 195 kg ha<sup>-1</sup> N at the end of the last growing season (Table 3.2). The corn ear yield (cob) averaged between 65 to 109 kg ha<sup>-1</sup> N and represented N that was removed from this cropping system. Prior to seedbed preparation in the second year, 7.5 to 8.3 kg N ha<sup>-1</sup> was found in the corn residue from the first growing season. The low amount of N in the corn residue indicates a rapid turnover of this pool.

### *Enrichment of tree N pools*

Enrichment of roots and leaf tissue was not significantly different, indicating uniform labeling of individual tree components (data not shown). Three weeks after <sup>15</sup>N injection and prior to coppicing, the labeled alder leaf tissue contained 3.981 A% <sup>15</sup>N enrichment (Table 3.3). Leaf tissue enrichment decreased throughout the first growing season; however, higher enrichment values were found before the trees were coppiced in the

second growing season indicating the use of both reserve and recycled  $^{15}\text{N}$  for the formation of new leaf biomass. Tree leaf tissue samples taken from unlabeled trees growing adjacent to injected trees were enriched with  $^{15}\text{N}$  (Table 3.3). Significant enrichment in the unlabeled trees was found at the end of the first and the beginning of the second growing periods showing the uptake of N from root turnover in the adjacent labeled trees.

Table 3.1 Average nitrogen concentration ( $\text{g kg}^{-1}$ ) and total N content ( $\text{kg ha}^{-1}$ ) in corn plants during 1994 and 1995 cropping season at 3 week intervals starting 6 weeks after corn planting (WAP). Row 1, 2, and 3 represents corn plants at 63, 127, and 190 cm from trees, respectively.

year		6 WAP		9 WAP		12 WAP		15 WAP	
		N - conc.	N - content						
1994	Row 1	0.352	50	0.245	196	0.206	230	0.196	295
	Row 2	0.350	61	0.244	213	0.200	245	0.183	288
	Row 3	0.352	62	0.244	211	0.207	254	0.179	282
1995	Row 1	0.384	54	0.377	251	0.255	188	0.218	268
	Row 2	0.408	71	0.390	287	0.253	213	0.211	266
	Row 3	0.409	72	0.364	268	0.237	199	0.191	240

Table 3.2 Average nitrogen content ( $\text{kg ha}^{-1}$ ) of corn N pools at harvest 1994 and 1995, 15 weeks after corn planting (WAP) and prior to planting in the second year. Row 1, 2, and 3 represents corn plants at 63, 127, and 190 cm from trees, respectively.

	1994 - 15 WAP		1995 - 0 WAP	1995 - 15 WAP	
	stalks	cobs	Residue	Stalks	cobs
Row 1	186	109	8.3	195	72
Row 2	181	107	7.7	194	72
Row 3	178	104	7.5	175	65

Table 3.3 Atom percent  $^{15}\text{N}$  excess in alder leaves in root and pruning plots during the 1994 and 1995 growing seasons. Sampling periods are expressed as weeks after corn planting (WAP). Standard errors in parentheses. Row 1, 2, and 3 represents corn plants at 63, 127, and 190 cm from trees, respectively.

Year	Sampling period	Labeled trees in "root plot"	Unlabeled alder in "root plot"	Unlabeled alder trees in "pruning plot"
1994	-1 WAP	3.981 (0.0252)	0	0
	9 WAP	0.534 (0.0131)	0.028 (0.0145)	0.004 (0.0014)
	15 WAP	0.374 (0.0812)	0.059 (0.0203)	0.012 (0.0002)
1995	-1 WAP	0.537 (0.0385)	0.142 (0.0245)	0.019 (0.0106)
	9 WAP	0.085 (0.0072)	0.015 (0.0014)	0.003 (0.0003)
	15 WAP	0.042 (0.0074)	0.014 (0.0033)	0.006 (0.0004)

#### *Enrichment of corn N pools with $^{15}\text{N}$*

Corn plants in row 1 growing next to labeled trees in the root plot were already enriched with  $^{15}\text{N}$  by the first sampling date, 6 weeks after planting (Figure 3.2a). Twelve weeks after planting, we measured the highest A%  $^{15}\text{N}$  enrichment values in this row. Corn tissue in row 2 was slightly enriched with  $^{15}\text{N}$  and no enrichment was found in row 3, furthest from the injected trees. Enrichment of row 1 was also highest in the second growing season, but differences in A%  $^{15}\text{N}$  enrichment between rows were not significant and values were much lower compared to the previous year. In the second growing season, a small enrichment was measured in corn tissue of the row furthest away from the injected trees (row 3). The enrichment of the corn plants in the third row was most likely caused by uptake of  $^{15}\text{N}$  enriched tree prunings and corn residues that was distributed and incorporated at the beginning of the second growing season.

Corn tissue A%  $^{15}\text{N}$  enrichment in the pruning plot increased steadily during the first growing season (Figure 3.2b). As would be expected, all the corn plants in the pruning plot were similarly enriched with  $^{15}\text{N}$  without significant differences except on one sampling date. Highest A%  $^{15}\text{N}$  enrichment values were found at the beginning of the second growing season. The A%  $^{15}\text{N}$  enrichment decreased during the remainder of the

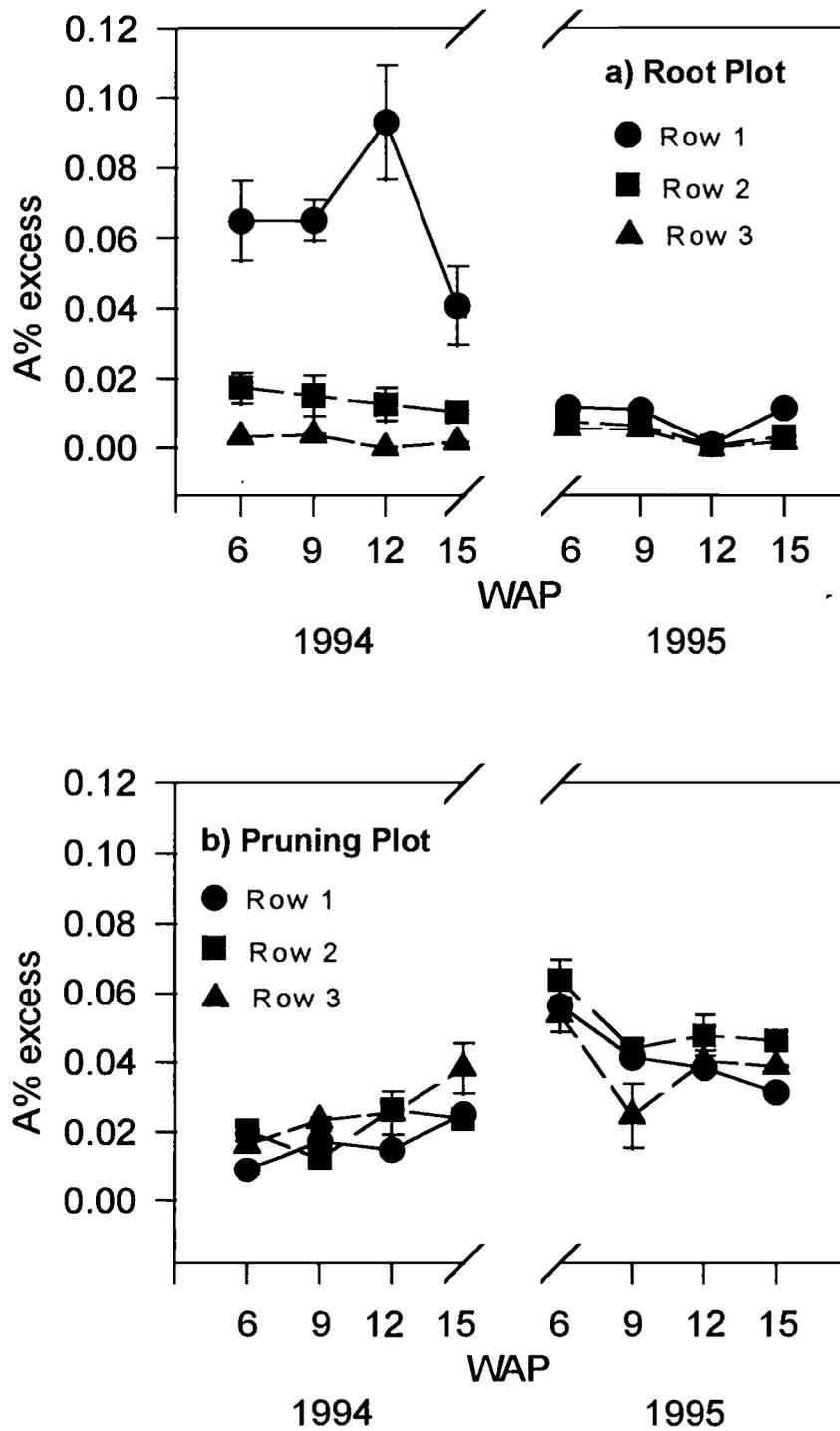


Figure 3.2 Enrichment of corn tissue in (a) root plot, and (b) pruning plot during two consecutive cropping seasons measured in 3 week intervals starting at 6 weeks after corn planting (WAP). Row 1 represents corn row next to trees at a distance of 0.63 m. Graph shows mean values; n=3, vertical bars=standard errors.

season without significant differences between rows. Neither in the pruning plot nor root plot was there a significant A%  $^{15}\text{N}$  enrichment difference between kernel and leaf tissues at harvest 15 weeks after planting. The spatial and temporal difference in the turnover of  $^{15}\text{N}$  between the above and below-ground tree components shows the importance of the different residues in supplying N to the corn plant throughout the growing season.

*Recovery of root and pruning  $^{15}\text{N}$  in corn tissue*

The enrichment data indicated that  $^{15}\text{N}$  in the corn plants was derived from both prunings and root tissues. The source of  $^{15}\text{N}$  for the corn plants depended on location in the plot. Labeled N recovered in corn tissues of corn rows 2 and 3 was derived predominantly from prunings. In row 1, on the other hand, 58% of the  $^{15}\text{N}$  in corn tissues was derived from root/stump tissues and 42% from the prunings. Nine percent of the  $^{15}\text{N}$  that was injected into tree root/stump tissues was recovered by the corn plants in rows 1 and 2 at the end of the first growing season (Table 3.4). Thirty-four and 38% of the  $^{15}\text{N}$  initially present in prunings was recovered in corn plants (independent of row location) by the end of the first and second growing season, respectively.

Table 3.4 Percent recovery of  $^{15}\text{N}$  in corn tissues at corn harvest, 15 weeks after corn planting. Values represent mean percent recovered from the  $^{15}\text{N}$  initially present in either root/stump or pruning tissues. Standard error in parentheses. Row 1, 2, and 3 represents corn plants at 63, 127, and 190 cm from trees, respectively.

	Root Plot		Pruning Plot	
	1994	1995	1994	1995
Row 1	7.4 (2.04)	1.8 (0.09)	8.9 (0.21)	10.57 (0.21)
Row 2	1.8 (0.09)	0.5 (0.01)	11.6 (0.09)	15.6 (0.16)
Row 3	0	0.2 (0.01)	12.9 (1.26)	12.4 (0.11)
Total	9.29	2.64	33.5	38.5

Uptake of  $^{15}\text{N}$  by the corn plants in the row next to the trees represented 3.8 % of the corn N requirement. In the other corn rows, between 2.8 and 3.1% of the N requirements were met in the first year. These values represent the turnover of above and below-ground alder components during the cropping season in which the green manure was applied. However, as we described above, crops take up nitrogen also from previous years' inputs. The long-term contribution of green manure N to crop N uptake under continuous applications was most likely underestimated and could not be addressed during the duration of this study..

#### *Distribution of $^{15}\text{N}$ in the plant-soil system*

The analysis of plant tissues showed that by the end of the first growing season, 30% of the  $^{15}\text{N}$  initially present in the labeled tree tissues was recovered in all the plant N pools of the root and pruning plot combined. Tree tissues contained 12% and corn tissues contained 18 % (Figure 3.3). Of the 18% in corn tissues, 5% was removed through harvest of corn cobs. The remaining 13 % present in corn stalks entered the soil N pool through mulching. Also entering the soil pool was the 1.5% of N contained in tree leaves falling at the end of the growing season.

Prior to coppicing trees in the second growing season, partially decomposed corn residues in root and pruning plot contained 1.2% of the total injected  $^{15}\text{N}$ . Thirteen percent was found in tree tissues. By the end of second growing season, corn plants contained 14 % of the originally injected  $^{15}\text{N}$ . Twelve percent was found in corn stalks and 2 % were removed from the system during harvest. Only 1.3 % of the original injected  $^{15}\text{N}$  remained in the trees.

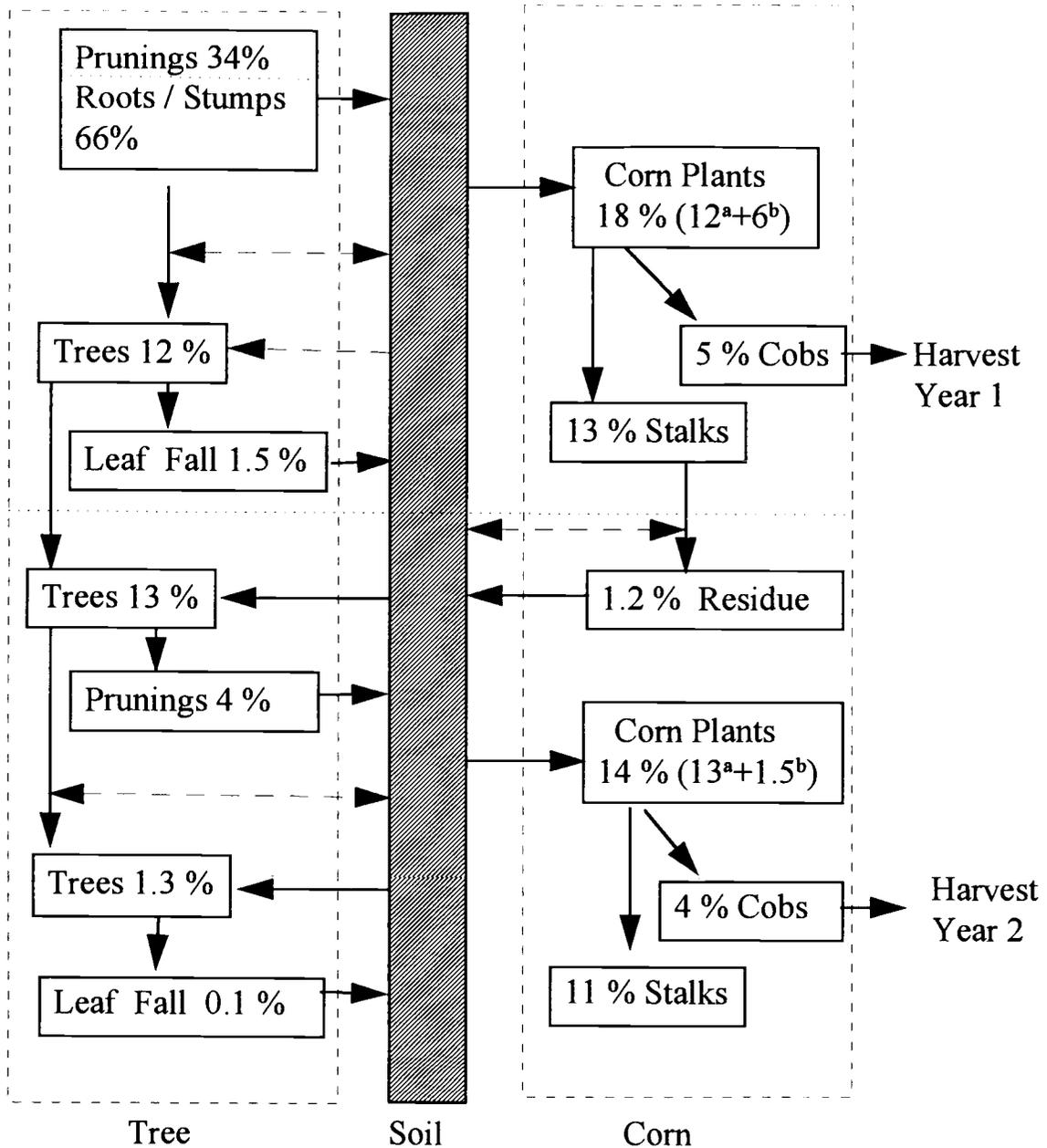


Figure 3.3 The flow of tree injected  $^{15}\text{N}$  through plant N pools of an alder-corn alley cropping system during two growing seasons. Values represent combined input from labeled root/stump and pruning tissues. Corn plant N pool represents the total  $^{15}\text{N}$  recovery in all corn plants independent of tree-corn distance and shows origin of N from either <sup>a</sup>prunings or <sup>b</sup>root/stump tissues.

During the second growing season, the percentage of  $^{15}\text{N}$  in soil N pools declined from 83.5 to 79.6% of the original injected  $^{15}\text{N}$  (Table 3.5). Incorporation of shredded prunings, which represented 34% of the total tree N, was an important pathway for the movement of the  $^{15}\text{N}$  label into soil N pools. Approximately one third of the soil  $^{15}\text{N}$  originated from the soil incorporated prunings; the remainder of the label found in the soil moved into soil pools via root litter N transfer.

Table 3.5 Recovery of  $^{15}\text{N}$  in various N pools of an alder-corn alley cropping system during the second growing season. Values represent mean percent recovered from the  $^{15}\text{N}$  initially present in all tree tissues. Sampling periods are expressed as weeks after corn planting (WAP). Standard errors in parentheses.

