Thesis

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PAULOWNIA/WINTER WHEAT INTERCROPPING
QUANTIFYING THE RELATIONSHIP BETWEEN
PHOTOSYNTHETICALLY ACTIVE RADIATION (PAR)
AND YIELD

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PAULOWNIA/WINTER WHEAT INTERCROPPING QUANTIFYING THE RELATIONSHIP BETWEEN PHOTOSYNTHETICALLY ACTIVE RADIATION (PAR) AND YIELD

by

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ABSTRACT

PAULOWNIA/WINTER WHEAT INTERCROPPING QUANTIFYING THE RELATIONSHIP BETWEEN PHOTOSYNTHETICALLY ACTIVE RADIATION (PAR) AND YIELD

By

Charles P. Chirko

A *Paulownia*-winter wheat intercropping experiment with a focus on photosynthetically active radiation (PAR) and root competition was conducted 60 km south of Zhengzhou (35^0 N 113^0 E), Henan Province, PR China, from September 1991 to July 1992 using a tree/crop interface approach. The middle row of three 240-m long rows of 11-year-old trees was studied for its effects on the yield of irrigated and fertilized winter wheat.

In one experiment PAR was quantified using a split-plot design with four blocks. There were 4 distance treatments (2.5, 5, 10, and 20 m) and 2 direction treatments (east and west of a north-south tree line). Results showed no difference in direction effects but PAR did affect total grain weight ($p=.0047$) between 2.5 m and 20 m. A regression equation was fit using the mean for each distance treatment: $Y = 391.7 + 4.57\ X$ with $r^2 = .9310$ indicating an increase of 4.57 g m^{-2} (45.7 kg ha^{-1}) over a distance of 2.5 m to 20 m from the trees.

A second set of experiments investigated the wheat and *Paulownia* root and PAR interactions under the trees. Plastic root barriers, 2 m long and 1 m deep, were placed between the tree and the winter wheat yield plots. Plots at 2.5 m with root barriers were compared to those without using a split-plot design. Barriers had no effect on total grain weight (p=.7635) or 1000-grain weight (p=.8583). Thus, in terms of below ground interactions, *Paulownia* is clearly compatible with winter wheat in fertilized and irrigated agroforestry intercropping.

In an orientation experiment, wheat yields were compared under the trees on the north, east and west sides. Contrasting directions E vs N and S, yield was significantly different for both total grain weight (p=.0026) and 1000-grain weight (p=.0246) with the E being greater.

In a shading experiment with trees and artificial shade as shade treatments, yield was greater in non-shaded plots {total grain weight (p=.0440) and 1000-grain weight (p=.0135)}. Controls (without trees) employed a different planting scheme and were not comparable to the plots with trees. PAR and other environmental factors and their effects on winter wheat yield component development throughout the growing season are discussed.

I would like to dedicate this to **Baha'u'llah** the source of my inspiration who said:

Walk thou high above the world of being
through the power of the Most Great Name,
that thou mayest become aware of the immemorial mysteries
and be acquainted with that wherewith no one is acquainted.

Verily, thy Lord is the Helper, the All-Knowing, the All-Informed.

Be thou as a throbbing artery,
pulsating in the body of the entire creation,
that through the heat generated by this motion
there may appear that which will quicken the hearts of those who hesitate.

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I would like to acknowledge two people in particular who worked very hard with me to complete this work. The first man was instrumental in providing leadership and guidance in a country that was completely alien to me. Without President Jiang, Jianping's constant support I would have been at a total loss from the moment I stepped onto Chinese soil.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1. INTRODUCTION

Agroforestry is a land use system that has many definitions (von Maydell et al., 1982). *The Diagnosis and Design User's Manual* (Raintree, 1987) states that agroforestry is a system that deliberately combines a woody perennial and an herbaceous crop(s) and/or animals in some form of spatial arrangement or temporal sequence. Intercropping, multiple cropping, and multi-story cropping are all types of agroforestry when they use a perennial tree or shrub crop as a component.

While farmers have practiced agroforestry for thousands of years, it has only been under scientific investigation since the late 1970's. During the 1970's, land and population pressures created problems that caused international notice. Shortages of land for production of food and fuelwood stimulated the scientific community to improve and promote agroforestry systems.

Agroforestry has many potential benefits. These generally include sustaining soil productivity and soil conservation, which encompasses maintenance of soil fertility and prevention of soil erosion (Young, 1987). Nevertheless, agroforestry is not a panacea. Sometimes disadvantages arise when placing trees into a land management scheme. Scientific research attempts to systematically determine the best cropping combinations to employ.

The primary objectives for agroforestry experimentation are to improve productivity and to extrapolate the system being examined to other locations (Huxley et al., 1989a). However, inherent in agroforestry experiments is the large size and longevity of trees. When compared to conventional agricultural experiments, the factors necessary to consider with intercropping are manifold. This often increases the size of the experimental agroforestry plot to unworkable dimensions.

The International Centre for Research in Agroforestry (ICRAF) has been refining a new experimental design called the tree/crop interface (TCI). The tree/crop interface attempts to examine the interaction between the tree and the crop in the zones where their above and below ground components meet and share resources. The yield of a crop in an interface plot is compared to the yield in plots of similar size that are under strong influence of the tree in one case and under no influence of the tree in another case.

Theoretically the tree/crop interface is where the sharing of water and nutrients below the soil surface, and of sunlight, one component of which is photosynthetically active radiation (PAR), above ground will take place. While it is often beneficial in an experiment to isolate and study one variable while standardizing the rest, it is also important to see how the major variables interact.

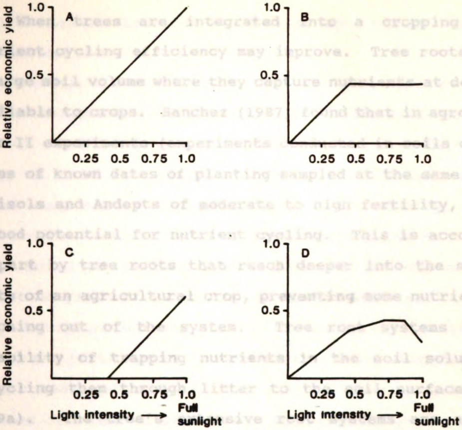
This project investigated the most widely used intercropping system in the world which is located in the temperate zone of the People's Republic of China. The system consists of a tree, *Paulownia spp.*, and winter wheat (*Triticum aestivum* cv. *You Zhi Bai Nong 3217*). Resource sharing at the tree/crop interface in this agroforestry system was studied to understand how the system works, describe the interactions involved, and determine the potential for extrapolation to other localities.

1.2. BACKGROUND

1.2.1. Agroforestry Intercropping -- Potential Advantages.

Agroforestry intercropping has both biological and socio-economic advantages. MacDicken and Vergara (1990) list 14 beneficial characteristics of putting trees in an agricultural system. For certain crops, one advantage is overstory shade which provides protection from direct solar radiation. Jackson (1989) illustrates this with one of the four crop-light responses (Figure 1.1) that he derived from cases in the literature.

As shown in D, Figure 1.1, a crop with a shade requirement decreases in economic yield as light intensity increases to full sunlight. However, in other scenarios, shading is not a problem (A in Figure 1.1). Ideally the proper tree and crop combinations will increase total production by capturing more solar radiation. Because trees present a multi-story effect,



A-Linear dependence
B-A degree of shade tolerance with low light saturation
C-Shade intolerance
D-Shade requirement

(after Jackson, 1989)

Figure 1.1. Economic Yield Versus Light Intensity.

they can increase the solar radiation capture of a given field in the vertical dimension.

When trees are integrated into a cropping system, nutrient cycling efficiency may improve. Tree roots exploit a large soil volume where they capture nutrients at depths not available to crops. Sanchez (1987) found that in agroforestry type II experiments (experiments conducted in soils of nearby sites of known dates of planting sampled at the same time) on Alfisols and Andepts of moderate to high fertility, there is a good potential for nutrient cycling. This is accomplished in part by tree roots that reach deeper into the soil than roots of an agricultural crop, preventing some nutrients from leaching out of the system. Tree root systems have the capability of trapping nutrients in the soil solution and recycling them through litter to the soil surface (Young, 1989a). The tree's extensive root systems are also very effective in soil moisture uptake which is advantageous in dry climates.

Trees are grown as windbreaks which function to reduce wind speed, helping to control wind erosion (Sheng, 1986). Forest nets (as they are called in China) or shelterbelts play a major role in microclimate amelioration. Relative humidity, soil temperature, and transpiration are all more favorable within the forest nets which modify microclimate and benefit an understory crop (Zhu, 1990). Zhu (1988) and Li and Xiao (1992) state that the forest nets reduce water evaporation and transpiration by lowering the temperature under the canopy and raising the relative humidity above the crop. Higher relative humidity and lower temperature reduce water stress which in turn inhibits stomata closure to reduce transpiration. With active transpiration the plant fixes more carbon, increasing dry matter production.

Brandle (1987) hypothesized that windbreaks tend to moderate climatic extremes such as cold, dry winds or hot, dry winds. Working in Nebraska with winter wheat from 1974 to 1986, he found that yields averaged 14.6% higher in sheltered areas compared to exposed areas. Generally yields were greater in sheltered areas in years where climatic conditions were normal or harsher than normal. Trees had a negative effect on yield in years with favorable weather.

Tree plantings may provide a disease barrier as well as a weed and pest control through breaks in the cropping pattern (Ewel, 1986; Altieri et al., 1983). Whereas monocropping systems decrease diversity and increase the food supply for specific insects, planting trees sometimes alters this pattern so as to limit a pest population's food supply (Altieri et al., 1983).

Trees provide shade which may sufficiently limit PAR to the understory, inhibiting weed growth. This is especially true in the case of aggressive C4 grasses often found in the tropics. Curtailing weeds is beneficial to the crop as weeds compete for water and nutrients. Wilson (1990) found that in nitrogen (N) limited areas, pasture grass benefitted from shade, possibly due to a soil N mineralization increase. In another case, Wilson states that grass grown under shade had better growth, higher N concentration, with total N uptake in the herbage 70% higher than grass in full sunlight.

Agroforestry systems contribute to the sustainability of farming systems with improved soil physical properties as tree roots enhance soil porosity and aeration (Sanchez et al., 1985). Constant root turnover offers channels for increased water infiltration. Bulk density decreases; earthworm activity under trees increases (Jackson et al., 1989); and populations of bacteria, *Actinomycetes* fungi, and soil fauna are greater under trees (Zhu, 1990).

Trees may help control soil erosion by providing ground cover which reduces the impact of rainfall on the surface soil. Litter has been found to be the most important factor in decreasing soil erosion by slowing runoff and permitting the rain water to infiltrate into the soil. Trees are also used as a barrier to slow water flow and trap soil up slope (Young, 1989b).

Depending on the tree/crop combination and management system employed, trees have been found to reduce fertilizer requirements. Nutrient cycling is important and, as trees can be manipulated, timely pruning may provide a nutrient source to associated crops. Kang et al. (1985) found that less N fertilizer is needed when clippings from an alley cropping system are used as green manure. Since repeated N fertilization, in the form of ammonia or other fertilizers subject to nitrification, acidify the soil (Foth, 1984), a reduction in N application may help maintain a suitable pH for nutrient availability and crop growth in acidic soils.

Nitrogen fixing trees supply N from the atmosphere through fixation by tree root (or stem) nodules in association with *Rhizobium* and *Frankia* bacteria. This fixed N benefits non-nitrogen fixing crops when the N is recycled via litterfall or when the nodules die during root turnover. Crops may even root graft with N fixing nodules and directly benefit from the available N (van Noordwijk and Dommergues, 1990).

Socio-economic benefits obtained from agroforestry include food, fuel, fodder, or timber, providing a variety of building materials. Sale of these products increases income. Spreading economic benefits over a whole year instead of a single crop and short growing season supplements family income in otherwise slack periods. Diversification of output also reduces economic risk. Trees introduced onto a farm, however, generally increase labor requirements. If this occurs when labor is plentiful it may (depending on the culture and labor profile) be very beneficial.

1.2.2. Agroforestry Intercropping -- Potential Disadvantages.

Trees are not always beneficial to crop production. One of the major biological disadvantages of agroforestry is the potential of increased competition for space, light (PAR), water, and nutrients. Proper selection of compatible trees and crops in a proper management scheme is essential to minimize this competition.

Sometimes tree seeds, leaves, bark, or roots excrete phytotoxic substances that stifle crop growth (Huck, 1983).

This is a major problem when the tree/crop combinations react unfavorably toward each other (either tree towards crop or crop towards tree). Rizvi and Rizvi (1985) state that biochemical interactions of plants with each other, allelopathy, is little understood and should be considered before introducing agroforestry combinations.

Trees may introduce obstacles to harvesting and cultivation. If crop harvesting is mechanized the trees may require the introduction of different crop harvesting patterns. Farmers are often reluctant to change their ways. If mechanization is not part of the farming system, then the trees may require the introduction of new weeding, or land preparation techniques for the crop. This is often an added cost and/or bother to the farmer -- one that he/she is not willing to undertake. A new technique in cultivation may increase risk of damage to a desired tree crop. Unfamiliarity with a new machine or different management practice often causes damage to a perennial through inattentiveness while working with the annual crop.

Land tenure may be problematic with agroforestry. Sometimes farmers resist planting trees on their farm land because it will change the ownership patterns. If there is to be a redistribution of land periodically and there are trees located on the land, farmers may have to harvest their trees before it is economically feasible in order to realize some gain. Otherwise they may lose the rights to the tree. To avoid this situation farmers may forego planting trees (Fortmann and Bruce, 1988).

Animals often damage trees and crops especially in systems designed to integrate trees, crops, and livestock. Trees may be the only source, or the most available source, of dry season fodder for animals. In most instances animals browsing on trees is detrimental to tree growth. Browsing also contributes to crop trampling and soil compaction (Borel, 1985).

While trees sometimes play a role in reducing erosion, at other times they might increase erosion. The tree canopy will capture rain and, depending on the size and shape of the leaf, will actually increase the size of the drop as it falls from the leaf. In trees with a high canopy this is especially troublesome with the impact of the drops contributing to soil erosion.

Pests are often attracted to trees. Trees are a home for birds or animals that might damage crops. Although trees provide diversity to an area discouraging insect buildup and disease problems, they have the potential to increase these problems. Insects may be partial to a particular tree species and use a neighboring crop as a backup food source. In addition, the tree may provide a necessary overwintering site or a niche for an insect to complete its life cycle. Some trees act as alternate hosts for parasites that could not continue their life cycle in a monocropping system.

Relative humidity also poses a potential problem. While an increase in relative humidity provided by trees is often beneficial to a crop, it also increases the incidence of fungal attacks. This is encouraged by a decrease in wind speed through the cropping area brought on by the presence of trees used as shelterbelts. Thus, there are many potential benefits and disadvantages to incorporating trees into an agricultural system. Agroforestry research is one method used to weigh these advantages and disadvantages of specific crop combinations for compatibility.

1.2.3. Agroforestry Experimental Objectives.

Agroforestry attempts to combine a tree crop and an agricultural crop spatially or temporally so that one increases the yield of the other. This concept is called complementary yield (Arnold, 1983). It is also found in the literature as protocooperation (Francis, 1986), facilitation (Vandermeer, 1989) or overyielding (Trenbath, 1976).

In agroforestry experiments, as with other experiments, it is desirable to first isolate the key variables that are to be studied and standardize all other variables. In multiple cropping systems this is often difficult to achieve. The number of variables that influence the yield outcome increases from 15 total factors with 105 possible two-way interactions for a single crop, to 26 factors with 325 possible two-way interactions for two crops (Francis, 1986). Francis groups the contributing factors into three subheadings which are genetic factors, cultural factors, and climate-soil factors. Table 1.1 lists the factors that belong to each group.

Table 1.1. Multiple Cropping System Variables.

GENETIC FACTORS	CULTURAL FACTORS	CLIMATE-SOIL
crop genotype (b)	separate plantings	night
genotype (a) x genotype (b)	relative planting dates	rainfall
pest genotype (a)	density (a)	soil type (a)
pest (a) x pest (b)	density (b)	soil type (b)
(a) x (b) x pests	spatial arrangemnt	wind
crop genotype (a)	harvest	topography
pest genotype (b)	land preparation	rain distributn
crop x pest	cultural practices	carbon dioxide
	fertilization	
	pest control	

(After Francis, 1986)

Trees also present an experimental design problem because of their size and longevity. In agroforestry, as in all good research, experiments must not become too large and unwieldy. It must take into account the number of potential treatments and the space needed to test each treatment effectively without interfering with each other or introducing bias (Huxley, 1989). ICRAF has been developing an experimental design which attempts to limit the overall size of the experiment and still obtains meaningful experimental results over time through study of the tree/crop interface.

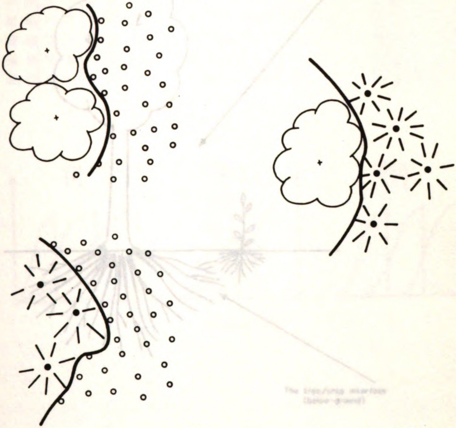
1.2.4. Tree/Crop Interface (TCI).

The tree/crop interface approach seeks to define the smallest experimental unit (Huxley, 1987) for agroforestry experimentation. The overall research problem is reduced to a comparison of three different zones. The first is the woody component alone, the second is the non-woody component alone, and the third is the interface between the woody and non-woody component (Huxley et al., 1989b). An example of the TCI from two perspectives is shown in Figure 1.2 and Figure 1.3.

To study the crop in relation to the tree, three locations should be selected: 1) directly under the tree; 2) at a distance where the tree and crop compete for PAR, nutrients, and water, such as the tree crown drip line; and 3) located at a distance from the tree where there is little competition. With regard to PAR studies, Jackson and Palmer (1989) define the TCI as any crop producing ground that is shaded by a tree.

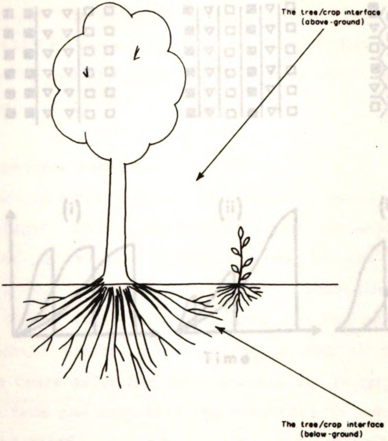
Experiments can be relatively simple and observational in nature. These are considered Stage I experiments (Huxley, 1987) where the objective is to determine what happens within an agroforestry system. Stage II experiments attempt to explain the results, such as yield, due to a tree and a crop interaction. These experiments require equipment to increase precision in data collection.

Huxley (1987) classified agroforestry research into three groups -- rotational, zonal, and mixed. Rotational research integrates trees and crops at different times depending on the age and rotation of the tree. Zonal and mixed groups concern the spacing of trees and crops in either a vertical or a horizontal manner as shown in Figure 1.4. These zonal and mixed groups can employ the TCI approach.



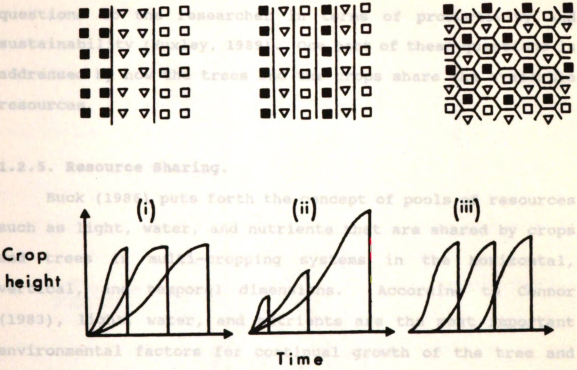
(After Huxley, 1985a)

Figure 1.2. Tree/Crop Interface (TCI) Examples.



(After Huxley, 1985a)

Figure 1.3. A Tree/Crop Interface (TCI)--At Its Simplest.



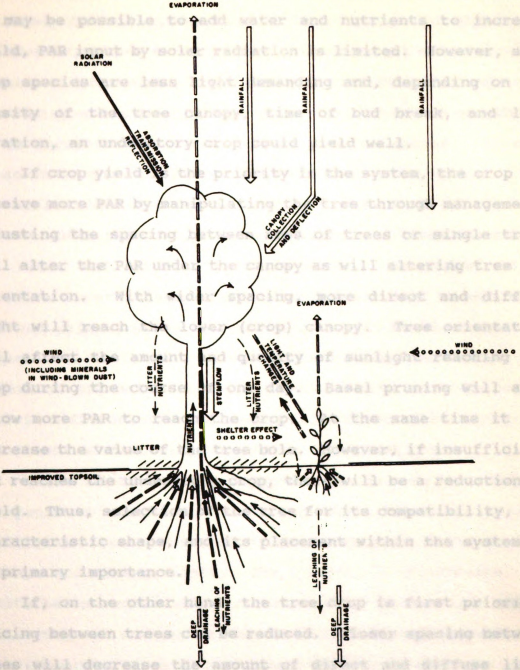
(after Cannell, 1983)

Figure 1.4. Three Spatial and Vertical Arrangements.

While the TCI limits the size of the area to be studied, it does not necessarily simplify the experiment. As Figure 1.5 illustrates there are many variables and possible interactions in the TCI. These interacting variables pose questions to the researcher in terms of productivity and sustainability (Huxley, 1989). One part of these questions is addressed by how the trees and the crops share the available resources.

1.2.5. Resource Sharing.

Buck (1986) puts forth the concept of pools of resources such as light, water, and nutrients that are shared by crops and trees in multi-cropping systems in the horizontal, vertical, and temporal dimensions. According to Connor (1983), light, water, and nutrients are the most important environmental factors for continual growth of the tree and crop. If these major factors are available in optimum amounts then the tree and crop have the potential to achieve maximum growth and yield. In discussing the tree and crop combination that is sought in agroforestry, Huxley (1985b) refers to an associative ideotype. This is a tree and associated plant that should contribute to the fulfillment of the system's objectives and still maximize environmental resource use through sharing in both space and time.



(after Huxley, 1985a)

Figure 1.5. Tree/Crop Interactions.

One potential problem in a multistory cropping system is the shading effect of the tree on the understory crop. While it may be possible to add water and nutrients to increase yield, PAR input by solar radiation is limited. However, some crop species are less light demanding and, depending on the density of the tree canopy, time of bud break, and leaf duration, an understory crop could yield well.

If crop yield is the priority in the system, the crop may receive more PAR by manipulating the tree through management. Adjusting the spacing between rows of trees or single trees will alter the PAR under the canopy as will altering tree row orientation. With wider spacing, more direct and diffuse light will reach the lower (crop) canopy. Tree orientation will affect the amount and quality of sunlight reaching the crop during the course of one day. Basal pruning will also allow more PAR to reach the crop. At the same time it may increase the value of the tree bole. However, if insufficient PAR reaches the understory crop, there will be a reduction in yield. Thus, selection of the tree for its compatibility, its characteristic shape, and its placement within the system is of primary importance.

If, on the other hand, the tree crop is first priority, spacing between trees can be reduced. Closer spacing between trees will decrease the amount of direct and diffuse light available to the understory crop as the canopy closes, limiting yield. However, the trees, because of their vertical dominance above the crop, will be able to intercept as much PAR as necessary unless they have to compete with other trees.

At relatively wider spacings the total tree biomass per hectare (ha) decreases (relative to individual tree biomass which may be at their maximum). Thus, management objectives must be determined first, then a balance sought where the tree biomass and the crop yield trade-off will be optimized.

Water and nutrients also play a major role in growth and in an agroforestry system they have to be shared. In many cases it is not feasible to add nutrients or to irrigate. If the agriculture crop is the priority, management of the tree must consider the possible adverse affects of trees dominating the water and nutrient resource pools. The ideal is to maximize the efficiency of the water and nutrient resources so that net primary production of the crop will not decrease when compared to the same crop not influenced by the trees. One method of enhancing resource sharing is to have the roots exploit different soil horizons. This further illustrates the importance of selecting compatible trees and crops.

Trees added to a cropping system may do more than compete for pools of nutrients, water, and PAR. Trees can provide beneficial effects on the microclimate and even increase yield (Zheng and Sheng, 1989; Zhu, 1990). Windbreaks and shelterbelts reduce water stress. Water stress can reduce photosynthesis and may be the limiting factor in growth. As high temperatures or drought conditions increase, the vapor pressure gradient increases and transpiration will increase to a point. Then, as available soil moisture decreases, stomata will close to reduce transpiration, increasing stomatal resistance and reducing the carbon dioxide flow through the stomata. The end result is a reduction in photosynthesis.

Trees not only reduce drying and windburn effects through windbreaks, they also ameliorate temperatures under the canopy resulting in cooler summer temperatures and warmer winter temperatures (Zhu et al., 1986). Zhu (1990) states that *Paulownia* trees create a temperature inversion under the canopy during the day with the tree crown becoming a barrier to radiation. The air below the crown becomes cooler than that above the ground and sinks. These cooler temperatures in the summer help reduce the vapor pressure gradient. At the same time the tree canopy traps some of the water vapor transpired by the crop and the tree, increasing the relative humidity under the canopy and decreasing the vapor pressure deficit. Zhu (1990) states that soil temperatures in the winter months are warmer under *Paulownia* trees. This helps reduce the risk of frost damage to the winter wheat crop.

All of these factors are interrelated. With plant water stress, water uptake and soluble nutrients decreases. If optimum quantities of water, nutrients, and PAR are not present at crucial times in the plant's lifecycle, yield is drastically reduced.

1.2.6. Systems Approach Versus A Single Variable Analysis.

Agronomists often feel that PAR is the primary ecological factor in crop competition (Pendleton and Weibel, 1965).

Zhu[1], states that PAR, in a *Paulownia*/crop with crops system, is the key factor as the energy to the crop and thus its yield is more significantly affected by PAR than water or nutrients. Jiang[2] calls investigation of PAR effects the cutting edge of *Paulownia* intercropping research.

Nevertheless, if one variable (PAR) is isolated from all others, it is not possible to see how the major factors interact within the system. Addressing the difficulties of isolating variables in tree intercropping with shade on coffee, Huxley (1967) states:

> "The effects of natural shade on mature trees are immensely complicated, not only by self and mutual shading, but by many factors other than shade *per se*. In such field experiments it is impossible to analyze the complex by testing the effects of one or a few factors at a time because so many interactions are involved."

This gives credence to a systems approach to agroforestry experimentation. However, to date, agroforestry systems are not developed to the point where cause and effect holistic models are available (Loomis and Whitman, 1983). Thus, one or two factor experiments are conducted. By using the monocrop as a basis for yield potential, primary factors (PAR, nutrients, and water) in an agroforestry system are isolated, manipulated and compared.

---

[1]Zhu Zhaohua -- personal conversation -- 1990.

[2]Jiang Jianping -- personal communication -- 1993.

1.2.7. PAR Characteristics and Canopy Penetration.

Anderson (1964) describes 2 types of light systems -- radiometric and photometric -- each with their respective terms and units. Irradiation is the term used when measuring intercepted radiant flux. Irradiance (interception per unit area) has units of Watts m^{-2} ($W\ m^{-2}$)[3,4]. The photometric system is used when quantifying intercepted illumination with units of candela m^{-2} ($cd\ m^{-2}$)[5]. The two systems are different and units do not readily convert. Plant studies are generally interested in irradiance and usually focus on a portion of the spectrum, from 400-700 nanometers (nm)[6] of the electromagnetic spectrum, which is called the range of photosynthetically active radiation (PAR).

PAR, measured in photons, is that part of the spectrum that plants use for photosynthesis. There is no international unit (SI) to quantify photons, however, 1 mole = 6.022×10^{23} photons (Avogadro's number)[7]. Biggs (1982) presents the following approximate values for full sun plus sky radiation,

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[3]All units will be in international units (SI), if available, with other systems, if mentioned, in a footnote.

[4]$cal\ cm^{-2}\ min^{-1}$

[5]lux or foot candles

[6]According to Ross (1975) the US and Western Europe use 400-700 nm while Russia and Eastern Europe use 380-710 nm.

[7]A mole is an SI unit; 1 mole = 1 Einstein.

for midday, midsummer, 41^0 North latitude:

PPFD[8] or Quantum Flux ≈ 2000 μmoles m^{-2} s^{-1}
Total irradiance ≈ 1000 W m^{-2}
Photosynthetic irradiance ≈ 500 W m^{-2}

and for 1 days integration:

Photosynthetic Photon exposure ≈ 60 moles m^{-2}
Total radiant exposure ≈ 8000 Wh m^{-2} (Watt hour m^{-2})
Photosynthetic radiant exposure ≈ 4000 Wh m^{-2}

For a single wheat leaf the photosynthetic process becomes light-saturated at one-third to one-half full sunlight (Evans et al., 1980; Simmons, 1987). However, canopy saturation is not the same as leaf saturation. Connor (1983) states that wheat communities light-saturate at 700 W m^{-2} while full sunlight is about 1360 W m^{-2} (the solar constant)(List, 1951). Monteith (1975) states that radiation is absorbed in its travel, by gases, and scattered by gases, dust, and water vapor, thus reducing the irradiance to an effective range of 700 to 1000 W m^{-2}.

With cloudless days PAR from direct radiation is much greater than diffuse and diffuse radiation can be neglected (Ross, 1975). Figure 1.6 compares atmospheric (S_p), total (S_t), direct (S_b), and diffuse (S_d) solar radiation. On very cloudy days all PAR would be from diffuse radiation. With alto-cumulus or alto-stratus clouds, the maximum diffuse radiation would be 350-450 W m^{-2} and with nimbo-stratus or stratus clouds, only 30-50 W m^{-2} (Ross, 1975). Thus, the additional amount of tree canopy that intercepts direct solar radiation can become important to the understory crop canopy.

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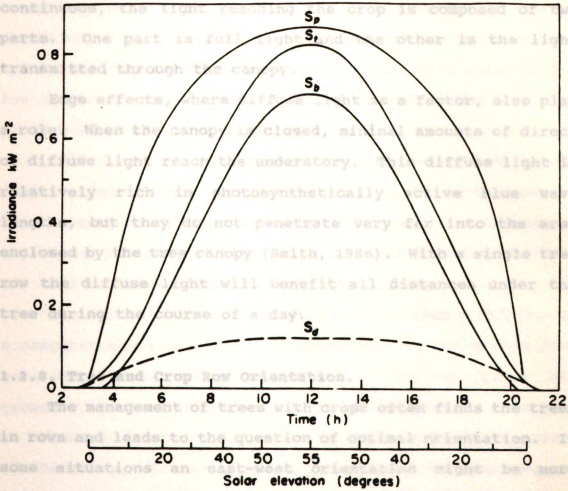
[8]Photosynthetic photon flux density or quantum flux density.

S_p=Atmospheric radiation,
dependent on solar elevation
and transparency of the atmosphere
S_b=Direct radiation at horizontal
surface of the plant
S_d=Diffuse radiation
S_t=S_b+ S_d



(After Ross, 1975)

Figure 1.6. Diurnal Direct and Diffuse Solar Radiation.

The focus in this research is on PAR under the tree canopy and its effect on wheat yield. These effects should be more pronounced under closer tree spacings. Jackson (1983, 1989) states that the study of light transmission through the canopy in agroforestry must consider the discontinuous canopy case. When trees are arranged so that the canopy cover is not continuous, the light reaching the crop is composed of two parts. One part is full light and the other is the light transmitted through the canopy.

Edge effects, where diffuse light is a factor, also play a role. When the canopy is closed, minimal amounts of direct or diffuse light reach the understory. This diffuse light is relatively rich in photosynthetically active blue wave lengths, but they do not penetrate very far into the area enclosed by the tree canopy (Smith, 1986). With a single tree row the diffuse light will benefit all distances under the tree during the course of a day.

1.2.8. Tree and Crop Row Orientation.

The management of trees with crops often finds the trees in rows and leads to the question of optimal orientation. In some situations an east-west orientation might be more beneficial than north-south. This will depend on the type of tree and its age, the crown shape, and the length of clear bole. Depending on latitude, time of year and crop, shading may be beneficial or harmful. The underlying crop may also do better in rows oriented in a certain direction.

In their work in Rwanda, Neumann and Pietrowicz (1989) found tree row orientation can have a significant effect on light penetration with strips of 8-year-old *Grevillea robusta* trees up to 15 meters (m) tall. Maize (*Zea mays*) was planted in the strips with 10 m between tree rows. Performance was better when rows were oriented east-west. The fact that Rwanda is near the equator meant the sun's zenith was always relatively high. With tree rows 10 m apart and trees having a full crown, a north-south tree row orientation meant only a few hours of direct sun to the crop around midday and crop yield was reduced.

Reifsnyder (1989), simulating equatorial conditions, demonstrated the east-west orientation to be more effective than a north-south orientation for solar radiation capture at the center of the tree rows. The emphasis seemed to be with the tree rows being relatively close together.

As latitude increases, time of year becomes a factor. In a computer model calculating shadows cast on the ground from non-light transmitting hedgerows of various sizes and geometry, Jackson and Palmer (1989) showed that on June 21st at 30^0 North latitude, trees one-fourth as tall as the width of the alley, allowed a greater percentage of irradiance to the alley when they were oriented in an east-west direction compared to a north-south direction. Incoming irradiance differences increased as the distance between tree rows decreased and/or trees became taller. However, in a north-south row orientation the daily pattern of radiation did not vary much with time of year.

In Henan Province, China, researchers at Henan Agricultural University (HAU -- 35^0 N) investigated both east-west and north-south tree row directions with *Paulownia* under field conditions. In both situations there were rectangular areas parallel and adjacent to the tree rows where wheat yield was reduced. However, with east-west tree rows the overall yield was less than with north-south rows. A contributing factor was the 4-6 m clear bole on the 8 to 12-year-old *Paulownia* trees. In the north-south orientation wheat received direct PAR at some time during the day while the east-west row had an area that only received direct PAR very early or very late in the day.

Zhu (1990) confirmed this in his study of 9-year-old *Paulownia* trees at 5 x 40 m spacing. In a north-south orientation the area of reduced wheat yield was 8.6 m wide while in an east-west orientation it was 8.8 m. However, the yield near north-south rows was reduced 6.7% while yield near east-west rows was reduced 22%. In the same study Zhu noted a clear bole of only 2.8 m reduced wheat yield by 14.2%, but only a 5.1% yield reduction was noted with 4.6 m of clear bole.

Wheat <u>row</u> orientation (in monocultures) may also have some bearing on yield. Three studies (Day et al., 1976; Erickson et al., 1979; and Kirkham, 1982) all stated that wheat yields were higher in east-west rows than in north-south. However, ANOVA's were either not significant, not given, or designated "significant" at p=.1600.

1.2.9. Previous Work with Crops Under Trees.

Some work in agroforestry with tree/crop combinations has been done with alley-cropping (Kang et al., 1985; Wilson et al., 1986) in Africa. In this agroforestry system trees are lopped or coppiced at systematic intervals to increase PAR to the crop grown between the tree rows.

The effects on yield due to a tree canopy reducing PAR availability have been studied with crops such as tea, *Camellia sinensis*; coffee, *Coffea arabica* and *C. canephora*; and cacao, (*Theobroma cacao*). However, shading affects an understory crop to different degrees depending on the soil moisture and nutrient status. Tejwani (1987) stated that unshaded tea on nutrient poor soils in India gave a lower yield than shaded tea. He also indicated that overly shaded tea gave a lower yield than medium or lightly shaded tea. Barua (1970), on the contrary, recommended that since 35^0 C is the upper limit for net photosynthesis in tea, most tea growing countries should remove the shade in their tea plantations. The exception he noted was Northeast India.

Water availability for the tea crop can play an important role in determining the need for shade with tea. McCulloch et al. (1965) found that in two rainfed areas of East Africa (1270 mm and 1778 mm of rainfall per year), shade reduced yield of tea plants in all quadrats at differing distances from the tree stem. Carr, (1972) on the other hand, found that water use with tea had conflicting results. During the dry season in Africa, he found that shading protected the tea from higher temperatures, but that the benefit was offset by reduced yield when the rains came.

In a nutrient and shade experiment with cacao in Ghana, Africa, Cunningham and Lamb (1959) designated four treatments -- with and without shade in combination with and without fertilizer. They found that no shade with fertilizer treatment yielded the best results followed by no shade with no fertilizer. In this study water stress was not mentioned, but in a follow up study in the second and third year with the same plants, Cunningham et al. (1961) found no changes in soil moisture in shaded and unshaded plots. Thus, nutrient and water availability are important considerations when conducting shading studies.