Nitrogen pools	1995		
	-1 WAP	9 WAP	15 WAP
<i>Corn cobs harvested in 1994<sup>1</sup></i>	4.8 (0.9)	4.8 (0.9)	4.8 (0.9)
Corn <sup>2</sup>	1.2 (0.1)	12.3 (1.1)	14.7 (0.3)
Trees	13 (0.6)	1.9 (0.1)	1.3 (0.1)
Soil <sup>3</sup> : "next to trees"	30.1 (2.3)	24.8 (0.7)	14.3 (0.2)
Soil: "away from trees"	53.4 (2.3)	57.1 (3.1)	65.3 (9.2)
Total	102.5 %	101.8 %	100.6 %

<sup>1</sup> Represents  $^{15}\text{N}$  that has been removed from the soil-plant system in the first year.

<sup>2</sup> Corn N pool at (-1 WAP) represents partially decomposed corn residue from the previous season that remained on the soil surface one week before corn planting.

<sup>3</sup> Soil was sampled to depth of 0.3 m. "Next to trees" represents  $^{15}\text{N}$  recovered in soil volume within a distance of 0.9 m from trees. "Away from the trees" represent soil volume in the remainder of the alley.

## Discussion

### *Uptake of tree root $^{15}\text{N}$ by corn*

Corn plants recovered a significant portion of the green manure  $^{15}\text{N}$  during the two years of study. Both prunings and root tissues contributed to corn N uptake. The temporal and spatial patterns of transfer from these two tissues were distinctly different. The  $^{15}\text{N}$  in the root/stump tissues was transferred only to corn plants growing in close proximity to the

injected trees. The distance between N fixing plants and crops also determined the spatial aspect of N transfer in other cropping systems. Fujita et al. (1990), for example, reported an increased N transfer to sorghum from soybeans growing in proximity to each other in a mixed legume-cereal intercropping system. Similarly, N transfer between alder hedges and apple trees increased with closeness between the two tree species (Delver and Post 1986). In their study, a certain degree of overlap between apple roots and the alder nodule zone had the same effect on the nitrogen nutrition of the apple trees as a certain amount of supplemented mineral nitrogen fertilizer in systems where no alder hedges were present.

Tree root tissue N was recovered by corn plants more quickly than pruning N. The immediate uptake of enriched N by corn plants growing next to labeled trees in the root plot suggested that below-ground turnover occurred shortly after coppicing of the injected trees. Horwath et al. (1992) estimated that 34% of the fine root pool in *Populus* turned over 2 to 6 weeks after injection with  $^{15}\text{N}$  showing the importance of below-ground N cycling processes. The components of the below-ground tree litter likely consisted of decomposing fine roots, nodules, exudates, and mycorrhizae. Fine roots of alley cropping trees and maize explore a similar soil volume (Jonson et al. 1988) and uptake of mineralized root tissue is likely to occur. In mixed species cropping systems other mechanisms of N transfer include the sloughing and decomposition of nodules and the excretion of N rich compounds (Patra et al. 1986; Burity et al. 1989; Dubach and Russelle 1994). These mechanisms become more important in soils of low mineral N status (Eaglesham et al. 1981; Brophy and Heichel 1989) and, therefore, may have played a role in the our alley cropping system where no mineral N was supplemented. Dubach and Russelle (1994) noted that the dominant pathway of N transfer differs among species grown in mixed cropping systems. Nodule senescence may be more important in some species while fine root turnover may be dominant in others (Ta and Farris 1987; Ofose-Budu et al. 1990).

Turnover of tree root N to the crop may have been enhanced by coppicing. It is frequently observed that root N is released after a severe stress has occurred to above-

ground plant parts (Whitney and Kanehiro 1967; Haystead and Marriot 1979; Chalk 1985; Brophy and Heichel 1989). Tree coppicing alters the ratio between above- and below-ground biomass (Sennerby-Forsse et al. 1992). In an attempt to restore an appropriate balance, trees may discharge below-ground root biomass. For example, Fernandes (1991) found that coppicing significantly reduced fine root biomass of alley cropping trees. Coppicing intensity was proportionate to decline in fine root biomass in his study. Severe pruning may also cause senescence of nodules (Bowen 1984). Danso et al. (1992) found that severe coppicing of *L. leucocephala* resulted in death of half of the nodules. In addition, tree coppicing may increase exudation of nitrogen rich root exudates similar to defoliation of annual plants (Bokhari and Singh. 1974). Root N released because of stress to one plant may not always be transferred to another plant. For example, Catchpole and Blair (1990) found that defoliation of *L. leucocephala* did not promote N transfer in alley cropping systems.

Nitrogen also may have been transferred directly from trees to corn through mycorrhizal connections. Several studies of intercropping systems indicate that N transfer was facilitated or enhanced by mycorrhizae (Haystead et al. 1988; Hammel et al. 1991). Johansen and Jensen (1996) suggest that arbuscular mycorrhizae play a significant role in the flow of N between two plants interconnected by hyphae when the root system of one is decomposing. We did not study mycorrhizal colonization but found that red alder (*A. rubra*) and corn roots were colonized by the same mycorrhizae species in alley cropping plots adjacent to the present experiment (Seiter 1997). The significance of this transfer mechanism may be more important during the later part of the growing season when mycorrhizal connections develop between the growing corn and trees.

#### *Uptake of pruning <sup>15</sup>N by corn*

Tree prunings represented the major green manure N source for corn plants. Pruning N recovery rates of 34% in the first year and 38% in the second year were higher than those observed in other alley cropping systems studies. Haggard et al. (1993) found that maize recovered 11.7% *Gliricidia* and 8.9% *Erythrina* mulch N in the year of application in a

tropical alley cropping system. In the study of Xu et al. (1993) only 2.6 % of the *Leuceana*  $^{15}\text{N}$  applied in the first year was recovered by the second maize crop. Uptake of  $^{15}\text{N}$  from labeled herbaceous legume residues are more similar to the values observed in our study. Recovery rates of 11 to 48% of legume N have been reported (Ladd et al. 1983; Hesterman et al. 1987; Bremer and van Kessel 1992).

The wide range of recovery rates found in various studies may be the result of differences in environmental factors and pruning quality. Environmental factors include climate and soil conditions as well as different pruning management (i.e. shredding, mixing, and soil incorporation). Pruning quality depends on the chemical composition of the tree residues. Various characteristics used to describe residue quality, such as C:N, Cellulose:lignin:N, lignin:N, and lignin + polyphenol:N have been correlated with decomposition rates of alley cropping prunings (Tian et al. 1992; Entry and Backman 1995, 1995; Handayanto et al. 1995). Kachaka et al. (1993) noted that alley cropping prunings are a heterogeneous mix of plant tissue consisting of material of varying degree of decomposability. Using soil covered meshbags, we observed that leafy alder tissues decomposed within 8 weeks, while the woody tissues remained intact (Seiter unpublished). In the present study, the pruning N recovered by the corn in the first season was probably derived from decomposed leaves in the pruning material. It appears that the low C:N ratio (Seiter 1997) of alder leaf litter contributed to rapid decomposition and subsequent N uptake by corn. Rapidly decomposing alder leaf litter also was observed by Kurdali et al. (1990). In their study, alder leaf litter contributed 10-15% of the total nitrogen uptake of *Populus* trees in *Alnus* -*Populus* interplantings. Similarly, Haggard et al. (1993) found that 55 % of the N released from alley cropping mulch came from an almost complete decomposition of the leaves of the mulch.

#### *Recycling of green manure $^{15}\text{N}$ in trees tissues*

Nitrogen transfer from labeled to unlabeled trees in the root plot suggested that nitrogen from decomposing roots and nodules was incorporated into new tree tissue during the first cropping season. In natural ecosystems many alder species derive a large percentage of N

from the atmosphere. Mead and Preston (1992) found that *A. sinuata* (the species used in this study) fixed 94 to 99% of its nitrogen from the atmosphere. McNeill et al. (1994) found N-fixation rates of *A. glutinosa* of up to 92 %. However, N sources for alder growing in alley cropping systems may be entirely different. Our results suggest that readily available N from root litter may provide an important N source, diminishing the importance of N-fixation under these conditions.

It is also possible that labeled N was transferred directly between trees. Mycorrhizal mediated N transfer between trees appears more likely than N transfer between crops and trees. By the time this study began, soil between the trees had not been tilled for 4 years, allowing undisturbed development of hyphal connections. In addition, spacing was closer between trees in the tree row than between crops and trees. Hammel et al. (1991) found that spacing is a critical factor in mycorrhizal mediated N transfer. They found N transfer only between plants growing in close distance in the same row. Another direct N-transfer mechanism may involve rootlets of one tree growing into the nodules of another, similar to what Gonchar and Zarbuenko (1972) have observed in mixed alder-ash stands. However, we have no evidence that direct N transfer processes occurred in our cropping system.

The increase in tree tissue enrichment between last sampling in year 1 and first sampling in year 2 indicated recycling of labeled nitrogen. The labeled N most likely came from nitrogen remobilization from roots to developing new leaf tissues. Millard et al. (1990) found that this mechanism is enhanced by low soil N availability (which was likely the case in our study after a corn cropping season without supplemental N fertilizer). The importance of N reserves in frequently coppiced alley cropping trees has not been thoroughly studied. Experiments with *A. glutinosa* growing in association with *Populus* showed that 28% of nitrogen in newly formed leaves was derived from reserves at the beginning of the growing season following  $^{15}\text{N}$  application (Domenach and Kurdali 1987). Nitrogen remobilization in fruit trees may be even higher. Sanchez et al. (1991), investigating recycling of nitrogen in pear trees, found that reserve N accounted for 48% of the N in new growth.

## Conclusion

Tree roots are an important source of nitrogen in an alley cropping system. Our study showed that root N is quickly transferred to associated crops and neighboring trees. For crops growing within the rooting zone, tree root tissues can constitute the major green manure N source. The yearly pruning N recovery rates of 34 to 38% observed in our study indicated that decomposing pruning tissues represented an important N source for crops growing further away from the hedge row. However, in this study, only a small percentage of the N required by corn was supplied through the turnover of prunings and below-ground components. Most of the corn N demand was met by mineralization of residual soil N. Higher contributions from the trees could be expected with increased pruning biomass input. Our study showed that green manure N moved quickly into the soil N pools. However, soil N derived from the alder components may not become readily available to associated alley crops. Perhaps the length of the study was not sufficient to address the long-term aspects of N cycling from the alder inputs. A small percentage of the green manure N is recycled by trees while a larger part is immobilized in the soil organic matter and biomass two years after labeling the trees with  $^{15}\text{N}$ . The synchronization between N mineralization from the hedgerow green manure components and nutrient uptake of the alley crop remains a major challenge in alley cropping and other green manure systems.

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## **Chapter 4**

### ***Alnus rubra* as a source of green manure in a sweet corn alley cropping system: influence on soil organic matter and soil chemical properties**

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**Manuscript to be submitted to  
Nitrogen Fixing Tree Research Reports,  
Publication of the Nitrogen Fixing Tree Association**

## Introduction

Tree prunings are used as green manure by farmers in many parts of the world. This technology is most prominent in tropical and subtropical areas where fast growing trees produce large amounts of biomass. Prunings are cut from wooded areas and hauled to the field, or originate from trees that are grown in the field with the crops. One of these intercropping systems is alley cropping, a technique in which crops are grown between periodically coppiced hedgerows of trees. Prunings are incorporated as green manure or left on the soil surface to serve as mulch.

Alley cropping also is explored in temperate regions. Tree species such as *Alnus rubra* (red alder) or *Robinia pseudoacacia* (black locust) exhibit fast growth and resprout quickly after repeated coppicing. *A. rubra* is a nitrogen-fixing tree native to the Pacific Northwest that enriches the soil with organic matter and nitrogen (Brozek 1990; Friedrich and Dawson 1984). *A. rubra*, therefore, may be a suitable species for temperate climate alley cropping systems. To evaluate its potential, we measured soil organic matter, nitrogen, and phosphorus content, along with cation exchange capacity before and after four years of alley cropping.

## Materials and Methods

The study was conducted at the Oregon State University Vegetable Research farm in Corvallis, Oregon on a Chehalis clay loam soil. In June 1991, we planted *A. rubra* in two planting arrangements in 9 x 4.5 m plots. From 1992 to 1995, the cropping area between the trees was planted to sweet corn (*Zea mays* var. Jubilee). Each of the 3 blocks in the randomized complete block design (RCB) contained two alley cropping and one monocropping planting arrangement (Table 4.1). During each growing season, except 1992, we pruned the trees twice to a vertical height of 30 cm. The first pruning occurred during corn seedbed preparation. The prunings, consisting of one-year-old woody shoots

and green leaves, were shredded with a tractor mounted tree chipper, distributed across the plot, and incorporated into the top 10 cm of the seedbed. Six weeks after planting, we pruned a second time to reduce shading of the corn by the trees. These prunings were left un-shredded in the tree rows. All plots were fertilized with 150 kg N, 130 kg P, and 75 kg K per hectare.

Table 4.1 Planting arrangements of monocrop and alley cropping systems. C represents corn rows; t represents tree rows.

Planting arrangement	Crop population/ Spacing	Tree population/ Arrangement
Monocropping: <u>CCCCCC</u>	70000 pl/ha 63.5 x 22.5 cm	0
Alley cropping A: <u>CtCtCtCtC</u>	70000 pl/ha 89 x 16 cm	350000 pl/ha Alternate single rows
Alley cropping B: <u>CCtCCC</u>	70000 pl/ha 63.5 x 19 cm	14000 pl/ha Center double row

Soil samples were collected in May 1991 before tree planting to establish baseline values for organic matter (Nelson and Summers 1982), total Kjeldahl nitrogen (Isaac and Jonson 1976), Bray phosphorus (Horneck et al. 1989), and cation exchange capacity (Rible and Quick 1960).. Four years later, in May 1995, we sampled soil in each of the alley cropping and monocropping plots from three soil depths: 0-15, 15-30, and 30-45 cm. In the monocropping (CCCCCC) and alley cropping (CtCtCtCtC) planting arrangements we collected soil from 15 randomly selected points across the plots. In the second alley cropping arrangement (CCtCCC), we collected soil at a distance of 30 cm and 150 cm from the trees. Each sample represented the composite of 15 thoroughly mixed sub-samples. Samples were air dried for 72 hours at 80 °C.

## Results and Discussion

### *Soil organic matter*

Soil organic matter (SOM) differed between planting arrangements after 4 years of alley cropping (Table 4.2). The monocropping plots contained the lowest organic matter. Highest organic matter was measured in alley cropping planting arrangement CtCtCtCtC. In alley arrangement CCctCCC, higher organic matter was measured near trees. High SOM levels in alley arrangement CtCtCtCtC correlated with greatest amount of green manure produced (Table 4.3). Higher levels of SOM near trees in alley cropping planting arrangement CCctCCC compared to further away from trees also may be explained by additional green manure that originated from two sources: (1) tree leaves and shoots of the second pruning which were left in the tree row and (2) tree litter accumulating after the growing season near the trees after annual leaf fall.

Beneficial effects of alley cropping on soil organic carbon was initially postulated by Kang et al. (1980) and more recently confirmed by Mazzarino et al. (1993) who found higher soil carbon in alley cropping systems compared to monocropping after nine years.

In 1995 alley cropped corn plots had superior SOM content compared to alley cropping plots. However, the original 1991 level of OM was not maintained in any of the treatments (Table 2). SOM levels may only be increased through alley cropping when initial levels are low and green manure input is very high. This was the case in the study of Gunasena and Hitinayake (1987) who found significant SOM increases in alley cropping plots by the commencement of the second growing season. Between 4.8 and 7.4 t/ha of green manure was added to a soil in their system which had initially only 0.98% SOM. In soils with higher initial SOM, however, green manuring may not increase or maintain SOM until a lower equilibrium is reached that is specific to a particular soil and management (Jenny, 1930; Allison, 1973).

Percent tissue nitrogen of tree prunings is similar to many herbaceous green manure crops which often fail to increase SOM levels (Table 4.3). The role of percent tissue nitrogen is disputed. Leuken et al. (1962) suggested that higher green manure percent N resulted in less SOM accumulation. Chater and Gasser (1970) found more SOM accumulation when they used a higher percent N green manure, while Mann (1959) and Dehaan (1977) reported no correlation between the two factors. MacRae and Mehuys (1985) conclude that these differing results are likely a function of other interacting soil factors.

Table 4.2 Soil chemical properties in 1991 and 1995 in monocropping and alley cropping planting arrangements. Values are the means of 3 measurements each composed of 15 sub-samples. Different letters denote statistically significant differences between planting arrangements within the indicated soil depth at a p-value of 0.05.

Year	Depth cm	Planting arrangements Location in plot	% SOM	% Soil N (Kjedahl-N)	Phos./ ppm (Bray-P)	CEC meq/100g
1991	0-45 avg	all	2.55	0.135	42.3	33.2
	0-15		2.57	0.135	53.9	32.8
	15-30		2.52	0.134	47.5	33.0
	30-45		2.54	0.136	25.4	33.9
1995	0-45 avg	<u>CCCCCCC</u>	2.11 b	0.133 b	46.2 a	34.2 a
		<u>CtCtCtCtC</u>	2.30 a	0.138 a	50.2 a	33.9 a
		<u>CCCttCCC</u> near trees	2.26 a	0.141 a	48.3 a	33.5 a
		<u>CCCttCCC</u> away f. trees	2.19 ab	0.135 ab	45.0 a	33.9 a
	0-15	<u>CCCCCCC</u>	2.25 b	0.137 b	65.0 a	32.7 a
		<u>CtCtCtCtC</u>	2.34 ab	0.140 ab	66.7 a	32.5 a
		<u>CCCttCCC</u> near trees	2.41 a	0.150 a	69.0 a	32.8 a
		<u>CCCttCCC</u> away f. trees	2.37 a	0.142 ab	63.0 a	33.0 a
	15-30	<u>CCCCCCC</u>	2.05 b	0.129 a	49.7 a	34.0 a
		<u>CtCtCtCtC</u>	2.35 a	0.131 a	56.0 a	33.5 a
		<u>CCCttCCC</u> near trees	2.15 b	0.132 a	51.3 a	33.2 a
		<u>CCCttCCC</u> away f. trees	2.13 b	0.132 a	51.0 a	33.3 a
	30-45	<u>CCCCCCC</u>	2.04 a	0.132 a	24.0 a	36.0 a
		<u>CtCtCtCtC</u>	2.20 a	0.143 a	28.0 a	35.7 a
		<u>CCCttCCC</u> near trees	2.22 a	0.141 a	24.6 a	34.5 b
		<u>CCCttCCC</u> away f. trees	2.07 a	0.132 a	21.0 a	35.5 a

Table 4.3 Green manure production in alley cropping. Values show the average of 1993 to 1995. First pruning occurred immediately before crop planting; prunings were soil incorporated. Second pruning took place 6 weeks after planting; prunings were left next to trees as mulch. Leaf fall was determined at the end of the growing season.

Planting arrangement / Location in plot	1st pruning		2nd pruning		Leaf fall		Total biomass t/ha
	biomass t/ha	% N in tissue	biomass t/ha	% N in tissue	biomass t/ha	% N in tissue	
<u>CtCtCtCtC</u>	2.64	2.10	0.9	3.18	0.43	3.1	3.97
<u>CCctCCC</u> near trees	1.13	1.97	0.7	3.08	0.19	3.1	2.02
<u>CCctCCC</u> away f. trees	1.13						1.13

### *Soil Nitrogen*

Similar to organic matter, soil nitrogen (N) was always lowest in monocropping soil and highest in alley arrangements CtCtCtCtC or CCctCCC near trees (Table 4.3). Compared to the baseline values in 1991, soil N levels were slightly lower in the monocrop planting arrangement and higher in the alley crop planting arrangement indicating a beneficial effect of added tree prunings. High levels of soil N near the trees in CCctCCC might have been caused by nitrogen from the tree roots. Seiter et al. (1995) showed that nitrogen from tree roots entered the soil and contributed to the N supply of corn plants growing next to trees.

Nitrogen is the primary nutrient contributed from green manure (Westcott and Mikkelsen 1988). Russel (1973) notes that green manure is more effective as a N source than as a source of organic matter. The effect of green manure from tree prunings on soil N varies widely. Several studies indicate that the addition of tree prunings significantly increased soil N (Yamoah et al. 1986; Mazzarino et al. 1993). Other studies show N decline after several years of alley cropping (Mathews et al. 1992).

Even though we found higher N and SOM levels in alley cropping plots compared to monocropped plots, our findings confirm that over time, green manure either maintains or increases soil nitrogen levels or maintains or increases organic matter, but not both (MacRae and Mehuys 1985; Allison 1973). Swoden and Atkinson's work (1968) demonstrated that low soil nitrogen levels will result in a slower decomposition of organic material, increasing the chance of organic matter accumulation. However, there are a number of other interacting factors, such as pH and soil microbial activity, that determine soil N and organic matter content.

### *Phosphorus*

Soil phosphorus (P) levels increased in both monocrop and alley cropping planting arrangements compared to the 1991 baseline. However, no statistically significant differences between planting arrangements were detected (Table 4.2).

In tropical areas, phosphorus is often the most limiting soil nutrient because of the highly P-adsorbing nature of the soil. Green manure has been suggested to reduce P-adsorption thus increasing P mobility (Bhat and Mohaparta 1978). There are a number of alley cropping studies investigating the effects of trees and alley cropping on soil P level and availability. The results of these studies are inconsistent, indicating that variable soil and environmental conditions play a major role in the outcome of the investigation. For example, Lal (1989) found no consistent effect on soil P by adding tree prunings in an alley cropping trial. In some studies, alley cropping reduced soil P (Hagar et al. 1991). The study of Yamoah et al. (1986) showed that the quality of prunings play a major role. Alley cropping with *Gliricidia* reduced soil P while *Cassia* and *Flemingia* increased soil P levels. Hagar et al. (1991) suggests that despite the inconsistent effect of alley cropping on soil phosphorus content, the efficiency of P cycling is usually improved through the ability of trees to exploit P temporarily unavailable for the crop and the subsequent continuous release of crop-available P from tree prunings.

### *Cation Exchange Capacity*

During the four years of alley cropping, cation exchange capacity (CEC) nearly remained unchanged between 0-30 cm soil depth. Between 30-45 cm depth, CEC increased over time in both monocrop and alley cropping treatments indicating no specific effect of the green manure.

Only a few studies report measurements of CEC in alley cropping systems. One example is Lal's study (1989) which indicated that exchangeable bases declined in alley cropping and that this decline varied strongly depending on tree species. No explanation for the decline is given. The few reports available may suggest that CEC has not been measured or as in our study, findings were inconclusive.

### **Summary**

After four years of continuous sweet corn production, green manuring with prunings from *A. rubra* resulted in higher soil organic matter levels compared to monocropping. However, original values from 1991 could not be maintained in both alley cropping and monocropping systems. Thus, green manuring, only prevented a more rapid decrease compared to monocropping. Green manuring increased soil nitrogen levels but had no measurable effect on soil phosphorus and cation exchange capacity.

Soil organic matter accumulation and nitrogen supply to the crop are the primary objectives of green manuring (Bouldin 1988). It is difficult to achieve both at the same time because organic matter is only accumulated when green manure does not decompose, in which case organic N is not available to the crop. It is possible however, that green manure from trees may offer both, fast decomposable organic material that provides crop nutrients and slow decomposable organic material that contributes to organic matter accumulation in the soil. In the *A. rubra* alley cropping system, "fast-N" is derived from

tree roots (Seiter et al. 1995) and probably the leafy parts of the prunings while “slow-N” is provided by the bulk of the prunings. The latter, however, can cause nitrogen immobilization, and crops such as sweet corn need additional nitrogen fertilization to produce acceptable yield.

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**Chapter 5**  
**Soil microbial dynamics in a temperate climate**  
**alley cropping system**

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## **Abstract**

Soil bacterial and fungal dynamics were measured in an alley cropping system using direct microscopy techniques. The alley cropping system involved hedgerows of alder trees (*Alnus rubra*) and sweet corn (*Zea mays*) grown in the alleys. Trees were periodically cut, and prunings were incorporated into the soil as green manure. Active bacterial and fungal biomass were greatest in tree rows and declined with distance from the trees. At a distance of 150 cm from trees, bacterial and fungal biomass were similar to monocropping plots, suggesting that prunings had no detectable effect on microbial biomass. Pruning biomass may have been too small for measurable effects. Absence of tillage and additional substrate from tree roots contributed to higher microbial counts in tree rows.

## **Introduction**

Alley cropping systems represent hybrids of agricultural and natural ecosystems. In these cropping systems, annual crops are grown in alleys between hedgerows of trees. Trees are coppiced periodically and prunings are incorporated into the soil as green manure. Alley cropping systems are designed to integrate the soil enriching processes of forests ecosystems into agricultural production systems (Nair, 1984; Kang et al., 1985). A primary objective is to create nutrient cycles in which nutrients from prunings and other plant litter are efficiently recycled into new plant biomass. The microbial biomass plays a central role in this recycling process (Paul and Clark, 1989). Microbes are responsible for the biochemical degradation of the organic litter and convert nutrients from organic to plant available, mineralized forms (Coleman and Crossley, 1996). More than 90% of all nutrients pass through the microbial biomass to higher trophic levels (Kennedy, 1995).

The composition of the microbial community influences the transformation of plant residues into soil organic matter and plant available nutrients (Beare et al., 1993; De

Ruiter et al., 1993). Therefore, separate assessment of the decomposer groups is essential to understand soil microbial dynamics. Also necessary are methods that determine whether fungi and bacteria (the two dominant decomposer groups) are functional. Failing to distinguish between active and inactive microbial biomass may lead to erroneous conclusions regarding nutrient cycling processes (Hunt et al., 1987). An assessment of active biomass also is important when considering long-term development and sustainability of an ecosystem (Klein et al., 1995). Microscopic methods offer opportunities to determine the composition of the microbial biomass and an assessment of its activity.

The composition of the microbial biomass is influenced by quantity and quality of organic matter input (Killham, 1994). Both vary considerably between tree rows and alleys of an alley cropping system. The major components of organic matter input to the soil in alleys are crop residues and tree prunings. In tree rows, leaf litter and prunings are added to the soil. Substantial organic matter input also is derived from below-ground sources such as root exudates, sloughed nodules (when nodulated N-fixing trees are planted), and decomposing roots (Brussaard et al., 1993). Different management of organic matter inputs also influences the microbial composition (Neher, 1995). Leaving plant residue on the surface (i.e., prunings and leaf litter in tree rows) selects for fungi while soil incorporation of prunings and crop residue in alleys will shift the balance towards bacteria (Hendrix et al., 1986; Holland and Coleman, 1987).

The objective of our study was to determine microbial dynamics in temperate climate corn-alder alley cropping systems. Because of the green manure additions, we expected to find greater microbial biomass in alley cropping systems compared to monocrop systems. We also expected to find variations in microbial biomass and composition within the alley cropping system due to differences in organic matter input and management. We hypothesized that if trees provide microbial substrate in form of labile, nitrogen rich compounds from root litter, then microbial activity will be higher in soil close to the trees compared to soil away from the trees. In addition we hypothesized that differences in

organic matter management will shift the microbial composition toward bacteria in the alleys and fungi in the tree row.

## **Materials and Methods**

### *Study site and field operations*

The study was conducted at the Oregon State University Horticultural Research Farm in Corvallis on a Chehalis clay loam soil. Low precipitation during the growing season requires regular irrigation of row crops, which in our study was supplied by overhead sprinklers. In April of 1991, one-year-old red alder (*Alnus rubra*) seedlings were planted in plots measuring 9 by 4.5 m (Figure 5.1). From 1991 to 1995, sweet corn (*Zea mays* var. "Jubilee") was planted in alley cropping plots and monocropping plots. The experimental design involved a randomized block design, replicated in three blocks.

Corn seedbed preparation in the alleys involved chisel plowing and rotary hoeing. Each year, all plots were fertilized with 170 kg N, 130 kg P, 100 kg K ha<sup>-1</sup>. Nitrogen was split into two applications. The first application was broadcast at planting in ammonium form; the second was side dressed as urea, 6 weeks after planting. No pesticides were applied. Weeds were controlled by hand and mechanical cultivation. After corn harvest, corn stalks were mowed with a flail mower and left on the soil surface until next year's seedbed preparation.

Trees were cut 30 cm above ground level and prunings were shredded with a tree shredder shortly before corn was seeded during the first two weeks of June (i.e., first coppicing). Shredded prunings were incorporated into the top 10 cm of the soil with a rotary hoe during seedbed preparation. A second coppicing was performed 6 weeks after planting when the corn reached a height of 30 cm. These prunings were not shredded and left in the tree row on the soil surface.



Total and active components of fungal and bacterial biomass were measured. Active fungal and active bacterial biomass were determined by measuring the length and width of fluorescein diacetat (FDA) stained hyphae and counting the number of FDA-stained bacteria respectively, using epi-florescent microscopy. Total fungal biomass was determined using DIC microscopy by measuring the length and width of all hyphae in a known volume of soil (Ingham and Klein, 1984). Total bacterial biomass was determined by counting the numbers and measuring diameters of all bacteria in soil suspension stained with FITC and filtered on Nuclepore black-stained filters (Babiuk and Paul, 1970). Microbial biomass was determined by converting biovolume to biomass using standard factors recommended by Van Veen and Paul (1979).

Soil samples were collected before tree planting in May 1991 to establish baseline values of soil chemical properties. Four years later, in May 1995, soil in the alley cropping and monocropping plots was sampled from 3 soil depths: 0-15, 15-30, and 30-45 cm. In alley cropping systems, soil was collected at a distance of 30 cm and 150 cm from the trees. Each sample represented composites of 15 thoroughly mixed sub-samples. Samples were air dried for 72 hours at 80 °C. Soil samples were analyzed for soil organic matter (SOM) (Nelson and Summers, 1982) and total Kjeldahl nitrogen (Isaac and Johnson, 1976).

The data were analyzed using SAS software (SAS 1987). Analysis of variance was performed for microbial biomass and soil chemical properties. When a significant treatment effect was found, standard errors were calculated and the Waller- Duncan method was used to compare treatment means.

## **Results**

### *Fungal biomass*

On several sampling dates, significant differences in active fungal biomass between the three sampling locations in the alley cropping system were observed (Figure 5.2a). Highest active fungal biomass occurred in the tree row (T), intermediate biomass on the

inside (I) and lowest biomass in the middle of the alley (M). The exception to this trend was the sampling in May 1994 when fungal biomass was similar in all three locations. In July of both sampling periods, we observed no significant differences between the two alley locations. However, fungal biomass in both alley locations was significantly lower than in the tree row.

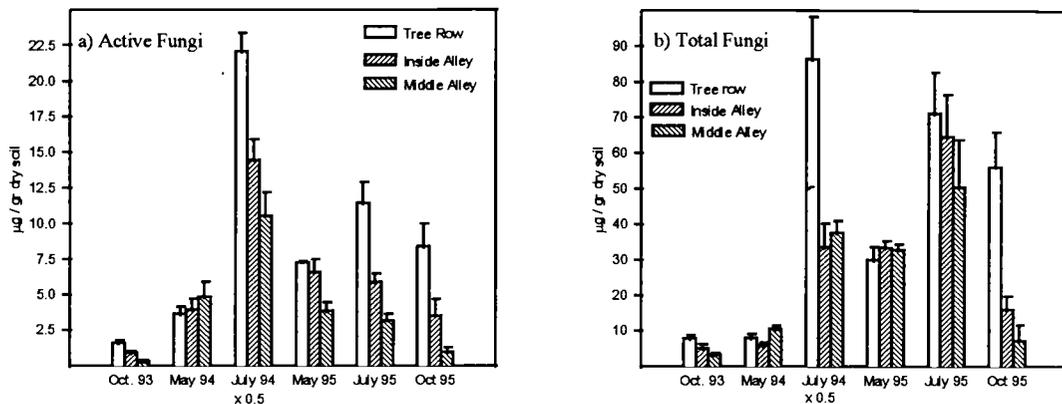


Figure 5.2 Fungal biomass in 3 sampling locations of an alley cropping system. Soil samples for “Tree row” were collected between trees of the double tree row, “Inside alley” samples were collected at a distance of 0.5 m from trees, and “Middle alley” samples were collected at a distance of 1.5 m from trees. Values shown are mean values of 3 replicate samples. Error bars represent standard errors of the means.

Active fungal biomass also changed seasonally. From May to July 1994, activity increased in all locations. Active fungal biomass increased approximately 12 fold in the tree row and 4 fold in the alley. In 1995, seasonal trends differed between sampling locations. Fungal biomass increased in the tree row between May and July and decreased in October. In the alley, we observed a decrease from May through July and October. Seasonal differences in the two alley locations were insignificant, except for the decrease from July to October in the middle of the alley.

Trends in total fungal biomass were less consistent compared to active fungal biomass. We observed significantly higher biomass in the tree rows only on two sampling dates (Figure 5.2b). On other dates, we found similar biomass in the three sampling locations or differences that fit no particular pattern. Seasonal changes of total fungal biomass mirrored those in active fungal biomass, both peaking in July. In 1995, total fungal biomass in the tree row remained high from July through October but decreased significantly in the alley. Comparisons between the same dates of the two sampling periods show that fungal biomass was similar in July 1994 and 1995, but was higher in May and October of the second sampling period.

#### *Bacterial biomass*

Mean active bacterial biomass was highest in the tree rows, except in May 1995 (Figure 5.3a). Differences between tree rows and alleys were statistically significant only in the last two sampling dates. Seasonal trends of active bacterial biomass were inconsistent across sampling locations and years. For example, in 1994, we found no significant changes from May to July. In 1995, however, we observed seasonal variations that differed between sampling locations. Active fungal biomass in the tree row increased from May to July and decreased in October. In the alley, on the other hand, the biomass decreased from May through July and October.

In 1995, we observed similar total bacterial biomass in all sampling locations (Figure 5.3b). The variations on earlier sampling dates did not follow a particular pattern. Seasonal trends of total bacterial biomass were different from those of fungal biomass. Bacterial biomass was greatest in May and decreased through July and October during both sampling periods while total fungal biomass was usually highest in July. We also observed a year to year differences in bacterial biomass. It is likely that the low bacterial biomass in October of the first year was caused by a lack of moisture. Because of the warm 1994 growing season, the corn was harvested early (September 8) and less than 12 mm of rainfall fell between the time when irrigation was turned off and microbial biomass

sampling on October 15 (Figure 5.4). In 1995, the harvest occurred later (September 19) extending the irrigation into mid-September. In addition, more rain fell prior to the soil sampling, creating favorable soil conditions and a less dramatic drop of bacterial biomass.