As McCulloch et al. (1965) pointed out with their work on tea, and Campbell et al. (1969) with their work on wheat, trees (or shading) provide shelter and the shelter effects from wind confound the shading effects of temperature. Indeed, Carr (1970) stated that shade was originally provided to tea in order to mimic the conditions found in the forest where tea was often found. However, the trees influenced the environment around the tea bush in so many ways that it was difficult to separate the factors involved. Thus, microclimate and shade may have to be regarded as a complex when integrating trees and crops.

In his experiments in Northern Mexico, Fischer (1975) was able to eliminate air temperature, a major factor in wheat development, from confounding his shading trials with PAR and irrigated, high fertility wheat. He stated that there were only small effects on the rate of crop development between plots with 76% shade and no shade at harvest (the warmest time for the crop) meaning air temperatures influence on wheat yield could be disregarded. In this location mean temperatures were 21^0 C which was within wheat's optimal range (10^0-25^0 C, Evans et al., 1980) for net photosynthetic response rate to temperature. However, trees were not used as a source of shading and they may confound the system.

As Corlett et al., (1989) pointed out, trees do provide shelter for the crop in the form of microclimate changes. Associated factors such soil moisture, air and soil temperatures, relative humidity, wind speed and direction, and rainfall all play an important role in these changes. When trying to investigate a single variable, such as PAR, to determine its significance, climatic variables and conditions must be considered. Any changes in the microclimate brought on by the trees can confound experiments.

Soil moisture effects due to trees also influence wheat growth and development underneath the tree canopy as opposed to away from the canopy. Soil-water differences may occur from stemflow and throughfall, wind effects, shading, or root competition.

Soil moisture effects due to stemflow and throughfall can confound the shading effects of the tree. This can be minimized with irrigation. With irrigation, high soil moisture is maintained so that excessive stresses are not placed on the trees or crops, thus moderating the problem.

Shelterbelts, however, may alter the rainfall pattern in the wheat field.

Darnhofer et al. (1989) studied rainfall distribution at the tree/crop interface of 3 m tall hedgerows and found that interception, throughfall, and stemflow were modified. Results showed that there was slightly less rainfall on the leeward compared to the windward side, but that there was an increase at the tree/crop interface. The main factors influencing the rainfall pattern were wind speed and direction relative to the tree line. The average rainfall deficit, due to the rain shadow effect, for the area 1.5 m from the hedge as compared to a reference area 5 m away was 18%. Thus, with hedges there was less rainfall nearer the hedge (1.5 m) than at a distance of 5 m. Once again the characteristics of wind flow and rainfall distribution may be different near a hedge as compared to a tree with a crown and a clear bole.

Wind direction and speed in relation to a tree line will affect the rainfall pattern as mentioned above, but it also plays a role with the relative humidity and air temperature. Winds become an especially important factor influencing the soil moisture status of wheat just before harvest. During the hot, dry winds which can occur after anthesis in many wheat growing regions of the world, the temperatures readily exceed 25^0 C, at the high end of wheat's optimum range. These winds send temperatures above 30^0 C for several days causing stomata closure and excessive carbohydrate respiration. Consequently, there is a reduction in yield. Nevertheless, Sheikh and Chima (1976) stated that the extent of a shelterbelt's influence on a wheat crop was at least 15 times the height of the trees. Any control downwind of the trees should be planned with this in mind.

It may be possible to plan experiments so that the microclimate and its changes can be incorporated into the results to help explain the differences in yield, if any, that occur.

1.2.10. Prior Work with Wheat and Trees.

Work on wheat under tree canopies has been done in many areas around the world. Akbar et al. (1990) examined the effects of four selected tree species (5 years old and 3 to 11 m tall) on wheat yield compared to a monocrop of wheat. The trees were located on the field boundary with 1 m x 1 m yield quadrats centered at 2, 4, 6, 8, 10, and 12 m from the tree line. In addition a control was established at 2, 4, 6, 8, 10, and 12 m from a field boundary without trees.

Results revealed that trees had no significant impact on wheat yield ($p > .1$). Possible reasons for the results were attributed to the combination of inconsistent control yields at the different distances and young trees with relatively small crowns.

Puri and Bangarwa (1992) compared irrigated wheat yield under 4 different tree species (single trees scattered about a field) at distances of 1, 3, 5, and 7 m; directions east, west, south and north; and for an open grown control in India (about 29^0 N). They found crop yield was always lower under the trees compared to an open grown control and that wheat yield increased as distance from the tree increased up to 5 m. Yield on the north side was reduced compared to the south side.

Azadirachta indica and *Prosopis cineraria* seemed to be compatible as agroforestry trees with wheat and experienced a 6-7 day delay in crop maturity. *Dalbergia sissoo* had some reduction in wheat yield and a 9-10 day delay. *Acacia nilotica* was not recommended as an agroforestry tree due to 40-60% wheat yield reductions under the tree and a 3 week harvest delay. Results could have been from PAR differences or nutrient levels. Temperature may have played a major role with April-October means above 32.0^0 C.

Rehman (1978), working in Pakistan, found that wheat planted between shelterbelts of one row of *Tamarix gallica*, two rows of *T. gallica* and *Arundo donax*, or three rows of *T. gallica*, *A. donax*, and *Colligonum polygonoides* increased in yield. However, he did not determine the effects of trees on the yield at different distances from the trees. Rather his yield plot consisted of the whole area between the tree rows. Rehman, also noted that soil moisture was higher with the shelterbelts. This possibly contributed to the increase in yield.

Trees were planted at right angles to the prevailing wind, however, no mention was made as to orientation and possible effects of shading. Thus, identifying the reason for an increase in yield cannot be conclusively determined.

1.3. PAULOWNIA AND WINTER WHEAT

1.3.1. Past and Present Work with Paulownia.

Paulownia intercropping has been under intensive scientific study in China since 1979 when the Ministry of Forestry listed it as a key project (Zhu, 1988). This was only a few years after the Cultural Revolution (1964-1975) during which forestry research practically ceased and researchers were displaced. At the start of this project very little infrastructure or forestry expertise remained, consequently progress was slow.

With the *Paulownia* tree, the first areas of interest aside from morphological and taxonomic characteristics and its propagation, were its uses in agriculture and as a fuelwood source. Originally, farmers kept this tree in their fields because wheat crops seemed to do well underneath. However, the trees were randomly scattered. Researchers took this system and improved on it through intercropping/spacing trials. They also attempted to introduce management practices to further increase economic yield (Zhu, 1988).

Because the government was very interested in the possible benefits for the farmer and the nation, they supported the program. However, the depth of research was stymied by a lack of trained people and available equipment. Thus, spacing trials (for the trees) were conducted to discover what the best spacing was for the most output depending on whether the tree or the crop had priority. In the early 1980's it was premature to address the question of

<u>why</u> a given spacing was best or <u>how</u> the components of the system interacted.

1.3.1.1. Chinese Academy of Forestry (CAF).

In 1983 the Chinese Academy of Forestry (CAF) with the help of the International Development Research Centre (IDRC) of Canada purchased land on a long term lease for *Paulownia* research. This research area consisted of about 22 ha[9] in two work units and is located in Anhui Province, Dang Shan County. At this experiment station, trials were established using a randomized complete block design with three blocks of five different densities (5 m x 6 m, 5 m x 10 m, 5 m x 20 m, 5 m x 40 m, and 5 m x 50 m). Each block was 0.2 ha[10] and yield plots were 0.6 m x 1 m.

In 1984 meteorological equipment was set up to measure air temperature, relative humidity, evaporation, precipitation, daily high and low air temperatures, soil temperatures at 5, 10, 15, and 20 cm depths and wind speed three times a day (0800, 1400, and 2000). Observations were recorded continuously for 6 years on ecological factors, biomass, mineral cycling, and energy flow. Measurement data were taken on the tree, both above and below ground, to describe its growth. Biomass of the tree was recorded and yield of the crops at the different spacings noted. Microclimate changes due to the trees were also recorded.

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[9]330 *mu*.

[10]3 *mu*.

Light penetration was recorded for different tree/crop combinations at different distances from the trees and at different times of the season using equipment procured from France. This equipment continuously measured light with spot readings for three days at distances of 1 m, 5 m, 20 m, and 39 m from two tree lines that were 40 m apart. The objective of the observations was to determine the key factors that influenced growth in different crops of wheat, maize, and cotton (*Gossypium hirsutum*) with different tree row spacing. Observations were made for six years and as of January 1991 IDRC's five year funding program had finished as had most of the active research. The results of this work have been compiled in a project summary report by Zhu (1990).

1.3.1.2. Paulownia Research Center -- Zhengzhou.

In the late 1980's a *Paulownia* research center was established in *Zhengzhou*, Henan Province under the direction of the Ministry of Forestry in Beijing. About 1988 they established a research station in Luyi County of eastern Henan Province. They too have begun spacing trials with *Paulownia* intercropping with crops. At present (1993) they have been awarded funds from the United Nations Development Program (UNDP) for a five year period to continue their research in many aspects of *Paulownia*. Many of their scientists are young and the institute is just becoming fully staffed.

1.3.1.3. Henan Agricultural University.

In Henan Province, where the *Paulownia*/wheat intercrop system seems to have originated, Professor Jiang Jianping of Henan Agricultural University (HAU) in *Zhengzhou* City has been working with *Paulownia* for 30 years (Jiang, 1990). During this 30 year period President Jiang and his staff have made more than 10 significant achievements in *Paulownia* silviculture and breeding. Since 1980 there has been an increasing focus at Henan Agricultural University on *Paulownia* intercropping.

In his book *The Silviculture of Paulownia* (Jiang, 1990 -- not translated into English), Prof. Jiang details the *Paulownia* research that has been conducted at HAU. The following is a list of the research areas:

1. *Paulownia* history
2. *Paulownia* distribution in China
3. Anatomy and morphology
4. Ecological aspects -- growth, light, temperature, and soil moisture.
5. Physiology
6. Growth and development stages
7. Breeding -- *Yu Xuan Yi Hao* and *Yu Za Yi Hao*
8. Nursery practices and procedures
9. Regeneration by seed and cuttings
10. Pruning techniques for stem straightening
11. Afforestation
12. *Paulownia* intercropping with crops
13. Insects and diseases
14. Timber uses

Presently the research at HAU is centered on three different aspects -- ecological, physiological, and utilization. Concerning the ecological aspect, the focus is on *Paulownia* intercropping with crops. The idea is to develop several models for the farmers to see and then implement. In the physiological area the main concern is to develop some cure or prevention for witches broom (*Mycoplasma* like organisms, MLO) that attacks *Paulownia*. Lastly, the utilization topic is intent on finding and improving the economic benefits that accrue from *Paulownia* trees.

There are several faculty and staff that form the *Paulownia* Research Institute at HAU with the objective of investigating what has been termed the Artificial Ecological System of *Paulownia* Intercropping with Crops (AESPIC). They are conducting agroforestry/*Paulownia* intercropping research at Henan Agricultural University and in the countryside on farmer's land. Current research interests include 1) light distribution and utilization; 2) water changes, distribution, and metabolism; 3) nutrient distribution, utilization and cycling; 4) and temperature. Some of these research areas are presently under investigation and some will be investigated in the near future. At present HAU is trying to find cooperative international organizations and scientists to help provide external funds and equipment for collaborative research.

This study was designed to fit in with current work at Henan Agricultural University. The aim was to explore the resource sharing of PAR, nutrients, and water at the tree/crop interface to help explain the relative contributions of these and other factors on resulting tree biomass, and crop yield. This coincided with the current areas of interest at Henan Agricultural University.

Outside of China there is little research with intercropping *Paulownia* species. Researchers in Australia and New Zealand have shown some interest (Stephen, 1988; and Reid and Wilson, 1986) and there is recent interest in *Paulownia* as a plantation species in Brazil, Paraguay, Argentina, the United States, Malaysia, Indonesia, Pakistan, New Zealand and Australia. Taiwan and Japan have had plantations for over 70 years, however, intercropping is not the major emphasis (Stephen, 1988).

1.3.2. Paulownia Characteristics.

Taxonomically *Paulownia* is in the *Scrophulariaceae* family. This tree is native to China and Jiang (1990) lists 9 species spread over most of the country. On the North China Plain the main *Paulownia* species are *Paulownia elongata* (*Lankau Paotong* or *Lankau Paulownia*), *Paulownia fortunei* (*Bai Paotong* or White Flowered *Paulownia*), and *Paulownia tomentosa* (*Mau Paotong* or Hairy *Paulownia*). One natural selection, *Yu Xuan Yi Hao* (Henan Selection Number One), an open pollinated *P. fortunei* hybrid and another hybrid, *Yu Za Yi Hao* (Henan Hybrid Number One), *P. tomentosa* by *P. fortunei*, are now in use in the North China Plain.

Yu Xuan Yi Hao was used in this research. It was first noticed in Shandong Province to the northeast of Henan Province. Seed was collected from the mother trees between 1972 and 1974 and seedlings were grown in a nursery. The best seedlings were selected for field planting and afterward the best of these were selected for root cuttings.

Research, at HAU, has shown that the root cuttings should be planted in March at 6000 to 7500 trees ha^{-1}. They will grow rapidly in July, August and September and can be harvested after the first frost or in the spring for transplanting. These "sticks" reach 3-4 m after one year. If, however, the cuttings are kept two years in the nursery, the stem is longer (6-8 m), survival is higher and value per "stick" is greater.[11]

Yu Xuan Yi Hao has several advantages over its parent tree. It grows faster, is more vigorous and the bole is longer and clearer. There is less forking so it does not have to be pruned to get a straight stem. At the top of the tree the branch angle is small relative to the main stem so the main stem is more obvious. In addition the stem form is good, with a long, narrow crown. The leaves are more oblong and a dark green. In China *Yu Xuan Yi Hao* has been planted along roads, along canals, in villages, around homes and for agroforestry intercropping.

Yu Xuan Yi Hao also grows in diverse conditions, and is widely distributed in several provinces. In Henan it does equally well in the mountains or on the plains.

There is one major drawback to *Yu Xuan Yi Hao* and that is its susceptibility to the disease witches broom. This factor led to continued search for more resistant hybrids. The result was a new hybrid *Yu Za Yi Hao* which is a cross of *P. tomentosa* and *P. fortunei*. Today *Yu Za Yi Hao* is the choice of the farmers because it is less susceptible to witches broom. At the same time its early growth is faster than *Yu Xuan Yi Hao*. Other characteristics include a main stem that

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[11]Jiang Jianping, personal conversation, October, 1990.

is easy to train so that the bole is straight, leaves that are more egg shaped and a little lighter green, and a crown that is rounded or egg shaped.

At present researchers in Henan are quite satisfied with the growth rate of *Paulownia*, however, witches broom is still a problem. The latest variety, still in the nursery stage, is called *Mau-Bai* 083323 (*P. tomentosa* by *P. fortunei*). It not only has faster growth than the other hybrids, it is also more resistant to witches broom.

1.3.2.1. Paulownia Growth and Development.

Paulownia is a fast growing broadleaf tree with a branching pattern and root morphology that make it suitable for intercropping. Zhu et al. (1986) list the following statistics on a few of the better growing trees:

Table 1.2. Fast Growing *Paulownia* Trees.

Species	Age (Yr)	dbh (cm)	Height (m)	Latitude
P.elongata	19	104	17.1	34^0 51′ N
P.elongata	13	73	17.5	34^0 50′ N
P.fortunei	75	134.4	44.0	28^0 06′ N
P.fortunei	31	100.5	21.7	28^0 06′ N
P.fortunei	11	75.1	22.0	25^0 00′ N
P.fortunei	80	202	49.5	26^0 13′ N

(After Zhu, 1986)

Paulownia is largely propagated by root cuttings. Cuttings are grown in the nursery for up to 2 years and planted as "sticks" with better stock being as tall as 7 m.

Planting usually takes place in the spring. The leaves grow rapidly and although large are generally sparse. The most rapid growth occurs from June to September which coincides with the period of maximum rainfall in eastern China. If tree form is poor after the first year, *Paulownia* can be coppiced at ground level and allowed to grow back.

Growth is indeterminant and continues until the first frost. Over the winter the apical and several top axillary buds become frost damaged, but the following spring bud growth renews at a lower axillary bud. Different species have different growth habits with some species having buds that assume apical dominance and others tending to branch. Also, some species tend to have growth spurts every few years while others experience steady growth.

In the first few years the tree basically has a pole form with few branches. During this time the root system is establishing itself. With intercropping at 5 m x 10 m shading becomes a problem about year 4 as the canopy begins to close. The crown will grow to about a 10 m diameter by year 10.

The inflorescence is a cyme that has a peduncle longer than the pedicels or that is sessile (Figure 1.7). Flowers develop at approximately year 5 with the inflorescence developing in the axil of smaller leaves in summer and autumn. The *Paulownia* tree leafs out in the spring later than most species, with flowers (if present) preceding leaves.

The root system has a distinctive morphology with two defined root zones -- an upper zone (0-80 cm) and a lower zone (below 80 cm). In the top strata 98% of the absorbing roots

1. Leaf
2. Fruit branch
3. Flower
4. Flower
5. Flower cross section
6. Pistil with corolla removed
7. Fruit
8. Pericarp
9. Fruit calyx
10. Seed
11. Leaf hair

(After Jiang, 1990)

Figure 1.7. *Paulownia fortunei* Leaf and Inflorescence.

are within a 4 m radius of the tree. Only 12% of these absorbing roots are in the upper 40 cm with 70%-85% located between 40 cm and 100 cm depths (Zhu et al., 1986).

The lower zone, which begins at .8-1 m, is comprised of larger anchor roots and smaller feeder roots. Three to five anchor roots extend into the ground in a claw shape and penetrate into this lower horizon where they spread out as far as 29 m horizontally (Zhu et al., 1986).

1.3.2.2. Litterfall.

In addition to rapid growth, *Paulownia* provides nutrients through litter. *Paulownia* leaves contain 2.96% N, 0.08% P, and 0.41% potassium (K) and one 7-year-old *Paulownia* tree contains 40 kg of leaves fresh weight (Jiang, 1990). If each ha has 60 trees[12] that are 7 years old, this will produce 1095 kg leaves ha^{-1} dry weight. This is the same amount of protein that can be obtained from an equal weight of bean casings.

Paulownia leaves fall in November during wheat's establishment phase and this may help the new crop. Since the *Paulownia* tree continues its growth late in the fall, when a frost comes the leaves will fall within a day or two making it easy to collect them at one time. If there is no quick freeze, farmers may from time to time be seen in their fields collecting the leaves. They use them to feed farm animals or to make compost. If the leaves are collected, litterfall will not have a great effect on the soil. However, should the

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[12]Four trees/*mu*.

leaves remain on the ground as litter they will enhance soil nutrients.

1.3.3. Winter Wheat cv You Zhi Bai Nong 3217 Characteristics.

The wheat cultivar, *Triticum aestivum* cv. *You Zhi Bai Nong 3217* (优质百农) a soft seed or common wheat, was developed in China and is widely used in Henan Province. The Agricultural Scientific and Technological Company in Henan Agricultural University (1990) published an information sheet about this cultivar. Some of its characteristics and advantages include the following: The seed protein content of this cultivar is higher than average as is the 1000 grain weight, ranging from 35 to 43 grams (g).

You Zhi Bai Nong 3217 is a dwarf species which stands 75 to 80 cm tall and this helps reduce losses due to lodging. At present not all farmers are interested in planting dwarf wheat. The ripening period is a little earlier than other cultivars which reduces the amount of time the wheat is subject to loss from harsh environmental conditions. This wheat resists low temperatures, drought and does well under poor soil conditions. In addition when fertilizer and water are added there is efficient utilization.

The time of planting is an important factor for seeding. *You Zhi Bai Nong 3217* has a long planting window -- from early October to mid-November. This is an important consideration on the North China Plain because there is often very little rain during the planting season. Often the farmers must wait for rain before sowing seed as they do not have irrigation.

When planting in moderately fertile soils, fertilizer is applied, then each hectare receives about 120 kg seed[13]. However, if planting is done late, more seed should be used (150-188 kg ha^{-1})[14]. This will help offset the possible lower survival rate due to harsh climatic conditions.

In addition to its dwarf height, the leaves form about a 45^0 angle and the head is a little bigger with more flowers and more seeds. It also has more tillers than other wheat cultivars which increases its yield potential. At the same time it has been found to be less susceptible to disease. One of its most noteworthy characteristics, though, is that it consistently yields 4500-6000 kg ha^{-1} [15].

1.3.3.1. Winter Wheat Growth and Development.

Wheat goes through several development phases during its lifecycle to produce grain. Wheat storage capacity consists of 1) establishing the number of grains or kernels and 2) filling them. The former occurs before anthesis and the latter after. Storage capacity is determined by several yield components that develop sequentially during wheat growth (Evans et al., 1980). These include 1) the number of ears per unit area (tillers), 2) the number of spikelets per ear (Figure 1.8), and 3) the number of florets per spikelet which

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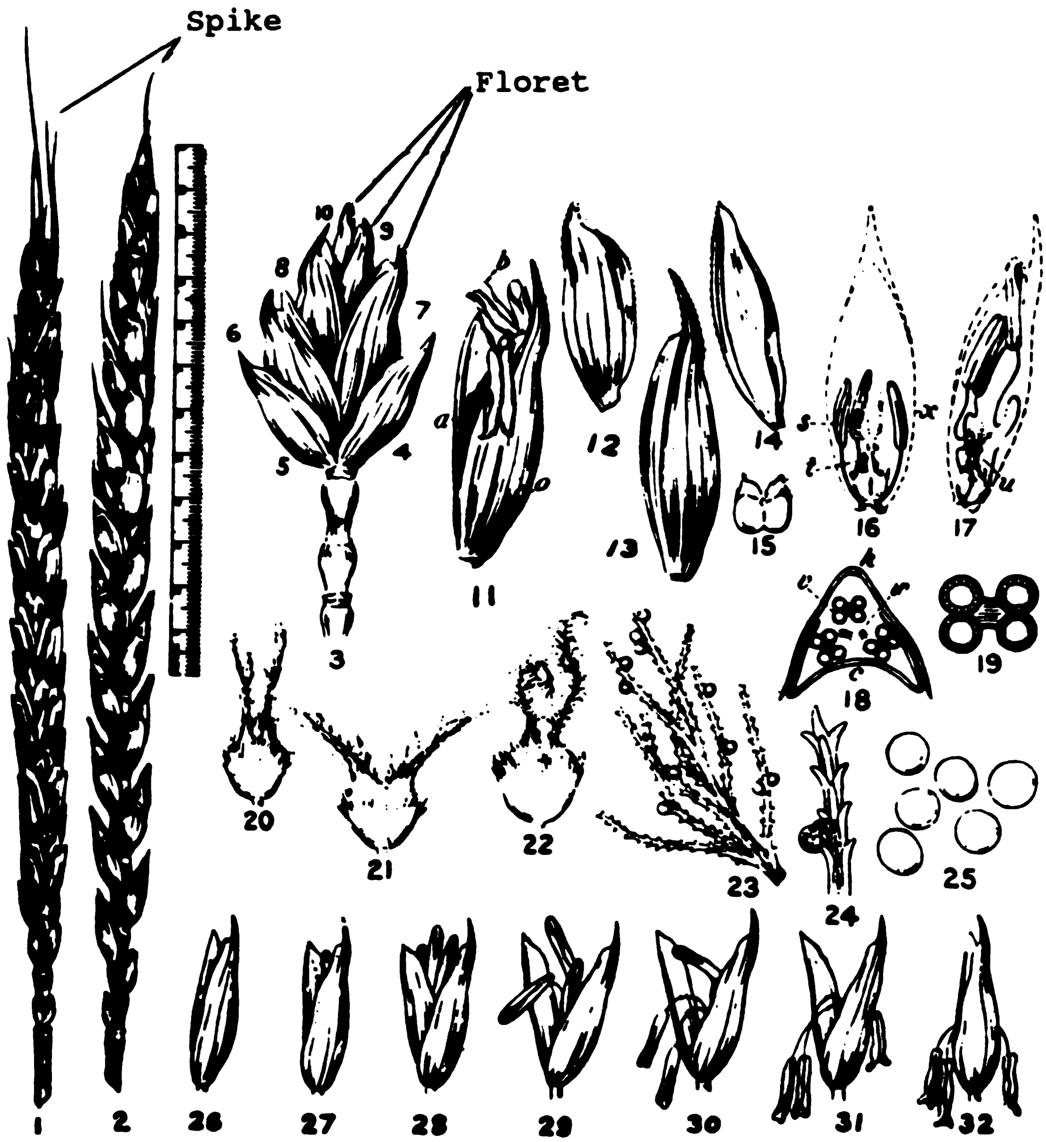
[13]15-16 *Jin* mu^{-1}.

[14]20-25 *Jin* mu^{-1}.

[15]600-800 *Jin* mu^{-1}.



(After Lersten, 1987)

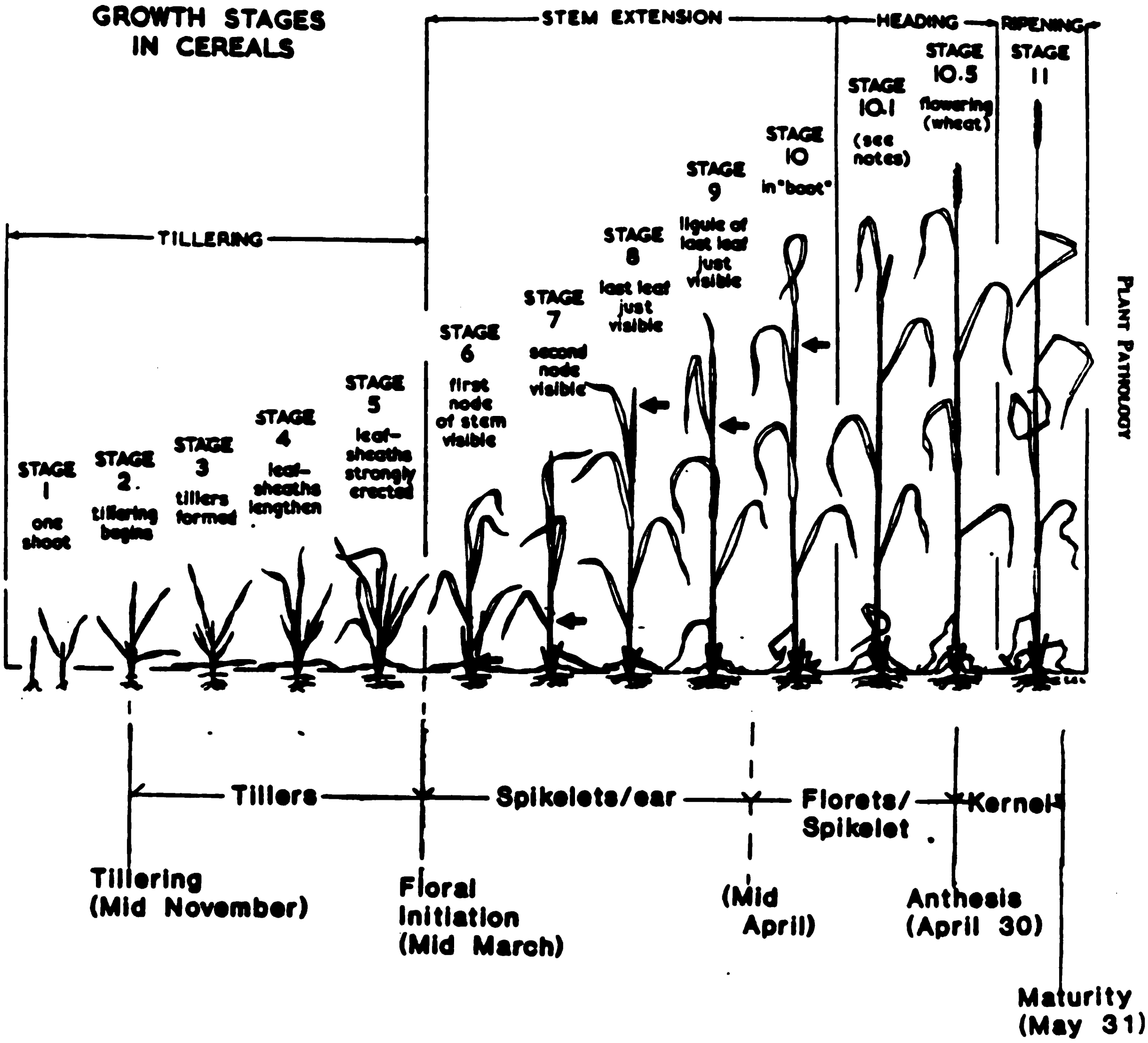
Figure 1.8. Wheat Inflorescence.

concludes at anthesis. The last stage is 4) kernel development or grain filling.

Winter wheat is planted in the fall and will have about 3 leaves in a normal year before overwintering. During the winter, wheat maintains a very slow leaf extension phase at temperatures below 0^0 C (Gallagher et al., 1979). Vernalization in winter wheat occurs at about 3^0 C (Evans et al., 1980) and with warmer temperatures there is renewed growth leading to floral initiation. This is the time when the effective ears/unit area or tillers develop (see stage 1-3 of Feeke's scale, Figure 1.9)

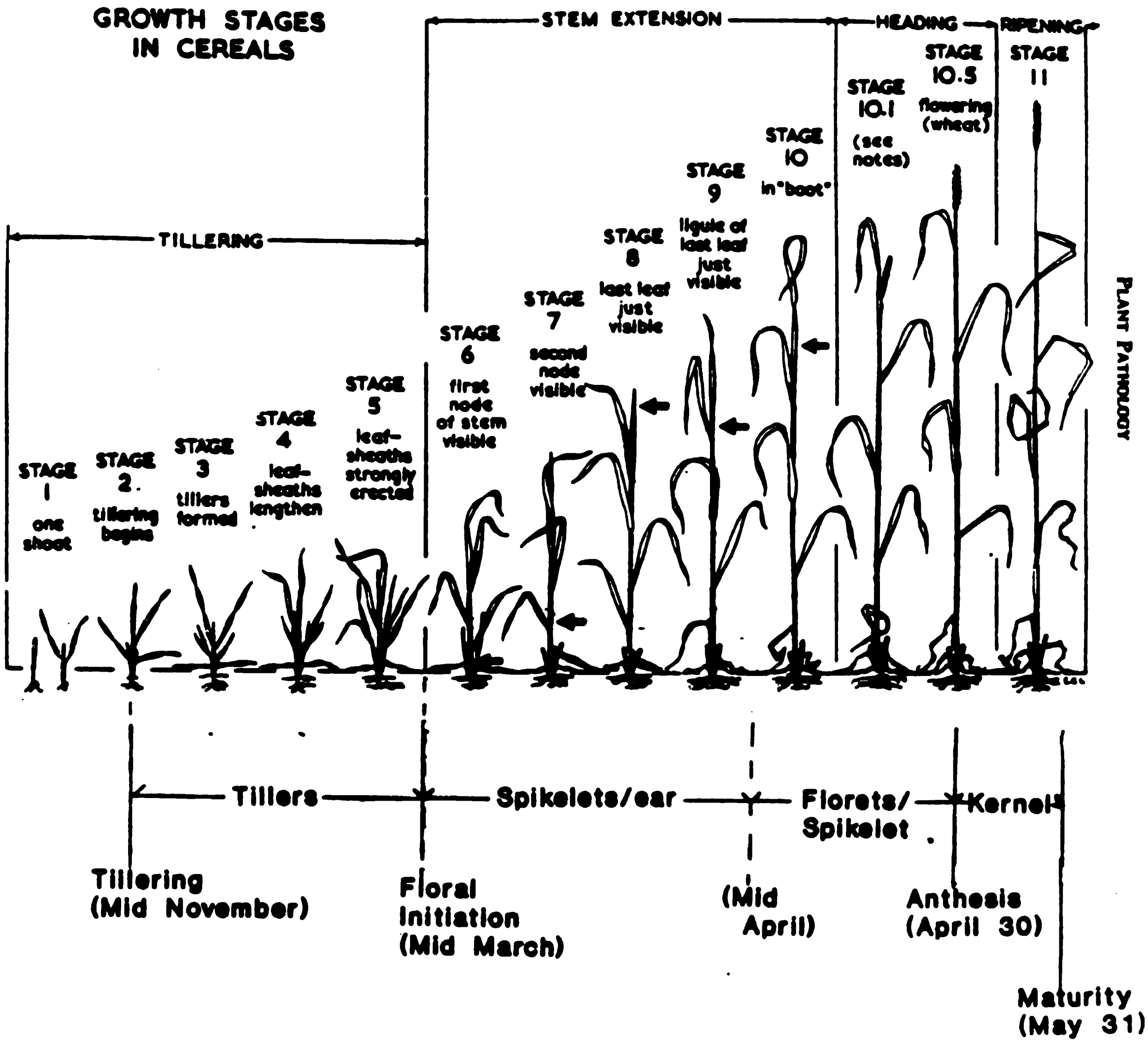
The period from floral initiation in the spring to anthesis (Figure 1.10) is a critical time in wheat's growth and development. During this time the number of spikelets/ear and florets/spikelet are developing and wheat needs optimum amounts of nutrients, water, and PAR to establish maximum grain production potential. This period corresponds to stem extension and heading (stages 6 to 10, Figure 1.9) and can take anywhere from two weeks to two months depending on the cultivar and environmental conditions.

Flowering, which in central China is in late April, occurs about 30 days before ripening. Following anthesis, the last yield component, the kernel, develops. The kernel has several stages of growth: 1) watery, 2) milky or early dough, 3) soft dough, 4) hard dough, and 5) hard (Lersten, 1987) (Figure 1.10).



(After Large, 1954)

Figure 1.9. Feeke's Scale (Wheat--Chang Ge, China 1991-92).



(After Large, 1954)

Figure 1.9. Feeke's Scale (Wheat--Chang Ge, China 1991-92).

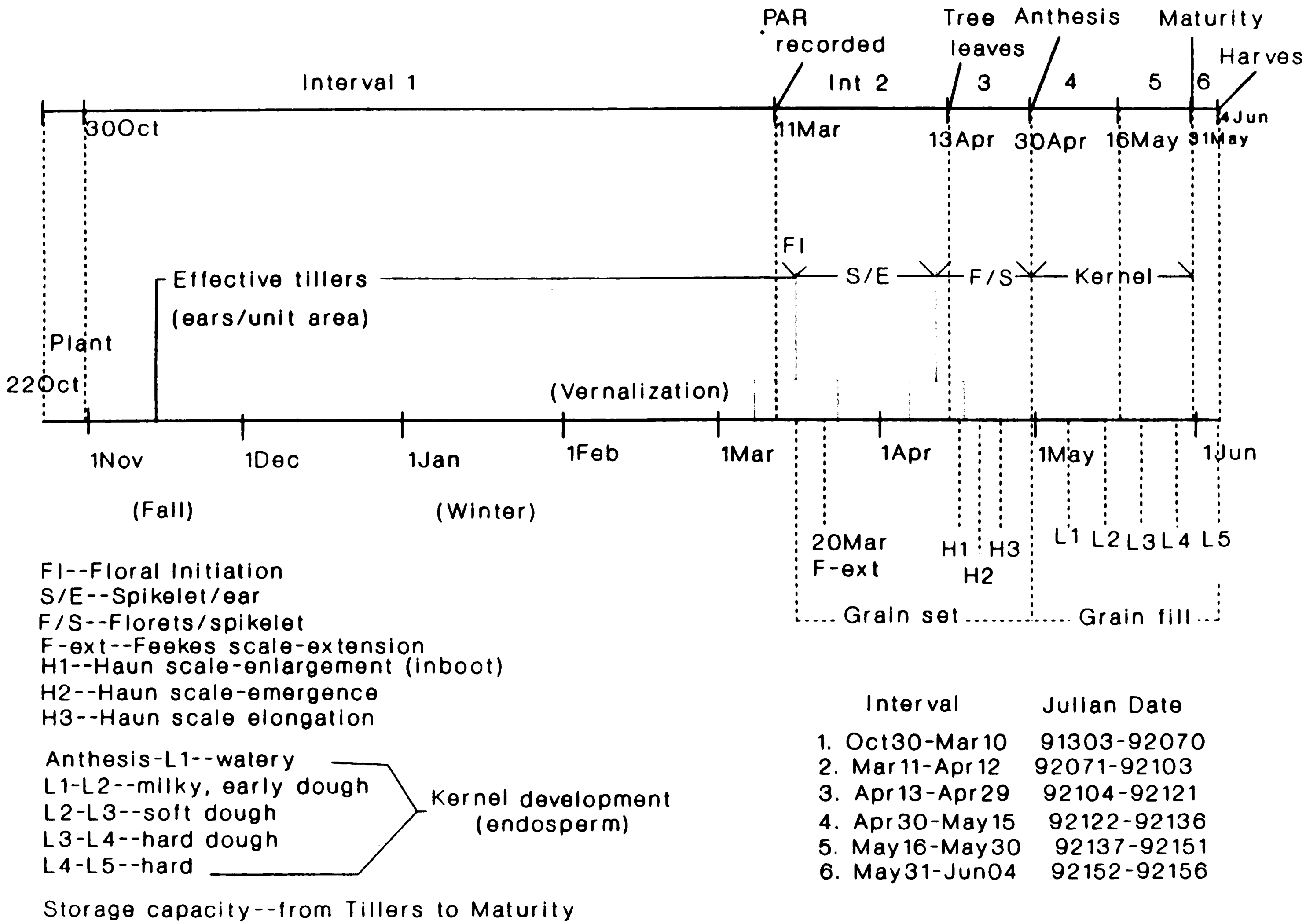


Figure 1.10. ***Paulownia*/Wheat Time Line--China 1991-92.**

Total grain weight is determined by the sequential development of the 4 yield components. If one component does not develop to its full potential due to environmental conditions, the other components generally compensate so that final yield is not reduced. The 1000-grain weight is dependent upon environmental conditions after anthesis. Since 1000-grain weight is one of the components of total grain weight, they are highly correlated.