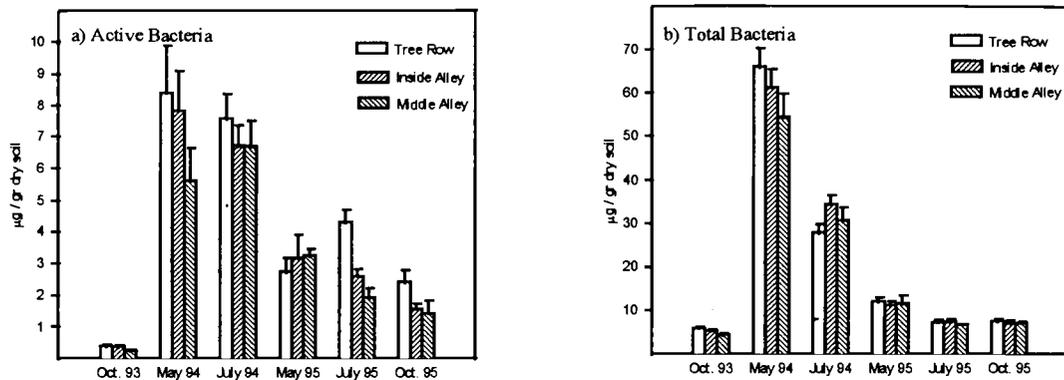


Figure 5.3 Bacterial biomass in 3 sampling locations of an alley cropping system. Soil samples for “Tree row” were collected between trees of the double tree row, “Inside alley” samples were collected at a distance of 0.5 m from trees, and “Middle alley” samples were collected at a distance of 1.5 m from trees. Values shown are mean values of 3 replicate samples. Error bars represent standard errors of the means.

#### *Ratio of Fungi to Bacteria*

We observed significant differences in the ratio of total fungi to bacteria between the sampling locations on two sampling dates (Figure 5.5). In July 1994 and October 1995, this ratio was more than 3 times larger in the tree row than in the alley. Seasonal trends in the ratio of fungal to bacterial biomass generally were characterized by an increase from May to July followed by a decrease in October. However, it remained high in the tree row during October 1995 while it dropped significantly in the alley.

The ratio of total fungi to bacteria in the tree row and on the inside of the alley was higher in 1995 compared to the same months in 1993 and 1994. However, in the middle of the alley, the values in October 1993 and 1995 were similar and had decreased to below one.

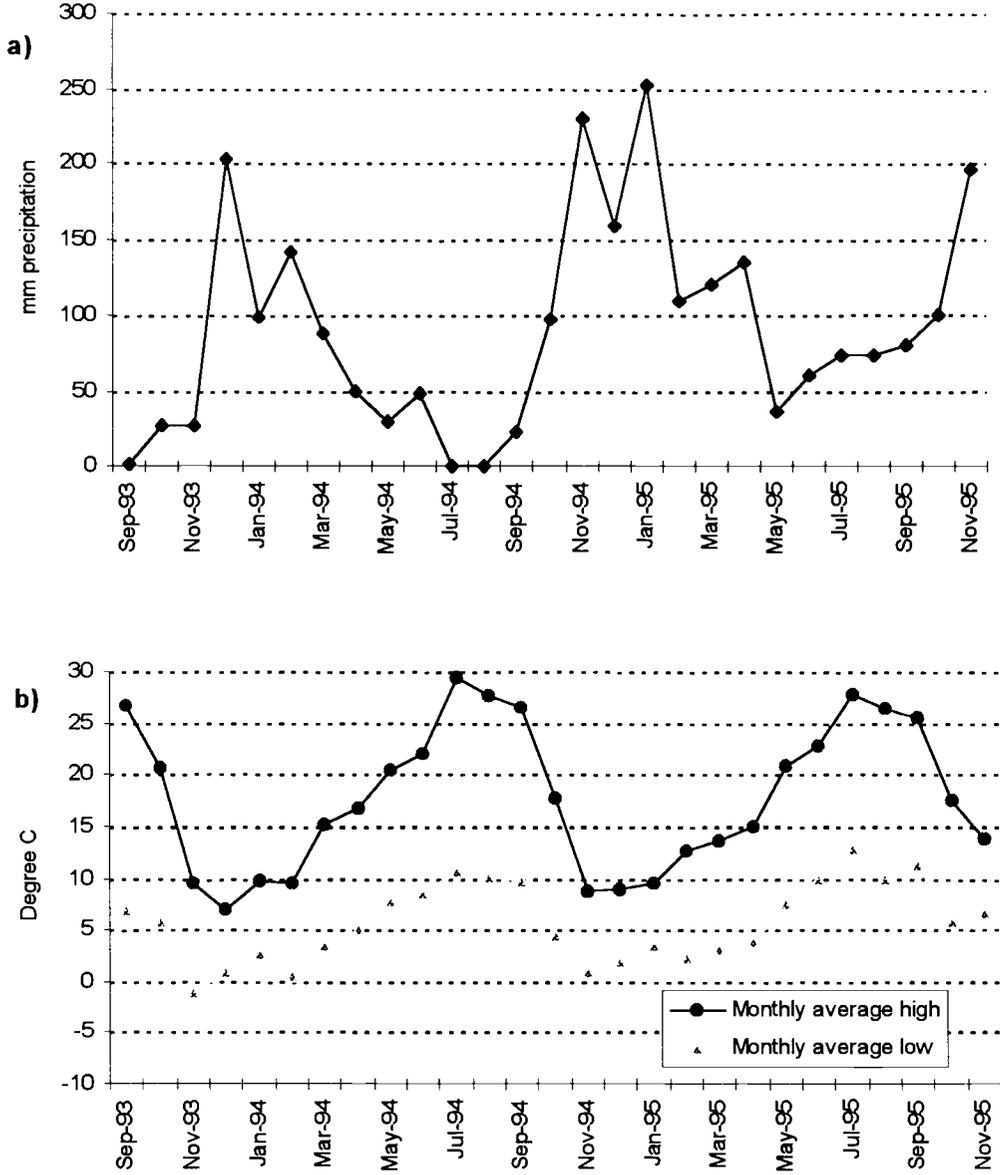


Figure 5.4 Monthly average (a) precipitation and (b) temperatures at the study site during the experimental period.

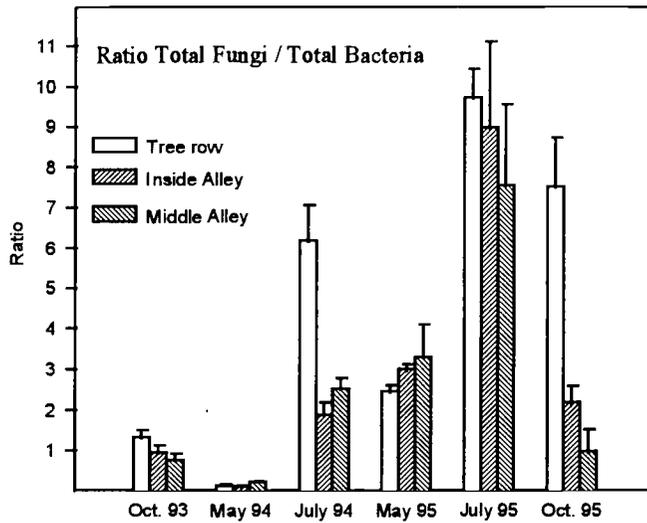


Figure 5.5 Ratio of total fungi to total bacteria in 3 locations of an alley cropping system. Soil samples for “Tree row” were collected between trees of the double tree row, “Inside alley” samples were collected at a distance of 0.5 m from trees, and “Middle alley” samples were collected at a distance of 1.5 m from trees. Values shown are mean values of 3 replications. Error bars represent standard errors of the means.

#### *Comparison between alley cropping and monocropping systems*

We found higher active and total fungal, and active bacterial biomass in the tree row of the alley cropping system compared to the monocropping system (Table 5.1). However, when we compared the soil in the monocropping system with the soil in the alley cropping area that received the shredded prunings but was treated the same otherwise (i.e., sampling location “M” of the alley cropping system), bacterial and fungal biomass was similar throughout the growing season.

Table 5.1 Microbial biomass ( $\mu\text{g} / \text{gr}$  dry soil) in alley cropping systems and monocropping. Sampling location "T" indicates tree row, "I" indicates inside of the alley at a distance of 50 cm from trees, "M" indicates middle of the alley at a distance of 150 cm from trees. Values shown are means of 3 replicate measurements. Different letters denote statistically significant differences between sampling locations at a p-value of 0.05.

	Cropping system / Sampling location	Sampling date					
		Oct. 1993	May 1994	July 1994	May 1995	July 1995	Oct. 1995
Active fungal biomass $\mu\text{g}/\text{gr}$ dry soil	Alley cropping / T	1.6 a	3.6 a	44.1 a	7.3 a	11.4 a	8.4 a
	Alley cropping / I	0.9 b	4.0 a	28.9 b	6.6 a	5.9 b	4.6 ab
	Alley cropping / M	0.3 c	4.9 a	21.1 b	3.8 b	3.3 b	0.9 b
	Monocrop				3.6 b	3.6 b	3.2 b
Total fungal biomass $\mu\text{g}/\text{gr}$ dry soil	Alley cropping / T	7.7 a	8.1 a	172.8 a	30.0 a	71.0 a	56.0 a
	Alley cropping / I	5.1 ab	5.8 b	67.4 b	33.5 a	64.6 a	16.0 b
	Alley cropping / M	3.2 b	10.6 a	75.4 b	32.8 a	50.4 b	7.2 b
	Monocrop				33.8 a	56.7 b	18.6 b
Active bacterial biomass $\mu\text{g}/\text{gr}$ dry soil	Alley cropping / T	0.4 a	8.4 a	7.6 a	2.7 a	4.3 a	2.4 a
	Alley cropping / I	0.4 a	7.8 a	6.7 a	3.2 a	2.6 b	1.6 ab
	Alley cropping / M	0.3 a	5.6 a	6.7 a	3.2 a	1.9 b	1.4 b
	Monocrop				3.0 a	2.1 b	1.2 b
Total bacterial biomass $\mu\text{g}/\text{gr}$ dry soil	Alley cropping / T	5.3 a	66.1 a	27.9 b	12.1 a	7.2 a	7.4 a
	Alley cropping / I	5.3 ab	61.4 a	34.6 a	11.2 a	7.4 a	7.1 a
	Alley cropping / M	4.4 b	54.5 a	30.8 ab	11.6 a	6.7 a	7.1 a
	Monocrop				11.3 a	6.4 a	7.7 a

We also compared soil chemical properties in the cropping area of both cropping systems. Differences were observed in the top 15 cm of the soil but not in the soil layers below (Table 5.2). We observed higher organic matter content and Kjeldahl-N in the top soil of the alley cropping locations. However, organic matter content in the monocropping and all locations of the alley cropping system were below the baseline values of samples taken in 1991, before the first season of alley cropping.

Table 5.2 Soil organic matter and soil nitrogen in cropping areas of the alley cropping and monocropping systems. 1991 measurements represent baseline values before alleycropping was practiced. 1995 measurement were taken in May, before the fourth year of sweet corn alley cropping. Sampling location "I" indicates inside of the alley at a distance of 50 cm from trees, "M" indicates middle of the alley at distance of 150 cm from trees. Values are means of 3 measurements each composed of 15 sub-samples. Different letters denote statistically significant differences between sampling locations within the indicated soil depth at a p-value of 0.05.

Year	Soil Depth	Cropping system / Treatment	% SOM		% Soil N (Kjedahl-N)	
1995	0-15 cm	Alley cropping / I	2.41	a	0.150	a
		Alley cropping / M	2.37	a	0.142	ab
		Monocrop	2.25	b	0.137	b
	15-30 cm	Alley cropping / I	2.15	b	0.132	a
		Alley cropping / M	2.13	b	0.132	a
		Monocrop	2.05	b	0.129	a
	30-45 cm	Alley cropping / I	2.22	a	0.141	a
		Alley cropping / M	2.07	a	0.132	a
		Monocrop	2.04	a	0.132	a
1991	0-15 cm	All	2.57		0.135	
	15-30 cm		2.52		0.134	
	30-45 cm		2.54		0.136	

## Discussion

### *Substrate from above-ground organic matter sources*

Tree prunings and crop residue are the major organic matter inputs into the alley soil, providing the substrate for microbial growth and, ultimately, nutrients for the crops. In our study, however, we did not observe significant differences in microbial biomass between the alleys and the monocropping system, suggesting that the annual addition of prunings were too small. Pruning yield in the present study (Table 5.3) was low compared to alley cropping systems in tropical and subtropical regions. Significant changes of microbial biomass (measured with chemical methods) were found in tropical alley cropping systems when the pruning biomass was much greater than in our study. For example, Van der

Mersch et al. (1993) found consistently higher microbial biomass in alley cropping systems than in a monocropping control after adding 21.7 t ha<sup>-1</sup> of *Leuceana leucocephala* and 15.23 t ha<sup>-1</sup> of *Senna siamea* prunings in one year. Similarly, Kachaka et al. (1993) found significantly higher microbial biomass C in soil that was amended with alley cropping prunings compared to controls.

Table 5.3 Above-ground organic dry matter (DM), carbon (C) and nitrogen (N) added to the soil in the alley cropping system. Values are means of 3 samples.

year	Above-ground organic matter input								
	Prunings 1st coppice			Prunings 2nd coppice			Leaf fall		
	DM t/ha	C kg/ha	N kg/ha	DM t/ha	C kg/ha	N kg/ha	DM t/ha	C kg/ha	N kg/ha
1993	0.74	370	14.6	0.27	135	8.3	0.16	80	4.96
1994	0.85	425	16.7	0.18	90	5.5	0.19	95	5.89
1995	0.95	490	18.7	0.41	205	12.6	0.21	105	6.51

However, in other studies with high pruning inputs, results were less conclusive. For example, Haggar et al. (1993) added 7.9 t ha<sup>-1</sup> of *Erythrina* and 11.4 t ha<sup>-1</sup> yr<sup>-1</sup> of *Gliricidia* prunings in an alley cropping system in Costa Rica. They observed that microbial N was 30% higher in alley crop treatments than the monocrop only at 105 days after the application of prunings but not at earlier or later sampling dates. Mazzarino et al. (1993) found no effect of pruning additions on microbial C and N in one season unless carbon inputs in the form of prunings and crop residues were more than 400% higher than in a control. Conflicting results of the effect of added prunings are likely due to interacting factors such as differences in soil, climate conditions, and the quality and quantity of organic matter input. The quality of organic matter deserves special consideration when comparing alley cropping and annual green manure studies. The added prunings in alley cropping consist of a unique mix of plant material of varying

decomposability (Kachaka et al., 1993) and may therefore affect soil microbes in a much different fashion than annual green manure residue.

In the tree row and the inside of the alley, green manure also originated from prunings of the second coppicing and leaf fall in the end of the growing season. The additional green manure from the second coppicing was not distributed across the entire plot but stayed near the trees. This organic matter input may have contributed to the observed higher active bacterial biomass in the tree rows in July (Figure 5.3a). Haskins et al. (1994) noted that low but concentrated organic matter input in arable cropping system leads to high bacterial activity but not necessarily high bacterial biomass.

In contrast to prunings of the first coppicing, plant residues of the second coppicing were not incorporated into the soil but stayed on the soil surface. More than other decomposers, fungi are able to use plant residues that are deposited on the soil surface because of their ability to grow across air filled space (Killham, 1994; Neher, 1995). The increased fungal biomass in the tree row and the inside alley during the July and October samplings may reflect the use of these prunings as a fungal substrate. During the May samplings, availability of annual crop residue as substrate for microbes in the alley eliminated any differences between locations. Each year, approximately  $2 \text{ t ha}^{-1}$  of corn residue was left shredded on the soil surface during the winter fallow.

Tree litter inputs near the trees may have contributed indirectly to the increased microbial activity because it provided substrate for the soil fauna. We observed that tree leaves appeared to be a favorite food source for earthworms (*Lubricus terrestris*) on our study site. Several weeks after the trees had shed their leaves, most tree litter had been pulled into earthworm channels. Similar to Hauser (1992), we observed significantly more earthworm casts in the vicinity of the hedgerows. Near the trees, earthworms, therefore, provide physical habitat and nutrient-rich substrate for soil bacteria and fungi.

*Substrate from below-ground tree litter*

Higher fungal and bacterial biomass in tree rows for most of the cropping season may have been caused by microbial substrate derived from below-ground organic matter. Decomposing fine roots and root exudates represent an important carbon source for microbes (Clarholm, 1985; Newman, 1985; Bradely and Flyes, 1995; Swinnen et al., 1995) and root effects on microbes extend beyond the immediate rhizosphere (Parmelee et al., 1993). Sloughed nodules and rapid fine root turnover also may have provided a nitrogen source for the microbes near alley cropping trees which contain up to 60 percent of the total plant N in their roots (Sanginga et al., 1990).

Root activity also may explain seasonal differences in the alley cropping system. Under present climate conditions, a peak of microbial growth usually occurs in spring, explaining the high values of bacterial biomass in the May samplings. During this time, rapid plant growth of the native alley vegetation and trees is accompanied by high root activity, which provides the necessary substrate for the microbial development (Lynch and Painting, 1980; Patra et al., 1995). Bacterial biomass remained high from May to July. The high July values in the alleys may actually present a second peak during which bacteria, after being reduced during seedbed preparation, responded to favorable conditions provided by rapid corn root growth coupled with ample soil moisture from irrigation. More frequent sampling could have helped to elucidate short-term microbial biomass fluctuations.

Near the trees, microbes likely responded to root substrate released after coppicing. Coppicing increases the speed of fine root turnover (Fernandes, 1991) and the speed of exudation of nitrogen rich root compounds. Danso et al. (1992) found that severe coppicing of *L. leucocephala* resulted in death of half of the nodules. Bokhari and Singh. (1974) demonstrated increased exudation when they removed herbage from annual plants. Ingham et al. (1985) found that clipping of range land grasses stimulated bacterial growth and overall microbial activity. Our hypothesis that nutrients from tree roots constitute an important microbial substrate source is supported by a separate study in which we found that *Alnus sinuata* trees labeled with  $^{15}\text{N}$  released a substantial amount of nitrogen from

roots into the soil. Soil microbe mediated transfer of  $^{15}\text{N}$  to corn plants growing in a distance of 0.63 m from the trees occurred within six weeks (Seiter et al., 1995).

### *Soil disturbance*

Differences in tillage between alleys and tree rows also contributed to changes in microbial biomass and composition. Fungal growth in alleys may have been adversely affected by tillage resulting in significant differences in fungal biomass between the alley cropping locations at the sampling dates after cultivation (i.e., July and October). Tillage often is more detrimental for fungi than bacteria because fungi grow as long strands easily broken during break-up of soil particles. In addition, fungi recover more slowly from a disturbance because of slower metabolic activity, longer generation time, and higher degree of food and habitat specialization (Andr n et al., 1990). As a result, fungi dominate the microbial biomass in undisturbed forest ecosystems and no-till agricultural systems (Hendrix et al., 1986; Holland and Coleman, 1987; Kennedy, 1995).

Tillage near the trees during seedbed preparation likely severed tree roots established during the previous growing period. The resulting tree root litter may have been used as microbial substrate. Rommel (1938) recognized that severing tree roots during trenching experiments can significantly affect microbial biomass.

### **Conclusion**

Management of soil microbes plays a key role in the effort to synchronize green manure nutrient release and crop nutrient uptake. This effort remains challenging because soil microbial dynamics are the result of many interacting factors. Our study showed that quality and quantity of plant residue interact with management activities such as coppicing and tillage. Below-ground organic matter sources also appeared to play a significant role in microbial dynamics. Other interactions were evident in seasonal changes when, for example, climate conditions favored microbial growth but management activities limited

substrate availability. Closer spaced sampling intervals would have provided a better insight into these interactions since microbial biomass and composition react quickly to changing conditions.

Differences in the response of fungi and bacteria to the alley cropping treatment demonstrated the need to distinguish between these two decomposer groups. Neher (1995) suggested that inclusion of perennial crops in agricultural systems shifts the soil foodweb more toward an ecosystem that is characterized by a higher fungi to bacterial ratio. In the uncropped area, we were able to confirm this hypothesis. However, in the cropped area the amount of incorporated prunings is critical. When pruning biomass is small along with frequent tillage no shift toward a fungal dominated ecosystem is evident in that part of the alley cropping system. The effects of larger green manure quantities on multiple trophic food web levels need to be examined to draw further reaching conclusions.

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**Chapter 6**  
**Dynamic systems modeling in a graphic-interactive simulation**  
**environment: a case study from agroforestry**

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**Manuscript to be submitted to Bioscience**

## **Summary**

The potential of modeling dynamic system interactions with STELLA, a recently developed software that uses an interactive simulation environment is discussed. An overview of model types and modeling approaches is followed by a case study describing the development of a STELLA model that simulates light penetration into an alley cropping canopy. Three activities are discussed: (1) creating a structural diagram, (2) simulating the outcome of the system interactions and (3) analyzing the response of the system to variation of certain conditions.

## **Introduction**

The research presented in this paper is part of a four-year study that explored various aspects of temperate climate alley cropping. The introduction of tree hedgerows in row crop production systems causes complex interactions among plant components. In irrigated, highly managed cropping systems where water and nutrient supplies are easily adjusted, partitioning of the light environment plays a major role in growth of both trees and crops. Modeling the light conditions in an alley cropping system provides opportunities to optimize the design of plant arrangements and the selection of appropriate plant species.

In this paper, we discuss the potential of modeling dynamic system interactions with STELLA, a recently developed software that uses an interactive simulation environment. We first give an overview of model types and modeling approaches before describing the development of a STELLA model that simulates light penetration into an alley cropping canopy.

## **Modeling in agriculture**

### *Model types*

Models are simple representations of complex “real world” systems. In agricultural research and management, models are constructed to increase scientific understanding, identify knowledge gaps and support agricultural decisions (Rimmington and Charles-Edwards 1987). Models of agricultural systems are designed on various organizational levels such as field, farm, and region (Teng et al. 1995, van Keulen and Wolf 1986). Field level models which address biological and ecological interactions as they relate to agricultural production, are the most prominent ones found in the agricultural literature. Farm and regional level models have only recently emerged to understand resource flows on larger scales.

On each organizational level, three basic types of models are used: (1) diagrammatic models that identify the major components and processes in a system; (2) empirical models that describe experimental data with a mathematical relationship; and (3) mechanistic models that elucidate the mechanisms of the interactions between the components of a system. One type of mechanistic model frequently used in agriculture are dynamic system models (i.e., simulations) that allow modelers to study dynamic processes over time (Kropff and van Laar 1993). Typical examples in agriculture include plant growth models which now exist for most major crops in the United States (Jones and Kinry 1986, Maas and Arkin 1980, Wilkerson et al. 1983).

### *Uses of dynamic systems modeling*

There are two basic steps in the development of a dynamic system model. The first step in the modeling process is the creation of a conceptual model (Hall and Day 1977). Conceptual models often are expanded into structural diagrams that facilitate the modelers’ understanding of the system’s behavior and their ability to communicate this behavior to other interested parties.

The second step in dynamic system modeling is the development of a simulation model that quantifies interactions between system components by defining mathematical relationships. Simulation models are used to explore the dynamic behavior of systems over time. This gives agriculturists an opportunity to analyze the response of a system to variation of certain factors and assess consequences of environmental or human influences. The quantitative nature of dynamic system models also creates opportunities to test the validity of field data and, more importantly, test assumptions derived from this data. In addition, dynamic systems models are excellent learning tools to generate and test hypotheses, thereby closing some of the existing knowledge gaps in agricultural science.

#### *Obstacles of dynamic system modeling*

Modelers are confronted by a number of obstacles when creating structural model diagrams or constructing simulation models. Common types of structural diagrams include causal loop diagrams and flow charts (Richardson 1991, Wilson and Moren 1990). The choice of an appropriate symbolic language used in these diagrams (usually icons or words) is crucial for the success of the modeling effort. A systems diagram may fail to communicate the structure of a system if functions are not clearly defined. For example, word- and icon-based diagrams typically depict a process (e.g. plant growth) with the same symbol as a quantity (e.g. plant biomass). In addition, structural diagrams often fail to distinguish between material flows and feedback linkages, both usually represented with solid lines. These shortcomings were recognized by Forrester, who developed the industrial dynamics language (Forrester 1961) and Odum (Odum and Odum 1976). Odum's symbolic energy language is built around 14 graphical symbols and has been used to model a wide range of dynamic systems including agricultural situations. With Odum's energy language, modelers are able to diagram a dynamic system in great detail. The same detail (made possible by the large number of graphic symbols), however, also results in diagrams that are difficult to analyze and communicate to others interested in a particular model.

The integration of mathematical models into computer models has allowed agriculturists to describe and predict the outcome of complex interactions between system components. However, there have been major operational obstacles for agriculturists who are interested in quantifying the relationships in a dynamic system. Traditionally, the development of a simulation model, including its construction, parameterization, and validation, has been a major time drain because modelers had to acquire a very specialized knowledge to accomplish these tasks. For example, predictive modeling required a detailed understanding of programming languages such as FORTRAN or PASCAL (Wolf et al. 1986). A relatively high skill level in differential equations, linear algebra, and matrix analysis also was required. Recently developed modeling tools, however, help address such obstacles. These modeling tools feature a graphic-interactive simulation environment, offering new opportunities for both those interested in creating explicit, unambiguous model diagrams and those interested in developing simulation models of dynamic processes in agricultural systems.

### **Modeling in a graphic-interactive simulation environment**

New modeling tools use a graphic user interface (GUI), taking advantage of a user's intuitive understanding of completing certain tasks. These modeling tools enable the modeler to create structural diagrams that communicate systems behavior more clearly because each graphical symbol in the model has a defined function. The modeling language in tools such as STELLA, VENSIM, or POWERSIM are built around graphical symbols similar to those used in Forrester's industrial dynamics language and Odum's symbolic energy language. Several of these symbols are combined into major building blocks. Models in STELLA (Systems Thinking Experiential Learning Laboratory with Animation), for example, are constructed with four building blocks (Figure 6.1): (1) *stocks* corresponding to Forrester's state variables; (2) *flows* corresponding to rates or flow valves; (3) *converters* corresponding to driving and auxiliary variables; and (4) *connectors* corresponding to information or effect flows. The differentiation of system components

into separate building blocks helps make the system structure less ambiguous and creates concrete connections between the system process and its structure.

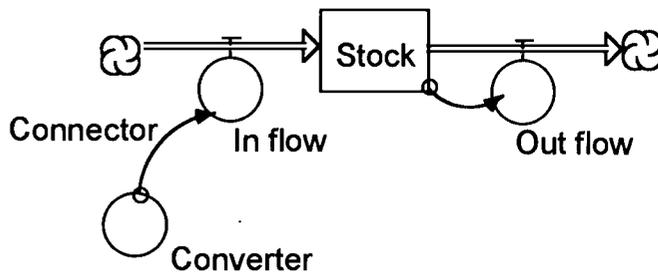


Figure 6.1 Basic building blocks in STELLA

A graphic-interactive simulation environment also simplifies construction and analysis of quantitative models. In his text book on modeling and simulation, Bossel (1994) summarizes advantages graphic interactive modeling compared to the traditional modeling approach: *“Although a set of differential equations contains the same information as its equivalent simulation diagram, graphical presentation of the model structure is intuitively much more easily understood by most people; it can be more easily changed and complemented; it is better suited as a common basis for discussion; and it is more easily and clearly communicated to others.”* In addition, influences on system behavior can be explored without sophisticated mathematical knowledge (Steed 1992). In STELLA, interactions between variables can be defined graphically, avoiding the use of complicated mathematical expressions for the definition of nonlinear relationships. STELLA employs an interactive input structure that significantly reduces the time required for model construction. Constanza (1987) notes that the ease of use makes simulation modeling feasible for the average research scientist. However, despite this simplicity, modelers are still able to run rigorous simulations (Richmond 1993).

Modeling in STELLA highlights the basic elements of systems: hierarchy, model components and their interactions, input and output, and model boundaries. Hierarchy is highlighted in two ways: model layers and submodels. In STELLA's modeling environment, the modeler navigates between a high level mapping layer, a model construction layer, and equations. Within the construction layer, submodels can be generated. Model components (building blocks) each have defined function as described above; rules define how the variables can be connected. Model boundaries are clearly defined in STELLA. For example, groups of variables are assembled in the boundaries of sectors. The sectors (or subsystems) can be simulated separately or in concert with the whole systems model.

In the following paragraphs we describe the development of an agroforestry model using STELLA. We focus on model construction to highlight major features of model and the interactive modeling environment. The potential of model validation and parameterization in this modeling environment is discussed briefly.

### **A case study: modeling light penetration in an alley cropping system with STELLA software**

#### *Theory*

Modeling the light environment in crop canopies is a key task in plant growth modeling because of the direct relationship between intercepted light and biomass production (Monteith 1965). Monocultures, with leaves homogeneously distributed in the horizontal plane, represent the simplest form to which mathematical formulas of light interception and attenuation can be prescribed. A model becomes more complex when plants grow in a row crop configuration (Thornely and Johnson 1990). Even more challenging is the description of the light environment in cropping systems that feature a mixture of plants species. This is the situation modelers face in an alley cropping system, where annual

crops are planted between hedgerows of trees. Typical management activities in this cropping system introduce yet another level of complexity. Alley cropping trees, for example, are periodically coppiced to provide green manure or mulch and to prevent shading of the annual crops. Coppicing during crop growth may cause sudden, localized changes in the light environment of an alley cropping system.

Mutual shading among and between species in an alley cropping system can significantly reduce crop and tree yield (Singh et al. 1989). The degree of shading during a certain time period is a function of plant arrangement and transmissivity of the plant canopies. Light attenuation in a canopy is generally described by the equation:  $I_{(a)} = I_{(in)} e^{-kl}$ , where  $I_{(a)}$  and  $I_{(in)}$  are the irradiances above and within the canopy respectively at cumulative leaf area index  $l$  and  $k$ , known as the extinction coefficient (Thornely and Johnson 1990). This formula is based on the Beer-Lambert law in physics. It postulates that the flux loss of a light beam passing through a medium other than free space is proportional to thickness of the medium and a coefficient which expresses the medium's transmissivity. Thus, light penetration into a canopy can be expressed as a function of vegetation thickness or light beam length in the canopy (Vandermeer 1989). The fraction of light inside the canopy is thus:  $I_{(a)}/I_{(in)} = 1 - e^{-Kl}$  where  $l$  is light beam length. Light beam length is variable and changes with the direction of the light beam and canopy thickness while  $K$  represents a constant. Hence, the main task during the model construction phase is to accurately model light beam length. Choosing an appropriate coefficient is part of model parameterization, a step completed later during the model development.

The following paragraphs describe the integration of the theory into a STELLA model of light penetration in an alley cropping system. Three activities are discussed: (1) creating a structural diagram, (2) simulating the outcome of the system interactions and (3) analyzing the response of the system to variation of certain conditions.

### *Creating a structural diagram*

The major tasks involved in creating a structural diagram are the same as those involved in the development of a conceptual model: (1) stating the problem, (2) defining the model purpose, (3) bounding the model in time and space, and (4) determining subsystems, key variables, and interactions. In most alley cropping systems tree and crop rows are grown close enough for mutual shading to occur. Designing a system that minimizes mutual shading requires intimate knowledge of the light environment in the systems canopy. The purpose of our model was to predict light penetration into the alley cropping canopy and explore management options such row distance, time of tree coppicing, or the effect of different tree species on light intercepted by the crop. The purpose effectively defined the spatial model boundary (i.e., field plot level). Temporal boundaries were defined by our objective to model light penetration over the course of one cropping season. Initially we used a daily time step (modeling light penetration at a certain time of day). More advanced model designs not described in this paper involved an hourly time step.

Model design in STELLA is accomplished on the model construction layer which features a mapping and a modeling mode. The mapping mode is used for the construction of the structural diagram including the main components and their interactions. In the design of a basic, conceptual model we assumed uniform height and diameter growth for crops and trees which resulted in a model of light penetration into a monocrop canopy (Figure 6.2).

We identified light beam coordinates and the light environment as interrelated subsystems. Design features in STELLA, such as sector frames around groups of variables and clouds which represent undefined sources or sinks, clearly outline system and subsystem boundaries. Key variables are defined within each of these subsystems. The model specifies state variables (stocks represented by rectangular boxes), constants and defined variables (converters represented by circles), inflows and outflows (flow valves regulating the stocks), and feedbacks. State variables in our model were plant growth parameters, such as row height and diameter. Length of the shadow, number of rows that a light beam hits when traveling at a certain angle, and light beam length can be directly computed from

the momentary values of the state variable and model parameters (e.g. row spacing). These variables are represented as circles.

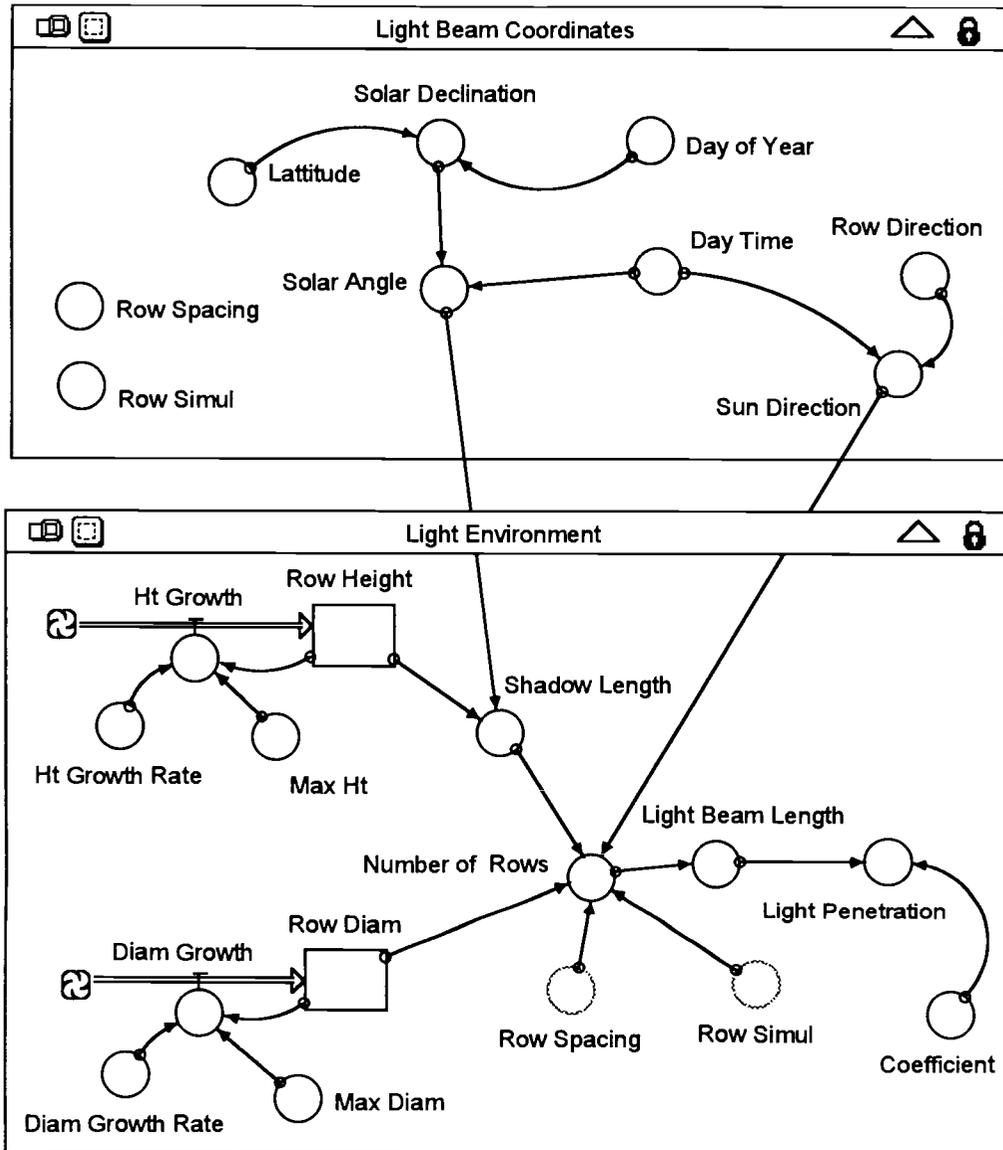


Figure 6.2 Structural model of light penetration into an alley cropping system

A second model design featured independent crop and tree growth rates for each individual row. The diagram representing this system featured row submodels for each of the plant rows (Figure 6.3). Embedded in each of the submodels were the same elements as in the basic model.