1.3.4. *Paulownia* and Wheat Compatibility.

Trees interspersed with crops may cause yield decrease of both trees and crops due to shading or they could increase crop yields due to sheltering effects. The degree of shading is determined in part by the phenology of the two crops. The wheat crop in Henan Province is planted in September or October or as late as November depending on the moisture availability. By early November, if the soil moisture is still insufficient, it may be necessary to irrigate if that is an option. Until mid to late November *Paulownia* trees may still have their leaves. In this case shading may be a factor during the establishment phase of the wheat.

During winter the tree is dormant, wheat grows slowly and there is no competition. With spring and wheat floral initiation the tree remains dormant. As Zhu et al. (1986) noted, the *Paulownia* tree leafs out in late April, later than most species. This allows the wheat to receive maximum amounts of PAR during the stem extension and heading period, when grain number is being determined.

During the middle and late part of April (just before wheat anthesis) *Paulownia* will begin flowering and leaf emergence. In the 7 to 10 days following wheat anthesis, Evans et al. (1980) state that low light will decrease endosperm production which takes place in the watery stage and early milky stage (early May). However, they also state that temperature, not light, is the primary influencing factor on wheat development during this time.

By mid-May the *Paulownia* leaves are about full size. Although large, their sparse presence allows PAR penetration. Starch formation begins in the milky stage (early to mid-May) and continues through to the hard stage or maturity (end of May). During this time there is a linear growth in kernel weight if PAR is sufficient and wheat is not stressed (Evans et al., 1980). By early June when the wheat is to be harvested the *Paulownia* canopy still permits 40% to 50% light penetration (Zhu et al., 1986). With good tree management practices (spacing, clear bole, tree row orientation) tree shade can be minimized.

The second (summer\fall) crop is influenced by a fully developed tree canopy. This crop should be chosen carefully and must be shade tolerant[16]. As an example in a cotton plant community, light-saturation is about 900 W m^{-2} (Connor, 1983), higher than wheat. As expected, the *Paulownia*/wheat-cotton

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[16]*Paulownia* species have a fairly thin canopy and allow 20% more light penetration than poplars, *Populus tomentosa*, 38% more than black locust, *Robinia pseudoacacia*, (Zhu et al., 1986) and 27% more than Tree of Heaven, *Ailanthus altissima* (Zhu, 1990).

intercropping system has reported a 20% yield decrease for cotton with 4-year-old trees at 5 m x 10 m spacings and a 14.5% decrease with 8-year-old trees at 5 m x 60 m (Zhu, 1988). With maize as the second crop a 27.7% reduction was noted with 8-year-old trees at 5 m x 50 m.

Aside from competition for PAR, there may also be root competition for water and nutrients. However, the *Paulownia* tree and wheat crop have limited competition. While wheat has 80% of its root system in the top 40 cm of the soil, the *Paulownia* tree is reported to have only 12% of its absorbing roots in this layer (Zhu et al., 1986). Also, tree roots, can be trained to a degree to occupy different soil strata. When the soil is plowed, tree roots are severed in the plow layer, with remaining roots found at deeper levels.

The shelter effects of trees on crops can increase crop yields by protecting against winds, reducing evaporation, or providing a more favorable environment for microorganisms. Li and Xiao (1992) state that 6 different agroforestry systems were investigated in China and the *Paulownia elongata* and crop system provided the best wind protection.

Zheng and Sheng (1989) found over a 12 year period a field with *Paulownia* spaced at 6 m x 30 m outyielded a control of monocrop wheat 4999 kg ha^{-1} versus 4513 kg ha^{-1}, respectively. This was 10.8% greater than the control and illustrates the sheltering benefits of the trees. However, no mention was made of irrigation or fertilization practices.

Zhu (1990) discussed the wheat yield increase in a *Paulownia*/crop intercropping system. He found at 5 m x 50 m tree row spacing with trees 1-3 years old, wheat yield was the same as a control with no trees. In year 4 there was a 5% increase in yield with the trees. By year 7 there was an 8-10% yield increase.

In the *Paulownia* tree/crop system little of the crop is displaced by the tree causing minimal competition for space. The wheat crop is grown between trees up to the base of the trunk. The amount of land used by the tree will be only slightly greater than the area of the diameter at breast height which for 11-year-old trees averages about 5.0 m^2 ha^{-1} [17] or 0.05% of the total wheat growing area.

1.4. CHINA -- THE RESEARCH SITE.

The research site was located in the People's Republic of China near the city of *Zhengzhou*, the provincial capital of Henan Province (Figure 1.11). Henan measures 167,000 square km (slightly smaller than the state of Washington with 176,479 square km) with 512 people per square km. *Zhengzhou* (with 1.66 million people) is approximately 35^0 North latitude and 113^0 East longitude. It is located on the North China Plain just south of the Huang He (Yellow River).

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[17]From the mean diameter at 1.5 m of 33.6 cm, an estimate of 40 cm diameter at ground level (20 cm radius) was used for 40 trees/ha (60 m between rows and 5 m spacing between trees in a row) at 11 years of age at the research site in *Shu Zhuang Cun*.

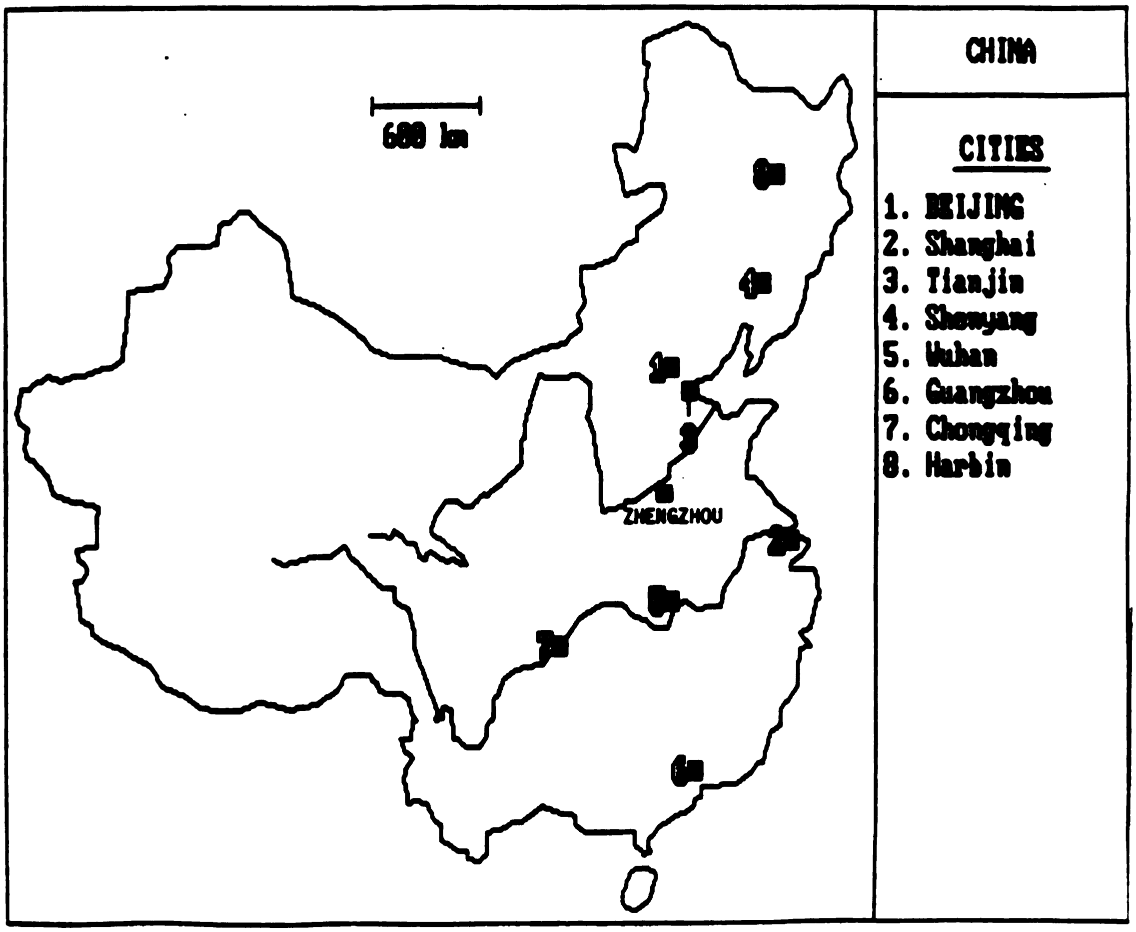

Figure 1.11. The Research Site.

1.4.1. The North China Plain.

The North China Plain is a large plain that encompasses the Huang (Yellow), Huai, and Hai rivers and their drainage systems. This plain includes the provinces of Henan, Shandong, Hebei, Anhui, Jiangsu and the cities of Beijing and Tianjin[18]. In Henan alone there are 3.33 million ha of agricultural land of which 2 million ha are *Paulownia* intercropping (Jiang, 1990).

In 1992, China's English language newspaper, the *China Daily* [19] stated that Henan was a major forested Province in China and that by October 1991 all 94 of its counties were green. This is quite an accomplishment considering that in 1981 the forest coverage on China's plains was only 2% and that by 1991 it was 12.8%[20]. These trees are primarily planted along roads, along canals, around homes, and around villages in the popular "4-side" program. The *China Daily* [21] calls these plantings tree walls and states that the middle and upper reaches of the Yellow River (*Zhengzhou* is in the middle reaches) had 67 million ha of trees planted in a 10 year program which helped reduce soil erosion by 15%.

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[18]China has three administrative areas called "cities". They are Beijing, Tianjin, and Shanghai. Each includes a city proper and surrounding area. Other cities in China are located within provinces or autonomous regions and are responsible to the provincial government. Recently, however, Special Economic Zones have been receiving more and more autonomy and in some ways can be considered city-states.

[19]March 11, 1992.

[20]*China Daily*, March 11, 1992.

[21]December 15, 1991.

Even though Henan is considered a "forested" Province, it is still in the heart of one of the largest wheat growing regions of China. In July 1991 the *China Daily* [22] reported that China was the world's largest wheat producer. This was attributed to the increase in wheat production due to new cultivars. There are 30 million ha of winter wheat in China and 23 million ha or 78% are in 10 major provinces which includes Henan[23].

1.4.2. Chang Ge County and Shu Zhuang Village.

Approximately 62 km to the South of *Zhengzhou* is *Chang Ge* County. *Chang Ge* County is actually a small city, but it is also an administrative area which includes an area of farmland (about 17 km by 49 km) outside the city proper. Within this area there are numerous small towns and villages which in themselves have 2 levels of local government.

About 9 km to the northeast of *Chang Ge* is a small village called *Shu Zhuang Cun* (Comfortable Village). The research site is located adjacent to *Shu Zhuang* which has a population of 957 and, as most villages in this area, it is surrounded by farmland. There is a primary school in the village, however, the secondary school is located in a neighboring village about 2 km away. Since this province has about 2% of the world's population (second largest in China), the villages are often very close to one another. The

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[22]July 31, 1991.

[23]*China Daily*, June 9, 1992.

neighboring village which is about the same size as *Shu Zhuang* is only a half kilometer (km) away. The local government that administers these villages and several others is called *Guan Ting Xiang* (Officer's Stop Village). *Guan Ting* is located approximately 5 km to the west of *Shu Zhuang Cun* proper on the major north-south rail line.

As with most of China's rural areas the younger population is looking for employment outside the village in township enterprises (factories and cottage industries) or are starting their own small private businesses. *Shu Zhuang*, however, is a bit far from the outskirts of the county proper where many factories are springing up.

1.4.3. Soils.

Farming is the major occupation in the *Shu Zhuang* area. Thus, the soil and its fertility are very important to the farmers. According to Wei (1979) who has written about the soils of Henan Province, the *Chang Ge* area soil type is basically called *You Huang Tu* or an Oil Yellow Soil (literal translation). This is a mixed fine sandy and silt soil. *You Huang Tu* is porous and allows good air and water flow while nutrient and water retention is average. The surface structure is granular, underlain with clay. At depth the structure is columnar. Table 1.3 further describes this soil.

Table 1.3. Henan Soils (After Wei, 1979).

	SOIL DEPTH		
SOIL ATTRIBUTE	0-25 cm	25-50 cm	50-100 cm
Organic Matter (%)	1.77	0.86	0.76
pH	8.2	8.25	8.25
Weight (g cm^{-3})	1.31	1.46	----
specific weight	2.46	2.41	----
pores (%)	46.7	40.0	0
Particle diameter (%) >0.05 mm	11.4	9.9	11.4
Particle diameter (%) 0.05-0.005 mm	62.3	59.8	62.3
Particle diameter (%) <0.005 mm	26.3	30.3	26.3
Soil type	Fen Sha Rang Tu (Silt Loam[24])	Fen Sha Nian Tu (Silt Clay)	Fen Sha Nian Rang Tu (Silt Loam)

The plow layer (using animal or human labor to pull a plow) was about 20 cm. With new prosperity a tractor was becoming more commonplace and the plow layer was expected to increase to 25 cm. The soil texture of the A and B layers (by feel) was about the same (more smooth than gritty) with a ribbon of 1-2 cm. The farmers felt that the soil contained about 70% silt and 30% sand (a silt loam). These were alluvial, loess soils and local expertise estimated the C horizon at about 20 m. In addition to this being a typical soil for the *Chang Ge* area, President Jiang[25] stated that the *Chang Ge* soils are typical of the *Huang Huai Hai* Plain.

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[24]Textural class taken from textural triangle.

[25]Personal conversation, July 1992.

1.4.4. Irrigation.

Because 80% of the annual rainfall (500 to 900 mm) in this area comes from mid-June to mid-September, irrigation is often necessary to insure adequate moisture for winter wheat. Irrigation is used in China's wheat growing area where available. Johnson and Beemer, (1977) on their trip to China as part of a US wheat delegation, were told that 80% to 85% of the wheat produced in China was under irrigation. However, the *China Daily* [26] emphasized the necessity to upgrade farming efficiency through irrigation as the gross irrigated land was only a little over 46.7 million ha and that much of the country still relied on rain from the "heavens" for a successful crop.

China has embarked upon a more efficient method of irrigation as the farmers begin to prosper and farm equipment becomes more available. In some areas instead of pumping water into earthen channels which lead to a section of a field to be irrigated, the farmers are now using collapsible plastic tubes to conduct the water. This saves a great deal in seepage.

In the *Guan Ting* area a reservoir was built on a small local river about 2 km to the west of *Shu Zhuang* which served as a source of water for agriculture. Irrigation projects are being expanded every winter during the slack season at the urging and with the supervision of the government. The fields to the south of *Shu Zhuang*, where the research was being

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[26] March 26, 1992.

conducted, had a new irrigation pump and electrical hookup installed in 1992.

1.4.5. Intercropping Systems.

The existing two season cropping system in *Chang Ge* and for much of Henan Province consists of admixtures of the tree *Paulownia elongata*, *P. fortunei*, or the hybrids, *Yu Xuan Yi Hao* and *Yu Za Yi Hao*, and wheat, followed by a second crop. This is a multi-story/multi-crop system with *Paulownia* growing 11 to 13 m tall in 10 years. Winter wheat is the primary annual crop and is harvested in early summer. Wheat and *Paulownia* are sometimes intercropped with rapeseed (*Brassica campestris*) which is harvested in May before the wheat crop. Towards the end of the wheat cycle the fall crop may be seeded between the wheat rows. After the wheat harvest the sequential crop may include cotton, maize, soya beans (*Glycine max*), sweet potato (*Ipomoea batatas*), or peanuts (*Arachis hypogea*) which have been grown with varying success rates under a tree canopy.

1.4.6. Tree Spacing.

Technology dissemination agents recommend three different spacing patterns for *Paulownia* trees and crops depending on the terrain and the farmer's desired output. In hilly areas where the soils are poor a wider tree row spacing is used. This may be anything from 5 m x 30 m to 5 m x 60 m or more. These areas are generally planted with the agricultural crop as the main emphasis. *Shu Zhuang* used this wider spacing.

The farmer's land was laid out perpendicular to the row of trees and because farmers only had small plots, each farmer would only have 1 to 3 trees on the land he/she worked using the household responsibility system. Thus, a community effort was necessary.

A middle range for tree spacing is about 5 m x 20 m. This is used on more fertile fields especially where fertilizer and irrigation can support the tree and the crop. Here, the farmer will be interested in both the tree and the agricultural crop. A more progressive group of farmers may plant the trees at 5 m x 10 m and then thin to 5 m x 20 m after five years.

When the tree is the primary crop the spacing will initially be 5 m x 5 m with crops grown between the trees during the first four to five years. Then, every other tree will be thinned about year four or five. Sometimes crops can still be grown between the trees after thinning, but it depends on the crop and the management practices. About year eight there will be a row thinned and the harvest will be between years 12 and 15. In systems where thinning is required, dissemination agent input is necessary to help the farmers understand and improve management techniques.

Zheng and Sheng (1989) state that 80% of the farms employing *Paulownia* use a spacing of 5 m x 20 m thinned to 5 m x 40 m. *Paulownia* is the preferred species because of its light transmission properties. Zhu (1988) also describes the optimum intercropping strategy for agricultural production as trees with an initial spacing of no closer than 5 m x 20 m for the first six to seven years. This is followed by thinning a row so that a 5 m x 40 m spacing is established and a new row of trees is planted where the others were harvested. Rotation lengths are 10-11 years and the mid-cycle replanting perpetuates the system.

President Jiang and his research staff at Henan Agricultural University feel that the optimum spacing for trees in areas where the soil conditions are of moderate to poor fertility should be no closer than 5 m by 30 m. Often a 5 m x 40 m or 5 m x 50 m spacing is recommended. This will ensure that the farmer is able to harvest a good agricultural crop and still have some trees for his/her own use.

1.4.7. Land Tenure.

Land tenure plays an important part in the development of the *Paulownia* intercropping system. In the area around *Chang Ge* County, land is redistributed to the farmers at intervals so that each farmer will have land to cultivate. At *Shu Zhuang Cun*, land was redistributed in 1983. The farmers decided as a group to plant *Paulownia* on their land as a collective effort. In order for the system to operate all of the farmers on this plot of land had to agree to plant and care for the trees. Depending on the size of the extended family, the area designated to each farmer would be different with larger families possibly working larger plots of land.

After consultation with the forestry officers in the area it was decided that the plots of land would run perpendicular to the row of trees. Each farmer would own the tree(s) on her/his plot of land, with 5 m spacing within the rows. Farmers could replant a tree should one die or remove a tree should it be of inferior quality.

When the makeup of the village changed to the extent that land needed to be redistributed to allow for newcomers (newly married couples) or for vacant land (due to a death or a move), the village leader would make the appropriate arrangements. At this time it would probably be necessary to cut the trees and start the process over. As of 1991 *Shu Zhuang Cun* was considering a land redistribution and the trees, which were about 10 years old, were ready for harvest. Thus, arrangements were made to keep the trees a little longer for experimental purposes.

Sometimes local or county governments can encourage villages to plant *Paulownia* trees to help the country and the local area meet established goals. This may be necessary to get the people to cooperate and plant the trees systematically so as to achieve the benefits of scientific development.

1.5. OUTLINE OF THE DISSERTATION

There are 3 chapters to follow. In the next chapter (2) the effects of distance and direction from a tree line, soils, temperature, and shading on the yield of wheat in a *Paulownia* and crop intercropping system are discussed. Chapter 3 investigates the interactions underneath the *Paulownia* trees, including wheat and tree roots as well as orientation, and their effect on wheat yield. The 4th chapter is a brief concluding chapter which attempts to delve into implications and future direction as a spin off from this research.

Chapters 2 and 3 are designed for conversion into journal articles (after editing). For this reason there is some redundancy. Chapter 2 gives a much more detailed methodology description than Chapter 3 so the reader is sometimes referred back to Chapter 2 for more explanation.

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CHAPTER 2

WHEAT YIELD IN A PAULOWNIA INTERCROPPING SYSTEM: EFFECTS OF DISTANCE, SOILS, TEMPERATURE, AND SHADING.

ABSTRACT

A *Paulownia*-winter wheat intercropping experiment with a focus on photosynthetically active radiation (PAR) and root competition was conducted 60 km south of Zhengzhou (35^0 N 113^0 E), Henan Province, PR China, from September 1991 to July 1992 using a tree/crop interface approach. The middle row of three 240-m long rows of 11-year-old trees was studied for its effects on the yield of irrigated and fertilized winter wheat.

PAR was quantified using a split-plot design with four blocks. There were 4 distance treatments (2.5, 5, 10, and 20 m) and 2 direction treatments (east and west of a north-south tree line). Results showed no difference in direction effects but PAR did affect total grain weight (p=.0047) between 2.5 m and 20 m. A regression equation was fit using the mean for each distance treatment: $Y = 391.7 + 4.57 X$ with $r^2 = .9310$ indicating an increase of 4.57 g m^{-2} (45.7 kg ha^{-1} or 6.1 jin mu^{-1}) over a distance of 2.5 m to 20 m from the trees.

In a shading experiment with trees and artificial shade as shaded plots, yield was greater in non shaded plots {total grain weight (p=.0440) and 1000-grain weight (p=.0135)}. Results of soils under the trees versus away from the trees were inconclusive. Controls employed a different planting scheme and were not comparable to the plots with trees.

2.1. INTRODUCTION

In the more developed countries much work has been done in monocropping systems to determine the factor combinations for maximum quantitative yield. The same is true for silviculture practices to obtain optimum tree harvest schedules. However, evaluation of specific tree and crop combinations is very new.

A case in point is the *Paulownia* tree, native to China, and wheat, China's leading staple crop. Agroforestry has a long history in China. With 1.17 billion people and only 7% of the world's arable land the Chinese people have long realized the importance of incorporating multipurpose trees into their agricultural units. This research was conducted on the temperate North China Plain in Henan Province, the second most populated province in China with about 2% of the world's population. In 1981 when the *Paulownia* trees were planted at this research site, wood was scarce, the farmers were poor, and soil fertility was considered medium to low. Farmers felt that *Paulownia* and wheat were compatible and were willing to try this new system with the support of the County Forestry Bureau.

Today (1993) China is changing very fast. Agroforestry systems with *Paulownia* are in their second generation. Planting schemes have been modified, land tenure reform has taken place and new *Paulownia* hybrids have been developed. Still, many of the basic relationships in this biological plant/tree system are only now being investigated in some part thanks to funding and personnel from research organizations outside of China. Cooperative research is expanding.

The literature reveals new methodologies such as the tree/crop interface (Huxley, 1987) that have been developed since 1985. Nonetheless, experimental results for specific tree/crop combinations are lacking. Research questions of interest include yield differences with and without trees, photosynthetically active radiation (PAR) interception at different tree spacings, and PAR infiltration at different canopy densities, arrangement, and orientation.

Nutrient inputs can be manipulated to explore effects on crop yield, and water can be applied or withheld to induce stress on the plants, thereby affecting nutrient uptake, stomatal closure or senescence. As they develop, tree/crop combinations should also be tested in different soil and climatic conditions before they are replicated on a large scale.

Tree and crop interactions are also of experimental interest. Previous work on crops under trees or wheat with trees has been reported, for example: Tejwani (1987), Barua (1970), McCulloch et al. (1965) and Carr (1972) with tea; Cunningham and Lamb (1959) with cacao; and Brandle (1987), Sheikh and Chima (1976), Akbar et al. (1990), Rehman (1978), Puri and Bangarwa (1992), Zhu et al. (1986), Jiang (1990), and Zhu (1990) with wheat. Shading studies with wheat include Fischer (1975), Willey and Holliday (1971) and Pendleton and Weibel (1965).

While the degree of competition between tree and crop roots for water and nutrients is an important question, studies done in monocropped systems with shade may not affect wheat the same as a tree would.

In agroforestry experimentation, PAR is often confounded with other factors and it is not possible to isolate PAR under a canopy from shelter effects such as wind, temperature changes or differences in soil moisture due to trees. It is necessary to evaluate environmental variables such as soil and air temperatures, PAR, precipitation, and wind to determine their extent of influence on yield through changes in the microclimate.

While it is important to analyze the interactions within a tree/crop system, it is necessary to determine the effects of an individual variable such as PAR on wheat yield. Only then can it conclusively be said that PAR is or is not a factor under certain conditions. At that point other variables (i.e., water, nutrients) can be isolated. With an established knowledge base for each individual factor, the system's interactions can be studied.

Henan Agricultural University (HAU) President, Professor Jiang Jianping and his research staff have an active, on-going research program with the tree *Paulownia*. One phase of their present research is the effect of PAR on wheat yield. This research was conducted in collaboration with the research staff of HAU's *Paulownia* research institute located in Zhengzhou, Henan Province, PR China (35^0 North latitude, 113^0 East longitude).

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2.2. OBJECTIVES AND HYPOTHESES

2.2.1. Objectives

This study focussed on one aspect of the system components, the tree/crop interface, in a *Paulownia* and wheat intercropping system. Within the interface, the objective was to isolate and determine the effects of PAR on the yield components of wheat.

Several experiments were designed to examine the effects of PAR on wheat yield at 2.5, 5, 10, and 20 m distances from a tree line in a *Paulownia* and wheat intercropping system. Microclimate variables were monitored to determine the extent of influence on wheat yield. While the main thrust of these experiments was the PAR under the tree canopy and its effect on microclimate and yield, the underground portion of the system also plays an important role. To prevent competition for nutrients and water, below ground root barriers were placed between the tree and the measured yield plots.

2.2.2. Hypotheses

Several questions were proposed as hypotheses:

1) Wheat yield in the *Paulownia*/wheat intercropping system will not be affected by different amounts of total daily PAR created by the tree canopy.

2) Relative to a *Paulownia* north-south tree line, wheat yield is not affected by east/west orientation.

3) Under irrigated conditions, soil moisture changes due to wind, shading, stemflow and throughfall under the tree canopy will not affect wheat yield.

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4) Different air temperatures caused by shade from the *Paulownia* trees will not affect wheat phenological development in various parts of the tree/crop interface.

5) Wheat yield in soils where 11-year-old *Paulownia* trees have been removed is no different than yield from soils that had no prior influence from the trees.

2.3. METHODOLOGY

2.3.1. Field Layout

The experimental fields were located "on-farm" adjacent to the village of *Shu Zhuang Cun* (Figure 2.1)(approximately 62 km south of Zhengzhou, Henan Provence). The large field south of the village gardens contained 3 rows of 11-year-old *Paulownia* trees. The rows were about 240-m long and ran north-south. Two rows were west of the north-south one-lane road in the center of the figure, the other to the east. The middle row of full grown trees contained the trees to be studied and the other two acted as guard rows. Yield plots were situated to the east and west of this tree line out to 20 m.

The 3 rows of full-grown trees had 5-m spacing between trees; the western row was 60 m and the eastern row about 70 m from the center row. Two control plots were located at the southern end of the tree area in a large open field. Two factors were taken into account when locating the control plot areas. First, the distance from the trees in the experimental site considering shading and the prevailing spring winds; second, the cropping history of the fields.

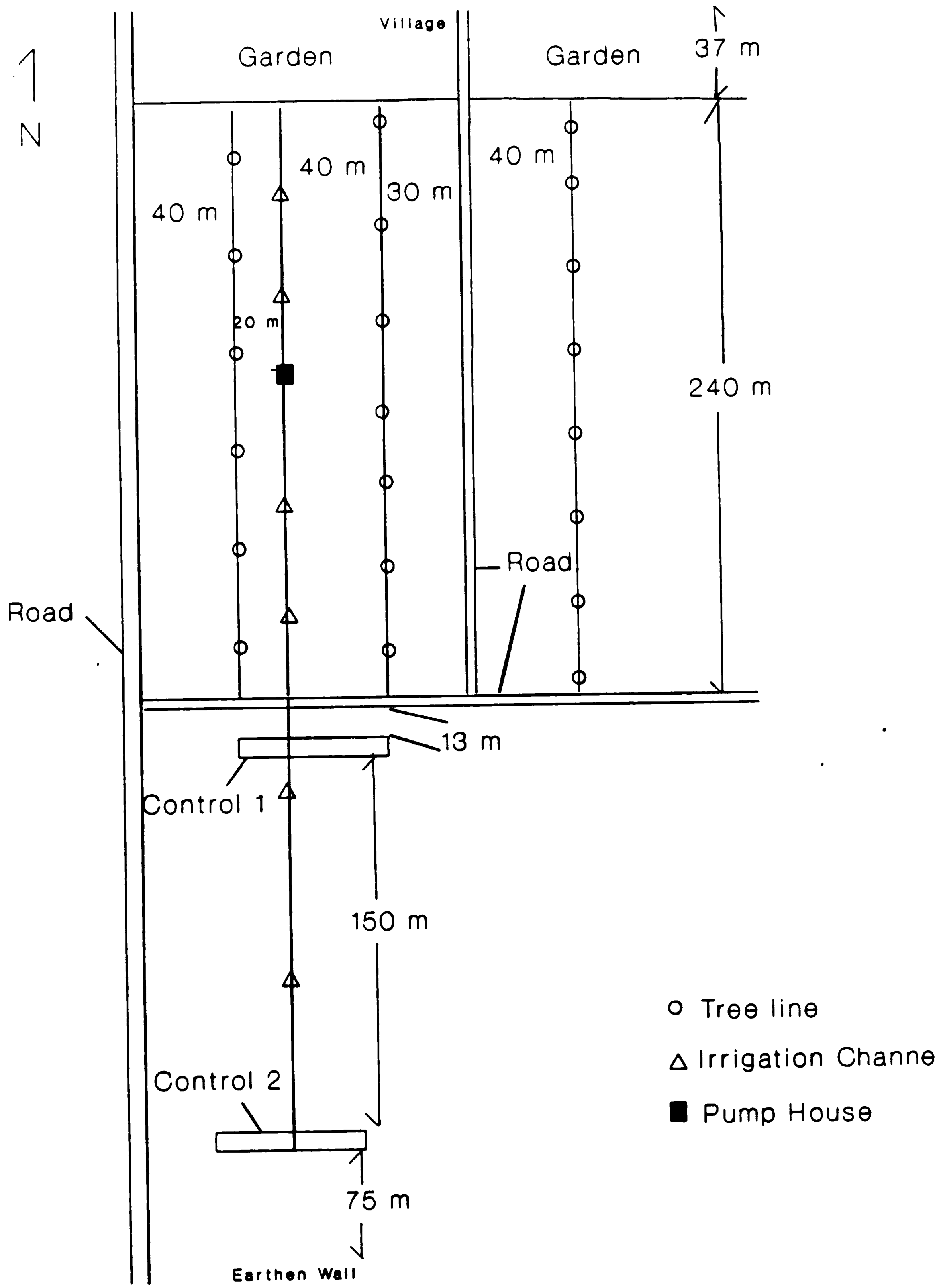

Figure 2.1. Research Area.

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The prevailing wind during the wheat development period, especially when the *Paulownia* leaves were present, was predicted to be primarily from the south. Thus, the first control was situated 20 m south of the tree area, well away from any tree shading. Control plot area 1 was located so as to avoid affects of trees on relative humidity.

Control plot area 2 was located further to the south (about 150 m) of control 1 as an extra precaution in case the winds proved to be from a non-southerly direction. The shelter effects from the 2 full grown tree lines to the east and west of the center row of trees offered the same wind protection because their distances and heights were very similar.

Figure 2.1 also displays the irrigation system that was used for this research project. In the middle of the area with the trees there was a pump house that had just been constructed. The control, however, was part of a different irrigation system and a special arrangement was made to make sure the controls were irrigated the same time as the tree area. The irrigation trough in the northern area was continued across the road to the 2 control areas and irrigated with water from the pump house in Fig 2.1.

2.3.2. Experimental Design

In this experiment wheat yield at different distances from the *Paulownia* tree line was quantified. The primary factor under study was the influence of PAR on wheat yield. Two other supporting experiments included: 1) a comparison of w

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wheat yield under artificial shade to an area with no trees and a third set of plots under trees to examine temperature and shading effects and 2) a comparison of wheat yield at two locations in an area where trees were removed just before planting wheat to investigate the effects of trees on soils.

2.3.2.1. Distance and direction experiment. A randomized complete block design with 4 blocks was employed (Figure 2.2) on a north-south tree line to counter the effects from differences in soil conditions and gradients, cultural practices, and tree size.

Within a block, trees of approximately the same size (height and crown diameter) were selected to insure uniform shading effects. Four consecutive trees were selected for each block. However, in block 3, two trees were deemed too small to be used as selected trees. Thus, there were 6 trees in the block and only 4 contained transects with yield plots. Each block also contained a guard tree on the north and the south end. Sometimes the guard tree was also one of the selected trees in the adjoining block. Two blocks were located in the northern end of the field while 2 blocks were in the southern end.

This was a 2 factor factorial experiment with 4 distance treatments and 2 direction treatments, replicated 4 times. Yield plots were randomly located on transects perpendicular to the north-south tree line at each selected tree. In each block, 4 treatments (distances) were randomly assigned to the east and west sides of the tree line. Each yield plot

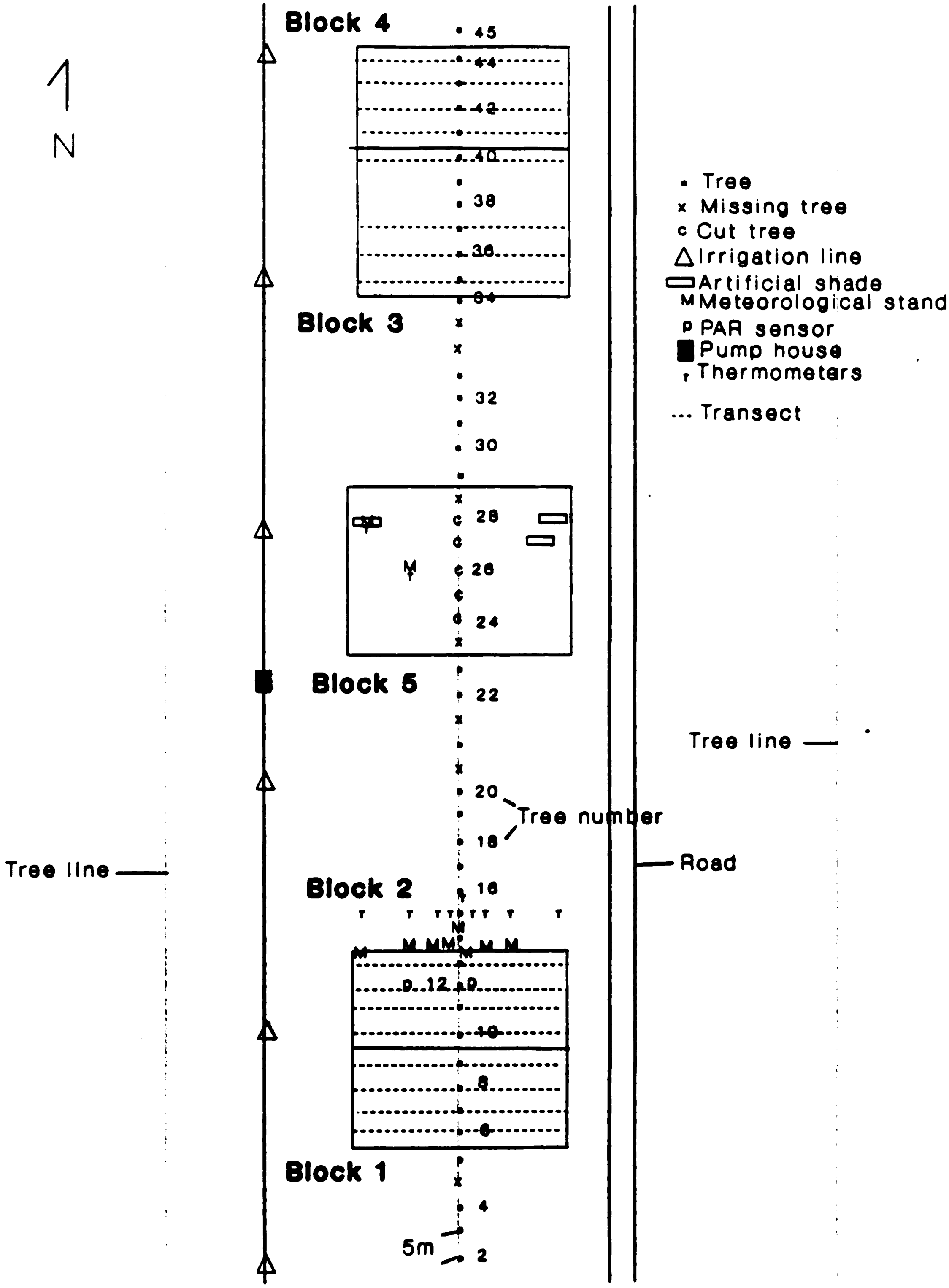

Figure 2.2. Distance and Direction Plot Plan.

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consisted of 3 quadrats (sub-samples), each measuring 1 m x 3 rows with rows 20 cm apart. A split plot design was employed using the model:

$$Y_{ijk} = Y_{..} + M_j + B_i + \alpha_{ij} + S_k + I_{jk} + \epsilon_{ijk}.$$

where M = Main plot treatment
B = Block
α = Main plot error
S = Subplot treatment
I = Interaction term
ϵ = Subplot error

The main plot treatments (the directions east and west) were not randomly chosen due to the fixed nature of their positions, however, it was assumed this model would still be valid. The subplot treatments consisted of selected distances from the tree line of 2.5, 5, 10, and 20 m and there were 3 missing points (see partial ANOVA Table 2.1 below).

Table 2.1. Partial ANOVA--Distance and Direction Experiment.

Source	df
Block	3
Main Plot-Direction	1
Main Plot-Error	3
Sub Plot-Distance	3
Linear	1
Quadratic	1
Cubic	1
Distance x Direction	3
Sub Plot-Error	15
Total Sub Plot	28

2.3.2.2. Temperature experiment. In the first supporting experiment -- temperature -- five trees were cut and three artificially shaded yield plots were established (Figure 2.3) in an effort to study the effects of temperature on wheat yield without the presence of the trees. A completely randomized design was used with the following model:

$$Y_{ij} = Y_{..} + T_j + \epsilon_{ij} \qquad \text{where}$$

T = treatments
ϵ = error

There were 3 treatments -- 1) the unshaded plots in the "cut tree" area, 2) the artificially shaded plots, and 3) the plots at 2.5 m East (2.5E) in Blocks 1, 3, and 4. Only 3 plots at 2.5 m were used so that there was a balanced design[27]. The unshaded plots were randomly located at 20 m West (20W) on transects where trees #24-#28 had been cut. The artificial

shade was located at the north edge of the "cut tree" area at 20 m West, 18 m East (18E) and 20 m East (20E). In both the unshaded and artificially shaded plots, 2 quadrats were harvested per plot and then averaged for the plot yield. The plots in Blocks 1-4 at 2.5E as mentioned earlier had 3 quadrats per yield plot (See ANOVA -- Table 2.2 -- below).

Table 2.2. Partial ANOVA--Temperature Experiment.

Source	df
Treatment	2
Error	6
Total	8

[27]Replication 2 was not used because there was good reason to believe this yield plot received excess trampling by numerous curious farmers who came to "visit" the researchers causing a low yield in this general position.

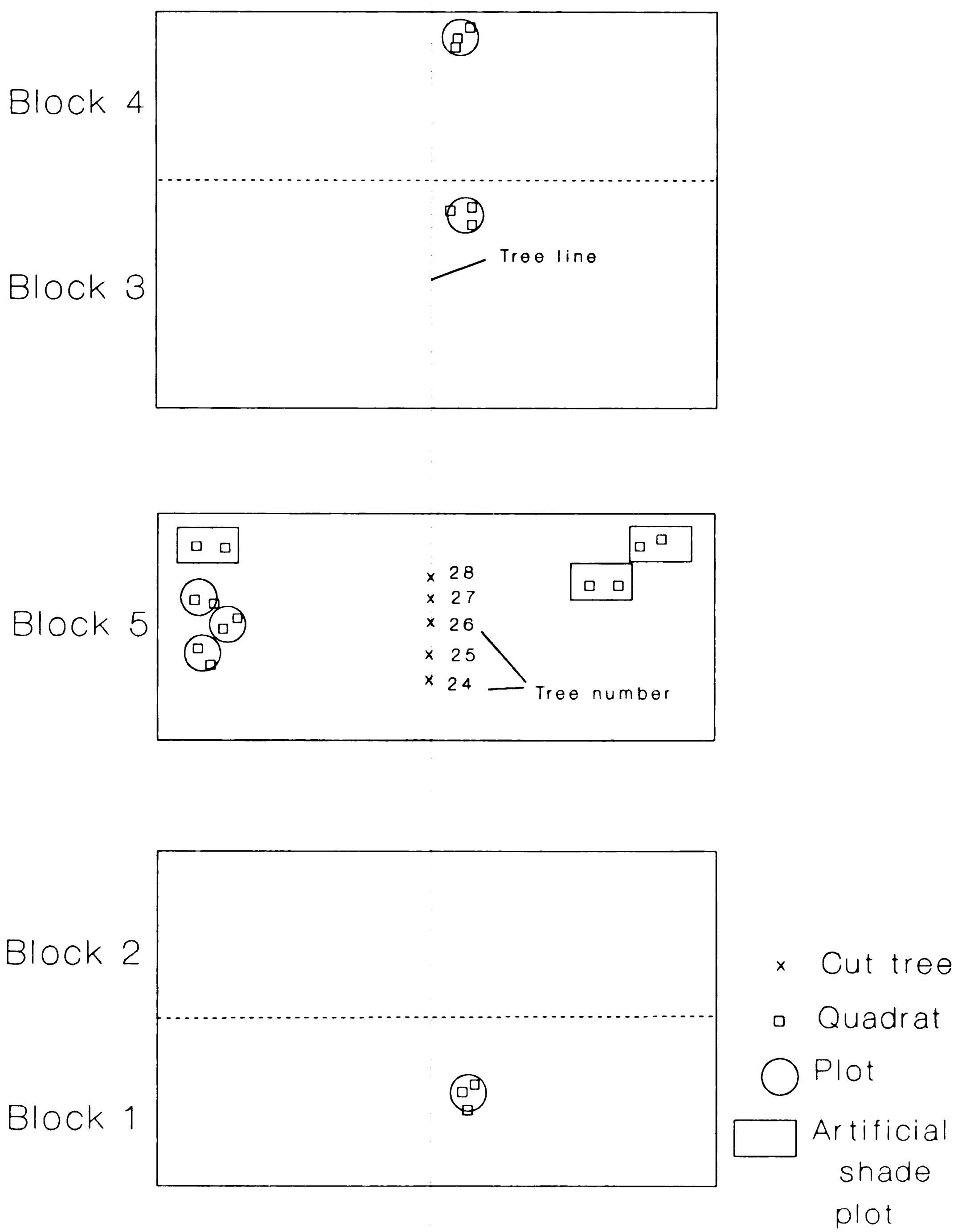

Figure 2.3. Temperature Plot Plan.

2.3.2.3. Soils experiment. The second supporting experiment -- soils -- was designed to investigate the soils in the "cut tree" area in yield plots at 2.5 m versus 20 m (Figure 2.4). This was a single factor experiment utilizing a randomized complete block design with the following model:

$$Y_{ij} = Y_{..} + B_j + T_i + \alpha_{ij} \qquad \text{where}$$

B = Blocks
T = Treatments
α = error

Each block consisted of a plot at 20W comprised of the mean of 2 quadrats and a plot at 2.5E. One farmer's plot was selected as one block to minimize variation in cultural practices including fertilizer application and irrigation. Blocks II and III, corresponding to cut trees #26 and #27, respectively, each used the mean of 2 quadrats per plot. However, it was necessary to average 6 quadrats at trees 24 and 25 for the 2.5 m plot due to a recording error which made it impossible to distinguish exact quadrat locations. These 6 quadrats were from Tree 24 -- 2.5W, and Tree 25 -- 2.5E and 2.5W.

Table 2.3. Partial ANOVA--Soils Experiment.

Source	df
Blocks	2
Treatment	1
Error	2
Total	5

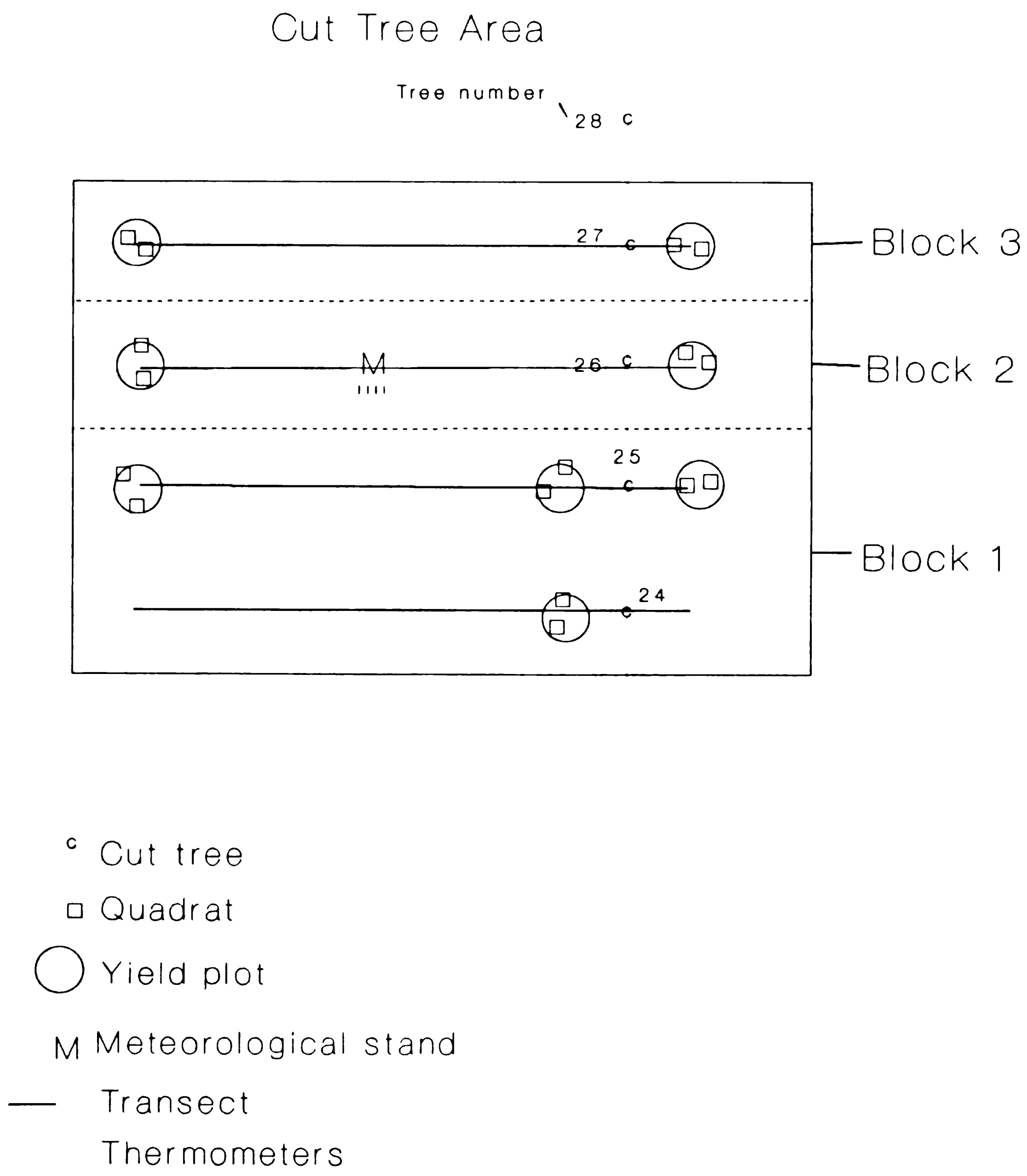

Figure 2.4. Soils Plot Plan.

2.3.2.4. Control area. The 2 control areas, located away from the influence of the trees, were each established with yield plots on one east-west transect (Figure 2.1). A simulated tree trunk about 20 cm high was placed in the control to mark the center point of the control area. Then plots were located at 2.5, 5, 10, and 20 m to the east and west of this simulated tree trunk.

2.3.3. Field History

According to local farmers, the area where the *Paulownia* trees were located maintained the same crops and crop rotation prior to tree establishment in 1981 as 1-year-old nursery stock and every year subsequently. The standard rotation was wheat sown in the winter followed by sequential cropping of intercropped corn (*Zea mays*) and soya beans (*Glycine max*) planted in the summer. The control area, on the other hand, belonged to a different village and they did not always plant corn and soya beans. The summer before the 1991 wheat sowing, some of the farmers in this large area had planted peanuts (*Arachis hypogea*) instead of corn. Thus, another consideration when determining the area for the control was to insure that the summer 1991 crop consisted of intercropped corn and soya beans.

2.3.4. Wheat Development

Wheat goes through several development phases during its lifecycle to produce grain. Wheat storage capacity consists of 1) establishing the number of grains or kernels and 2) grain filling (Figure 1.10). The former occurs before anthesis and the latter after. Storage capacity is determined by several yield components that develop sequentially during wheat growth (Evans et al., 1980). These include 1) the number of ears per unit area (tillers), 2) the number of spikelets per ear, and 3) the number of florets per spikelet which concludes at anthesis. The last stage is 4) kernel development or grain filling which has several stages of growth: 4a) watery, 4b)milky or early dough, 4c) soft dough, 4d) hard dough, and 4e) hard (Lersten, 1987) (Figure 1.10). Exact dates for these events, except for anthesis, are difficult to establish visually and their time of occurrence varies from year to year depending on cultural and environmental conditions.

Total grain weight (TGW) is determined by the sequential development of the 4 yield components. If one component does not develop to its full potential due to environmental conditions, the other components generally compensate so that final yield is not reduced. The 1000-grain weight (1000-GW) which is dependent upon environmental conditions after anthesis, is generally highly correlated to total grain weight because it is one of its components.

2.3.5. Cultural Practices

Wheat yield depends on planting density, cultivar, and fertilization. To ensure standardization a tractor and a mechanical planter were used and only one cultivar was sown. Fertilizer was broadcast by hand and soil analyses indicated possible N, P, organic matter and pH differences. Cultural practices included composting, plowing, fertilizer treatments, irrigation procedures, seed selection and treatment, planting methods, tree litter use, weeding, and interplanting of the sequential crop.

2.3.5.1. Compost. Compost was made in the village and applied to the fields each fall. The compost was made in large pits some of which were 5 m x 10 m and 2 m deep. The farmers used mainly corn and wheat stalks, human and animal manure, soil (about 10% of the compost), and leaves (whatever was available). The leaf of choice was *Paulownia* because the tree was fast growing and produced many leaves quickly. They were also large and easy to collect. However, poplar (*Populus spp*), elm (*Ulmus spp*), black locust (*Robinia pseudoacacia*) and other tree leaves were also used. The compost was left in the pit or pile for about two months before it was applied to the soil. Before plowing, the compost was hauled to the field and deposited in piles about 5 m apart. Later it was spread and incorporated either by tractor, animal, or human drawn plow.

2.3.5.2. Plowing. This was the first year that *Shu Zhuang Cun* was able to afford the use of a tractor for their plowing. A small 12 horsepower (hp) tractor and plow were used to plow the corn, bean stubble, and roots while mixing in the previously spread compost. By September 26, 1991 (Julian date -- 91269) the fields for blocks 1-5 (Figure 2.2 with trees and the "cut tree" area) had been plowed and harrowed.

The controls, however, were not part of the *Shu Zhuang* fields and they used the traditional methods of plowing -- a small horse or mule pulling the plow. The field was harrowed by an animal pulling a weighted board (the weight often a child) or pole of some kind. The 2 control areas were plowed after October 4, 1991 (91277).

2.3.5.3. Fertilizer. Chemical fertilizer was added to the fields to ensure that there was limited stress on the wheat due to nutrient deficiencies. Farmers added the fertilizer and then plowed it under. Enough fertilizer was distributed to apply 450 kg ha^{-1} of NPK (15/15/14) and 150 kg ha^{-1} of urea ($(NH_2)_2$ CO) with 46% N. Farmers broadcast the fertilizer on their 1/15th or 2/15ths ha plots.

2.3.5.4. Irrigation. The Fall of 1991 was one of the driest years in Henan Province in over 60 years[28]. In a normal year July and August is the flood season. However, in 1991 the rainfall in the Yellow River Valley was 30% to 50% of average[29]. Due to drought many of the farmers in Henan Province waited for rain before they planted. In *Shu Zhuang* the farmers waited a week past their normal planting dates (October 5th -- 91278 to October 10th -- 91283) in hopes that it would rain. However, beginning on October 16th (91289) the fields were irrigated.

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[28]Personal conversation with staff at Henan Agricultural University.

[29]*China Daily*, September 26, 1991.

For about 48 h the tree area, "cut tree" area and controls were soaked, section by section. In order to control the flow of water into a section, embankments were prepared using shovels and hoes to mound the soil and keep the water in a certain area of the field. These embankments were not as extensive as they would be later after planting when each farmer would cordon off his/her respective plots.

The intent was to minimize water stress on the wheat. Several times during the growing season it was necessary to irrigate. With spring regrowth soil moisture was monitored. Soil cores were taken on March 11th (92071) and then each week from March 25th (92085) until the harvest began on June 2nd (92154)[30].

The Fall and Winter were extremely dry necessitating a second irrigation in mid-February. This lasted 4 days (92045-92048) and covered the area with the trees and "cut tree"s. The 2 controls were not irrigated until February 27th (92058) for Control 1 and February 28th (92059) for Control 2. Another dry spell towards the end of April called for another irrigation which began on April 24th, included the controls and lasted 5 days (92115-92119).

Before harvest a final irrigation took place. On May 26th (92147) the controls were irrigated as they were very dry. Then in the evening there was a hail storm followed by

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[30] A reading of 6% according to local expertise was considered very dry for these soils and action needed to be taken. The farmers knew when it was necessary to irrigate so the problem became one of economics. Negotiations between farmers and researchers on who would pay how much sometimes caused slight delays in irrigation.

some light rain which helped the whole area. The 4 blocks with trees were not irrigated at this time as the rain added sufficient moisture until the harvest one week later.

2.3.5.5. Seed cultivar and treatment. In order to ensure that the wheat cultivar was the same for the entire experimental site, the farmers were all asked to plant the same seed source. The seed used was called *You Zhi Bai Nong 3217* (优质百农) which loosely translated means "excellent quality white agricultural 3217". Its characteristics were described in the background section under wheat characteristics (Chapter 1). It is a soft, dwarf species (75-80 cm tall) that is drought resistant, cold tolerant and has a long planting window. Yields are stable between 4500-6000 kg ha^{-1}.

The seed was treated with an insecticide before planting. The insecticide was called *Shui Ran Liu Lin Rui You*[31] (水胺硫磷乳油) which means "water ammonium 6 P suspension". One cap full of 5 ml was added to 10 kg of seeds in a large wok-shaped pan and thoroughly stirred with a shovel before planting.

2.3.5.6. Planting. Planting began on October 22, 1991 (91295). The 12 hp tractor pulled a 6-row planter with 20 cm between rows. Seed was automatically dispersed at a constant

[31] Chemical name: 1-methylethyl 2((methoxy phosphino amino thionyl) oxy) benzoate (estimated by Michigan State University Pesticide Research Center).

interval of 150 kg ha^{-1} [32]. However, on tree #13, Block 2 (Figure 2.2) instead of a tractor pulling the planter, a mule was used. The planter only had 3 rows and not 6, however, it was the same type of mechanical planter. Also in block 4 for part of the area near tree 43 and tree 44 a 3-row planter was pulled by 6 people using ropes and a harness. Farmer's plots were about 70 m long and rectangular shaped areas that ran perpendicular to the tree line or east-west. Depending on the size of the family, these plots were 5 m to 15 m wide.

The 2 controls were also planted on October 22, 1991 (911295), however, they used animal and human power. In Control 1 closest to *Shu Zhuang* (Figure 2.1), an old wooden 3-row planter was pulled by 2 farmers and they double planted (went back and forth on the same rows). The old wooden planters dispersed about half the rate of the new steel planters that *Shu Zhuang* used. Thus, the 2 passes should have equaled one pass with the new planter. For Control 2 the farmer also used an old 3-row planter, however, he used a horse to pull the planter. Again this farmer made a double pass. These controls were planted east-west with farmer's plots about 200 m long.

In both the controls and the tree area, after planting, the farmers delineated their plots by mounding the soil on the boundaries using hoes and shovels. This was done very systematically with all parties present and sometimes using string to mark the borders.

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[32] 20 *jin* mu^{-1} or 10 kg mu^{-1}.

2.3.5.7. Litterfall. The initial plan was to collect tree litter. However, the leaves fell gradually and winds scattered them widely. As early as September, there were a few leaves scattered about. They were not collected and were plowed into the soil. On November 12th (91316) the first frost occurred and many leaves began to fall soon afterwards. The farmers collected a great deal of the leaves, and the remaining leaves were easily blown about as the wheat was still very short (sprouting occurred on October 29th-91302) and provided no barriers to the leaves.

2.3.5.8. Weeds. Weeding was the responsibility of each farmer and generally, although not exclusively, the women carried out this work. Some farmers were more conscientious than others in their weeding. In a few cases the weeding was very poor, however, sometimes this was due to an illness or even hospitalization. In the artificially shaded plots where the quadrats had been enclosed by a frame and encircled by a restraining wire, the researchers weeded.

A weed that appeared with the wheat (*Xiao mai*) crop was barley (*Da mai*). This could have occurred because of an uncertified seed source (which has been a problem in China). The barley usually matured earlier than the wheat and if farmers saw it and broke it off before it matured this would prevent the barley from being harvested. The problem was most noticeable in the "cut tree" area and yield plots were selected so that the barley was not included.

2.3.5.9. Interplanting the sequential crop. On May 20, 1992 (92141) about 2 weeks before the wheat harvest began, the farmers began to interplant the new maize (corn) crop. Farmers walked along a row of wheat with a long tube or a shovel and a pouch of corn seeds. Two seeds were dropped down the tube about every 10 cm and then covered by soil pushed over the seeds by the farmer's foot. Where a shovel was used, a cut was made in the soil and the seeds dropped in the groove. Then the farmer used his foot to cover the seeds with soil.

Corn was planted between every third row of wheat (about 60 cm between corn rows). This caused some disturbance to the wheat, however, it was assumed that all areas were affected equally. The corn took about 1 week to sprout and it had emerged by the time the wheat was harvested. The soya beans were not planted until after the wheat had been harvested and carried away.

2.3.6. Experiment Preparation

Although planting was initiated in the Fall of 1991, some work was accomplished before this date. In particular 1) trees were pruned to eliminate some of the witches broom (*Mycoplasma* like organism-MLO), 2) selected trees were removed, and 3) root barriers were inserted. Later in the season 4) stumps were placed in the controls, and 5) artificial shade was constructed.

2.3.6.1. Branch pruning. The trees under investigation were *Yu Xuan Yi Hao* (open pollinated *P. fortunei*). This tree was somewhat susceptible to witches broom disease (*Mycoplasma* like organisms, MLO). Witches broom was pruned to achieve the leaf canopy density and typical morphology of *Yu Xuan Yi Hao*. When pruned of witches broom, *Yu Xuan Yi Hao* would resemble the degree of shading of the *Yu Za Yi Hao* hybrid (*P. fortunei* x *P. tomentosa*) the current choice of the farmers.

2.3.6.2. Selected tree removal. On September 24, 1991 (9 1267) a section of trees was removed towards the center of the tree line (Figure 2.2 -- trees 24 to 28 labeled "c"). There were several factors considered to decide which trees to cut. First, the number of trees cut was to be kept to a minimum. This helped maintain the continuity of the tree row and thus, offered minimal change in the microclimate due to wind, relative humidity, and temperature differences for the blocks being investigated with the trees present.

Secondly, adjacent trees were selected allowing fewer trees to be cut. Where the 4 blocks from Experiment 1 all had guard trees to insure shading of yield plots, the "cut tree" group also had missing tree positions as their guard (to the north and the south) to insure that shade was not a factor with the yield plots. The trees removed were approximately the same height and crown size suggesting that they had approximately the same above ground and below ground influence on the soil from previous years due to litterfall and root interaction.

Trees were felled using axes and hatchets. First a hole about a half meter deep and extending out about a meter in all directions was dug around the trunk to expose the roots. Then an axe was used to sever the roots. Although no taproot was noted each tree had 3 to 5 main roots that anchored the tree and went down like a claw as opposed to out. As the roots were severed a shovel was used to push the tree over in the desired direction[33].

2.3.6.3. Root barriers. Plastic was used as a barrier to separate the *Paulownia* roots from the wheat roots to eliminate competition for nutrients and water. Barriers were put in place on September 29, 1991 (91272) after plowing. Trees were selected in each block using a random number table for the 2.5E and 2.5W treatments. Trenches about 50 cm wide and 1 m deep were dug at a distance of 1 m from the tree on the east side or west side depending on the 2.5 m yield plot location. Several trees had large roots severed so that the plastic could be inserted. The 2 m long barrier was inserted parallel to the tree line. About a half meter on each end was angled towards the yield plot. When the trench was being dug care was taken to heap the soil on the tree side of the trench so

[33] It took about 1 hour for one person to fell one tree (average dbh at 10 years about 32 cm). After felling the branches were pruned and taken with their leaves back to the village. The leaves were used for making compost or for fodder and the branches could be burned as fuelwood. For a tree bole that was 3 to 4 m long the farmer could arrange for a buyer to come with a truck to take it away. A ten-year-old tree would be worth about 60 Yuan or $10 to $12 (1990 prices) and it might be used for export, furniture making or house building material.

that the yield plot did not have soil mixed from lower depths. A clear plastic, 0.12 mm (+/- 0.02) thick, was inserted in the trench and the soil filled in so that the plastic did not slip to the bottom of the trench.

The plots at 5 m were tested to see if there were tree roots that might affect the wheat in these plots. Zhu et al. (1986) stated that 98% of *Paulownia* absorbing roots between the soil surface and a 1 m depth (for 9- to 12-year-old trees with a 9 to 10 m crown diameter) were within a 4 m radius of the tree. Several small holes were dug at about 4 m to see if there were any tree roots. A few samples turned up some possible tree roots so barriers were also inserted for the plots at 5 m. These barriers only went down to 50 cm.

2.3.6.4. Stump placement in controls. The control yield plots were established on an east-west transect as done with the trees. To mark a center point to represent the tree, a tree stump was placed at a given point and the transect was drawn from that point. The stump was situated so that the length of the transect was within an area in which corn and beans had been planted the previous summer.

The stumps in both Control 1 and 2 were initially put in place on March 11, 1992 (92071). At this time the wheat had grown high enough that the stumps would "hide" in the wheat to help prevent inadvertent relocation. Stumps were 18-20 cm tall and 15-20 cm in diameter. The stump in Control 2 was missing on March 25th (92085) and after replacement was removed a second time. The hole that remained, marked the place and the distance from the road to the stump position was noted.

2.3.6.5. Artificial shade construction. Shading was constructed over 3 yield plots to simulate the shade of a *Paulownia* tree. The plots were located in the "cut tree" area so there would be no shading from existing trees. The plots were selected at least 15 m from the tree line to ensure that the soil was not under the influence of the tree over the previous years. These plots were compared to plots in the "cut tree" area at 20W for temperature differences, phenological differences, and wheat yield. The shading was constructed so that the shade was in place as the *Paulownia* leaves emerged and grew. Prior to bud burst and leaf expansion, the wheat received a little shading from the crown branches and trunk.

The first artificial shade plot was located approximately 20W from the original position of tree 28 (Figure 2.2). The frame was constructed of *Paulownia* saplings in the shape of a rectangle with a sloping roof towards the south. It was about 3 m high at the north end to accommodate an equipment stand and box. The southern side was a bit less than 2 m high. The length and width (4 m x 2 m) were determined so that a plot of at least 2 m x 2 m was shaded for the same length of time as the 2.5E plots along the tree line. A 3.5 m x 1 m piece of shading material was fastened to the top of the frame.

The 2.5E plot was used as the standard because it had the longest diurnal duration of shading during the time of most intensive PAR availability (solar noon). The initial shade cloth selected was a screening used for windows to keep flies and mosquitos out of the homes. This provided about 26% shade.

On April 16th (92107) 3 days after the *Paulownia* leaves emerged, the second artificial shade plot was located on the transect at tree #28, 20E (Figure 2.2). This frame was also of *Paulownia* poles or limbs, however, it was only about 2 m high and 3 m x 3 m with a shade material of 180 cm x 215 cm. Again slats were used as the shading until the shade cloth could be used.

The third shade frame was erected on April 22nd (92113) at approximately 18E and on the transect where tree 27 was initially found. It was approximately the same size and height as the frame for the second artificial shade plot. With this frame a 2 m x 2 m size shade material was employed. Initially, only slats were necessary.

On April 27th (92118), 11 days after bud break, the slats were taken off and the screening tied to the frames. This was sufficient until May 15th (92136) when a shade cloth was added to the existing shade screen. A final shade test was conducted on May 28th (92149) just before harvest and the results showed that the artificial shade (about 75%) was a little more than the actual tree shade (about 64%).

2.3.7. Equipment, Observations and Measurements

After the winter wheat seed was sown, meteorological equipment stands, thermometers, PAR sensors with a data logger, and automatic, 24-h recording temperature and relative humidity recorders were placed in the field. In addition basic equipment such as hoes, shovels, hand scythes, and backpack sprayers were used during the research period.

Measurements and observations were taken from planting until after harvest in June 1992 including: 1) PAR data, 2) soil moisture, 3) air and soil temperature, 4) wind and precipitation data from *Chang Ge* County, 5) tree growth, 6) soil samples, 7) wheat phenology, 8) slides of wheat and *Paulownia* growth, 9) *Paulownia* floral development, 10) yield plot observations, 11) pests and diseases and 12) yield harvest for number of ears, grain yield and 1000-grain weight.

2.3.7.1. Meteorological stands. Meteorological stands were placed between trees 13 and 15 (Figure 2.2) to house the equipment for recording air temperature and relative humidity. The stands were 4-legged metal frames with a wooden slatted box on top. Inside the box were placed thermometers and/or automatic recording devices. The stand legs were buried so that the instruments within the box were at 1.5 m above the ground to comply with international standards for temperature and relative humidity measurements. These measurements could be compared with the meteorological station in *Chang Ge* County.

On October 27, 1991 (91300) two stands each were placed in the fields at positions 2.5E and 20W of the east-west transect (4 stands total). These were located at the northern edge of Block 2 (Figure 2.2) to the north and south of tree 14 and about 3 to 4 m apart. Thermometers were placed in the northern most meteorological boxes and data recorded manually while the southern most boxes held automatic recording temperature and relative humidity instruments.

The 2.5E and 20W positions were used because this would give the largest contrast in temperature and relative humidity. The 2.5E plot would receive the most shade during the warmest time of the day and the 20W plot would receive the most direct sunshine during the warmest times. Duplication of equipment provided a cross check for accuracy and allowed interpolation for times that manual readings were not available.

On November 19, 1991 (91323), 6 more equipment stands were employed and 4 were placed at 10E, 5E, the tree line, and 5W. This ensured instrumentation at the tree crown border (5E and 5W), under the trees (tree line), and away from the trees (10E and 20W)(Figure 2.2). Equipment stands were also placed in the "cut tree" area (Figure 2.2) and in the northern most control (Control 1)(Figure 2.1). These 6 additional stands contained manually read thermometers.

2.3.7.2. Growth intervals. A total of 6 growth intervals were established for this experiment (Table 2.4) in order to correlate PAR with wheat component development. Where possible the intervals coincided with tree or wheat phenological events (Figure 1.10).

Table 2.4. Development Intervals.

Interval-Dates	Julian Date	Interval Definition
1. Oct30-Mar10	91303-92070	Wheat planting-Mar10, 1992
2. Mar11-Apr12	92071-92103	Start PAR recordings-Apr12
3. Apr13-Apr29	92104-92121	Tree leaves emerge-Apr29
4. Apr30-May15	92122-92136	50% of wheat flowered-May15
5. May16-May30	92137-92151	May16-maturity
6. May31-Jun04	92152-92156	May31-harvest

2.3.7.3. PAR. Two LI-COR ES 220 quantum sensors were used to measure PAR just above the wheat plant. Sensors recorded PAR in millivolts and were stored as μmoles m^{-2} s^{-1} between March 11, 1992 (92071) and June 4, 1992 (92156). The sensors were connected by a cable to a 2 channel data logger which used a data storage module (DSM) and continuously recorded the PAR readings at specified time intervals.

Three data recording/positioning schemes were established. In Scheme I sensors were positioned at 2.5E (under the tree) and 10W (outside of the crown) and left unattended. Each sensor took two instantaneous readings at 5 minute intervals and an average of the two readings was recorded and stored in the DSM every 10 minutes.

In Scheme II once a week the sensors were set at reading and recording intervals of 1 minute. During the course of the day the sensors were repositioned so that one was in the sun as a control and the other was at one of the 9 positions (from 20W to 20E) shaded by the tree. Scheme III also used the 1 minute time interval, however, the sensors were placed at 5E and 5W approximately once a week for an entire day.

There were 2 data storage modules that were downloaded regularly. Using a Zenith PC (Zenith SupersPort 286 Portable Computer) data was downloaded from the DSM onto a diskette using Bitcom software program and stored. Then the DSM was inserted into an Eprom erasing ultraviolet lamp (Spectroline PE-140T/F), erased, and reinserted into the data pod for further data collection.

Sensors were placed in the field from sunrise to sunset each day from March 11th (92071) to harvest on June 4th (92156). There were some gaps in daily measurements due to equipment problems; replacement, download and erasure of the data storage modules; travel between download site and field site; and daily set up and disassembly.

2.3.7.4. Soil moisture. Periodic soil cores were taken to determine soil moisture. Cores were taken on November 28, 1991 (91332), March 11, 1992 (92071) and then weekly from March 25th (92085) until harvest. A soil auger was used to extract the soil in the top 20 cm. Each sample was placed in a metal tin. The 8 yield plot positions (20E, 10E, 5E, 2.5E, 2.5W, 5W, 10W, and 20W) and the tree line were sampled. Except for the first sampling in the spring (which had only one sampling in the south end, in Blocks 1 and 2, and one in the north end, in Blocks 3 and 4) samples were taken from each tree area block (1-4). In addition the 2 controls; the "cut tree" area at 2.5E, 2.5W, 20W and sometimes 20E from the original tree line; and the artificially shaded areas, once established, were sampled.

The metal tins with soil were weighed on a 500-g capacity scale in the nearby village. Later soils were oven dried at 100^0-110^0 C for about 68 h in the laboratory at Henan Agricultural University and weighed again to determine the percent soil moisture. After the first 2 sampling dates, the soil samples were weighed at the site before taking them to the laboratory to dry and reweigh.

2.3.7.5. Air temperature. Several different types of thermometers were utilized. A dry bulb thermometer measured air temperature and a wet bulb thermometer helped determine relative humidity. A barometer was located in the village to obtain atmospheric pressure readings to derive relative humidity. Two other thermometers were present. One registered the daily high temperature and the other the daily low temperature. These two thermometers were placed only in the boxes at 20W and 2.5E.

Farmers were hired to read the thermometers each day from October 28, 1991 (91301) through to June 4, 1992 (92156) at 08:00, 14:00, and 20:00 hours and temperatures were recorded in a log book for the 20W and 2.5E positions. This included the wet bulb, dry bulb, daily high, and daily low temperatures as well as atmospheric pressure.

2.3.7.6. Wind and precipitation. Meteorological data were collected at the county weather bureau located in *Chang Ge* County 12 km south of the research site. Average daily wind direction and wind speed were recorded at 10.5 m above the ground for 16 directions. These were grouped and averaged into 8 directions such that each cardinal direction (N, E, S, W) used the average of 3 directions (ex. North averaged NNW, N, and NNE). The directions NE, SE, SW and NW comprised the other 4 directions. Daily precipitation was also obtained.

2.3.7.7. Tree measurements. At the start of the experiment the trees were measured to obtain baseline measurements. On September 9, 1991 (91252) the middle row of trees (Figure 2.2) was measured for height, diameter at 1.5 m, and crown width (in an east-west direction). All 45 trees were measured (the entire length of the tree line) including the 5 trees that were later cut in the "cut tree" area.