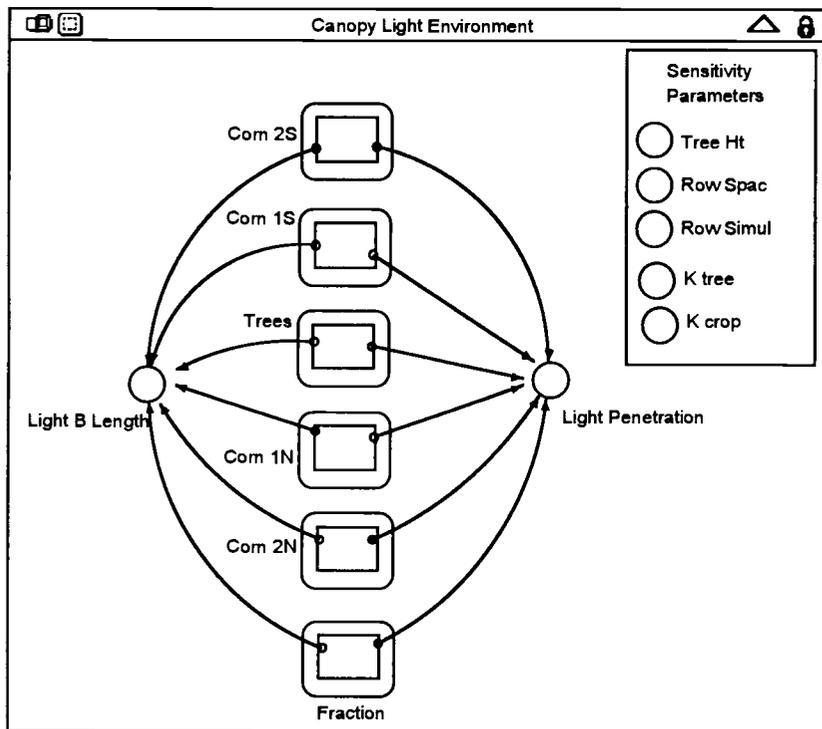


Figure 6.3 Structural model of light penetration including row submodels

#### *Simulating the outcome of system interactions*

Simulations require definition of mathematical relationships between system variables. This task is accomplished in STELLA in the modeling mode on the model construction layer. When switching from the mapping mode where the structural diagram has been constructed to the modeling mode, a “?” appears in each building block which has not been fully defined. Upon selecting a building block, the interactive input structure requires

the user to define the relationships between the building block and all variables that are connected to it via connectors or flows. Logical and mathematical built-in functions facilitate the definition of complex relationships. STELLA automatically generates a list of simultaneous equations specified by the model. The equations can be viewed by toggling to the equation layer.

Wide-row configurations, such as those in alley cropping systems, are amenable to geometric simplification because clumped leaf elements (i.e., canopies) and gaps are regularly distributed (Allen 1974). For the purpose of our simulation, we assumed that the cross sectional area of crop and tree rows are rectangular, described by a certain row height and diameter. Trigonometric relationships could therefore be used to calculate light beam length through each row. During the initial simulations, we assumed uniform density of leaves within this cross section. Initially, light beam length was calculated for each day of the season at solar noon for an alley cropping system in which crop and trees rows are planted in east-west direction (i.e., light beam perpendicular to the rows). Solar angle, declination, and sun direction as a function of latitude, longitude, and time of the year and day were computed according to Hodges and Evans (1990). Sun direction defines the light beam angle relative to the plant rows and is required only for times other than solar noon.

Field data of crop and tree row height and diameter (collected during the 1996 growing season) were used for the simulation. STELLA input functions facilitate field data entry into a model. Field data can be entered as numeric values or more conveniently, as a graphical relationship between time and a particular input variable (e.g. crop row height). The definition of a relationship, however, changes how variables are displayed in a STELLA model. Variables that can be computed from other variables are not state variables (stocks) in STELLA language; they become converters.

Before simulations can be run, constant model parameters have to be defined. In our model these included row spacing, time of the day, day of the year, and spatial coordinates

that describe a point in the canopy for which the model calculates the light beam length (i.e., length that a light beam has traveled through row canopies before hitting that point). This point determines the light beam's entry point into the canopy (Figure 6.4). Because of the variable growth rate of individual crop and tree rows, a light beam may travel through the entire row canopy width (when entering along the side of the rectangular cross section) or travel only through part of the row canopy width (when entering from the top). Total light beam length thus is calculated as the sum of light beams through the multiple rows and their fractions.

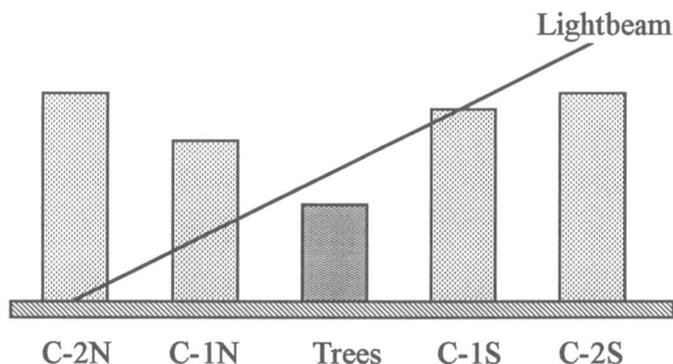


Figure 6.4 Path of a light beam in an alley cropping system. “C”, “N”, and “S” represent crop rows, north, and south, respectively.

Light beam length is calculated in each row submodel (Figure 6.5). Crop height (C Ht) and diameter (C Diam), and angle of the sun (Solar Angle) determine light beam length; row spacing (Row spac), row number of subsystem (Row) and the row number of the hitting point (Row Simul) determine coordinates of the light beam in the alley cropping

system; "hit 1N2" is an auxiliary variable that indicates whether the light beam is traveling through that particular row canopy or not.

Model output in STELLA is displayed on graphs or tables. Any combination of model variables can be selected as model output. STELLA calculates the values of these variables and plots the graphs during the time of the simulation. The modeler can observe dynamic plotting of the graphs instantaneously. The simulation can also be observed in an animated display of the structural diagram where the levels of state variables, flows and parameters are represented by corresponding dials. Both of these instantaneous simulation display features add substantially to the conceptual understanding on how system components interact (Mandinach 1994).

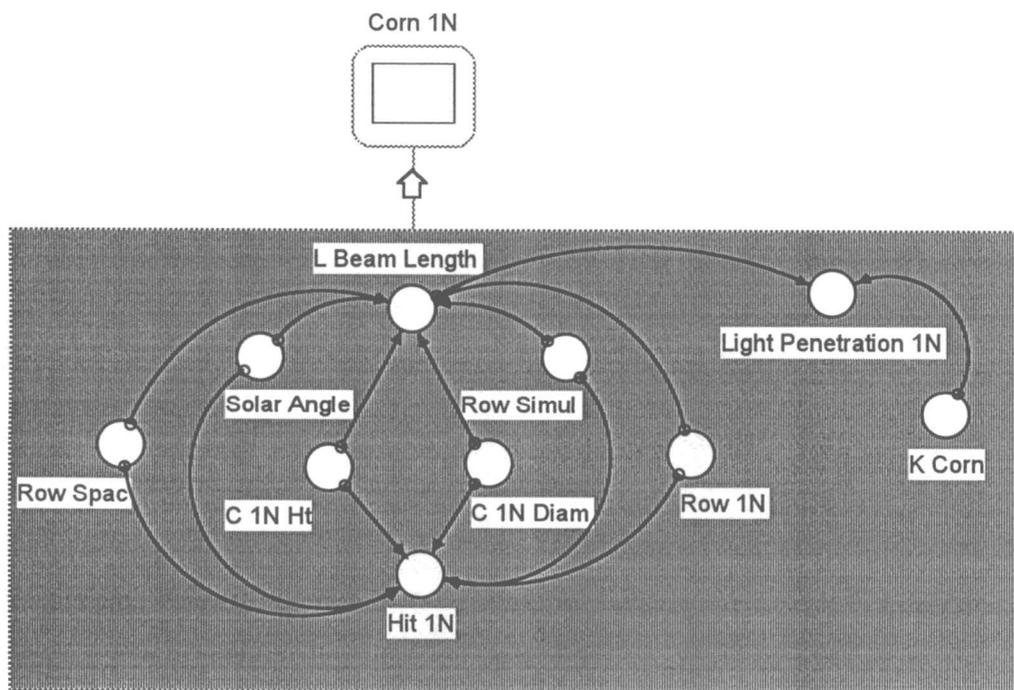


Figure 6.5 Row submodel

Figure 6.6 shows a graph of simulated light beam length through individual row canopies of an alley cropping system. In this example, we determined light beam length for the coordinates of a point in the canopy specified in figure 2: crop row 2N; row center; ground level. The light beam travels through several row canopies as the solar angle decreases during the season and plants grow taller. The graph shows that the light beam travels through the crop row south of the trees (C-1S) before it passes through the tree canopy. Total light beam length actually decreases between days 57 and 80 as the light beam enters row 1N (LB 1N) and the fraction of row 2N (LB frac) from the side at a decreasing solar angle (Figure 6.7). The changes in light penetration (calculated with arbitrary crop and tree k values) mirror those of light beam length.

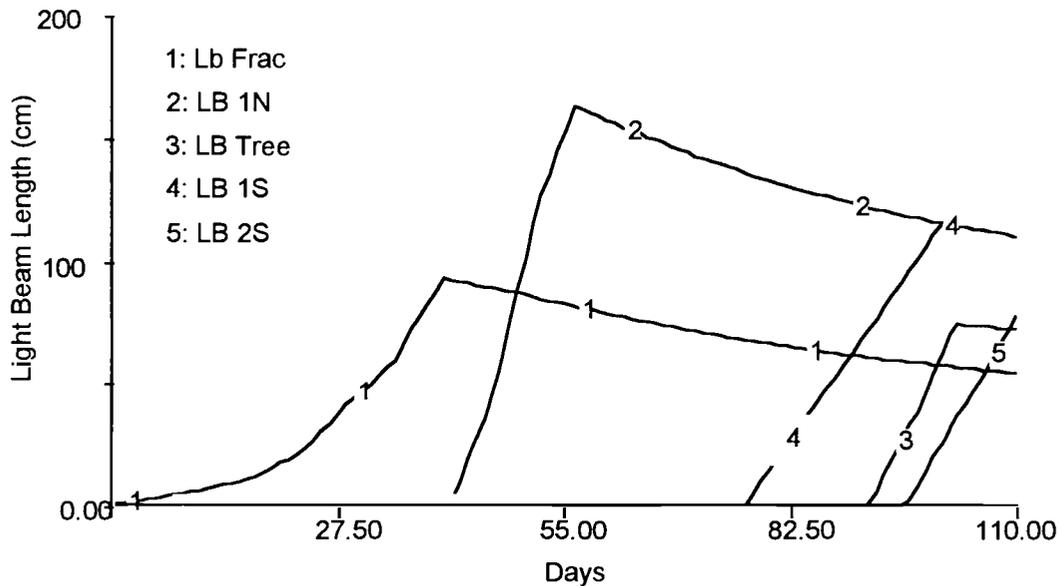


Figure 6.6 Simulated light beam length through individual row canopies of an alley cropping system

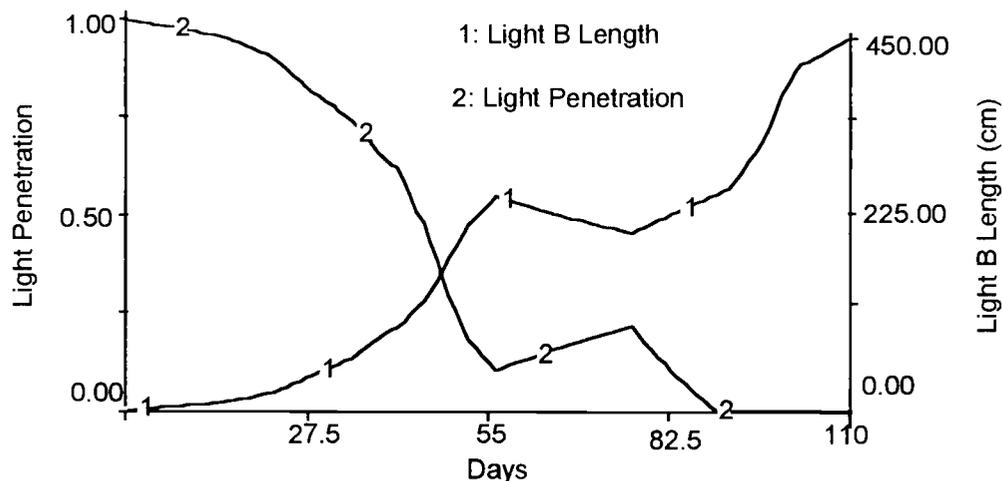


Figure 6.7 Simulated total light beam length and light penetration in an alley cropping system

*Analyzing the response of a system to variation of modeled conditions*

The analysis of a system's response to variation of certain conditions is used for two main purposes: (1) model parameterization to test robustness, plausibility, and behavioral and empirical validity of the model; and (2) to explore consequences of parameter variations and structural changes in the model (i.e., optimization). Instantaneous display of several simulations in STELLA provides an invaluable tool to evaluate the influence of any parameter or structural variations on system behavior. STELLA also features a special sensitivity analysis tool. Any variable can be entered into a dialog box in which the modeler defines the number of runs in the sensitivity session and how the variable's values are distributed (e.g. incremental, normally distributed, or user defined, "ad hoc" values).

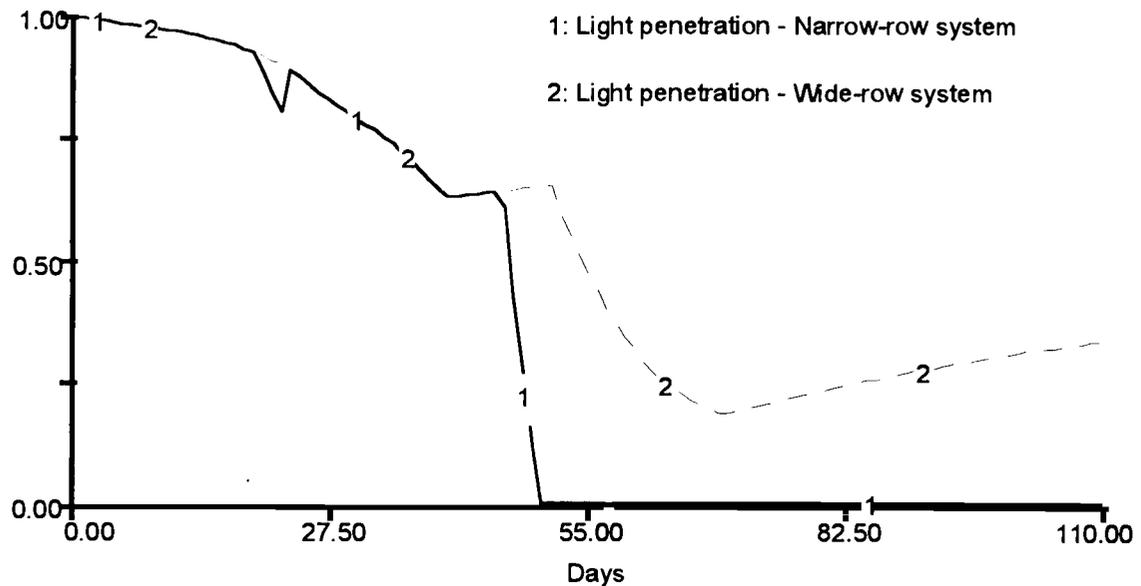


Figure 6.8 Light penetration into an alley cropping system with narrow row spacing (curve 1) and wide row spacing (curve 2)

The influence of two different row spacing on light penetration in our alley cropping system is displayed in Figure 6.8. Light penetration in the narrow-row scenario (curve 1) decreased to 0% by day 48. Light penetration was significantly different in the wide-row scenario (curve 2) because the light beam travels through the same row canopies at different angles. Timing and severity of pruning could be explored in a similar fashion (i.e., by changing data input of tree height). The transmissivity of tree canopy expressed as  $K_{tree}$  could be changed to investigate the effect of different tree species on the light environment at any spatial point inside the alley cropping canopy. These examples demonstrate how STELLA incorporates design aids to anticipate the effects of alternate model systems.