To measure the total height a clinometer (*Zhi Gao Qi SC-II* 测高器SC-II which means "measure-tall-instrument") was used. The measurement was recorded in meters and tenths of a meter. A diameter tape was used to measure diameter at 1.5 m above the ground. The crown width was measured from the trunk to the west and to the east. The north and south directions had a closed canopy.

On November 26, 1992 (91330) when most of the leaves were absent, the bole of the tree, from the ground to the crown branches, was measured and recorded. Total height on the remaining 40 trees was remeasured.

Tree measurements were taken again on June 10, 1992 (92162) on trees within blocks 1-4 and guard trees on the south side. This included trees 5 through 13, trees 34 through 37, and trees 39 through 44 (Figure 2.2). Total height (less ground height), bole height, diameter at 1.5 m, and crown diameter in the east-west direction were measured.

2.3.7.8. Soil samples. As noted in Wei (1979) the soils in this general area are 0-25 cm-silt loam; 25-50 cm-silty clay loam. Local expertise estimated the C horizon at about 20 m. Soil samples were taken before wheat planting, before regrowth in the Spring, and after the wheat harvest. Four different analyses were made from each sample -- pH, soil organic matter, available N, and available P. The Fall sampling was necessary to establish soil baseline data at the research site. This occurred on September 19th (91262) and 20th (91263), before fertilizer and compost application, but after the summer crop was harvested.

Soil augers were used to deposit soil into mixing basins and the soil was placed into labeled paper bags for transport. Samples were taken at two depths -- the surface soil to 20 cm corresponding to the plow layer and 21 to 40 cm corresponding to the layer below the plow layer where 80% of the wheat roots were distributed (Zhu, 1990).

Each soil sample was a composite of 5 soil cores, mixed thoroughly, and then placed in a paper bag. This included 8 distances (20W-20E) and the tree line in the blocks with trees; 2.5E, 2.5W, 20E, and 20W in the "cut tree" area; and once established, two cores from the artificial shade area. A composite of 10 cores was taken for each control. Samples were analyzed in the Henan Agricultural University soil laboratory.

2.3.7.9. Haun scale. The Haun scale was developed (Haun, 1973) to provide a continuous number scale for monitoring winter wheat according to its phenological and morphological development (Figure 1.10). On March 25th (92085) the first Haun scale observation was made and records were kept weekly through April 27th (92118) when flowering began. The Haun scale was used to determine if the wheat in one block was developing faster than another or if the wheat at one treatment distance was developing faster than another within the same block.

For each recording a yield plot was selected (i.e. 2.5E) and 3 to 7 of the taller wheat stalks were observed. Leaves per plant were counted and the stage of development for the last leaf (on a .0 to .9 scale) noted. A range was recorded (5.9-6.3)[34] and then averaged (5.5). Enlargement (inboot) was coded as 18, emergence as 28, and elongation as 38 (Figure 1.10) also having a range of .0 to .9 depending on the stage of development. Anthesis was coded as 100. This evaluation was subjective, but did describe trends in phenological development.

2.3.7.10. Tree and wheat photographs. Throughout the Spring of 1991 and the 1991-1992 wheat season, photographs and slides were taken of the wheat and tree at progressive development stages. The purpose was to document the

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[34]5.9 meant the last leaf was #5 and it was 9/10 fully developed. 6.3 meant leaf 6 was 3/10 developed. The flag leaf was designated as #8 and readings were relative to that. Wheat leaf pictures aided in assigning the values.

phenological development of the wheat in relation to the tree's leaf emergence and subsequent growth.

2.3.7.11. *Paulownia* floral development. In April 1991 (the season before the present research) the *Paulownia* trees at *Shu Zhuang* had many flowers. The flowers started blooming about April 25th (91115) and were at their peak by May 3, 1991 (91123). The flowers preceded the leaves, however, before the flowers were completely gone the leaves had begun to emerge. As of May 9, 1991 (91129) the flowers were mostly absent and the leaves were growing rapidly.

In February 1992 the trees had very few floral inflorescences (Figure 1.7). Thus, few flowers were expected in the Spring of 1992. On April 16, 1992 (92107) a few of the *Paulownia* trees in *Shu Zhuang* village had blossomed and one of the farmers stated that they had begun about April 12th (92103). The trees at the research site did not flower in the Spring of 1992.

2.3.7.12. Yield plot observations. After planting and during the growing season the plot locations were monitored to determine if there were any abnormal growth patterns or problems. From time to time events occurred that could have affected the yield. If there was any experimenter caused damage or if there was a disease infested area, these locations were not used for yield sampling, rather an area as close as possible that was not damaged was selected.

2.3.7.13. Pests and diseases. Two problems, aphids and a fungus, were noted while observing the crop. On about April 10th (92101) some farmers began spraying their crop to combat a wheat aphid. Farmers surveyed their own crop and decided if they needed to spray. For the aphid problem the tell-tale sign was a wilting flagleaf. The application of dimethoate[35] (*Yang Hua Luo Guo* 氧化落果) which means "oxidized Luo Guo" at 1000:1 or pirimicarb (Pirimor)[36] (*Kang Ya Wei*) or "against aphid powerful" at 10 g in water for 1/15 ha[37] or fenvalerate[38] or malathion[39] (*Mie Sha Bi* 灭杀毙) meaning "destroy kill dead" at 3000:1 was recommended for combatting this problem. This was usually applied twice.

The other problem that occurred on the research site was a white powdery mildew (*Erysiphe graminis* DC) called *Bai Fen Bing* (白粉病) or "white powder sickness". This fungus was treated with a spray of triadimefon (Bayleton)[40] (*Fen Xiu*

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[35] 0,0-dimethyl-S-(N-methylcarbamoylmethyl) phos-phorodithioate.

[36] 2-dimethylamino-5, 6-dimethylpyrimidin-4-yl dimethylcarbamate.

[37] 1 *mu*.

[38] (RS)- -Cyano-3-phenoxybenzyl RS-2-(4-chloro-phenyl)-3-methylbutyrate or cyano (3-phenoxyphenyl)methyl 4-chloro-(1-methylethyl) benzeneacetate or cyano-3-phenoxybenzyl 2-(4-chlorophyenyl)-3-methylbutyrate.

[39] 0,0-dimethyl phosphorodithoate of diethyl mercaptosuccinate or diethyl mercaptosuccinate, S-ester with 0,0-dimethyl phosphorodithioate.

[40] 1-(4-chlorophenoxy)-3,3-dimethyl-1-(1H-1,2,4-triazol-1-yl)-2-butanone.

*Ning*粉锈宁) which means "powder rust peaceful" used at 800-1000:1.

A backpack sprayer was used to apply both of the sprays. The insecticide was mixed with water at the road near the farmer's plot, poured into the sprayer, and then carried on the back. The spray was applied as the farmer walked down the rows of wheat. The farmers would be responsible for their own plots, but the sprayer was shared by many. From mid-April up to the harvest in early June, farmers would periodically be seen in their fields spraying.

2.3.7.14. Harvest. The harvest began on the afternoon of June 2, 1992 (92154) and each research area was harvested just before the farmers harvested the remainder of the plot. Control 2 and part of Control 1 were harvested on the first day because they were drier than the other blocks and matured a couple days earlier. In the morning of June 3rd (92155) the remaining parts of Control 1 were harvested as well as the "cut tree" area, the artificially shaded area, and Block 4 nearest the village (Figure 2.2). In the afternoon Block 3 and most of Block 1 were harvested. Finally, in the morning of June 4th (92156) the remainder of Block 1 and Block 2 were harvested.

Through consultation among the research group, it was decided that each quadrat would be 1 m long and 3 rows wide. On each side of the quadrat there would be buffer rows so that there were no large gaps between rows. The quadrat yield area then was 0.6-m^2. However, since this was such a dry year it was also decided that 3 yield samples (quadrats) should be taken at each yield position (yield plot). As long as the crown shade was continuous the actual quadrat position could be selected to the north or south of the east-west transect if abnormal growing conditions required. However, for some quadrats (2.5E, 2.5W, 5E and 5W) root barriers had been placed in the soil. In these locations any movement was restricted to an area still protected by the barrier.

To mark the quadrat area for harvest, a 2 m iron bar about 3 cm wide and half a centimeter thick was used as a frame and bent in the shape of a "U" so that the base was 1 m and the uprights were each about a half meter. This bar was then slipped down between the wheat guard row and the first row by bending the guard row down. The legs of the "U" shaped frame were then slid into the wheat perpendicular to the row at ground level and pushed through the second and third row so that the 1 m section of the bar was at the base of the first wheat row and the legs extended through the second and third rows.

Once the quadrat was established, a hand scythe was used to gather and cut the wheat. The wheat was placed in sacks and labeled as to block, plot, and sample number (1, 2, or 3). Measurements were made for the number of ears per quadrat, grain weight m^{-2}, and 1000-grain weight. Biomass was not calculated.

2.3.7.14.1. Ears. As the wheat was harvested and placed in sacks it was stored in a farmer's home. Then as time permitted the wheat was taken out of the bag and the spikes with ears were counted.

2.3.7.14.2. Grain yield. The bags of wheat were oven-dried at about 80^0 C for 5 to 10 h and afterwards pounded with a club to break the grains free. Next, a bag was opened and the contents were poured into a dust pan that had a flat bottom, raised sides and back, and a flat front.

The grains were mostly free of the chaff but mixed together. To separate the two, several fans were placed on the floor in a line and a basin was put in front of the second fan. The dust pan with the wheat and chaff was held over the second fan and its contents were fed out of the front and into the windstream. The chaff blew ahead and the wheat grains fell into the basin. If there was an excessive amount of chaff in the basin after the first cleaning, there was a second cleaning. To weigh the grains a 500-g scale was used. This gave the results of a 0.6-m^2 yield quadrat which was converted into 1-m^2 yield.

2.3.7.14.3. 1000-grain weight. Afterward the grains were spread on a table top and divided into 4 sections. One section was taken to count two 500-grain piles which were weighed separately. The 1000-grain weight was the sum of the two weights.

2.4. RESULTS

An analysis of variance (ANOVA) was employed for the principal and supporting experiments and if the findings were significant at $p < .05$ further analyses were conducted as appropriate. The analysis of variance assumed a fixed effects model with random error components. For the split plot, two error components were identified and when testing with one as random the other was assumed fixed. All models assumed that the error terms were independently and normally distributed with a mean of zero and a common variance. In addition it was assumed that the mean was additive. These assumptions were tested in each experiment and the results by test are located in Table A.1, Appendix A. All tests rejected the null hypothesis if $p > .05$. For each experiment the assumptions were not violated.

2.4.1. Distance and Direction Experiment

There were three missing points and these were calculated with loss of three degrees of freedom (Snedecor and Cochran, 1967). As shown in the ANOVA table (Table 2.5)[41], there was no interaction between the direction and distance for total grain weight (p=.4952) or 1000-grain weight (p=.5840). No difference was found in direction either for total grain weight (p=.3206) or 1000-grain weight (p=.7153). However, there was a highly significant increase in yield with distance from the tree line for total grain weight (p=.0047).

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[41]All tables, figures and discussion have data adjusted from yield per 0.6-m^2 (a quadrat) to yield m^{-2}.

Table 2.5. ANOVA--Distance and Direction Experiment--TGW, 1000-GW.

Total Grain Weight (TGW)						
Source	df	SS	MS	F	p	Signif
Block	3	5,815				
Direction	1	1,081	1,081	1.41	.3206	NS
error a	3	2,301	767			
Distance	3	32,292	10,764	6.58	.0047	**
Linear*	1	30,064		18.34	.0006	***
Quadratic	1	2,119		1.29	.2728	NS
Cubic	1	108		.06	.7944	NS
Dist x Dir	3	4,097	1,366	.83	.4952	NS
error b	15	24,523	1,635			
Total	28	70,109				

1000 Grain Weight (1000-GW)						
Source	df	SS	MS	F	p	Signif
Block	3	45.22				
Direction	1	.48	.48	.16	.7153	NS
error a	3	8.86	2.96			
Distance	3	37.19	12.40	1.28	.3180	NS
Dist x Dir	3	19.48	6.49	.67	.5840	NS
error b	15	145.56	9.70			
Total	28	256.79				

*Orthogonal Coefficients:

treatment	c_1	c_2	c_3
1	-11	20	- 8
2	- 7	- 4	14
3	1	-29	- 7
4	17	13	1

Figure 2.5 illustrates the mean total grain weight by distance from the tree line (treatment means tabulated in Table B.1, Appendix B). The fitted equation using the 4 treatment means was:

$$Y = 391.7 + 4.57\ X \qquad \text{with } r^2 = .9310$$

indicating an increase of 4.57 g m^{-2} (45.7 kg ha^{-1} [42]) for each meter as the distance from the trees increased over a distance of 2.5 m to 20 m. Using orthogonal coefficients a linear relationship (p=.0006) accounted for 93% of the variance (p=.0006). The 1000-grain weight distance treatments (means tabulated in Table B.1, Appendix B) were not significant (p=.3180) (Table 2.5).

A correlation between total grain weight and 1000-grain weight was determined with the Pearson correlation coefficient ρ =.8148.

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[42]6.1 *jin* *mu*$^{-1}$.

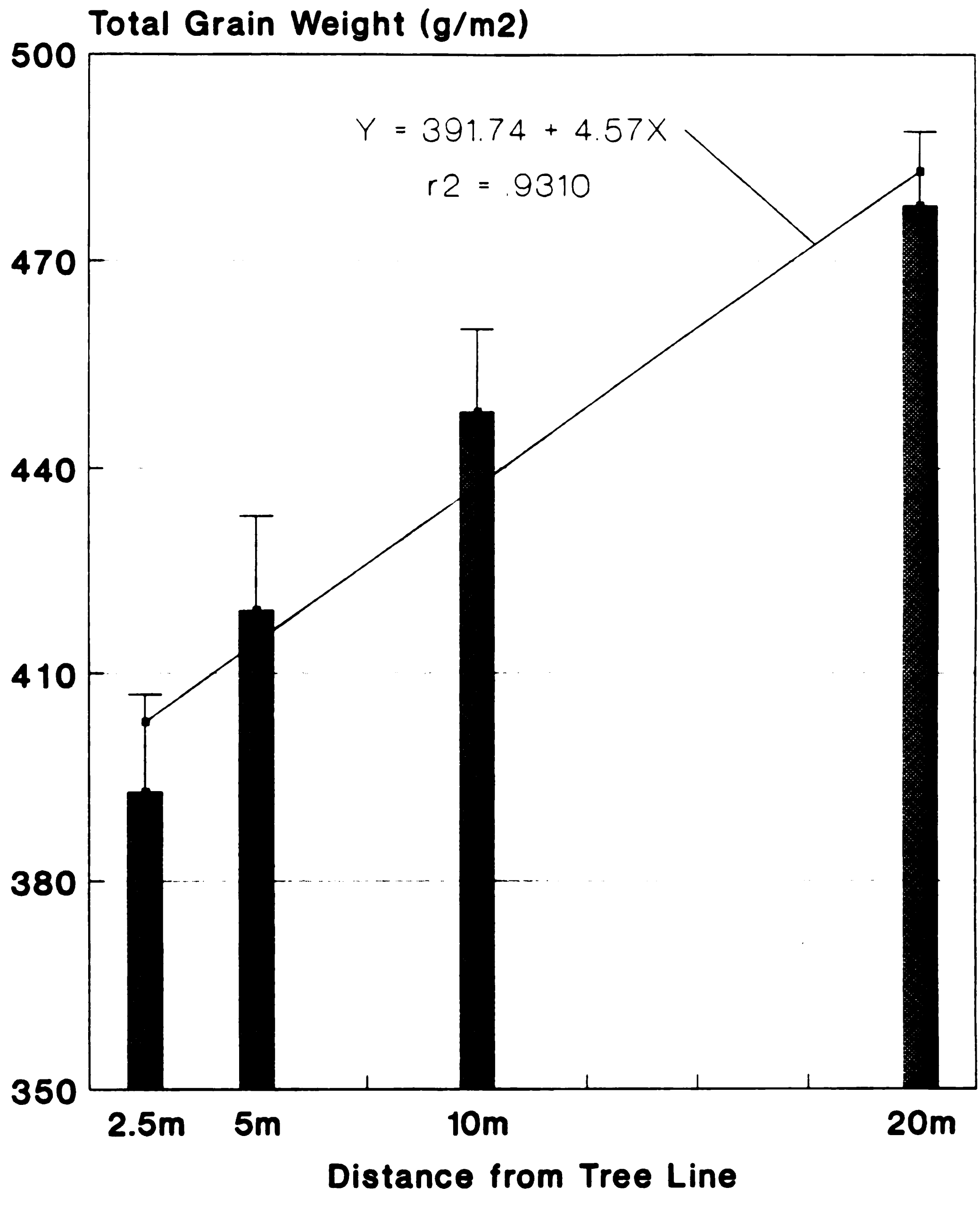


Figure 2.5. Yield vs Distance--TGW.

2.4.2. Temperature/Shade Experiment: Shaded vs Unshaded Plots

There was a significant difference in shaded versus unshaded groupings of treatments for total grain weight (p=.0440) and 1000-grain weight (p=.0135)(Table 2.6).

Table 2.6. ANOVA--Temperature/Shade Experiment--TGW, 1000-GW.

Total Grain Weight (TGW)						
Source	df	SS	MS	F	p	Signif
Treatment	2	11639	5820	3.256	.1103	NS
Shade vs No Shade	1	11552	11552	6.461	.0440	*
Residual	1	87	87	.049	.8321	NS
Error	6	10725	1788			
Total	8	22365				

1000 Grain Weight (1000-GW)						
Source	df	SS	MS	F	p	Signif
Treatment	2	41.75	20.88	8.432	.0181	*
Shade vs No Shade	1	29.64	29.64	11.971	.0135	*
Residual	1	12.11	12.11	4.891	.0690	NS
Error	6	14.85	2.476			
Total	8	56.60				

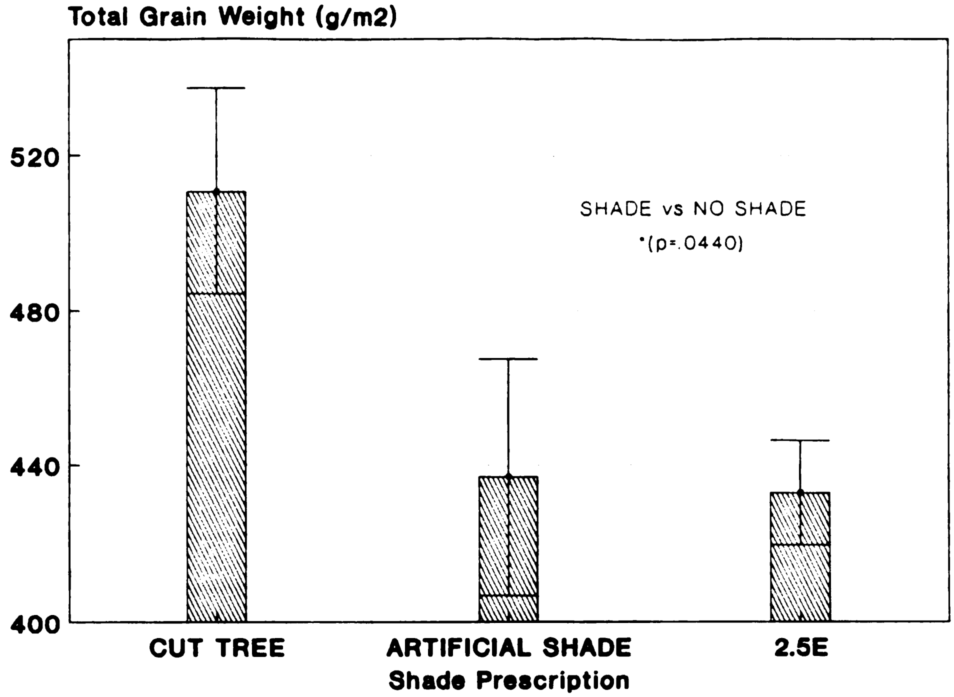
Scheffe's test was run to compare the treatment means (tabulated in Table B.2, Appendix B) for the 1000-grain weight (Table 2.7) as the individual treatments were significantly different (p=.0181). The unshaded ("cut tree") and the artificially shaded plots showed a significant difference at α = .05 while the tree shaded plots compared to the unshaded plots did not. Thus, there was no 1000-grain weight difference between tree shaded (at 2.5 m) and unshaded (the "cut tree" area) plots.

Table 2.7. Scheffe Test--Temperature/Shade Experiment--1000-GW.

Treatment	Mean (g)	Std Error	Scheffe Test[43]
Cut tree	35.7	1.2	A
Tree reps (2.5E)	33.3	.8	A B
Artificial shade	30.4	.7	B

Figure 2.6 illustrates the treatment means for total grain weight and 1000-grain weight (treatment means are tabulated in Table B.2, Appendix B). Air temperatures in each plot differed by less than 1.1^0 C as explained in 2.4.6.

[43]Treatments followed by the same letter are not significantly different (α=.05).



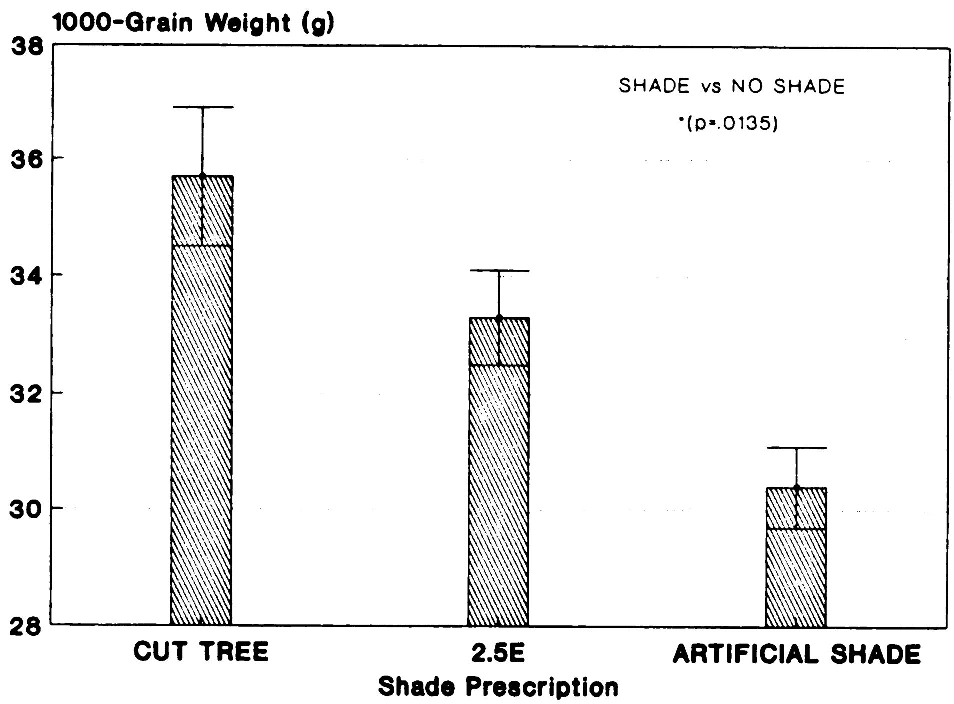


Figure 2.6. Temperature Experiment--Means--TGW,1000-GW.

2.4.3. Soils Experiment: The "Cut Tree" Area

Neither the total grain weight (p=.0652) or the 1000-grain weight (p=.0893) showed a significant difference between 2.5E and 20W in the "cut tree" area (Table 2.8). Means and standard errors for total grain weight and 1000-grain weight versus distance are shown in Table B.1, Appendix B.

Table 2.8. ANOVA--Soils Experiment--TGW, 1000-GW.

Total Grain Weight (TGW)						
Source	df	SS	MS	F	p	Signif
2.5E vs 20W	1	937	937.0	13.9	.0652	NS
error	2	135	67.6			
Total	5	7508				

1000 Grain Weight (1000-GW)						
Source	df	SS	MS	F	p	Signif
2.5E vs 20W	1	4.00	4.00	9.72	.0893	NS
error	2	.82	.41			
Total	5	29.49				

2.4.4. Yield by Treatment -- Means and Standard Errors

Figure 2.7 shows the means and standard errors for 1) ears m^{-2}, 2) total grain weight (g m^{-2}) and 3) 1000-grain weight (g) by each treatment with distance treatments (2.5 m to 20 m) summed over blocks 1-4. Means and standard errors are tabulated in Table B.1, Appendix B. Because of the different densities direct comparisons between the controls and the other treatments should not be made.

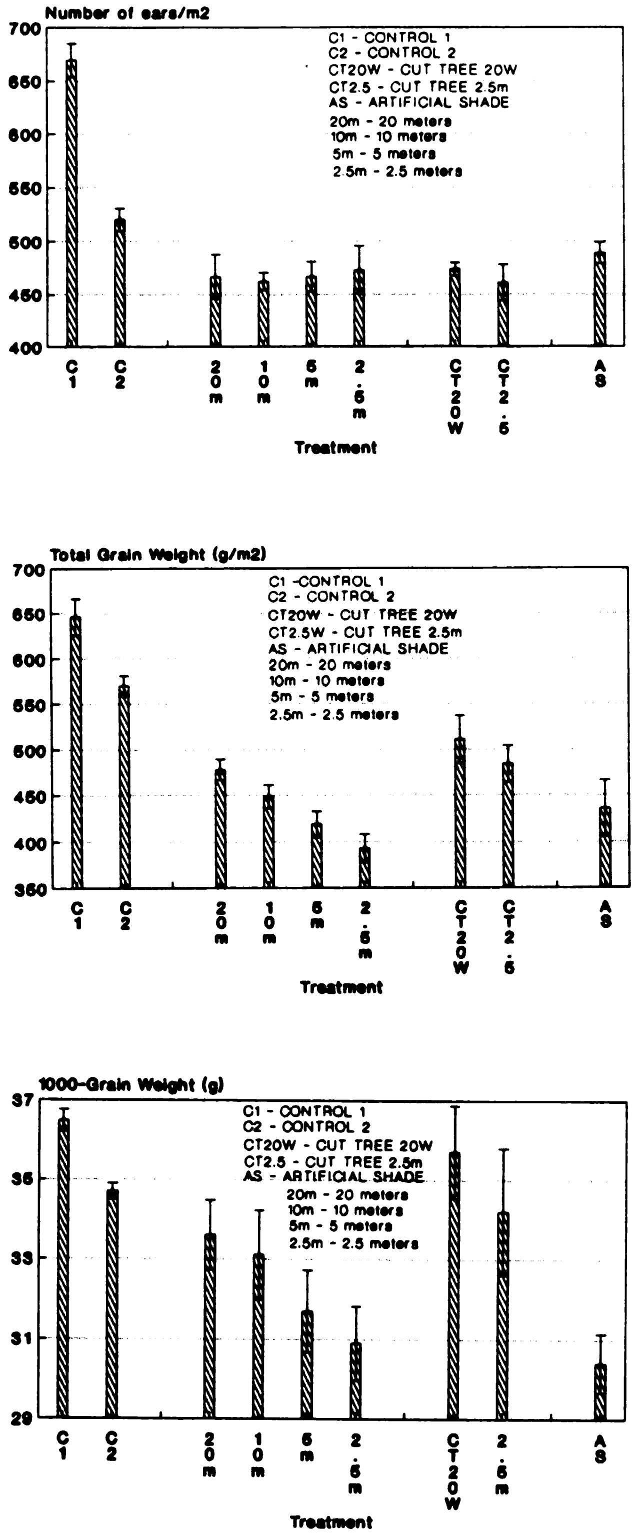


Figure 2.7. Treatment Means (20 m - 2.5 m as Block Averages).

2.4.5. PAR

Figure 2.8 shows 1) average daily theoretical maximum along with 2) the average daily unshaded PAR in moles m^{-2} day^{-1} and Figure 2.9 illustrates unshaded PAR as a percent of theoretical[44] maximum both by interval (Table 2.4). The number of grains per ear are determined in intervals 2 and 3 (before anthesis) and intervals 4 and 5 reflect grain filling time (kernel development).

[44]Theoretical maximum was supplied by a computer program showing total irradiance for 100% sunshine at 34^0 latitude converted to approximate moles m^{-2} day^{-1} of PAR using conversions from the LI-COR manual (Biggs, 1982).

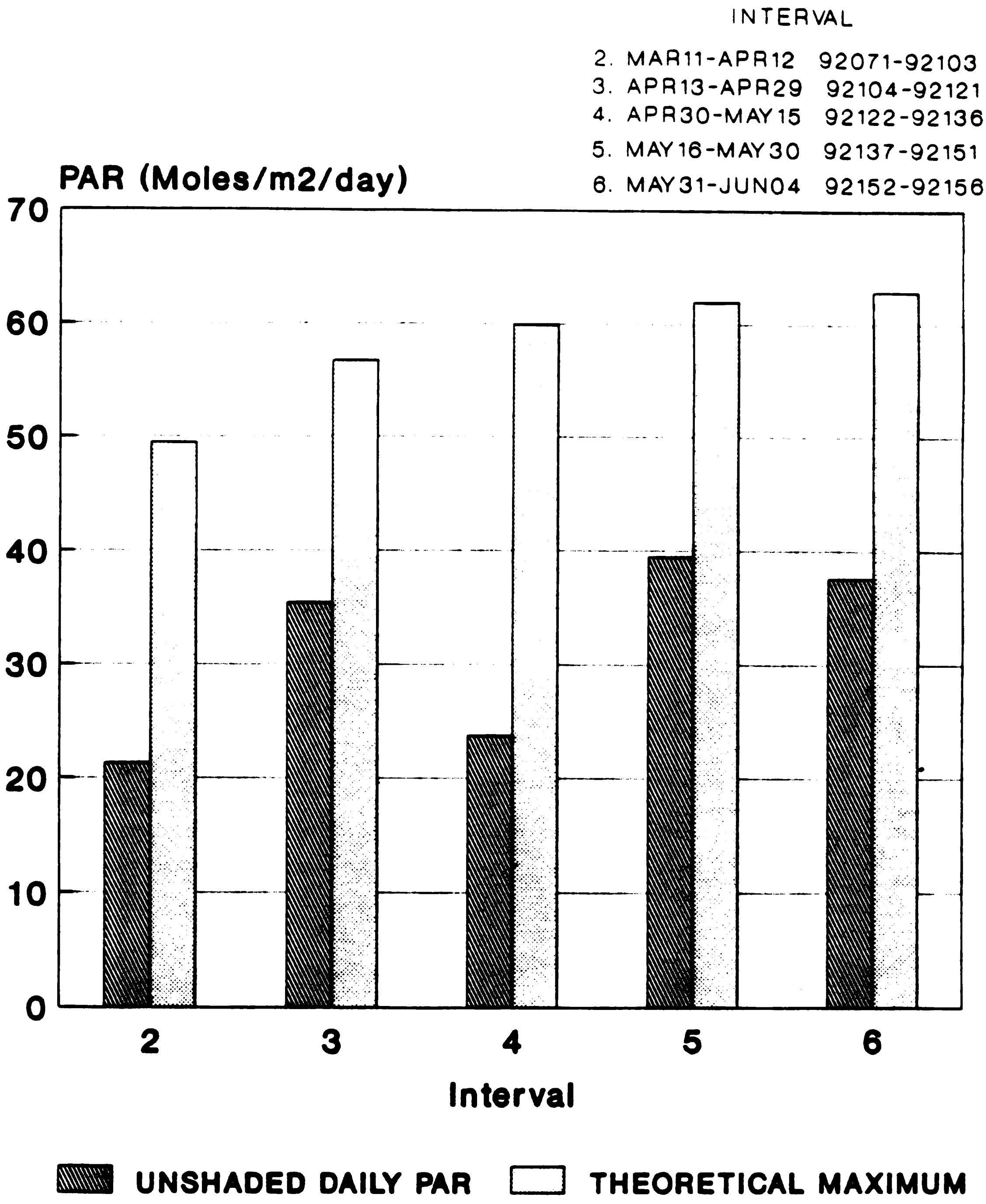


Figure 2.8. Average Daily PAR by Interval.

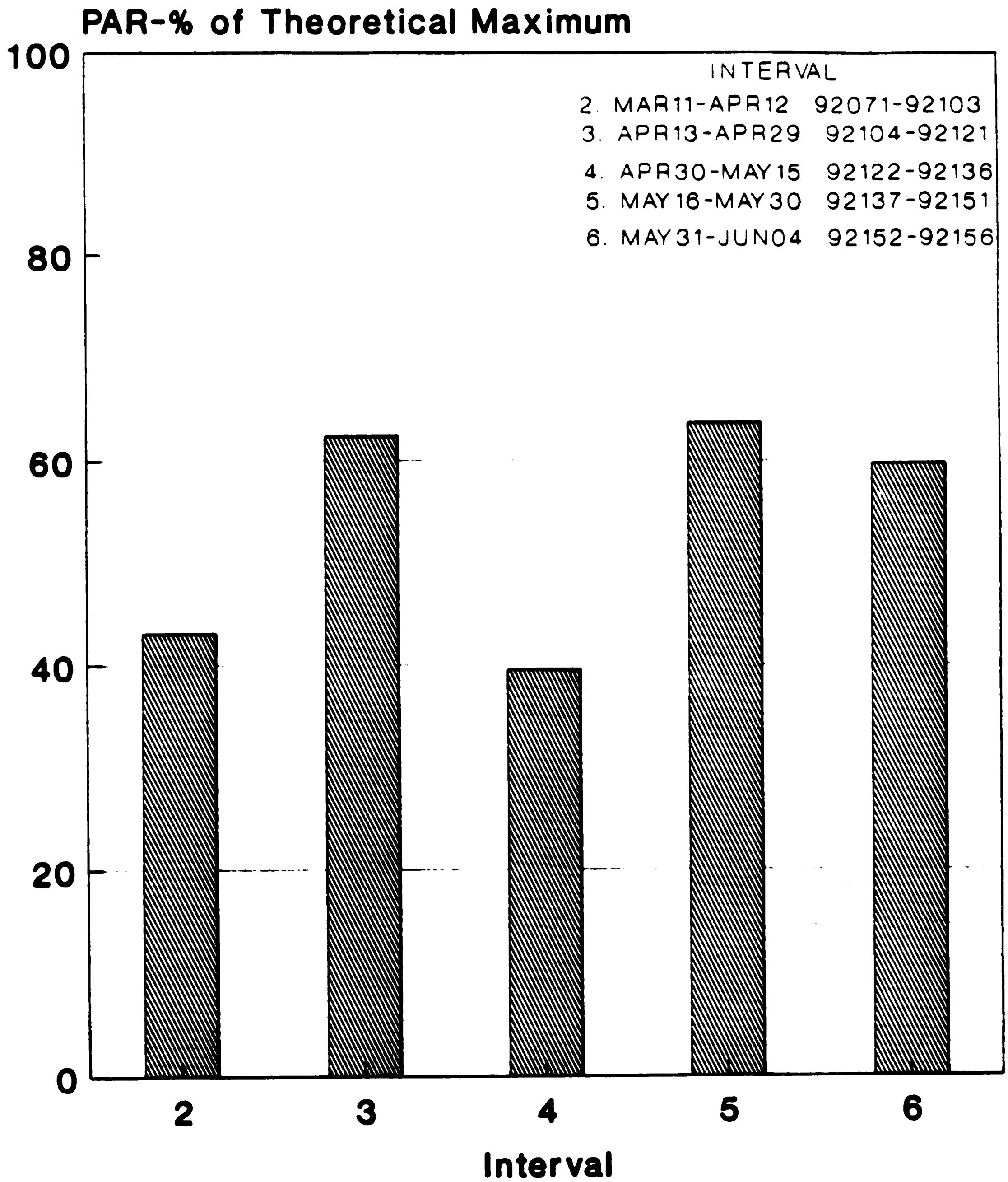


Figure 2.9. Average Daily PAR by Interval (%).

Figure 2.10 differentiates unshaded PAR and theoretical maximum by day. This shows atypical spring/early summer weather with many cloudy days. The days from the start of anthesis (92118) through May 9 (92130) are important for endosperm production. Extremely low PAR values occurred during this time and at the start of starch production the 7 ensuing days.

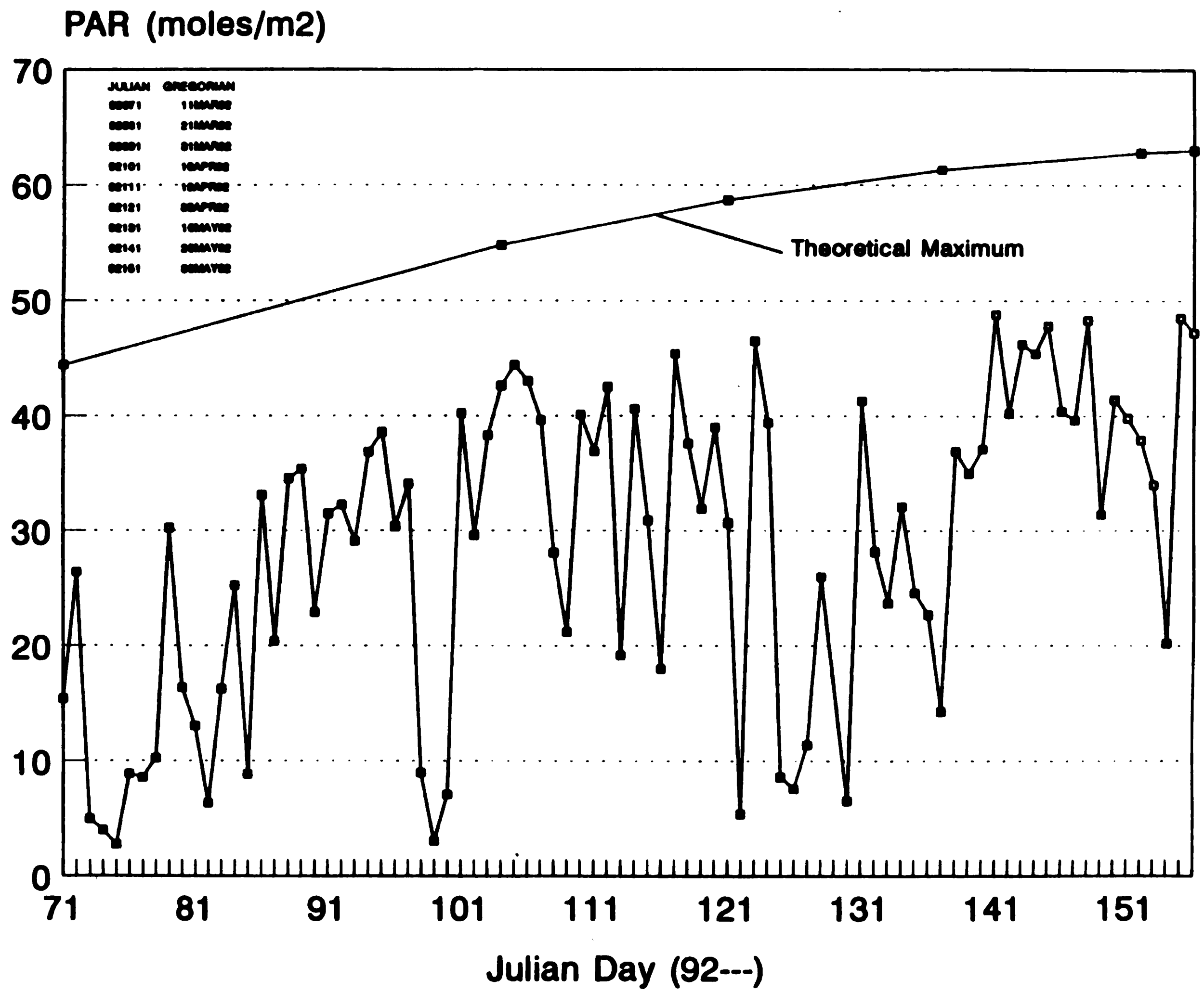


Figure 2.10. Total Daily PAR.

As the season progressed shade times at each distance and for each day increased. The percent of tree shaded versus unshaded PAR for each yield plot as the season progressed (Scheme II -- 1 minute reading intervals with one sensor repositioned to each yield plot position during its shaded time) is shown in Figure 2.11. Figure 2.11 was developed by averaging two clear days within intervals 2, 3, and 5 (Table 2.4) and 1 clear day for interval 6. A clear day for interval 4 was not available. This shows the difference in tree shade as the leaves emerged (92104). The large gap between intervals 3 and 5 was due to leaves growing quickly but cloudy conditions preventing measurement in interval 4.

The results of Scheme III -- 1 minute reading interval but sensors only at 5E and 5W during their shaded times -- show the effect of cloudy days (Figure 2.12). Dates 101, 108 and 115 were approximately at weekly intervals prior to anthesis and 130, 142 and 149 were after anthesis, but not at weekly intervals. Before anthesis, tree shading played a minor role so 5W (morning shade) and 5E (afternoon shade) both received high levels of tree shaded PAR relative to unshaded plots. However, afternoon clouds did appear. On day 92115 (April 24th) with a clear morning and cloudy afternoon, the afternoon tree shaded plot (5E) received 94% of the unshaded PAR while the morning tree shaded plot (5W) received 77% of the unshaded PAR.

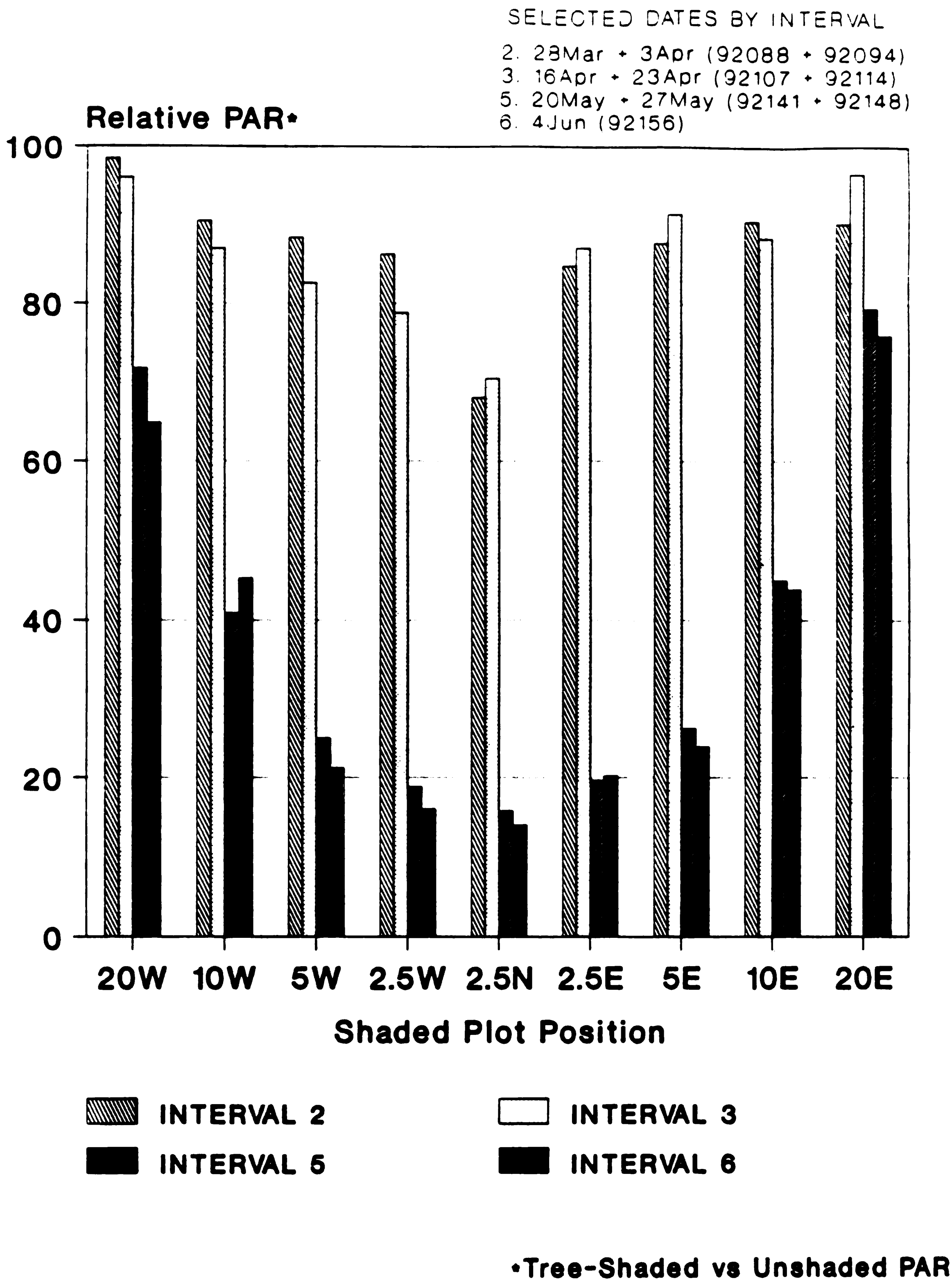


Figure 2.11. Tree Shaded vs Unshaded PAR--Scheme II.

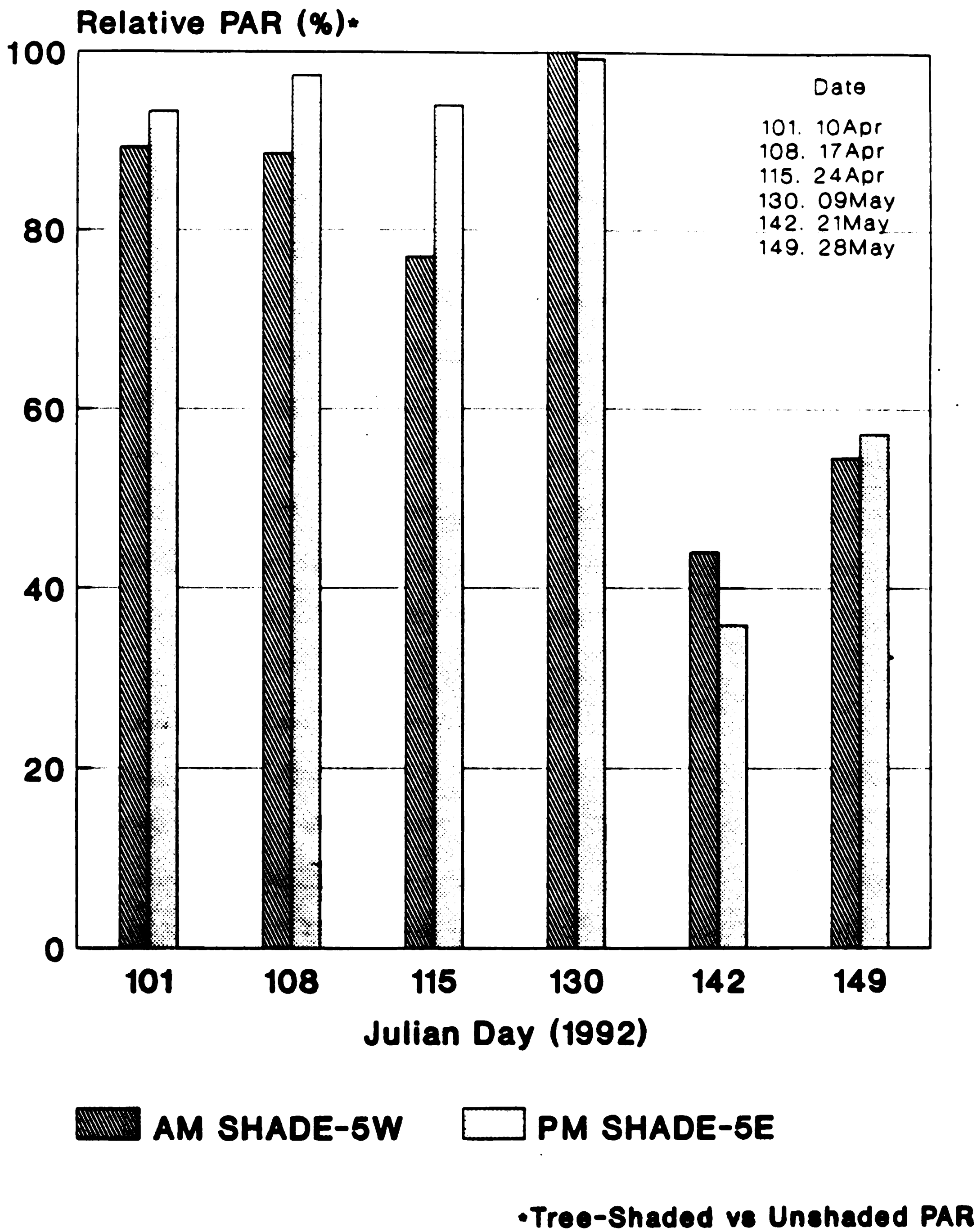


Figure 2.12. Tree Shaded vs Unshaded PAR--Scheme III.

After anthesis the tree shaded PAR as percentage of unshaded PAR decreased due to tree leaves. However, on May 9th (92130), 26 days after tree-leaf emergence, it was extremely cloudy (6.5 moles m^{-2}) and PAR to positions under the tree was the same as away from the tree. Both situations show with clouds present, tree shaded positions receive about the same PAR as unshaded positions (close to 100% on May 9th) in the form of diffuse radiation.

PAR from positions 2.5E and 10W were contrasted using Scheme I with data from 80% of the 85 total days recorded, from March 11th (92071) to June 4th (92156). During this time 87% of the total unshaded PAR reached the wheat at 10W, while at 2.5E only 72.2% was received. Figure C.1 in Appendix C shows PAR levels for 2.5E (tree shaded plots) compared to unshaded plots (control) by interval.

2.4.6. Temperature and Degree Days

Figure D.1, Appendix D shows the cumulative degree days (base temperature = 0^0 C) from October 30, 1991 (91303) to June 4, 1992 (92156) by location (2.5E versus 20W) for intervals 1-6. At tree bud break (92104) 20W had accumulated 32.3 more degree days. It took two days for 2.5E to make up this difference (in the following two days 2.5E accumulated 31.4 degree days). At anthesis (92121) there was still a 32.8 degree day difference, but in the following two days 2.5E recorded 35.6 degree days. There was a difference of 27.8 more degree days in 20W than in 2.5E at maturity (92151).

This was about 1 day's difference (the following day had 26.4 degree days).

As the tree leaves increased size and the canopy filled out (intervals 3-5) there was an increase of degree days in 2.5E as compared to 20W relative to intervals 1 and 2. This was due to daily low temperatures that were higher under the trees as the leaves grew while daily high temperatures both under the tree and away from it were about the same.

Air temperatures at 1.5 m above the ground were compared in 11 locations -- in Block 2 there were 8 locations 20W, 10W, 5W, 2.5W, tree line (2.5N), 2.5E, 5E, and 10E; 10 m West in the "cut tree" area (unshaded); in an artificial shaded plot (Figure 2.2); and in Control 1 (Figure 2.1). Hourly readings on selected days showed that the mean air temperatures in each location over the course of a day through to harvest whether shaded or unshaded differed by less than 1.1^0 C from each other. While recording days were not always clear-sky days, temperatures did climb as high as 32^0 C.

Two other figures (Figure D.2 and Figure D.3) depicting temperature are shown in Appendices. Figure D.2 shows the range between maximum and minimum daily temperatures at 2.5E and 20W from the first day of anthesis through the following 9 day period. In Figure D.3 the maximum daily temperatures are shown from March 11th (92071) to harvest on June 4th (92156). Only temperatures for 20W were included as 2.5E temperatures were at or below those of 20W. The line at 25^0 C represents the maximum optimum temperature for wheat net photosynthesis (Evans et al., 1980).

2.4.7. Haun Scale

Table E.1, Appendix E lists the Haun rating means for each block by the Julian date. Some differences can be seen at earlier dates, however, as anthesis approached on April 24th (92115), all blocks were at about the same point on the Haun scale.

In Table E.2, Appendix E the blocks with trees (blocks 1-4) were grouped by yield plot direction and distance and their means were listed against the date. No difference was noted between positions under or away from the tree.

2.4.8. Wind

The number of days and the average wind speed by interval beginning February 23, 1992 (92054) for 8 directions is shown in Table F.1, Appendix F. Of the 106 days with data available, there was a north wind in 35 days (33%) and a northerly wind (NW, N, NE) in 39 days (37%). In 37 days (35%) there was a south wind and in 49 days (46%) there was a southerly wind (SE, S, SW). However, by interval the wind was evenly distributed between north (N) and south (S) through May 30th. Thus, one direction did not predominate during the wheat growing period. The wind speed was a little stronger from the north compared to the south through April (4.0 m/s versus 1.8 m/s).

2.4.9. Precipitation, Soil Moisture, and Irrigation Dates

The precipitation is listed in Table G.1, Appendix G along with the percent soil moisture and irrigation dates.

From October 22, 1991 (91295) until harvest on June 4, 1992 (92156), there was a total precipitation of 148 mm (recorded in *Chang Ge* 12 km to the south of the research site). Only 3 days had greater than 10 mm of precipitation -- March 1st (92061)-13.3 mm, April 9th (92100)-12.8 mm, and May 5th (92126)-30.2 mm.

In Table G.2, Appendix G, the soil moisture for yield plot distances and directions for blocks 1-4 are shown with sampling dates. When comparing the soil moisture at the different distances there is practically no difference between 2.5 m through 20 m irrespective of direction. The ANOVA for April 24th (92115), when percent soil moisture was only 4-5%, was not significant for distance ($p=.4292$) or direction ($p=.4029$) (Table G.3, Appendix G).

2.4.10. Soil Samples

<u>Nitrogen.</u> The research fields were fertilized so that soil nutrients would not be limiting. Nitrogen levels in all blocks were well above response levels and differences were minimal. This was based on an available N requirement of 220 kg N ha^{-1} for an extremely high yield goal of 6720 kg ha^{-1} (Dahnke and Johnson, 1990). At 1 mg N kg^{-1} = 2.24 kg N ha^{-1} furrow slice[45] using the lowest soil test N from the September 19, 1991 (91262) test for the area in the 0-20 cm layer (73.4 mg N kg^{-1} or 164 kg N ha^{-1}) an additional 56 kg N ha^{-1} was needed to meet the yield goal. Dahnke and Johnson (1990) (after

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[45]MSU soil testing laboratory for a bulk density of 1.3 and a depth of 15.9 cm.

Buchholz et al, 1981) also showed silt loams to loams at 2.0% organic matter with a cool season crop required 22 kg N ha^{-1}. Farmers in China were given the equivalent of 136.5 kg N ha^{-1}. Thus, N should not have affected yield on the 2.5 m to 20 m plots. An ANOVA for the February sampling showed no significant difference for direction (p=.0611) or distance (p=.5201) for 0-20 cm or for 21-40 cm (p=.8015) and (p=.4590) (Table H.1, Appendix H).

Phosphorus. Phosphorus needs were maximum in the spring from the inboot stage (Figure 1.10) through the milk stage (7-10 days after anthesis) of grain filling (Halvorson et al., 1987). During this time the ANOVA for the February sampling (92057) in the tree area (Table H.1, Appendix H) showed P levels were not significant for direction (p=.1659) but significant for distance (p=.0069) in the 0-20 cm level. The ANOVA for distance and Scheffe's test are found in Table H.2 and H.3, respectively, Appendix H. Scheffe's test at α=.05 showed P significantly greater at 5 m compared to 10 and 20 m but not 2.5 m. The 21-40 cm layer was not significant (p=.7293) and (p=.1678)(Table H.1, Appendix H).

For a pH of 8.4 (calcareous soils in semi-arid regions) less than 10 mg kg^{-1} of P is considered low (Halvorson et al., 1987). Li and Xiao (1992) also state that wheat in semi-arid regions of China will experience a yield increase with addition of P when P-soil tests ($NaHCO_3$) are less than 16 mg kg^{-1}. This means soils in the experimental plots were suboptimal for P and wheat yield may have increased due to higher levels under the trees. However, Matar et al. (1992) with wheat found that P-soil tests ($NaHCO_3$) of 4 to 5 mg kg^{-1} had no response to fertilizer in wet years (above 300 mm rainfall).

This research site, being irrigated, should respond as wheat in wet years so the difference in P should have minimal effect on yield. During the dry spell leading up to April 24th (92115)(Table G.1, Appendix G) there may have been a response to P. If this were the case plots at 5 m and 2.5 m would have benefitted, however, yield was greater at 10 m and 20 m (not under the trees). Thus, P may have had a mitigating influence on yield outcome at 2.5 m and 5 m versus 10 m and 20 m. Table H.4, Appendix H, shows the P levels for blocks 1-4 and block 5 the "cut tree" area.

Potassium and sulfur, 2 other essential nutrients for wheat growth were not tested, however, K was applied (NPK 15-15-14) at about 52.3 kg ha^{-1} and no known sulfur deficiency existed.

Organic matter (OM). Soil OM for each block had means predominantly between 1.0% and 2.43%. Generally means were about the same as the typical soil of this area or 1.77% (Wei, 1979) in the upper 0-20 cm depth. No clear pattern of accumulation or depletion by block was evident as the season progressed and distance did not seem to be a factor with the ANOVA at both 0-20 cm and 21-40 cm not significant for direction or distance (Table H.1, Appendix H).

pH. Soil pH did show a significant difference in the 0-20 cm layer for direction (p=.0313) (Table H.5, Appendix H) but not for distance. In calcareous soils a higher pH would have the effect of making P less available. Neither distance nor direction were significant at the 21-40 cm level (Table H.1, Appendix H). All readings for direction and distance were very close to the typical soils for this general area that have a pH of 8.2 for both levels.

2.4.11. Tree Measurements

Table I.1, Appendix I, lists block means for tree height, clear bole, diameter at 1.5 m and crown diameter. Over the course of the experiment, September 1991 to June 1992, average tree height was 12.8 m; the diameter at 1.5 m was 32.0 cm; the average bole length measured 5.9 m; and the crown diameter had an average 9.2 m east-west span (Table I.2, Appendix I).

2.5. DISCUSSION

The discussion will center primarily on explaining the results for total grain weight and 1000-grain weight at different distances from the *Paulownia* tree line. Cultural factors contributing to wheat yield were described in 2.3.4. and the emphasis here will be on environmental factors. The discussion will follow the intervals established in Table 2.4 with two basic sections -- before anthesis and after anthesis.

Before anthesis the total grain weight is determined by sequential development of the number of ears per unit area and the number of grains per ear (Figure 1.10). In turn the number of grains per ear result from development of spikelets per ear followed by florets per spikelet. Several yield studies point to the importance of PAR at different stages of wheat development before anthesis. In addition, environmental factors such as soil nutrients, temperature and soil moisture can play a major role.

After anthesis the kernel begins to grow with two key physiological processes occurring, endosperm production and starch formation. The 1000-grain weight which is determined during this time will also influence the total grain weight. Because kernel development, which determines 1000-grain weight, is just one of 4 yield components that comprise total grain weight, there may be a strong correlation between total grain weight and 1000-grain weight. Yield studies also emphasize the importance of PAR, soil moisture, soil nutrients and temperature for growth after anthesis.

Other aspects of the discussion will include 1) an evaluation of the temperature effects on wheat yield; 2) an investigation of yield in soils under the trees versus away from the trees at 2.5 m and 20 m in an area where trees were removed before planting wheat; and 3) a study of wheat yield in controls grown away from the sheltering effects of the trees.

2.5.1. Trees and Wheat -- the Distance Effect

This experiment showed that total grain weight per plot differed significantly (p=.0047) (Table 2.5) as the distance from the tree in an east or west direction increased from 2.5

m to 20 m. However, no significant difference was found in the 1000-grain weight (p=.3180) over the same distance even though there was a strong correlation between total grain weight and 1000-grain weight ρ=.8148. Thus, differences in yield for total grain weight probably occurred before anthesis. Reasons for these differences are due to multiple factors, including environmental, that may give rise to compensatory responses during wheat growth and development.

2.5.1.1. Pre-anthesis -- total grain weight

2.5.1.1.1. Ears per unit area -- tillers. Environmental conditions affected yield from tillering, early in the growing cycle (Fall), almost to maturity (Figure 1.10). Tiller number determines ears/unit area. In addition to nutrients and cultivar, the number of ears per unit area is strongly affected by solar radiation (Evans et al., 1980). Although tree leaves were present during some of the early tillering stage, they were largely absent through the period (November 1991-February 1992) when effective tillers were being formed. During this time solar radiation was only minimally affected by the tree stem and branches. Figure 2.11, interval 2, showed that 85% of the unshaded PAR, except for trunk shade at plot position 0 (tree line or 2.5N), still reached the tree shaded areas through April 3rd (92094) which was after floral initiation. This was well after tillering had ceased to become an important factor.

Fischer (1975) found that a 67% light reduction due to artificial shading during the tiller forming stage (fall and winter) did not affect yield. Both Fischer (1975) and Willey and Holliday (1971) stated that other factors compensated for low radiation levels during the tillering stage so tiller number was relatively unimportant in final grain yield.

Farmers in China knew that soil moisture played an important role in the number of tillers per plant. As previously mentioned the Fall of 1991 was the driest in over 60 years. Even with irrigation, soil moisture was limited and tillers per plant were lower than previous years. However, those plots under the tree were not noticeably different in ears/unit area from those away from the tree. This was confirmed by a count of ears m^{-2} at harvest (Figure 2.7 and Table B.1, Appendix B).

2.5.1.1.2. Number of grains per ear

2.5.1.1.2.1. Yield studies. Studies testing effects of shading on wheat generally do not apply shading at certain times of the day (as occurs under trees in the field), but rather at certain times of the development cycle at whole-day intervals. Biologically or phenologically, these intervals last days, weeks, months or throughout the entire wheat growing period. Thus, shading trials represent an extreme amount of shade for a very short duration compared to tree shade. In contrast, tree shade is diurnally periodic on a continuing basis throughout the crop development cycle.

Wheat shading trials in England (Willey and Holliday, 1971) and Mexico (Fischer, 1975), tested different light intensities. In England light intensities (converted to approximate moles m^{-2} day^{-1} of PAR) for intervals 2 and 3 were about 24 moles m^{-2} day^{-1} averaged over a 3 year period (theoretical maximum of 63 moles m^{-2} day^{-1}) with shading intensities of 28% (17.3 moles m^{-2} day^{-1}) and 54% (11.0 moles m^{-2} day^{-1}). In Mexico there were about 35 moles m^{-2} day^{-1} averaged over a 4-year period (theoretical maximum of 42 moles m^{-2} day^{-1}) with shading of roughly 13% (36.5 moles m^{-2} day^{-1}), 35% (27.3 moles m^{-2} day^{-1}), 48% (21.8 moles m^{-2} day^{-1}), 55% (18.9 moles m^{-2} day^{-1}) and 68% (13.4 moles m^{-2} day^{-1}). Both studies showed that shade from flower initiation to anthesis (intervals 2 and 3) reduced yield by reducing the grains m^{-2} (spikelets per ear and/or florets per spikelet).

The Chinese research site normally received high PAR levels in the spring. However, as Figure 2.8 indicates, average daily PAR (21 and 35 moles m^{-2} day^{-1} for intervals 2 and 3, respectively) prior to anthesis was closer to unshaded levels in England for interval 2 and those of Mexico for interval 3. The China study was in agreement with the results of Mexico and England in that there was low PAR before anthesis and there was reduced yield in more shaded areas.

2.5.1.1.2.2. Spikelets per ear. Evans et al. (1980) state that photoperiod, nutrient levels, PAR, and temperature influenced spikelet number per ear well before anthesis (roughly interval 2) (Fig 1.10). Photoperiod was the same for the distances 2.5 m to 20 m. Available N was greater than the response level. Towards the end of spikelet formation P may have been needed as the inboot stage approached (April 14 -- 92105). However, soil moisture levels were above 10% (92107)(Table G.2, Appendix G) meaning no response was anticipated.

PAR during interval 2 from March 11th (92071) to April 12th (92103) was only slightly impeded by the trees (Figure 2.11), however, this atypically was a time of limited PAR due to clouds as shown in Figure 2.10 of daily PAR compared to the theoretical maximum. Interval 2 only received about 43.1% of the theoretical maximum PAR (Figure 2.9). However, differences between PAR under the trees (2.5E) and a control away from the trees were small (Figure C.1, Appendix C). At 2.5E the control received 336 moles m^{-2} versus 306 moles m^{-2} in the tree shade. A control and 10W (shaded) both received about 115 moles m^{-2} (not shown)[46].

In cloudy periods PAR differences under trees and away from the trees are reduced and diffuse light becomes prevalent. Higher levels of morning PAR (no clouds) signified a lower percentage of PAR at the tree shaded plot compared to a full sun plot. In contrast, on very cloudy days tree shaded plots in the morning and afternoon received over 99% of the unshaded PAR. This suggested relatively equal but low PAR

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[46]This comparison only accounted for tree shaded time which diurnally was less at 10W than 2.5E. Thus, 10W PAR was less than 2.5E.

levels to all positions as diffuse light during cloudy conditions.

Thus, total PAR received by the wheat during interval 2, while reduced due to clouds, did not affect positions under the tree differently than away from the trees because of similar PAR levels from diffuse radiation. This was supported by Fischer's (1975) work where he found that small reductions in radiation had little effect on yield at any stage of development.

Wheat development through interval 2 using the Haun scale to visually check for differences across the yield plot spectrum from 20W to 20E (Table E.2, Appendix E) showed only minor differences (92086, 92093, 92101). Cumulative degree days from planting (Figure D.1, Appendix D) were employed to show average temperature differences and their effect on development. A look at interval 2 shows a small difference (6.4 degree days or about 1/2 a day). Thus, the Haun scale and degree days helped confirm that wheat development under the tree and away from the tree were similar with temperature not playing a significant role on spikelets per ear. The lack of difference in photoperiod, nutrient status, PAR and temperature from 2.5 m to 20 m suggested that development of the number of spikelets per ear were not affected.

2.5.1.1.2.3. Florets per spikelet. The stage of development in the 2-3 weeks prior to anthesis is florets per spikelet. PAR, water availability, P, and temperature affected the number of florets per spikelet during this time.

PAR. Stockman et al. (1983) studied an 8 day interval (from 14 to 6 days before anthesis) where shading reduced the number of florets per spikelet. Fischer (1975) also noted a period, about 2-3 weeks before anthesis, where shading influenced both spikelets/ear and florets/spikelet development stages and ultimately affected overall yield. This corresponded to interval 3 (Table 2.4) where the tree leaves began to emerge (17 days before anthesis). To determine the effect of shading on wheat during this interval the amount of PAR available (above the canopy) must be considered. In addition, PAR that the plant received at 2.5 m versus 20 m due to tree shade effects must be factored in.

During interval 3 there was an overall increase in unshaded PAR to 62.4% of theoretical maximum (35.4 moles m^{-2} day^{-1} average) (Figures 2.9 and 2.8, respectfully). As PAR increased in interval 3 and the tree leaves emerged resulting in more shading at 2.5 m, less PAR was available at 2.5 m relative to 20 m (as illustrated in Figure C.1, Appendix C).

As shown in Figure 2.11 (interval 3) for 2 sunny days during interval 3, tree shaded PAR in all plots was still approximately 80% or greater of unshaded PAR. However, shading time differed. Shading at 2.5 m was roughly 3-4 h per day during midday when unshaded PAR was high (1720 μmoles m^{-2} s^{-1} at 12:40 on 92117 -- a clear day). At 10 m and 20 m shading lasted only 1-3 h during early and late times of the day when unshaded PAR was low (600 μmoles m^{-2} s^{-1} at 08:00 on 92117). The time of day that shading occurred, as well as the length of time, may have been a distinguishing factor in grain storage potential. This difference during the two weeks prior to anthesis could have decreased floret development in the 2.5 m plots compared to the 20 m plots.

Working in Mexico, Fischer (1975) discussed a possible critical threshold in radiation received by wheat due to a short period of unusual cloudiness. He stated that a simple radiation total during a given development interval may not adequately describe the development process. Thus, in China, if total available (unshaded) PAR was low and shading increased (as from interval 2 to 3) on plots under the trees during a critical stage of wheat development, there may have been a slower rate of development at 2.5 m due to less PAR received.

Soil moisture. Just before anthesis soil moisture was limiting (Table G.2, Appendix G). On 92115, just a few days before flowering began (92119), soil moisture readings ranged from 4.3-5.5% for 2.5 m-20 m. Li and Xiao (1992) working in China, point out that with silty soils, moisture in the top 0-10 cm can be lower than the wilting point while deeper layers can have 14%-16% moisture by dry weight, thus minimizing soil moisture effects. Since the plants did not look too stressed it is likely that plant water stress was not too serious at this time. Irrigation began on 92115 to help alleviate the stress (Table G.1, Appendix G). Also, wheat was under relatively uniform water stress across locations (Table G.2, Appendix G).

P. As anthesis approached, low soil moisture may have caused a yield response from P. However, higher P levels were found at 2.5 m and 5 m as compared to 10 m or 20 m (Table H.1 and H.4, Appendix H). A response to P would have increased yield at 2.5 m and 5 m whereas actual results showed yield was greater at 10 m and 20 m. Thus, higher yield at 20 m should not be due to water stress or soil P. The differences that did occur may have been ameliorated by P.

Temperatures. In interval 3 (92104-92120) air temperatures were generally in wheat's optimum range (10^0-25^0 C) or very close with only 6 days above 25^0 C and the highest only 28.5^0 C (Figure D.3, Appendix D). Figure D.1, Appendix D, shows no difference for cumulative degree days in interval 3 at 2.5E and 20W. At anthesis 2.5E and 20W were only about 2 days development apart (32.8 degree days). The Haun scale (Table E.2, Appendix E) also shows no difference in wheat development leading up to anthesis (92118) over the range of distances. Thus, temperature did not play a significant role in florets per spikelet.

2.5.1.1.2.4. Recap

In summary, both an increase in average daily PAR and an increase in tree shade as the leaves grew contributed to a reduction in florets per spikelet at 2.5 m versus 20 m. Since average daily PAR increased from interval 2 to 3, a greater proportion of direct radiation relative to diffuse was potentially available. This would amplify differences between shaded and unshaded plots.

At the same time daily tree shading increased due to rapid tree leaf growth. This resulted in lower total daily PAR levels at 2.5 m due to losses from midday shade as opposed to daily PAR losses at 20 m from early morning or late afternoon shading. This combination of increased direct PAR and the shading effect at different times of day should have resulted in fewer or smaller florets/spikelet and less storage capacity at 2.5 m than 20 m. Higher soil P levels at 2.5 m and 5 m may have served as a mitigating factor by contributing to higher yield at 5 m and 2.5 m under the trees.

2.5.1.2. Post-anthesis -- 1000-grain weight. With anthesis the storage capacity or number of grains/ear was fixed. During fertilization optimal temperatures (18-24^0 C with a minimum of 10^0 C and a maximum of 32^0 C) were recorded. Figure D.2, Appendix D, shows temperatures from the start of anthesis on April 28th (92119) throughout this period were not limiting (slightly below 10^0 C on two days and well under 32^0 each day). After anthesis kernel growth began.

2.5.1.2.1. Endosperm cell division. Endosperm cell division is the primary metabolic process the first week following anthesis. This is a critical time for grain filling. Simmons (1987) stated that the number of endosperm cells in each kernel influenced the rate of growth and final weight. Influencing factors are PAR, temperature, water availability, P and genotype.

Temperature was not a factor as daily high and low temperatures during the week after anthesis (Figure D.2, Appendix D) differed by less than 2^0 C between 2.5E, under the trees, and 20W, away from the trees. Water availability was not a factor as irrigation (Table G.1, Appendix G) completed during the 5 days before anthesis (92115-92119), assured adequate soil moisture. With high soil moisture, P was not limiting. Also, genotype was not a factor as all wheat was of the same genotype.

Daily PAR recorded in 15 out of 16 days following anthesis (Figure 2.10) was low (92119-92134). Figure 2.9 showed interval 4 with only 39.5% of theoretical maximum PAR available due to clouds. In cloudy conditions tree shaded plots received over 99% of unshaded PAR which suggested distances from 2.5 m to 20 m should all receive similar PAR levels. Thus, PAR differences among distances were reduced, soil moisture was high, and temperature differences were minimal. Under these conditions endosperm production was probably about the same in 2.5 m to 20 m locations.

2.5.1.2.2. Starch formation. Starch formation (milk stage) begins in the kernel about the second week after anthesis. During this phase there is a linear increase in kernel dry weight which lasts 2-4 weeks (through the hard dough stage -- Figure 1.10) depending on temperature, water stress, and cultivar (Simmons, 1987).

Cooler temperatures in the period after anthesis allowed for a longer grain filling time. Optimum temperatures for wheat photosynthesis were less than 25^0 C. From Figure D.3, Appendix D, the maximum daily temperatures stayed near or below 25^0 C until May 17th (92138) or almost 3 weeks from the start of anthesis. Towards the end of May (92154-interval 5) daily maximum temperatures reached 35^0 C which tended to speed up maturity and induce water stress (Table G.1, Appendix G). However, by this time the milk stage was completed and soil P was not required.

In Figure 2.9, interval 5, PAR increased to 63.7% of the theoretical maximum or an average of about 39.5 moles m^{-2} day^{-1} (Figure 2.8). This was important because 70%-90% of the carbohydrates in the kernel come from carbon dioxide fixed after anthesis (Simmons, 1987). Towards the end of grain filling on May 20th (92141) and 27th (92148) (Figure 2.11, interval 5) there were marked PAR differences in tree shaded plots compared to unshaded plots.