Testing the response to changes in a model structure can significantly improve its empirical validity. Changing the model structure may involve reexamination of the initial

assumptions and simplifications that were employed for model construction. For example, assuming uniform transmissivity (a proxy for leaf density) within the row canopies may be a simplification that is justified in plant growth models that require an approximate estimate of light interception. For a more detailed model of light penetration, however, it may be an over simplification. Low leaf density just above the ground and the top of the plant result in much higher light penetration when light beams travel through those sections compared to the center of the plant where leaf density is much higher. Using simple trigonometry, total light penetration could be calculated by determining light beam length in segments of the row canopy to which different leaf density coefficients are assigned (Figure 6.9). Any number of density factors could be introduced but three might suffice to represent leaf density distribution in a plant canopy (Hanks et al. 1972, Saeki 1963).

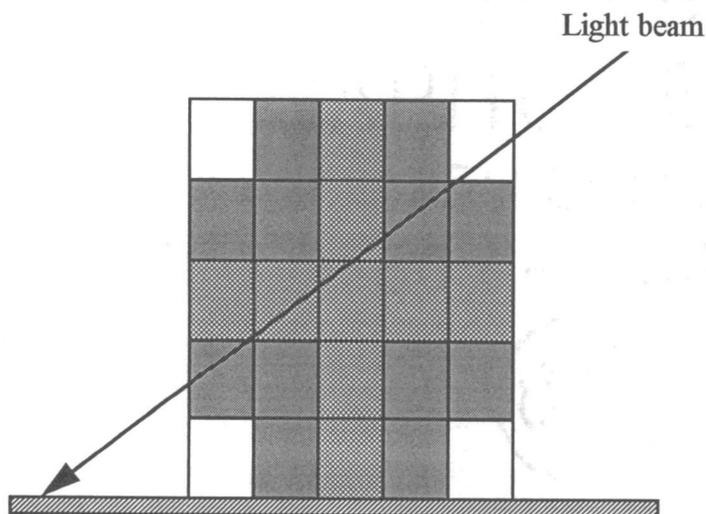


Figure 6.9 Model of a plant canopy in which canopy segments are assigned one of three density coefficients

The integration of row canopy submodels that feature several transmissivity coefficients into the existing STELLA model revealed limitations of the graphic modeling interface. Model construction became very cumbersome even with extensive use of the standard "Copy and Paste" commands. For each segment in each row (25x5) light beam length had to be defined by creating the appropriate graphical symbols for each variable and defining the relationships. Unlike standard programming languages, it is not possible to use arrays (algebraic checkerboards) that organize variables into groups (Bossel 1994). Model simulations that included the row submodels also ran significantly slower. This may be because the STELLA software is written in PASCAL which slows the numeric integration routines of complex models compared to assembly programming languages such as FORTRAN (Constanza 1987). Another limitation we encountered involved the lack of certain built-in functions. For example, an "arc sin" function to describe certain solar geometry parameters was needed in our model, but was not available. Although, STELLA supports a wide variety of functions and logic expression, it is not possible to add more functions since a standard programming language can not be used. These limitations must be taken into account when selecting an appropriate tool to model and quantify relationships in a dynamic system.

## **Conclusion**

Although there were certain limitations, modeling with STELLA provided a powerful learning tool to explore complex interactions in agricultural systems. It helped us to organize and make explicit our mental models of light penetration in an alley cropping system. STELLA engaged us in an interactive learning environment that stimulated the creative fun of model development. This type of a learning environment facilitates the mechanistic understanding of complex system interactions and strengthens the conceptual, analytical, and integrative skills of the modeler (Steed 1992). The combination of these skills is essential for agricultural students who need to integrate information from diverse perspectives and disciplines and have a solid understanding of how to introduce desired

emergent properties in dynamic systems (Jiggins 1994). To meet this challenge, some universities have redesigned their curriculum to train agriculturists in hard systems approaches such as dynamic system modeling along with soft systems and the traditionally emphasized basic and applied science research (Bawden et al. 1984). The time conserving features of STELLA provide a rigorous modeling experience that still allows students to accomplish other tasks within each of the inquiry approaches. New versions of STELLA enable model builders to embed their models in highly interactive learning environments (Richmond 1985). Teachers of students ranging from elementary school to college age use these features to enhance students' knowledge acquisition and higher order problem solving skills (Mandinach 1994).

The changing nature of agricultural production problems, markets, and social pressures also requires higher levels of conceptual, analytical, and integrative skills from farmers. STELLA or similar modeling tools may provide an opportunity for future collaboration between farmers and agricultural professionals. Time constraints may limit farmers' involvement in the entire process of model development; however, participatory events could be designed in which farmers define key variables, exogenous influences, and interactions in a particular system. The demand for such events apparently exists. For example, Alessi et al. (1994) report enthusiastic participation of farmers in the development and testing of farm management modeling tools. Due to the interactive input in STELLA, farmers could tailor the system structure to their needs once a basic model is designed. This experience would allow them to explore various management options and observe various simulation scenarios instantaneously, and thereby enhance their research and management capabilities.

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**Chapter 7**  
**Farmers design integrated crop-tree systems**

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## Summary

We facilitated farmers' design of integrated crop-tree farming systems using Participatory Rural Appraisal techniques. Farmers designed models of improved farming systems and debated the models' feasibility. Proposed models included crop-tree intercropping systems as well as zonal systems in which trees and crops are separated in space. Farmers perceived integrated crop-tree combination as diverse systems that provided multiple benefits to humans and the environment. Sustainable resource management for farmers involved two interconnected elements: the enhancement of the natural resources and securing an economically viable farming system. Participatory techniques were effective tools during the facilitation process but had to be modified to fit socioeconomic conditions and farmers' learning styles.

## Introduction

When European settlers came to the Willamette River valley in Western Oregon, they encountered a patchwork of tall grass prairie, stands of deciduous trees, conifers, and shrubby vegetation. Local farmers report that their forefathers removed woody vegetation in the valley floor to make way for agricultural fields on which high yielding annual row crops and grass seed are produced. In recent years, however, we observed that innovative farmers have expressed interest in growing trees. Some of them have started small plantations while others planted individual trees or hedgerows.

In Oregon, the public asks farmers to produce food and fiber with minimal impact on the environment. Farmers are looking for ways to meet this demand and sustain soil productivity for future generations (Hatfield et al, 1994). Integrating trees into annual cropping systems may be an important strategy in the farmers' goal of sustainable resource management. The potential benefits of trees in annual cropping systems is well

documented. These range from providing cash income from fruits, nuts and fiber to supporting functions such as shelter, wildlife habitat, green manure, or soil stabilization (Nair, 1984).

Our goal was to facilitate farmers' design of integrated crop-tree farming systems. At the same time, we expected to gain insights in farmers' perception, strategies, and decision-making process regarding rapidly changing opportunities and constraints in agricultural production.

### **Methodology, tools and techniques**

This inquiry is one segment of our research program investigating biological, ecological, and social interactions in agroforestry systems. The overarching methodology in this program is adapted from the Systems Agriculture Model (Bawden, 1991) developed at the Hawkesbury College in Australia. Similar to the Hawkesbury model, we were conducting research at four levels, each representing a different degree of complexity and integration: basic science, applied science, optimized systems and human action inquiry (Seiter and William, 1996). In the research program, these four levels are closely connected (Srikandarajah, 1991); learning within each research level is integrated into the inquiry on other levels.

In our human action inquiry that has focused on the design of integrated crop-tree systems, we were blending Participatory Rural Appraisal PRA (Chambers, 1992), Soft Systems (Checkland and Scholes, 1991), and other approaches such as Agroecosystems Analysis (Conway, 1985). To us, PRA offers the philosophical basis for our research with its focus on learning, self-development, and participants' ownership of process and results. In addition, PRA offers a wide variety of techniques to facilitate farmers' learning. Soft Systems offers a step by step procedure that moves toward action. The soft systems process begins by assembling a rich picture of the current situation, the factual information

and the *weltanschauungen* or worldviews of the people who solicit, own and control the information (Wilson and Morren, 1990). Next, models of an improved future are designed and necessary transformations described. Before changes are implemented, pictures of the future are compared to reality, and feasibility and desirability of the proposed changes are debated from multiple perspectives.

Human action inquiry is participatory in nature. The application of participatory research methodologies and techniques to address agricultural issues has been used predominantly in developing countries. However, Ison (1992) points out that, for example, Rural Appraisal can be a relevant tool in developed countries. Inglis and Lussigne (1995) note that, though still rare, there are now a number of PRA and RRA studies that have been conducted in the past few years in developed countries (Crawford and Hurley, 1995; Kievelitz and Forster, 1994; Scheuermeier and Ison, 1992).

In the United States, participatory research is mainly focused within on-farm research where farmers are included in various project phases. Most projects limit the interaction with farmers to the traditional extension methods such as one-on-one or group discussion and field plot demonstration. However, participatory research offers the opportunity for closer and more fruitful farmers-researcher interactions. As Pretty and Chambers (1994) note, participatory approaches provide the condition in which learning takes place through experience, open and equal interactions, and personal exploration. Active learning by doing plays an important role in PRA and other Action Research methodologies. Several studies in the United States found that students with farming backgrounds prefer learning by experience over learning by reading or listening to abstract concepts (Skadds, 1992, Roberts and Lee, 1977). Thus, our challenge was to design participatory events that considered farmers' learning styles and local conditions while the farmers envisioned improved farming systems.

Our "grab-bag of techniques" included informal interviews (Rhoades, 1985), aerial photo and map analysis, matrix scoring, drawing maps and pictures, impact diagrams, time lines

and historic accounts (RRA Notes 7, various authors, 1989), mind-mapping (Buzan, 1983), and Farmer-Scientist-Focus-Sessions (Lev et al , 1993). The following chapter describes when and how we used the various techniques during each step of our inquiry. The study targeted innovative farmers identified by extensionists and other farmers. We included farmers who derive most of their income from annual crop production.

### **The inquiry**

The first step of our inquiry was to describe the current situation. On aerial photographs and maps, farmers pointed out and drew the major farm features including woody vegetation. When available, historic photographs were used to assemble an historic account. Time lines were constructed that pointed out past and present tree and crop planting arrangements on the farm. Using semiformal questions, we learned about farmers' perceptions of differences between annuals and trees, and agricultural systems and tree systems. When desired, we provided a collection of slides that showed diverse functions of trees in integrated systems from around the world. A discussion followed regarding the farming systems in other regions and the farmer's own situation and objectives of integrated crop-tree systems.

#### **Steps during the inquiry process**

1. Describe the current situation
2. Develop models of an improved farming system
3. Compare models to reality
4. Document changes in practices and attitudes

The next step focused on developing a model of a future farming system. On large sheets of paper, farmers drew the major features of the current farming system and added woody vegetation and other features that represented a future model of the farm. Seasonal calendars of

activities and impact diagrams were constructed to clarify changes in farming practices, and time and space management. Informal question focused on economic and social changes that might occur with the transition to a different farming system.

In the third step, farmers and researchers compared the constructed models to reality and debated feasible and desirable changes. The format of this discussion was a Farmer-Scientist-Focus-Session (FSFS) as described by Lev et al (1993). After each farmer presented his or her model, we focused on changes that would occur when implementing the future model. Discussion focused on common themes and the potential of managing these changes. Matrix ranking demonstrated farmers' perception of major constraints and opportunities. Finally, we discussed farming system productivity, stability and sustainability, three of the major agroecosystems properties as described by Conway (1985).

The last step of our inquiry was a documentation of possible changes in farming practices, operations and attitudes as well as an evaluation of the research methodology and techniques. For this purpose, we used informal interviews in combination with a short survey questionnaire.

### **Farming systems designs: strategies for change**

The vision of future farming systems varied widely among participating farmers. They ranged from no foreseeable changes to completely altered farming systems. Farmers designed systems in which crops and trees were intercropped and others in which crops and trees were separated in space and time. Only a few models are depicted in the following paragraphs demonstrating a variety of innovations.

Hedgerows were a major component in future farming system designs. For example, in one design all fields were surrounded with low-growing hedgerows that provide habitat for birds and predatory insects. Hedgerows consisted of multi-species shrubs that also

include fruit for human consumption. The other hedgerow component was a strip of insectary herbaceous plants on both sides of the shrubs .

More complex systems were designed by other farmers. For example, one farmer has already started replacing several acres of brush with a complex intercropping system (Figure 7.1). A row of low-growing shrubs form the edge to a cropping area on which vegetable row crops are raised. Several rows of trees at staggered height were planted in parallel rows. The lower tree rows closest to the agricultural cropping area were interplanted with annual row crops such as sweet corn. In the middle section where trees are higher, shade requiring medicinal herbs were grown on raised beds. Further back, where the cultivated area meets the riparian tree zone, the farmer seeded a grain mixture to encourage wildlife.

Growing trees in areas that are difficult to manage was a common theme among the many growers. For example, many of the larger row-crop farms operate center pivot irrigation systems. The circular path of this irrigation system doesn't reach corners of square fields. To grow crops in these corners requires extra irrigation pipes be installed several times during the growing season when labor is in short supply. Several farmers have decided to plant hybrid poplars; fast growing, short rotation trees for paper pulp in these corners.

While some farmers choose to intercrop crops and trees others separated the two components in space. The farm model in Figure 7.2 depicts the old farm and the vision of the new farm. The only trees in the old farm are individual trees around the houses and a single row of woody vegetation along one field. In the future, the farmer will be planting several small fruit orchards as well as multi-species hedgerows the around the entire property. Tree planting has already started.

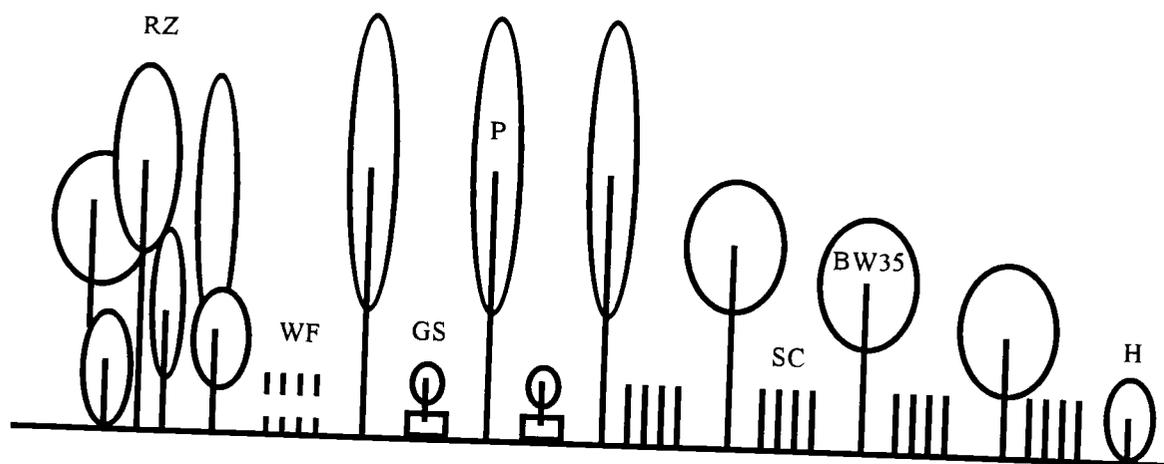


Figure 7.1 An integrated crop-tree system involving a multi-species riparian zone - RZ, Poplar (*Populus* spp.) - P, Black Walnut (*Juglans nigra*) pruned to x ft height - BW 35, Sweet corn (*Zea mays*) - SC, and a perennial herb Goldenseal (*Hydrastis canadensis*) - GS, wildlife food mixture - WF, and a multi-species hedgerow - H consisting of Filbert (*Corylus*), Cascara (*Rhamnus purstiana*) - Elderberry (*Sambucus*).

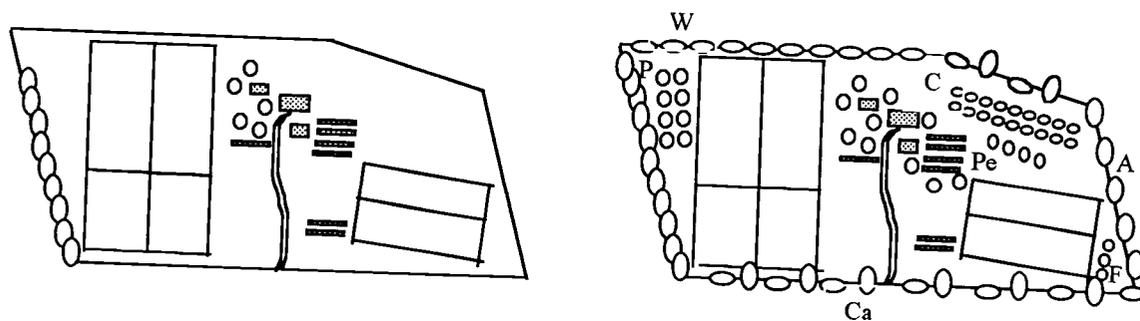


Figure 7.2 Model of an existing and envisioned farming system. The old farm (left side) showing fields, buildings and trees. The future farming system (right side) showing hedgerows, windbreaks and fruit orchards. Multi-species hedgerows and wind breaks include Willow (*Salix* spp.) - W, Alder (*Alnus* spp.) - A, and Cascara (*Rhamnus purstiana*) - Ca. Fruit orchards include sweet cherries (*Prunus avium*) - C, peaches (*Prunus persica*) - Pe, persimmon (*Diospyros virginiana*) - P, and figs (*Ficus*) - F.

Usually, farmers' models involved several changes from the existing farming systems. Animals such as sheep were included, creating agrisilvopastoral agroforestry systems. For example, in one farming system, existing woodlots will be converted from unused to highly managed pasture areas that also will yield valuable timber. In addition, hybrid poplar plantations will be interseeded with a grass-legume mixture providing further pasture area for the sheep.

### **Farmers' objectives to create integrated systems: goals for change and coexistence**

A major objective for farmers to integrate trees into existing farming systems was to maintain and enhance natural resources. Farmers were aware of the ability of trees to prevent damage from periodic floods in the Willamette valley. They described how they are maintaining tree and shrubs growing along the river and creeks to reduce the current and to prevent soil erosion and the deposition of debris in their fields. They felt that the benefit of this practice outweighed the fact that crop yield and quality is reduced by shading from the tree. Existing trees were valued by farmers also for their function as wildlife habitat, source of fuel and construction wood, aesthetics, and as wild and recreational areas.

Farmers perceived integrated crop-tree systems as diverse environments that provided several benefits to humans and wildlife. For example, hedgerows surrounding row-crop fields served multiple purposes. Farmers expected that hedgerows will reduce the reliance on pesticides by providing habitat for birds and predatory insects that would feed on insect pests. Farmers also included hedgerows as barrier against pesticide drift from neighboring farms, as living fences to replace electric fencing on livestock operation, and as visual barriers.

Growing a wide diversity of trees in close association with crops was perceived by some farmers as a way to enhance the natural resources on farm and move toward more

sustainable farm ecosystems. When increasing plant diversity, most growers choose species that created monetary value such as fruits and nuts. Including fruit trees in the design of future farming systems was popular especially among farmers who sold their products directly to consumers.

Changing market opportunities encouraged farmers to design intercropping systems in which trees fulfilled service functions. Currently in demand are high value salad greens, medicinal plants, and ornamentals. Farmers observed that late season salad greens grown under trees experience less frost damage. Main season salad greens' improve in flavor and texture when grown in association with trees, benefiting from partial shading. Trees also provide shade for perennial medicinal plants such as Goldenseal (*Hydrastis canadensis*), and the production of rhododendron, a popular ornamental plant in the Pacific Northwest. On another farm, partial shading and favorable soil characteristics allowed the cultivation of native flowers and grasses along forest edges.

Increasing land values motivated farmers to plant trees on areas not suited for annual crop production such as sloping ground or less favorable soils. However, in some cases, trees have been planted on superior soil because other factors such as labor cost were more important. An example is the previously described hybrid poplar plantations in the corners of fields irrigated with center pivots. Thus, minimizing costs was a major incentive to integrate trees into the existing farming system. Farmers reported that the simplicity of tree establishment and management added to the appeal of hybrid poplar plantations.

Hybrid poplars plantations also reflects the growers adaptation and expectation to changing markets. Timber from forests has been the economic mainstay in western Oregon. However, public objection to continued logging of old growth forest and the demand for multiple-use-forests have resulted in environmental policies that reduce timber harvest. Some farmers believe that this trend will continue and expect hybrid poplar to become an important fiber source in the future.

Integrating trees into existing farming systems symbolized for many farmers an investment in the future. Several farmers included long rotation trees such as black walnut (*Junglans nigra*) from which they will receive only limited revenues. However, the plantations increased the value of the farm and will provide cash income for future generations.

### **Farmers' decision making for sustainable resource management**

Sustainable resource management for farmers involved two interconnected elements: the enhancement of the natural resources and securing an economically viable farming system. During the development of the farming systems models, farmers were asked to describe the transition to their improved farming system design. A timeline of implementation of crop-tree systems showed a cautious step by step approach by most farmers. Uncertainty about biological and economic feasibility of these systems are a major obstacle to faster implementation.

Farmers who have already started to create integrated crop-tree systems have acted mostly upon their intuition and ecological knowledge derived from their own observations as well as formal and informal education. However there was a strong demand for research information from locally implemented crop-tree systems. Farmers expressed various information needs ranging from very specific to very general depending on how much the current farming system had already progressed toward integration. Since all farmers were experienced crop farmers, information needs focused mostly on the woody component. Species specific information on tree and shrub ecology and their value as habitat were mentioned frequently. Farmers were also interested in the economic value of tree components. In intercropping situation, information on spatial arrangement of crops and trees was needed.

## **Evaluation of techniques**

In this study, we used popular PRA and FSR/E techniques. To traditional Extensionists in the United States, participatory techniques as used by PRA practitioners in developing countries may seem less sophisticated and ill-fitted for today's "Cyber-farmers". Adapting and modifying the methods to local conditions is one of the ground rules of PRA (Chambers, 1992). We attempted to adapt the techniques used during the facilitation to the socioeconomic conditions such as resource availability or educational standards. Still, some of the techniques worked better than others.

Aerial photo analysis and the drawing of field and farm maps seemed to be customary activity for all participating farmers. The photos and maps were practical tools around which the semi-formal interview could be structured. Other activities such as drawing impact diagrams in form of mind-maps were much more difficult to facilitate. Farmers very reluctantly attempted this task and preferred oral over visual descriptions. As pointed out earlier, the farmers are praxis-oriented and learn best by doing (Skadds, 1992, Roberts and Lee, 1977). However, psychological preference studies show that the majority of farmers prefer reflection over interaction (Jose and Crumly, 1993). It is difficult to generalize psychological preferences of an entire occupational group and extrapolate to the small group of our study. However, our experience supports the findings.

Jose and Crumly (1993) made another observation that is important for our study and in general for action research that focuses on future improvements. They found that fact gathering is the most important activity for farmers as opposed to considering the options and future possibilities. These issues must be addressed and methodologies and techniques used must be carefully evaluated before implementation.

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## Chapter 8 Conclusion

During the studies presented in this dissertation, my co-researchers and I explored the biological, ecological, and social dimensions of integrating trees into a vegetable production system. Specifically, we explored interactions in the biophysical environment of an alley cropping system (i.e., crops, trees, soil). We found that the two tree species we tested met the basic requirements of a suitable alley cropping species (fast growth, coppicability, etc.); however, green manure yield of both species was small in planting arrangements in which acceptable crop yield was produced. The study of different planting arrangements showed that resource capture is dependent but not linearly related to space available to each plant component of a crop-tree intercropping system. A modeling exercise indicated that simulating the light environment can potentially optimize these planting arrangements. The studies of soil microbial dynamics and nitrogen cycling helped us to quantify complex effects and interactions in the plant-soil environment.

The results of our studies improved our understanding of the interactions in temperate climate alley cropping. However, many questions remain unanswered. For example, at the onset of this research we identified interactions between tree and crop roots as a key factor determining the system's output. However, results from a study (not presented in this dissertation) involving root rhizotrons (i.e., clear tubes in the soil to observe root growth) were inconclusive because we were not able to distinguish between tree and crop roots. We also were not able to clearly identify the reasons why crop rows next to trees yielded higher in the first but not the following growing seasons. Increased light or root competition, or the build-up of undecomposed, nitrogen immobilizing green manure tissues in the soil may have contributed to the change.

I found the Hawkesbury model (i.e., a spiral symbolizing several interrelated levels of inquiry) a powerful and challenging research methodology. By applying this model, the research was kept flexible and open to changing demands and insights. Insights among studies were integrated on the same level of inquiry (horizontally on the spiral) and different levels of inquiry (vertically). For example, insights from the nitrogen cycling study informed the discussion on microbial dynamics and vice versa, representing horizontal linkage among research studies.

The vertical integration of the results and insights (“spiraling up and down”) could have been improved. For example, it would have been important to demonstrate how relevant the basic processes such as microbial dynamics or nitrogen cycling are to agricultural production. I was able to explore a broad range of single issues in alley cropping. The depth of research needed to adequately address these issues, however, left us little time to reflect on the interactions between these issues and develop a more vertically integrated approach.

There was a lack of a direct linkage between the study of the social dimension of integrated crop-tree systems and the other studies. As I noted in chapter one, ideally, a research process begins with inquiry on the human activity systems level. On this level, opportunities and problems are identified with the participation of all stakeholders. This leads to the formulation of research objectives and the selection of appropriate levels of inquiry to investigate the identified situations. Our research, however, did not follow this order. Farmers (as major stakeholders in agricultural research) were not directly involved in the decision to explore temperate climate alley cropping or which components of this cropping system should be investigated. These decisions were made by me and my co-researchers. We hypothesized that based on experience and scientific literature, the study of temperate climate alley cropping would provide valuable insights for the development of agricultural systems that integrate profitable crop production with environmental stewardship. I believe that we have gained these insights. However, involvement of farmers in all phases of the research process may have provided us with a clearer focus

and required us continually to integrate “hard science” observations with the social component of agricultural production.

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## Appendix

Figure A1 1995 sweet corn yield in corn rows next to black locust and red alder trees with and without root barriers in alley cropping pattern C C tt C C. Values shown are the mean values of 3 measurements. Different letters denote statistically significant differences in corn yield at  $p = 0.05$ .

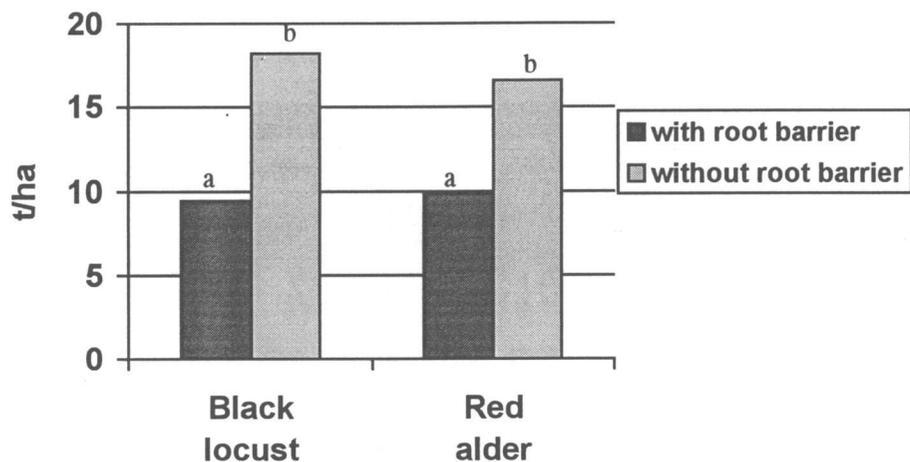


Figure A2 1994 sweet corn yield (t/ha) in monocrop and alley cropping systems at four rates of nitrogen fertilizer; average yield per cropped area is shown in figure a); average yield per total area (including area occupied by trees) is shown in figure b). The alley cropping system featured *Alnus sinuata* planted in planting arrangement CCctCCC.

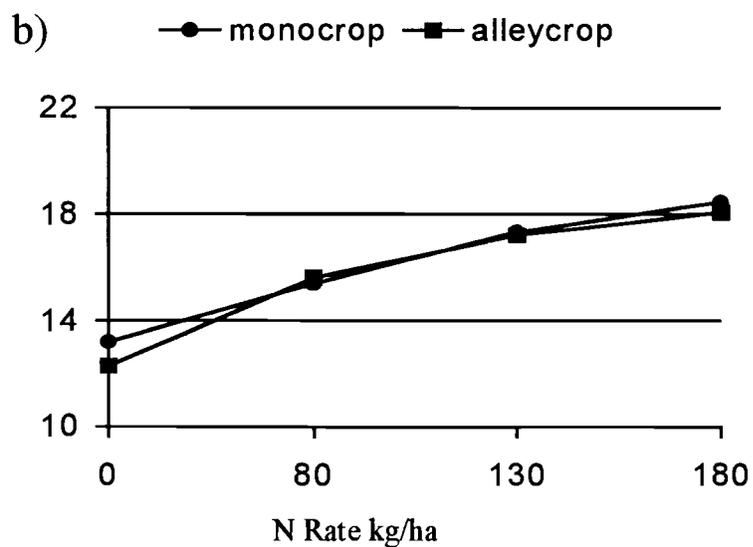
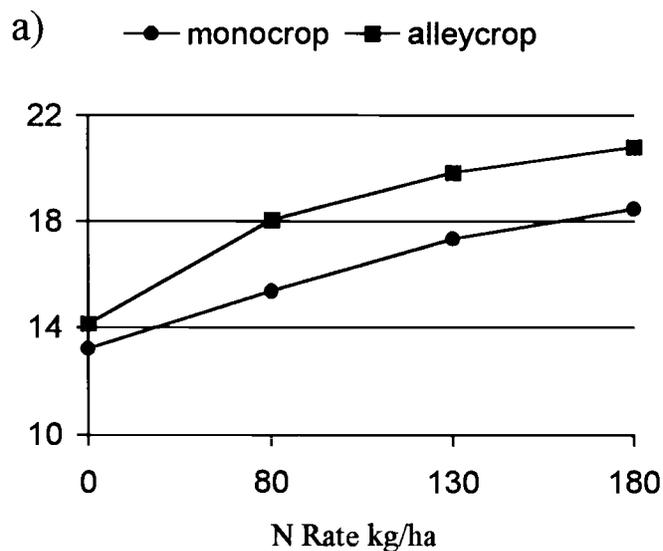


Figure A3 1995 sweet corn yield (t/ha) in monocrop and alley cropping systems at four rates of nitrogen fertilizer; average yield per cropped area is shown in figure a); average yield per total area (including area occupied by trees) is shown in figure b). The alley cropping system featured *Alnus simuta* planted in planting arrangement CCcttCCC.

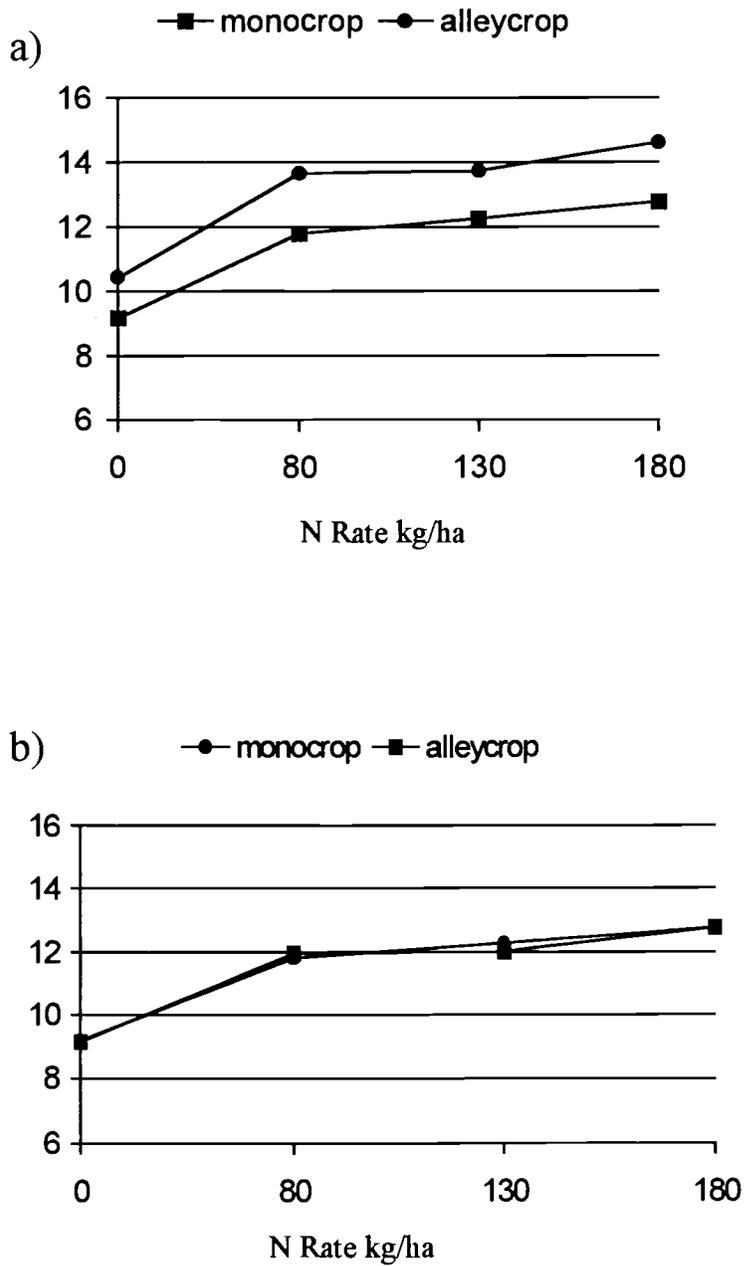


Figure A4 Percent PAR intercepted in an alley cropping system involving double tree rows of *Alnus rubra* in planting arrangement C C tt C C. Measurements were taken inside the canopy, 5 cm above ground level at solar noon, 6 times during the season. The first two measurements were taken the day before and after pruning four weeks after corn planting (4WAP-a and 4WAP-b, respectively).