Low levels of PAR in interval 4 when endosperm development occurred, signified similar numbers of endosperm cells at 2.5 m and 20 m. When starch was being formed the higher levels of PAR at the end of interval 5 in 20 m plots were not great enough to cause a significant yield difference in 1000-grain weight.

Fischer (1975) in high PAR situations (average PAR before anthesis of 34.7 moles m^{-2} day^{-1} and after 45.1 moles m^{-2} day^{-1}) found that the 1000-grain weight or kernel weight actually increased as total grain yield decreased when shading was applied before anthesis possibly due to a compensatory response. However, Willey and Holliday (1971) reported that shading before anthesis did not affect (raise or lower) the 1000-grain weight in low light conditions (average PAR before anthesis of 21.6 moles m^{-2} day^{-1} and after 18.4 moles m^{-2} day^{-1}). Willey and Holliday's finding is supported by our data from China as the shading under the trees did not result in a compensatory difference in 1000-grain weight (average PAR before anthesis 27.3-moles m^{-2} day^{-1} for intervals 2 and 3 and after 31.6 moles m^{-2} day^{-1}) with less PAR due to tree shade.

To summarize, low interval 3 PAR levels and tree shade before anthesis in the 2.5 m yield plots reduced the number of grains/ear by decreasing the florets/spikelet more than those at 20 m. In low light conditions the midday PAR became very important and the 2.5 m position received lower PAR. The 1000-grain weight was not significantly different from 2.5 m to 20 m and did not influence the total grain weight. A compensatory increase in 1000-grain weight for shaded plots may not have been realized because the average daily PAR received after anthesis when 70-90% of the CO_2 was fixed in the kernel was less than some critical threshold. Since the 1000-grain weight at 2.5 m and 20 m was not significantly different and the 1000-grain weight and total grain weight were highly correlated (ρ=.8148), the reduction in total grain weight can be attributed to PAR differences before anthesis caused by tree shading in interval 3.

2.5.2. Temperature and Yield

Results from the temperature and shade experiment (Figure 2.3) indicated that air temperature did not affect yield (less than 1.1^0 C difference between shaded and unshaded plots throughout the day). A significant difference in shaded versus unshaded yield plots was detected for total grain weight (p=.0440) (Table 2.6) with a 74 g m^{-2} higher yield (Table B.2, Appendix B) in the "cut tree" area compared to shaded blocks (2.5E and artificial shade).

The 1000-grain weight was significantly different between the artificial shade and the "cut tree" area, but not between the "cut tree" area and under the tree at 2.5E (Table 2.7). The artificial shade, while set to shade the same hours as at 2.5E, may have been heavier than the tree shade the first 2 weeks after anthesis. Since 70-90% of the kernel weight is determined by PAR after anthesis this excess shading may have caused the artificial shade 1000-grain weight to be significantly lower than the unshaded "cut tree" area.

2.5.3. Soils and Yield

Soils in the tree area were investigated by a supporting experiment (see Figure 2.4). Five trees were cut prior to sowing the wheat in an attempt to address the question of whether trees influenced the soil (over time) and therefore positively or negatively affected wheat yield. Soil samples taken from the "cut tree" area (2.5E, 2.5W and 20W), revealed N levels well above the response rate. Phosphorus levels (Table H.4, Appendix H) ranged from 5.4 to 7.7 mg kg^{-1} (Block

5) in the February sampling (92057). Under irrigated conditions there should be no response at these levels (Matar et al., 1992). In dry conditions between irrigations, 2.5W would have benefitted from higher P levels, as compared to 2.5E and 20W P levels which were similar.

Results from the analysis of variance (Table 2.8) showed that 20W yield, (although not statistically significant at the 5% level, p=.0625, for total grain weight and p=.0893 for 1000-grain weight), averaged 25 g m^{-2} higher and 1000-grain weight 1.5 g higher than 2.5 m plots. As there was no tree shade, PAR and temperature could not have had an effect on wheat yields. Also, soil moisture for this "cut tree" area was not a factor as 2.5 m and 20 m plots were irrigated at the same time. Soil moisture results show no clear pattern of one plot always greater than the other.

In the "cut tree" area, measurement plots were only taken at 2.5 m and 20 m. Thus, it was not possible to compare the "cut tree" area to the 4 yield plot positions on a transect as in blocks 1-4. However, total grain weight at 20 m (Figure 2.7 and Table B.1, Appendix B) in the "cut tree" area was 511 g m^{-2} versus 478 g m^{-2} for blocks 1-4. This difference of 33 g m^{-2} is relatively small compared to the difference of 91 g m^{-2} at 2.5 m (484 g m^{-2} and 393 g m^{-2} for the "cut tree" area and blocks 1-4, respectively). Thus, all plots except 2.5 m under the trees received more PAR (less shading) and had higher yield. While this confirms shading reduced yield, it does not explain why total grain weight at 2.5 m in the "cut tree" area was lower than 20 m in blocks 1-4.

The 1000-grain weight for the "cut tree" area was 35.7 g (20 m) and 34.2 g (2.5 m)(Figure 2.7 and Table B.1, Appendix B). These compared favorably to the 1000-grain weight for 20 m in blocks 1-4 (33.6 g). Under the trees at 2.5 m in blocks 1-4 the 1000-grain weight was only 30.9 g. This can be attributed to greater PAR in the "cut tree" area and at 20 m due to less tree shading in the two weeks leading up to maturity.

The literature does not mention any allelopathic properties of *Paulownia* to help explain the higher yield in the "cut tree" area at 20W relative to 2.5 m. There is no obvious explanation for the trend towards significance at 20W except some residual effect due to the tree that was impeding wheat growth. Thus, the tree's effect on the soils in this experiment was inconclusive and may have been minimized due to fertilizer application and irrigation.

2.5.4. Controls

2.5.4.1. Planting density. Two controls were harvested that were clear of the tree shade (and to the south). Although the cultivar sown was the same as that sown in the tree areas, the method of planting differed. Thus, the planting density was not comparable to the other yield plots. As Figure 2.7 and Table B.1, Appendix B shows, Control 1 averaged 669 ears m^{-2}, Control 2 averaged 520 ears m^{-2} and the tree area averaged 466 ears m^{-2}.

In addition to the different planter used in the controls, farmers in China often increase the seeding rate when they think it will be a dry year to compensate for fewer tillers. This may have been the intent of the farmers in the controls. They were not as closely involved in the research program, being from a different village, and did not have the same incentive to follow the research plan.

Another problem with Control 1, located only 20 m south of the tree rows, concerned the wind. As Sheikh and Chima (1976) noted, shelterbelts decrease the wind speed at distances up to 15 times the height of trees. Generally during the spring there was a prevailing southerly wind. However, as Table F.1, Appendix F shows, from late February through May there were about as many days with a northerly as a southerly wind. The trees may have provided a sheltering effect on Control 1. Control 2 was much further to the south (170 m) and did not experience the effects to the same degree.

Wheat development before anthesis using the Haun scale (Table E.1, Appendix E) showed no large differences between the controls and the other areas. The percent soil moisture (Table G.1, Appendix G) did start to show some differences just before anthesis (92115). On May 4th (92125) just after irrigation the soil moisture in the controls was 7% lower than the other areas. Towards the end of May as temperatures rose (92138) (Figure D.3, Appendix D) temperature differences leading to lower soil moisture in the controls (92141) resulted in an extra irrigation (92147) and harvest a couple days early.

2.5.4.2. Soils. Soil analyses on the controls showed that N levels were above the response level. Phosphorus in Control 2 for the 0-20 cm layer in February (92057) was 9.3 mg kg^{-1}. This could have been a factor contributing to increased yield. The controls were drier than the area with trees before anthesis and before harvest. Lower soil moisture signalled a possible positive response to P. Li and Xiao (1992) state that wheat yield does increase with addition of P when a P soil test ($NaHCO_3$) is below 16 mg kg^{-1} with dryland farming. Soil pH was in the 8.0 to 8.4 range as in other blocks and organic matter 1-2.1% for the upper 20 cm which was also comparable.

2.5.4.3. Yield. Because of the planting density difference, direct comparisons could not be made, however, a couple observations were noted. First, the total grain weight (Figure 2.7 and Table B.1, Appendix B) for Control 2 was 570 g m^{-2} with 520 ears m^{-2} versus 478 g m^{-2} with 467 ears m^{-2} at 20 m in the tree area. Within the experimental tree plots even the "cut tree" area yielded only 497 g m^{-2} with 482 ears m^{-2}. Considering that the distances less than 20 m in the tree area yielded less than yield at 20 m, the control area clearly outyielded the tree area on a per unit area basis. When converted to kg ha^{-1}, Control 1 yielded 6460 kg ha^{-1}, Control 2 had 5703 kg ha^{-1} and the tree area yielded 4610 kg ha^{-1} [47].

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[47]Assuming the tree row was at the center of the ha, tree rows were 60 m apart and the maximum yield for the area was realized at 20 m (ie. 30 m -- between rows -- yielded the same as 20 m).

Looking at the 1000-grain weights (Figure 2.7 and Table B.1 Appendix B), Control 2 was comparable to the 20 m yield plot 1000-grain weight of the tree area and the 1000-grain weight from the "cut tree" area (34.7 g versus 33.6 g and 34.9 g, respectively). Control 1 was only slightly higher at 36.5 g. This can be explained as the amount of unshaded PAR after anthesis in all areas was approximately equal.

In these comparisons with the controls it must be remembered that there is often error introduced when estimating yields from small yield plots. Casley and Kumar (1988) found up to 20% overestimates when converting 1-m^2 plots of rice into a per ha basis.

2.6. CONCLUSIONS

Several hypotheses were under investigation. Two of them dealt directly with PAR. With full grown 12 m *Paulownia* trees in a north-south row there was no difference in grain yield or kernel weight between the east side and the west side of the trees. However, there was a difference in grain yield that was under the tree compared to 20 m away from the tree line.

It is difficult to pinpoint in the wheat growth cycle exactly where, and how, PAR affects yield. This is due to compensatory responses in yield components that occur when growth at one stage is deficient. It is also due to the many environmental and cultural factors that occur during wheat development.

Several very important factors allowed for a compatible combination between wheat and *Paulownia* and helped to minimize the effect of tree shade on the wheat crop. These include: 1) tree form, 2) row orientation 3) row spacing and 4) phenological development. As this research illustrated, with a long clear bole the wheat under the trees was able to receive PAR in the morning and afternoon.

With trees having approximately 6 m of clear bole, overall wheat yield was higher with tree rows in a north-south direction. With the sun moving in an east-west plane, direct PAR reached all wheat at sometime during the day. If the trees were in an east-west row the north side would receive only very early morning or very late afternoon direct sun and only towards the end of the wheat growing cycle.

The spacing of the tree rows also determined how much daily shade affected wheat at different distances from the trees. The 60 m spacing between rows translated into limited shading time in plots away from the trees and into less shaded area on a per ha basis.

Paulownia is compatible with wheat development because the tree leaves emerge late in the wheat cycle. This ensures a minimum amount of shading from the tree leaves. The leaves began to emerge a little over 2 weeks before wheat anthesis. While the leaves seemed to have an effect, especially on the number of florets/spikelet, the total shade was less than other trees which usually leaf out earlier or that are allowed to retain long crowns to ground level.

It would be risky to draw conclusions from this research about wheat yield compared to areas without trees for several reasons. First, the different planting densities used in the controls made direct comparisons inappropriate. However, more importantly, in this research the intent was to isolate and study PAR by eliminating nutrient deficiencies and water stress. This reduces some of the major advantages of trees in rainfed systems. Yields are improved tremendously by planting *Paulownia* trees with wheat in areas that do not irrigate or fertilize which is the case for much of China.

Another consideration is the amount of PAR that was available during the 1992-1993 wheat-growing year. The plant requires PAR to develop and produce mature grains. Depending on many factors a decrease in PAR due to clouds and trees may be yield limiting where a sunny area with trees may not be limiting. As this was an atypical spring in China with many cloudy days, a further PAR decrease due to *Paulownia* tree shade may have caused abnormal results. Even though having trees with wheat as in this study may seem detrimental to yield under irrigated and fertilized agriculture, further studies should be conducted in a more typical year with a comparable control.

Another question that was posed was the effect of *Paulownia* trees on air temperature at different distances from the trees. Yield should not have been affected during the day due to the trees as there was less than 1.1^0 C difference in air temperature at any position from the trees at all hours of the day even with temperatures greater than 30^0 C. At night, after the tree leaves emerged, temperatures remained warmer (about 1^0 C) under the trees. This increased the number of degree days under the tree relative to away from the tree but not enough to surpass the total cumulative degree days away from the trees.

Soil moisture under the trees versus away from the trees in irrigated conditions was addressed. Rainfall was only 148 mm during the wheat growing time and the hot dry winds during May did not materialize. There was no difference in soil moisture between 2.5 m and 20 m and this was expected because of irrigation. The controls, however, were drier as temperatures rose just before harvest. Control areas were harvested 2-4 days earlier than the tree areas.

The last question concerned soils that had been influenced by *Paulownia* trees for 11 years. In these soils with trees removed, yield was lower than in soils 20 m away that had not been directly under the trees. Trees generally improve soil conditions unless there is some allelopathic effects which none are known for *Paulownia*. This research could not adequately address this apparent contradiction.

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CHAPTER 3

STUDYING INTERACTIONS UNDER *PAULOWNIA* TREES: A. WHEAT AND TREE ROOTS AND B. ORIENTATION AND THEIR EFFECT ON YIELD

ABSTRACT

A *Paulownia*-winter wheat intercropping experiment with a focus on photosynthetically active radiation (PAR) and root competition was conducted 60 km south of *Zhengzhou* (35^0 N 113^0 E), Henan Province, from September 1991 to July 1992 using a tree/crop interface approach. The middle row of three 240-m long rows of 11-year-old trees was studied for its effects on irrigated and fertilized winter wheat yield.

A series of experiments investigated the wheat and *Paulownia* root and PAR interactions under the trees. Plastic root barriers, 2 m long and 1 m deep, were placed between the tree and the winter wheat yield plots. Plots at 2.5 m that had root barriers were compared to those without using a split-plot design. Barriers had no effect on total grain weight (p=.7635) or 1000-grain weight (p=.8583). Concerning the underground component, *Paulownia* is clearly compatible with wheat in agroforestry intercropping, however, wheat grew better on the east side compared to the west as determined by total grain weight (p=.0190) and 1000-grain weight (p=.0154).

In an orientation experiment wheat yields on the north, east and west sides under the trees were compared. A difference was noted among the three directions for total grain weight (p=.0068). Contrasting directions E vs N and S, yield was significantly different for both total grain weight (p=.0026) and 1000-grain weight (p=.0246). PAR and other

environmental factors and their effects on winter wheat yield component development throughout the growing season are discussed.

3.1. INTRODUCTION

3.1.1. Tree and Root Competition

Buck (1986) puts forth the concept of pools of resources such as light, water, and nutrients that are shared by crops and trees in multi-cropping systems in the spatial and temporal dimensions. According to Connor (1983), light, water, and nutrients are the most important environmental factors for continual growth of the tree and crop. If these major factors are available in optimum amounts then the tree and crop have the potential to achieve maximum growth and yield. In discussing the tree and crop combination that is sought in agroforestry, Huxley (1985) refers to an associative ideotype. This is a tree and associated plant that should contribute to the fulfillment of the system's objectives and still maximize environmental resource use through sharing in both space and time.

Water and nutrients play major roles in growth and yield via plant root uptake. In an agroforestry system these resources have to be shared. If the agriculture crop is most important, management of the tree must be directed towards reducing the trees domination of water and nutrient resources. The ideal is to maximize the efficiency of water and nutrient resource use so that crop net primary production will not decrease when compared to the same crop not influenced by trees. In spatial terms, one method of enhancing resource sharing is to have the roots exploit different soil horizons. This further illustrates the importance of selecting compatible trees and crops.

Many studies have been conducted to assess yield differences due to roots in intercropping systems. Using two annual crops (pearl millet, *Pennisetum glaucum* (L) Br. and groundnut, *Arachis hypogaea, L.*) with root barriers placed between them, Willey and Reddy (1981) suggested any yield advantages were due to above ground interactions and not below ground. However, with root barriers between a tree row (*Leucaena*) and a millet crop in an alley cropping system in the semi-arid tropics of India, Corlett et al. (1989) attributed a reduction in yield to root competition for water. Singh et al. (1989) used root barriers in an alley cropping experiment also in semi-arid India and found the barriers eliminated yield reductions due to roots with a sorghum (*Sorghum bicolor Moench*) and *Leuceana* intercrop.

In sub-humid and droughty temperate regions of China, *Paulownia* roots were found to have a distinctive morphology with two defined root zones -- an upper zone (0-80 cm) and a lower zone (below 80 cm). In the top strata 98% of the absorbing roots were within a 4 m radius of the tree. Only 12% of these absorbing roots were in the upper 40 cm with 70%-85% located between 40 cm and 100 cm depths (Zhu et al., 1986). By contrast, in the *Paulownia*/winter wheat intercrop, nearly 80% of wheat roots occur in the top 40 cm indicating the roots occupy different zones.

For *Paulownia* the lower rhizosphere, which begins at 80-100 cm, is comprised of larger anchor roots and smaller feeder roots. Three to five anchor roots extend into the ground in a claw shape and penetrated into this lower horizon where they spread out as far as 29 m horizontally (Zhu et al., 1986).

3.1.2. Orientation

Trees interplanted with crops are often placed in linear rows, raising the question of optimal orientation. In some situations an east-west orientation might be more beneficial than north-south. This will depend on the type of tree, its age, crown shape, and length of clear bole. Depending on latitude, time of year and companion crop, shading may be beneficial or harmful. The underlying crop may also perform better in rows oriented in a certain direction.

In their work in Rwanda near the equator, Neumann and Pietrowicz (1989) found tree row orientation can have a significant effect on light penetration with strips of 8-year-old *Grevillea robusta* trees up to 15 m tall. Maize was planted in the strips with 10 m between tree rows. Performance was better when rows were oriented east-west.

Reifsnyder (1989), also working near the equator, demonstrated the east-west orientation to be more effective than a north-south orientation for solar radiation capture at the center of the tree rows. The emphasis here seemed to be with the tree rows being relatively close together.

As latitude increases, time of year becomes a factor. In a computer model calculating shadows cast on the ground from non-light transmitting hedgerows of various sizes and geometry, Jackson and Palmer (1989) showed that on June 21st at 30^0 North latitude, trees one-fourth as tall as the width of the alley, allowed a greater percentage of irradiance to the alley when they were oriented in an east-west direction compared to a north-south direction. However, in a north-south row orientation the daily pattern of radiation did not vary much with time of year.

In Henan Province, China, researchers at Henan Agricultural University (HAU -- 35^0 N 113^0 E) investigated the effects of both east-west and north-south tree row directions on winter wheat under field conditions. In the east-west tree rows the overall wheat yield was less than with north-south rows. A contributing factor was the 4-6 m clear bole on the 8 to 12-year-old *Paulownia* trees. Zhu (1990) confirmed this in his study of 9-year-old *Paulownia* trees at 5 x 40 m spacing.

Wheat row orientation may also have some bearing on yield. Three studies (Day et al., 1976; Erickson et al., 1979; and Kirkham, 1982) all state that wheat yields were higher when planted in east-west rows than north-south. However, ANOVA's were either not significant, not given, or "significant" at p=.1600.

An active, on-going research program with the tree *Paulownia* is located at HAU in *Zhengzhou*, Henan Province, PR

China. This research was conducted on farmer's fields in collaboration with HAU.

3.2. OBJECTIVES AND HYPOTHESES

3.2.1. Objectives

Based on literature indicating that *Paulownia* and wheat roots occupy different locations within the soil profile, they should be compatible in their exploitation of soil nutrients and water. An experiment was devised to test the effect of the *Paulownia* roots on the yield of wheat using plastic barriers to separate plant roots.

In a second experiment wheat yield was investigated under the tree canopy at different directions from the tree line. This experiment was conducted in conjunction with the distance experiment in Chapter 2 in which the directions east and west were not significantly different for total grain weight ($p=.3206$) or for 1000-grain weight ($p=.7153$). However, in that experiment the distance from the tree line included plots at 2.5, 5, 10 and 20 m. In this experiment a closer look is taken at the 2.5 m plots on the east and west sides and a third direction (north) between the trees at 2.5 m to determine the effect of PAR on wheat yield.

3.2.2. Hypotheses

Wheat yield under 11-year-old *Paulownia* trees in a north-south row is unaffected by root barriers.

Wheat yield under the tree canopy is unaffected by location (north, south, east, or west) relative to *Paulownia* trees in a north-south tree line.

3.3. METHODOLOGY

This was a subsidiary experiment to that described in Chapter 2 which focused on PAR. Fertilizer and irrigation were employed in an attempt to minimize any yield differences due to nutrient or soil moisture deficiencies. A thorough presentation on the cultural practices, experimental equipment, observations and measurements was presented in Chapter 2. This chapter, after explaining the field layout and experimental design, will discuss the experiment preparation and briefly summarize important sections from Chapter 2 as necessary.

3.3.1. Field Layout

The experimental fields were located adjacent to the village of *Shu Zhuang Cun* (Figure 2.1)(approximately 62 km south of *Zhengzhou*, Henan Provence). The large field south of the garden but closest to the village contained 3 rows of full grown 11-year-old *Paulownia* trees. The rows were about 240-m long and ran north-south. Two rows were to the west of the north-south one-lane road in the center of the figure and the other was to the east. The middle row of full grown trees contained the trees to be studied and the other two acted as guard rows. Yield plots were situated to the east and west of this middle row at 2.5 m and between trees in the tree line.

The 3 rows of full-grown trees had 5 m spacing between trees; the western row was 60 m and the eastern row was about 70 m from the center row. Irrigation channels are also indicated (Figure 2.1).

3.3.2. Experimental Design

3.3.2.1. Root barrier experiment. The primary factor under study was tree and wheat root competition. A randomized complete block design with 4 blocks was employed (Figure 3.1) on a north-south tree line. Blocks were selected to counter the effects from differences in cultural practices, soil conditions and tree size.

Within a block the trees were selected to be approximately the same size (height and crown diameter) and it was assumed that root development would correspond approximately to the crown. Four trees were selected for each block with no missing trees within the block. In three of the blocks the trees were in consecutive order. However, in block #3, 2 trees were deemed to have crowns too small to be used as selected trees. Therefore block #3 included a span of 6 trees and only 4 contained transects with yield plots. Each block also contained a guard tree on the north and the south end.

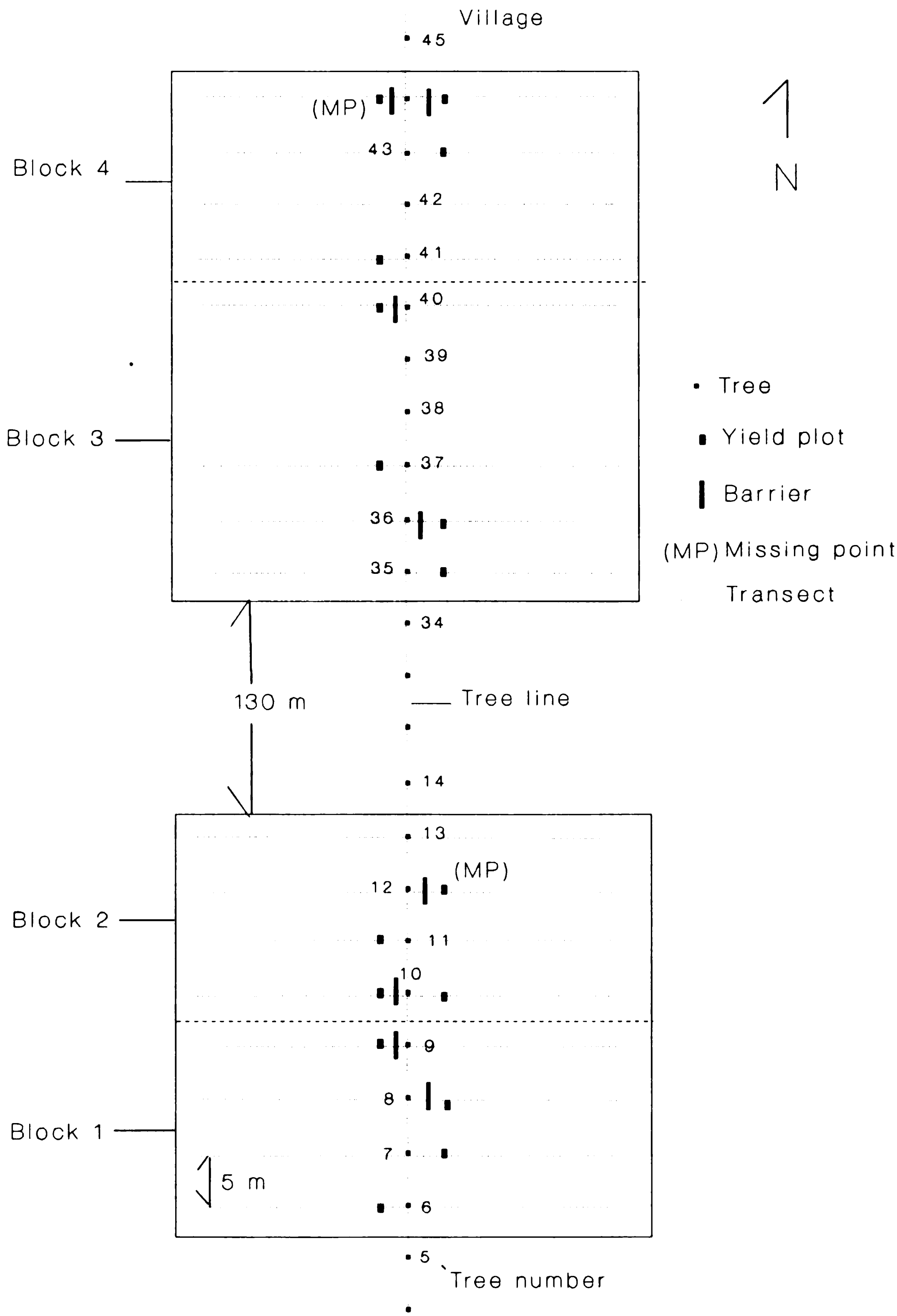

Figure 3.1. Root Barrier Experiment Plot Plan.

Sometimes the guard tree was one of the selected trees in the adjoining block. Two blocks were located in the northern end of the tree row and 2 blocks in the southern end.

This was a multifactorial experiment with barrier (B) and no barrier (NB) treatments and 2 direction treatments (east and west) replicated 4 times. Yield plots were randomly located on transects perpendicular to the north-south tree line at each select tree. In each block the barrier (B) treatment was randomly assigned to a transect on the east side and the west side of the tree line. Afterward the NB treatment was determined from the remaining 3 transects for each direction. Each yield plot consisted of 3 quadrats (sub-samples) each measuring 1 m x 3 rows with rows 20 cm apart.

A split plot design was employed using the model:

$$Y_{ijk} = Y_{..} + M_j + B_i + \alpha_{ij} + S_k + I_{jk} + \epsilon_{ijk}$$

where M = Main plot treatment (Direction)
B = Block
α = Main plot error
S = Subplot treatment (B vs NB)
I = Interaction term
ϵ = Subplot error

The main plot treatments (the directions east and west) were not randomly chosen due to the fixed nature of their positions, however, it was assumed this model would still be valid. The subplot treatments consisted of barrier and no barrier plots at 2.5 m from the tree line with 2 missing points (see partial ANOVA Table 3.1 below).

Table 3.1. Partial ANOVA--Root Barrier Experiment.

Source	df
Block	3
Direction	1
Error a	3
B vs NB	1
(B vs NB) x Direction	1
Error b	4
Total	13

3.3.2.2. Orientation experiment. This was a single factor experiment with 3 direction treatments (east, west and north) replicated 4 times (Figure 3.2). A randomized complete block design was used with the model:

$$Y_{ij} = Y_{..} + T_i + B_j + \epsilon_{ij}$$

where T = treatment
B = block
ϵ = error term

Blocks were selected as in the root barrier experiment.

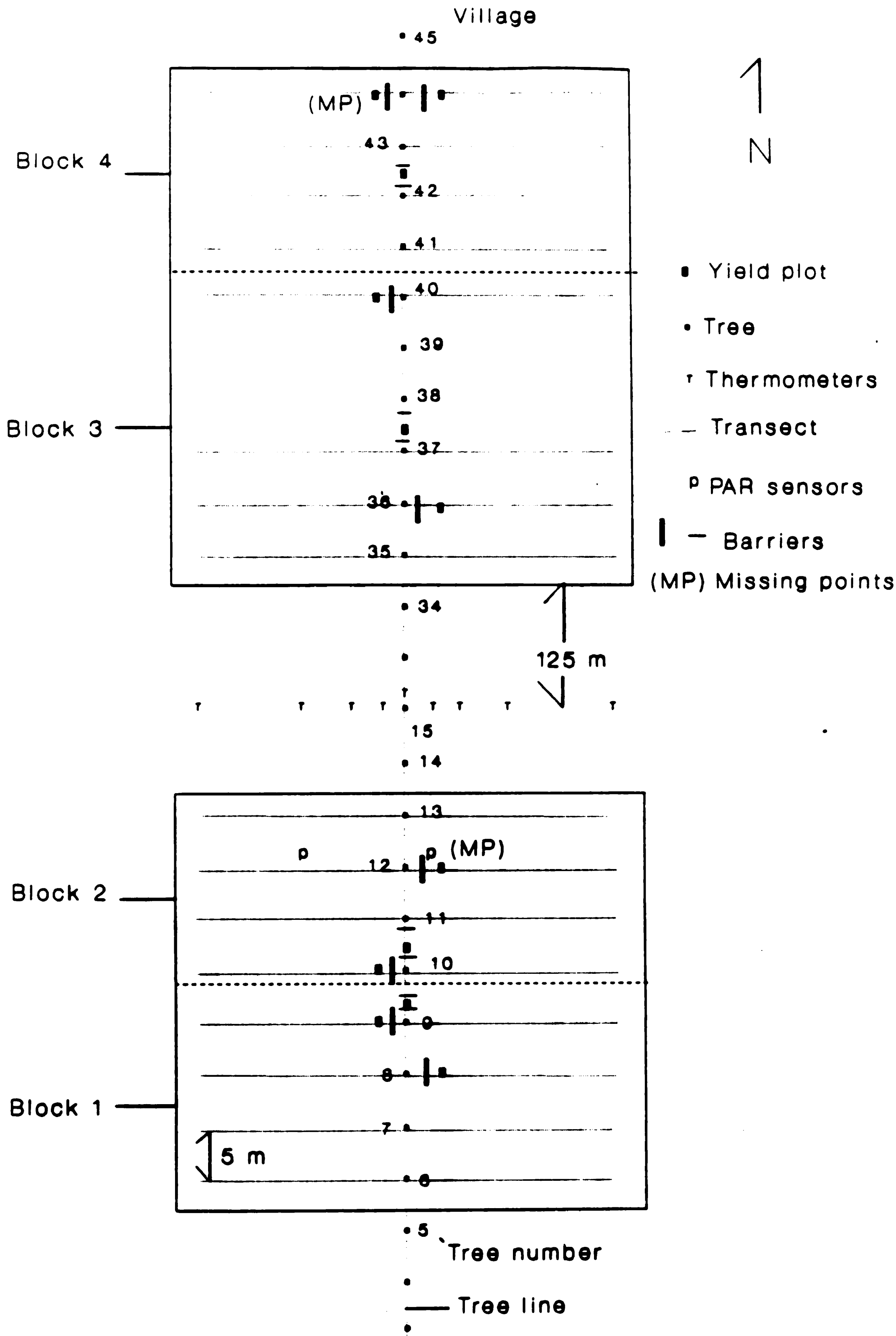

Figure 3.2. Orientation Experiment Plot Plan.

Plots were randomly situated to the north, east, and west of a tree at 2.5 m. All yield plots had barriers to a 1 m depth placed between the tree and the wheat. The plot located to the north of a select tree had barriers on both its north and south sides as there were trees in each direction and there were two missing plots (see partial ANOVA Table 3.2 below).

Table 3.2. Partial ANOVA--Orientation Experiment.

Source	df
Block	3
Direction	2
Error	4
Total	9

3.3.3. Field History and Cultural Practices

In these experiments the entire area had been previously planted with wheat followed by corn and beans. The yield plots were clustered about the tree base at 2.5 m east, west and north. Cultural practices, as detailed in Chapter 2 (composting, plowing, fertilizing, irrigating, treating wheat seeds, planting, collecting litter, weeding and planting the sequential crop) were identical on the east, west and north sides of the trees.

3.3.4. Experiment Preparation

In preparation for this experiment, 2 operations were performed on selected trees -- branch pruning and root barrier insertion.

3.3.4.1. Branch pruning. The trees under investigation were *Yu Xuan Yi Hao* (open pollinated *P. fortunei*). This tree was somewhat susceptible to witches broom disease (*Mycoplasma* like organisms, MLO). Witches broom was pruned to achieve the leaf canopy density and typical morphology of *Yu Xuan Yi Hao*. When pruned of witches broom, *Yu Xuan Yi Hao* would resemble the degree of shading of the *Yu Za Yi Hao* hybrid (*P. fortunei* x *P. tomentosa*) the current choice of farmers.

3.3.4.2. Root barriers. Plastic was used as a barrier to separate *Paulownia* roots from wheat roots to eliminate competition for nutrients and water. Barriers were put in place on September 29, 1991 (91272) after plowing, but before planting. Trees were selected in each block using a random number table for 2.5E, 2.5W and 2.5N treatments. Trenches 1 m deep x 50 cm wide were dug at a distance of 1 m from the tree on the east side or west side depending on the 2.5 m yield plot location. Several trees had large roots severed so that the plastic could be inserted.

For the 2.5E and 2.5W plots the 2 m long barrier was inserted parallel to the tree line. About a half meter on each end was angled towards the yield plot. When the trench was being dug care was taken to heap the soil on the tree side of the trench so that the yield quadrat did not have soil mixed from lower depths. Clear plastic, 0.12 mm (+/- 0.02) thick, was inserted in the trench and the soil filled in so that the plastic did not slip to the bottom of the trench. The same procedure was followed for the 2.5N plots except that barriers were positioned perpendicular to the tree line to the north and south of the plot.

3.3.5. Equipment, Observations and Measurements

Distinctive phenological growth intervals for the wheat and tree were established to facilitate analysis. PAR data was collected with two LI-COR quantum sensors and a data logger. Measurements for this experiment were also obtained for soil moisture and soil nutrients using soil cores. Thermometers were used for air temperature and soil temperature. Observations included use of the Haun scale for wheat development and yield plot observations for pests, diseases or other abnormalities. At harvest ears per plot, total grain weight, and 1000-grain weight were measured (see Chapter 2 for details).

3.3.5.1. Growth intervals. A total of 6 growth intervals (Table 2.4) were established for this experiment (Figure 1.10). Where possible the intervals coincided with tree or wheat phenological events.

3.3.5.2. PAR. Two LI-COR ES 220 quantum sensors were placed on stands 80 cm above the ground just above the height of the mature wheat plant. The sensors recorded PAR at specified time intervals in μmoles m^{-2} s^{-1} between March 11, 1992 (92071) and June 4, 1992 (92156). A 2-channel data logger with a data storage module (DSM) continuously recorded PAR readings at specified time intervals.

Two data recording/positioning schemes were established. In Scheme I sensors were positioned at 2.5E (under the tree) and 10W (outside of the crown). Each sensor took two instantaneous readings at 5 minute intervals and an average of the two readings was recorded and stored in the DSM every 10 minutes. In Scheme II once a week the sensors were set at reading and recording intervals of 1 minute. During the course of the day the sensors were repositioned so that one was in the sun as a control and the other was in the tree shade at 2.5E, 2.5W, or 2.5N.

There were 2 data storage modules that were downloaded regularly. Using a Zenith SupersPort 286 Portable Computer, data was downloaded from the DSM onto a diskette using Bitcom software program and stored. Afterward the DSM was inserted into an Eprom erasing ultraviolet lamp (Spectroline PE-140T/F), erased and reinserted into the data pod for further data collection.

3.3.5.3. Soil moisture. Soil cores were taken to determine soil moisture approximately each week after March 25th (92085). A soil auger was used to extract the soil in the top 20 cm at 2.5E, 2.5W and 2.5N for each block.

3.3.5.4. Soil samples. Soil samples were taken before wheat planting, before regrowth in the Spring, and after wheat harvest. Four different analyses were made from each sample -- pH, soil organic matter, available N, and available P. Samples were taken at two depths -- surface to 20 cm corresponding to the plow layer and 21 to 40 cm for each direction and each block. Each soil sample, a composite of 5 thoroughly mixed soil cores, was analyzed in the Henan Agricultural University soil laboratory.

3.3.5.5. Air temperature. A dry bulb thermometer, located inside meteorological stands, measured the air temperature at a height of 1.5 m. Farmers were hired to read the thermometers each day from October 28, 1991 (91301) through to June 4, 1992 (92156) at 08:00, 14:00, and 20:00 hours. Temperatures were recorded in a log book for the 20W (away from the trees) and 2.5E positions (under the trees). Measurements were also taken hourly on selected dates approximately weekly after April 16th (92107) until harvest (92156).

3.3.5.6. Soil temperature. Huxley (1983) stated that standard depths for soil temperature measurements were 5, 10, 20, 50, and 100 cm, however, equipment restrictions only allowed readings at the surface and at depths of 5, 10, 15, and 20 cm. From March 26th (92086) to harvest (92156), soil temperatures at 5, 10, 15, and 20 cm for 20W and 2.5E at 08:00, 14:00, and 20:00 were recorded daily (from May 21st (92142) onward surface temperature was also recorded).

Thermometers were first placed along the transect perpendicular to tree 12 (Figure 2.2) where the light sensor posts were located. In mid-April, due to trampling of the wheat around the thermometers, they were moved to tree 15 and placed inside the wheat for the April 23rd (92114) reading. They remained in these positions until after harvest. Also beginning on April 23rd (92114) on a weekly basis, hourly readings were recorded until harvest (92156) at each yield plot position. While temperatures may not be very accurate due to instrumentation they should be precise enough to give a reasonable comparison between 2.5E, 2.5W and 2.5N.

3.3.5.7. Haun scale. The Haun scale was developed by J.R. Haun (1973) to provide a continuous number scale for monitoring winter wheat according to its phenological and morphological development (Figure 1.10). On March 25th (92085) the first Haun scale observation was made and records were kept weekly through April 27th (92118) when flowering began. The Haun scale was used to determine if wheat in one block was developing faster than another or if wheat on the east side was developing faster than the west or the north within the same block. Details were presented in Chapter 2.

3.3.5.8. Yield plot observations. After planting and during the growing season the plot locations were monitored to determine if there were any abnormal growth patterns or problems. From time to time events occurred that could have affected the yield. If there was any experimenter caused damage or if there was a disease infested area, these locations would not be used for yield sampling, rather an area as close as possible that was not damaged would be selected.

3.3.5.9. Pests and diseases. Two problems, aphids and a fungus, were noted. On about April 10th (92101) some farmers began spraying their crop to combat a wheat aphid. Farmers surveyed their own crop and decided if they needed to spray. For the aphid problem the tell-tale sign was a wilting flagleaf. The other problem that occurred on the research site was a white powdery mildew (*Erysiphe graminis* DC) called *Bai Fen Bing* (白粉病) or "white powder sickness". To treat both problems a backpack sprayer was used.

3.3.5.10. Harvest -- ears, total grain weight, 1000-grain weight. On the morning of June 3rd (92155) Block 4 nearest the village (Figure 3.1) was harvested. In the afternoon Block 3 and most of Block 1 were harvested. Harvest was completed the morning of June 4th (92156) with the remainder of Block 1 and Block 2 being cut.

Each harvest quadrat was 0.6-m^2 with buffer rows on each side. It was also decided that 3 yield samples (quadrats) should be taken at each yield position (yield plot). The actual quadrat position could be selected to the north or south of the east-west transect if abnormal growing conditions required (east or west for the plots at 2.5N). However, where root barriers had been placed in the soil, movement was restricted to an area still protected by the barrier.

Measurements were made for 1000-grain weight, total grain weight per quadrat, and the number of ears per quadrat. Biomass was not calculated. Further discussion on cleaning and scaling the wheat and a more comprehensive explanation in all aspects of the methodology can be found in Chapter 2.

3.4. RESULTS

An analysis of variance (ANOVA) was employed for the root barrier and the orientation experiments with further partitioning of treatments using orthogonal contrasts[48]. In addition a simple correlation was run on total grain weight and 1000-grain weight.

3.4.1. ANOVA for Root Barrier Experiment

There were two missing points and these were calculated with loss of two degrees of freedom (Snedecor and Cochran, 1967). As shown in the ANOVA (Table 3.3)[49], there was no interaction between the direction and treatment for total grain weight (p=.2602) or 1000-grain weight (p=.5774). No significant difference was found in treatment (B vs NB) either for total grain weight (p=.7635) or 1000-grain weight (p=.8583). However, there was a significant increase in yield

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[48]The analysis of variance assumed a fixed effects model with random error components. For the split plot two error components were identified and when one was considered random the other was assumed fixed. All models assumed that the error terms were independently and normally distributed with a mean of zero and a common variance. In addition it was assumed that the mean was additive. These assumptions were tested in each experiment and the results by test are located in Table A.1, Appendix A. All tests rejected the null hypothesis if $p > .05$. For each experiment the assumptions were not seriously violated to the degree that they invalidated the analysis of variance test.

[49]All tables and figures and discussion have data adjusted from yield per 0.6-m^2 (a quadrat) to yield per m^2.

with direction for total grain weight ($p=.0190$) and for 1000-grain weight ($p=.0154$).

The simple correlation for total grain weight and 1000-grain weight was $\rho = .4898$. Means and standard errors are shown in Figure 3.3 and tabulated in Table B.3, Appendix B for ears m^{-2}, total grain weight ($g\ m^{-2}$) and 1000-grain weight (g).

Table 3.3. ANOVA--Root Barrier Experiment--TGW, 1000-GW.

Total Grain Weight (TGW)						
Source	df	SS	MS	F	p	Signif
Block	3	5,988				
Direction	1	7,928	7928	21.38	.0190	*
error a	3	1,112	371			
B vs NB	1	168	168	.104	.7635	NS
Dir x (B vs NB)	1	2,778	2778	1.718	.2602	NS
error b	4	6,469	1617			
Total	13	24,444				

1000-Grain Weight (1000-GW)						
Source	df	SS	MS	F	p	Signif
Block	3	37.55				
Direction	1	44.22	44.22	24.97	.0154	*
error a	3	5.31	1.77			
B vs NB	1	.30	.30	.036	.8583	NS
Dir x (B vs NB)	1	3.06	3.06	.367	.5774	NS
error b	4	33.38	8.35			
Total	13	123.84				

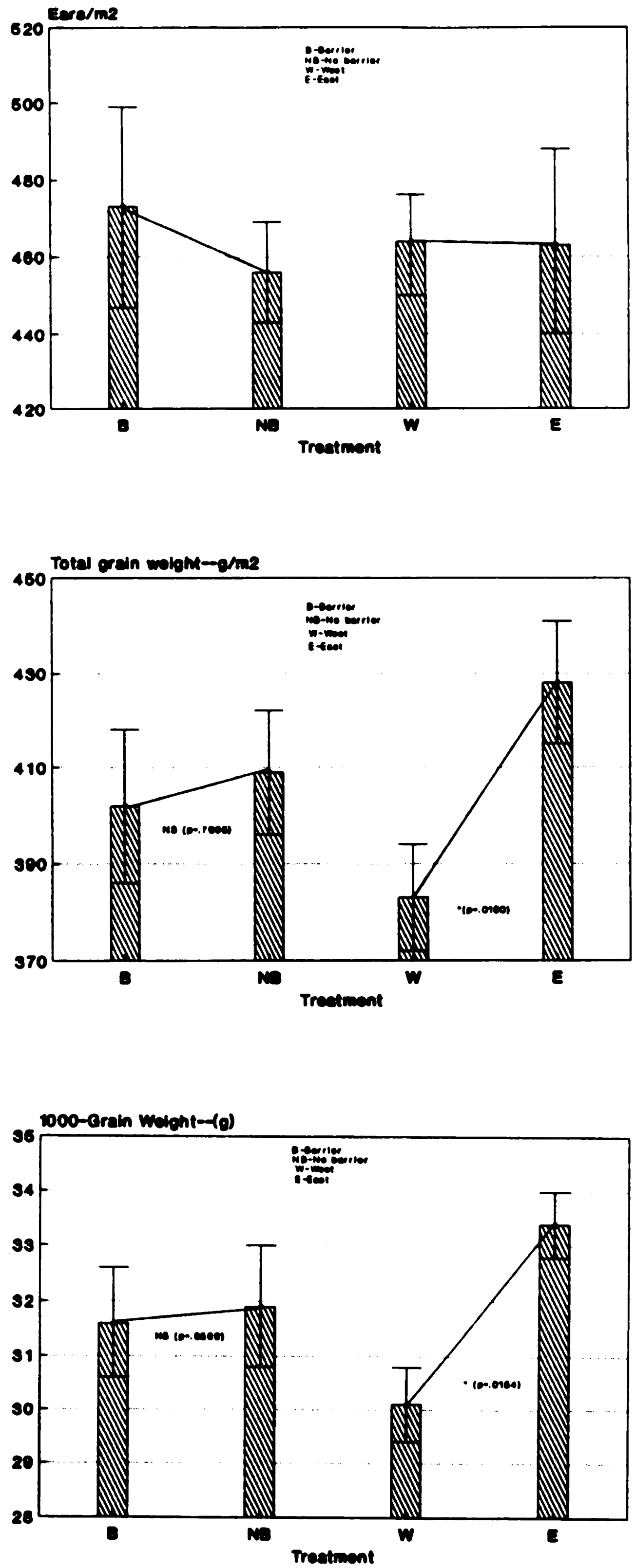

Figure 3.3. Means--Root Barrier Experiment.

3.4.2. ANOVA for Orientation Experiment

There were two missing points and these were calculated with loss of two degrees of freedom (Snedecor and Cochran, 1967). As shown in the ANOVA (Table 3.4), there was a significant difference among the 3 directions for total grain weight ($p=.0068$). Contrasting directions E vs N and W, yield was significantly different for both total grain weight ($p=.0026$) and 1000-grain weight ($p=.0246$). The simple correlation for total grain weight and 1000-grain weight was $\rho = .8045$. Means and standard errors are shown in Figure 3.4. and listed in Table B.4, Appendix B for ears m^{-2}, total grain weight (g m^{-2}) and 1000-grain weight (g).

Table 3.4. ANOVA--Orientation Experiment--TGW, 1000-GW.

Total Grain Weight (TGW)						
Source	df	SS	MS	F	p	Signif
Block	3	4,979				
Direction	2	14,512	7256	22.33	.0068	**
E vs (N &W)	1	14,494	14494	44.60	.0026	**
Residual	1	18	18	.06	.8261	NS
error	4	1,300	325			
Total	9	20,791				

1000 Grain Weight (1000-GW)						
Source	df	SS	MS	F	p	Signif
Block	3	11.57				
Direction	2	27.55	13.78	6.186	.0597	NS
E vs (N & W)	1	27.52	27.52	12.341	.0246	*
Residual	1	.03	.03	.013	.9147	NS
error	4	8.91	2.23			
Total	9	48.03				

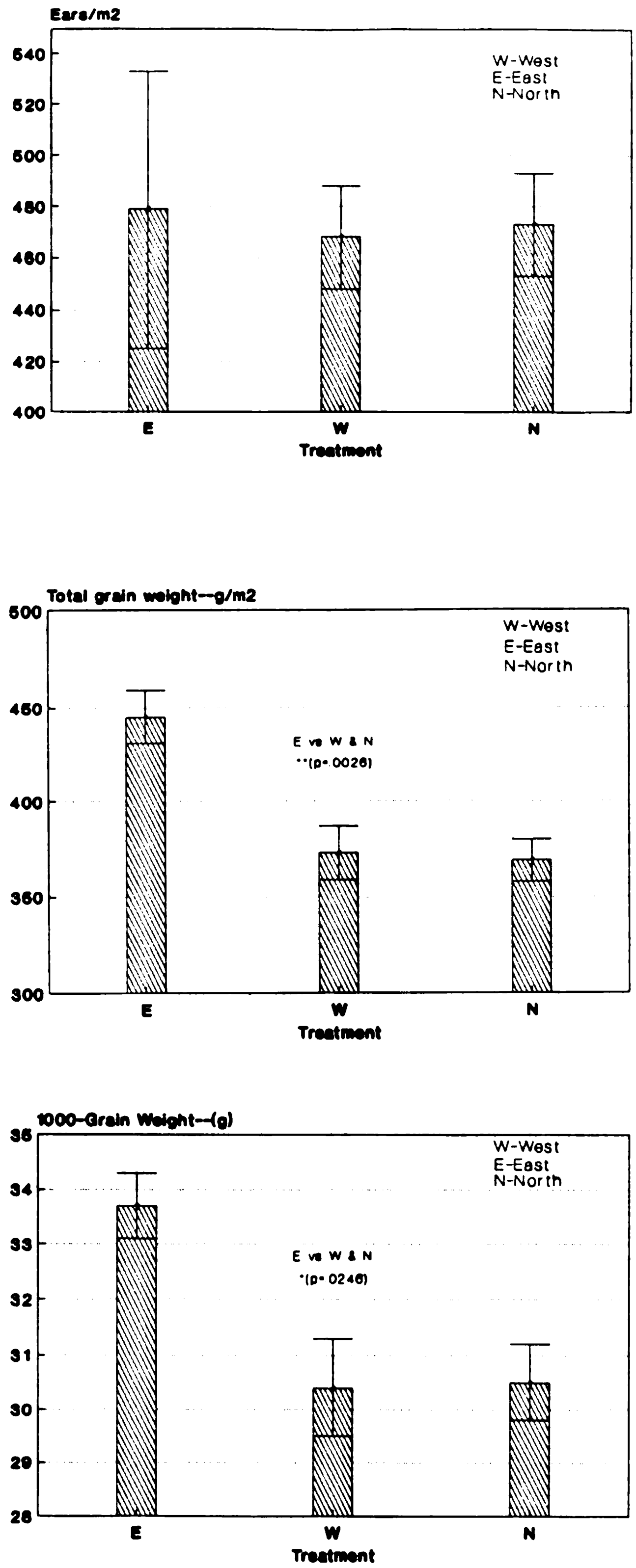

Figure 3.4. Means--Orientation Experiment.

3.4.3. PAR

As the season progressed shade times at each distance and for each day increased. Generally the 1991-1992 wheat season was atypical with many cloudy days (Fig 2.10). Figure 2.8 also illustrates this, showing the average daily unshaded PAR by interval in relation to the theoretical maximum.

Results reflecting the percent of tree shaded versus unshaded PAR per yield plot as the season progressed (Scheme II[50] from Chapter 2) is shown in Figure 2.11. Figure 2.11 was developed by averaging two clear days within intervals 2, 3, and 5 (Table 2.4) and using 1 clear day for interval 6. A clear day for interval 4 was not available. Once the leaves emerged (92104) the tree shaded PAR increased until the leaves were at their maximum size on approximately May 20th (92141). The large gap between intervals 3 and 5 (Figure 2.11) was due to leaves growing quickly but cloudy conditions preventing PAR measurement. A summary by date and interval for 2.5E and 2.5W of 1) the average full sun PAR 2) PAR under tree shade in μmoles m^{-2} s^{-1} and 3) the percent PAR under tree shade is shown in Table 3.5 along with wind speed and direction.

[50]In scheme 2 sensors were set at reading and recording intervals of 1 minute and repositioned during the day so that one was in the tree shade at 2.5E, 2.5W, or 2.5N and the other was in full sun.

Table 3.5. Full Sun vs Tree Shaded PAR.

Julian Date	Day	Interval	Time of Reading	Total Time (min)	Position	Full Sun[a] ave umole m^{-2} s^{-1}	Tree shaded ave umole m^{-2} s^{-1}	% PAR under tree shade	Wind Dir /Speed (m/s)
92088	Mar 28	2	1103-1200	57	2.5W	1453	1259	86.7	S/.8
			1301-1400	59	2.5E	1557	1304	83.8	
92094	Apr 3	2	1101-1200	59	2.5W	1512	1302	86.1	S/2.5
			1301-1400	59	2.5E	1456	1251	85.9	
92107	Apr 16	3	1057-1155	58	2.5W	1530	1302	85.1	SSW/3.
			1234-1331	57	2.5E	1545	1395	90.3	
92114	Apr 23	3	1046-1145	59	2.5W	1615	1177	72.9	SW/2.5
			1234-1331	58	2.5E	1534	1331	86.8	
92141	May 20	5	1031-1130	59	2.5W	1691	296	17.5	W/1.3
			1231-1330	59	2.5E	1760	422	24.0	
92148	May 27	5	1031-1130	59	2.5W	1727	338	19.6	S/.8
			1301-1400	59	2.5E	1740	263	15.1	
92156	Jun 4	6	1032-1130	58	2.5W	1418	227	16.0	SE/1.8
			1305-1359	55	2.5E	1683	340	20.2	

[a] Full sun plus sky for midsummer about 41^0N = 2000 μmoles m^{-2} s^{-1}.

3.4.4. Soil Moisture

As noted by Wei (1979) the soils in this general area were 0-25 cm-silt loam; 25-50 cm-silty clay loam which conformed to on site estimates. In Table G.4, Appendix G, soil moisture means at 2.5E, 2.5W and 2.5N along with their ANOVA p values are shown for blocks 1-4 from March 11th (92071) to harvest (92154). On April 24th (92115) just before anthesis began (92118) there was a significant difference in soil moisture (p=.0248). Table G.5 and G.6, Appendix G, show the ANOVA and Scheffe's test, respectfully, on 92115 with soil moisture in plots at 2.5E significantly less than 2.5N and 2.5W.

3.4.5. Soil Samples

Nitrogen levels in all blocks were well above response levels (see Chapter 2 for further discussion) with an ANOVA for the February sampling showing no significant differences between 2.5E, 2.5W and 2.5N for 0-20 cm (p=.2454) and 21-40 cm (p=.9714)(Table H.7, Appendix H). ANOVA's for soil organic matter showed no significant difference in either layer (p=.5021 and p=.5732 for the upper and lower layers, respectfully)(Table H.7, Appendix H). Soil pH did show a significant difference (p=.0209) in the 0-20 cm layer (Table H.8, Appendix H) with Scheffe's test showing 2.5W significantly higher than 2.5E but not 2.5N (Table H.9, Appendix H). The 21-40 cm pH level was not significantly different (p=.2618).

The P ANOVA for the February sampling (92057) was significant (p=.0218) for the 0-20 cm layer (Table H.10, Appendix H). Scheffe's test at α = .05 showed P significantly greater on the west side compared to the east but not the north (Table H.11, Appendix H). However, the 21-40 cm layer was not significantly different (p=.4440)(Table H.7, Appendix H). Table H.12, Appendix H, shows the P levels for each block.

3.4.6. Air Temperature

Air temperatures at 1.5 m above the ground were compared at 2.5E, 2.5W and 2.5N. Results showed virtually no difference with the mean air temperatures in each location over the course of a day through to harvest (92156) whether shaded or unshaded, differing less than 0.6^0 C. While recording days were not always clear-sky days, temperatures did climb as high as 32^0 C.

3.4.7. Soil Temperature

As expected, morning temperatures were warmer on the north and east sides with maximum differences for surface, 5 cm and 10 cm of 3.5^0 C at 12:00 on April 23rd, 2.1^0 C at 11:00 on May 21st, and 0.9^0 C at 12:00 on April 23rd, respectively (Table J.1, Appendix J). The afternoon temperatures were warmer on the west and north sides with maximum surface, 5 cm and 10 cm differences of 5^0 C at 15:00, 3^0 C at 16:00, and 1^0 C at 17:00, respectively, on May 27th. A daily maximum air temperature of about 31^0 C was reached on May 27th.

3.4.8. Tree Measurements

Block means for tree height, clear bole, diameter at 1.5 m and crown diameter are shown in Table I.1, Appendix I. During the course of the experiment, September 1991 to June 1992, average tree height was 12.8 m; the diameter at 1.5 m was 32.0 cm; the average bole length measured 5.9 m; and the crown diameter had an average 9.2 m east-west span (Table I.2, Appendix I).

3.4.9. Haun Scale

No differences were noted in wheat development using the Haun scale up to anthesis by block (Table E.1, Appendix E) or by yield position (Table E.2, Appendix E).

3.5. DISCUSSION

The experiments were designed to 1) investigate the relationship between *Paulownia* tree roots and winter wheat roots as they affect wheat yield and 2) determine if PAR had an effect on wheat yield at different orientations from the trees. All plots were located directly under the trees at 2.5 m.

3.5.1. Root Barriers

The ANOVA revealed no significant difference between plots with or without barriers for total grain weight ($p=.2602$) and 1000-grain weight ($p=.8583$)(Table 3.3). Thus, inclusion of root barriers to prevent underground competition for nutrients and water between *Paulownia* and wheat roots showed that the tree and wheat crop are compatible. This supports the morphological studies completed in China (Zhu et al., 1986; Zhu, 1990; Jiang, 1990) and the thesis that *Paulownia* root morphology makes it an excellent species for a winter wheat-agroforestry system.

3.5.2. Direction

In the root barrier experiment direction -- east or west of the tree line -- was significant (p=.0190 for total grain weight and p=.0154 for 1000-grain weight)(Table 3.3) with the east side outyielding the west (Table B.3, Appendix B). In the distance experiment from Chapter 2, direction east or west was not significant when treatments were 2.5, 5, 10, and 20 m. Investigating this more closely with just the 2.5 m plots under the tree the result is significant. The above discussion indicates that the tree roots did not play a major role in wheat yield difference between 2.5E and 2.5W yield plots. Further investigation of direction was conducted in the orientation experiment.

3.5.3. Orientation

In this subsidiary experiment a closer look was taken at the area under the trees at 3 directions (north, east and west) all at 2.5 m from the tree. There was a yield difference (p=.0068) for total grain weight and for 1000-grain weight when contrasting east versus north and west (p=.0246)(Table 3.4) with wheat yield on the east side greater than the west and north sides (Table B.4, Appendix B). This can be largely attributed to above ground factors as no underground competition for water and nutrients was detected between barrier plots and non-barrier plots at 2.5E and 2.5W. To help understand the reason for an increase in yield on the east versus the north and west sides, environmental factors are considered as they affect total grain weight before and after anthesis and 1000-grain weight after anthesis.

3.5.3.1. Pre-anthesis -- total grain weight

Total grain weight is influenced by changing environmental factors that occur throughout wheat phenological development. Before anthesis, intervals 2 and 3 (Table 2.4), the number of grains per ear (when the spikelets/ear and florets/spikelet are developing -- Figure 1.8 and 1.10) are determined. The difference in total grain weight from 2.5 m to 20 m was attributed to greater shading under the trees in interval 3 when the florets/spikelet were developing (see Chapter 2 for discussion). At this time, tree leaves were expanding rapidly, shading 2.5 m plots, in contrast to plots less influenced by tree shade (at 5, 10, and 20 m).

However, in the orientation and root barrier experiments, plots at 2.5 m east had a significantly greater total grain weight yield compared to plots at 2.5 m west and north. Several factors at each location were compared during intervals 2 and 3 to discern possible reasons for a difference including soil moisture, air temperatures, soil temperatures, soil nutrients and PAR.

3.5.3.1.1. Soil moisture. Soil moisture prior to anthesis (92115) reached a low of 4.3% for 2.5E while the 2.5W and 2.5N plots were at 5.1% (Table G.4, Appendix G). The ANOVA was significant (p=.0248) with 2.5E plots lower than 2.5W and 2.5N (Scheffe's test $\alpha = .05$ -- Table G.6, Appendix G). The moister soils should have favored 2.5W and 2.5N causing less stress on the wheat. However, Li and Xiao (1992) point out that in these silty soils, moisture in the top 0-10 cm can be lower than the wilting point while deeper layers can have 14%-16% moisture by dry weight, thus minimizing soil moisture effects. Soil moisture also plays a role with P as will be discussed later.

3.5.3.1.2. Air temperature. Air temperatures during intervals 2 and 3 differed by less than 0.5^0 C among the three directions during the course of a day. Temperature maximums were about 28^0 C with only 6 days above 25^0 C (Figure D.3, Appendix D) -- slightly above wheats optimal net photosynthesis range (10^0-25^0 C) (Evans et al., 1980). By itself this should have caused only minor differences among the direction treatments.

3.5.3.1.3. Soil temperature. Soil temperatures on April 23rd (92114) and April 29th (92120) (Table J.1, Appendix J) during interval 3, differed by 3.5^0 C in the morning with 2.5W being the coolest and 3.3^0 C in the afternoon with 2.5E being the coolest. At a 5 cm depth, differences were less than 2^0 C and at 10 cm less than 1^0 C. These differences may have indicated differences between treatments. Even though air temperatures were only slightly above the ideal for wheat net photosynthesis, in combination with the 5% soil moisture conditions there may have been greater stress on the wheat at 2.5W in the afternoon. With warmer surface temperatures and dry conditions the wheat at 2.5W may have stopped photosynthesizing via stomatal closure to retard evapotranspiration, while at 2.5E, with cooler temperatures it was able to fix CO_2 for longer periods. However, the extent of differences would depend on the time under the dry conditions and warm temperatures in interval 3 which was not great (see Chapter 2).

3.5.3.1.4. Soil nutrients. The research plan was to fertilize the fields so that soil nutrients would not be limiting. As explained in Chapter 2, this was the case for N. ANOVA's for directions north, east, and west, for organic matter were not significant and were in agreement with the typical soils for this general area (1.77%) for both 0-20 cm and 21-40 cm levels (Table H.7, Appendix H).

Soil pH was higher in the 0-20 cm layer on the west side (p=.0209, Table H.7 and H.8, Appendix H) compared to the east but not the north (Scheffe's test α = .05) (Table H.9, Appendix H). Since these were calcareous soils a pH increase of 8.2 to 8.6 would have the effect of making P less available at higher pH's.

Phosphorus was different (p=.0218) with 2.5W and 2.5N receiving higher P levels (Tables H.10, H.11, and H.12,

Appendix H). Li and Xiao (1992) working in China, state that dryland wheat will experience a yield increase with addition of P when P-soil tests ($NaHCO_3$) are less than 16 mg kg^{-1}. However, Matar et al. (1992) working with wheat found that P-soil tests of 4 to 5 mg kg^{-1} ($NaHCO_3$) had no response to fertilizer in wet years. Table H.12, Appendix H, shows the lowest P soil test at 4.0 mg kg^{-1}. Since this research site was irrigated, the difference in P should have had a minimal effect on yield.

As pointed out in Chapter 2, P needs are greatest from the inboot stage to the milk stage (intervals 3 and 4, Figure 1.10). The inboot stage which is shown in Table E.2, Appendix E, as 18 -- the Haun rating of enlargement -- began on about April 15th (Figure 1.10). The Haun ratings also showed no difference in wheat development between the east, west and north sides through anthesis (Table E.2, Appendix E). During the dry spell leading up to April 24th (92115)(Table G.1, Appendix G) there may have been a response to P. If this were the case 2.5W would have benefitted, but only to the degree that P was not limited by the higher soil pH at 2.5W. However, yield was greater at 2.5E and this difference may have been ameliorated by any response to P in interval 3.

Thus, soil moisture, soil nutrients and soil temperature may have had a counterbalancing effect on yield component development (spikelets/ear and florets/spikelet) in intervals 2 or 3 while air temperature had no effect. Soil moisture should have aided 2.5W more than 2.5E if it was a factor. Soil P during dry conditions may be important and this too would have a more positive effect on 2.5W over 2.5E. Soil temperature, however, indicated a possible advantage at 2.5E as these plots with cooler temperatures might have been able to fix CO_2 longer than 2.5W during the warmer afternoon hours.

3.5.3.1.5. PAR. Figures 2.8, 2.9 and 2.11 present PAR levels during intervals 2 and 3. Figure 2.11 shows a dip at 2.5N due to trunk shade during the monitoring time. During their shaded time 2.5E and 2.5W received at least 72% of the PAR that unshaded plots received. Comparing 2.5E and 2.5W in interval 2 for 2 clear days, the average percent of tree shaded PAR in 2.5W was 1.7% greater than 2.5E (86.5% to 84.8%) (Table 3.5) where daily PAR averaged 21.3 moles m^{-2} (Figure 2.8). In Table 3.5 (data from Scheme II) looking at 2 days within this interval (92088 and 92094) there is a relatively small difference in μmoles m^{-2} s^{-1} under tree shade suggesting no PAR differences between east and west during interval 2. Shading at this stage was primarily from tree branches and twigs. Differences may have occurred due to crown symmetry or branch density in relation to the stationary and non-integrating PAR sensors.

In interval 3 (92107 and 92114) (Table 3.5) the percent of tree shaded PAR was greater in 2.5E than in 2.5W by an average of 9.5% (88.5% to 79.0%) with an average of 35.4 moles m^{-2} day^{-1} (Figure 2.8). During this interval the leaves were growing and tree shade was increasing. Percent PAR under tree shade was greater at 2.5E for April 16th (92107) and April 23rd (92114) (Table 3.5). A closer look at April 23rd (92114) shows that the average PAR under tree shade was greater at 2.5E even though the average full sun PAR (in μmoles m^{-2} s^{-1}) was less at 2.5E than 2.5W.

The reason for greater PAR at 2.5E relative to 2.5W is not exactly clear. The recordings at both positions were taken during tree shaded times on a clear day. A possible explanation would be tree leaf orientation allowing greater PAR penetration through the canopy at 2.5E. Wind direction and speed (Table 3.5) were approximately the same on both 92107 and 92114 eliminating this as a force on leaf orientation. With many cloudy or partly cloudy days (Figure 2.10) and mostly optimum temperatures for net photosynthesis in interval 3 (maximum near 25^0 C), florets/spikelet in 2.5E should be favored by increases in PAR which the data in Table 3.5 suggest.

Thus, a significantly higher total grain weight at 2.5E compared to 2.5W and 2.5N was due, in part, to PAR in interval 3. Greater PAR under tree shade at 2.5E compared to 2.5W and more hours of afternoon photosynthesis at 2.5E due to higher afternoon soil temperatures at 2.5W, appear to have been more influential than any effect due to higher soil P readings at 2.5W with low soil moisture. If PAR was close to a critical threshold due to relatively low total PAR available (from cloudy days), the number of florets/spikelet determined by interval 3 PAR could have resulted in greater yield capacity at 2.5E as opposed to 2.5W or 2.5N. This is supported by Evans (1978) who studied the influence of irradiance on wheat and found that grain number m^{-2} was the main determinant of grain yield. Thus, the number of grains per ear were greater at 2.5E versus 2.5W due to more developed florets per spikelet.

3.5.3.2. Post anthesis -- 1000-grain weight

Using orthogonal components with east versus north and west, the 1000-grain weight was significant (p=.0246) in the orientation experiment (Table 3.4) with the east side being higher than the north or west (Table B.4, Appendix B). This corresponded to the direction component of the barrier experiment where east was significantly higher than west (p=.0154). Correlation between total grain weight and 1000-grain weight was high (ρ=.8045).

Fischer (1975) and Willey and Holliday (1971) found that low 1000-grain weights reduced total grain weight. Kernel weights were determined during intervals 4 and 5. Factors affecting 1000-grain weight, and therefore total grain weight, were soil nutrients, soil moisture, soil temperature, and PAR.

3.5.3.2.1. Soil moisture and P

Available P was probably not a factor in interval 4 as soil moisture was above 16% (92122-92136, Table G.4, Appendix G) suggesting no yield response (see discussion 3.5.3.1.4. for further explanation). As the soils dried in interval 5 the milk stage of endosperm development was completed (Figure 1.10) reducing the P requirement. Soil moisture the 2 weeks before harvest (92148 and 92154 -- Table G.4, Appendix G) was under 11%. Gusta and Chen (1987) found that plant water stress severely reduced net photosynthesis in the flag leaf. This could have resulted from a stomatal response, a rise in the CO_2 compensation point, or a mesophyll resistance to CO_2 transport. Thus, conditions were conducive to reduced photosynthesis in interval 5.

3.5.3.2.2. PAR and temperature

Fischer (1975) discussed a compensating factor in 1000-grain weight when PAR was reduced before anthesis. This would be expected on the west side as 2.5E was predicted to have more grains m^{-2} (3.5.3.1.5). However, a necessary requirement for compensation is high PAR after anthesis. The first 2 weeks after anthesis (interval 4) average daily PAR was low (Figure 2.8) at 23.7 moles m^{-2} day^{-1} and no compensating factor occurred.

Wardlaw (1970) noted that low light in either of two periods from 1-10 and 11-25 days after anthesis caused a reduction in kernel weight. During interval 4 a direct comparison of PAR at 2.5E and 2.5W was not available, but the average daily PAR was low at 23.7 μmoles m^{-2} day^{-1} (Figure 2.8). PAR during tree shaded hours in interval 5 (Table 3.5) on 92141 and 92148 for average μmoles m^{-2} s^{-1} under tree shade were similar. On May 27th (92148) both 2.5E and 2.5W received less than 20% of the full sun PAR.

While PAR was available at similar levels at 2.5E and 2.5W, all of it may not have been useable for photosynthesis. In interval 5 (92148) surface soil temperatures were 5^0 C warmer in the afternoons on the west side (Table J.1, Appendix

J). Downes (1970) working with light intensity and leaf temperature in the laboratory found net photosynthesis (at PAR levels estimated to be 40 moles m^{-2} day^{-1}) increased with temperature with 25^0-30^0 C being optimum. Above these temperatures transpiration increased causing sharp declines in net photosynthesis.

In interval 5, PAR averaged 39.5 moles m^{-2} day^{-1} (Figure 2.8) and surface temperatures reached 32^0 C. The combination of low soil moisture and warmer afternoon surface temperatures at 2.5W may have stressed the wheat at the end of grain filling causing less CO_2 fixation at 2.5W. Since 70% to 90% of the CO_2 fixed in the grain is accumulated after anthesis this would explain the reduction in 1000-grain weight at 2.5W and 2.5N relative to 2.5E. With a high correlation between 1000-grain weight and total grain weight, a reduced 1000-grain weight at 2.5W and 2.5N would contribute to a reduction in total grain weight.

In summary, total grain weight was probably reduced at 2.5W and 2.5N compared to 2.5E due to reduced CO_2 fixation both before and after anthesis. Before anthesis in interval 3, grain number/ear, via fewer florets/spikelet, decreased at 2.5W and 2.5N relative to 2.5E due to less available PAR under tree shade. To a lesser extent 2.5W may have fixed less CO_2 in interval 3 as soils dried and wheat stress increased. If the west side received more shading in interval 3 prior to anthesis, thus limiting grain capacity, a compensating factor with the 1000-grain weight might be expected. However, this did not occur due to the low levels of PAR (from cloudy days and tree shade) in intervals 4 and 5 at 2.5W and 2.5E.

After anthesis kernel weight was reduced at 2.5W and 2.5N relative to 2.5E due to decreased CO_2 fixation from photosynthesis in interval 5. This occurred as water stress and higher temperatures became factors in the afternoons in the 2 weeks before harvest inhibiting CO_2 fixation at 2.5W and 2.5N. The difference in kernel weights at 2.5W and 2.5N versus 2.5E contributed to significant differences in total grain weight.

3.6. CONCLUSIONS

This research verified that under irrigated and fertilized conditions, 11-year-old *Paulownia* trees do not compete with wheat for water and nutrients which makes the two crops compatible for underground resources. However, *Paulownia* is a perennial tree and wheat is an early season (spring) crop. The literature does mention that the summer crop grown with *Paulownia* (corn or cotton) experiences greater yield losses than wheat. The extent of the loss due to root competition could possibly be tested with a similar root barrier experiment. A yield difference by direction under the trees was revealed where one was not apparent when plots away from the trees were also considered.

Two factors may be of interest for further investigation. One is the possible threshold of PAR that affects the number of grains per ear -- including formation of spikelets/ear and florets/spikelet. This could be studied in areas of cloudless days with shaded plots that mimicked the time and duration of shade under the tree but with several different shading intensities. By recording the moles m^{-2} day^{-1} received instead of the percent of shade, a pattern may be established that would explain how much PAR was required at each stage of wheat component development. Care should be taken in trying to use laboratory conditions to test PAR thresholds. Constant levels of PAR are not identical to natural conditions and glass can change the angle and intensity of PAR.

Another factor to consider is net photosynthesis at different directions under the tree through the course of a day especially during grain filling. During this time, afternoon surface temperatures often increase above the optimum for wheat. The increased shade at 2.5E in the early afternoon hours when PAR is high may be beneficial by increasing the period of net photosynthesis relative to 2.5W and 2.5N. While this may prove interesting, the practicality may be questionable. The area involved (about a 4 m wide strip) in relation to the whole field is about 6.7% with 60 m spacing between tree rows. However, it may be useful to consider for border plantings along roads.

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CHAPTER 4

CLOSING STATEMENTS

4.1. IMPLICATIONS

There is a danger in taking one set of readings or one seasons work and claiming broad applications. In this research the cautions are maybe more noteworthy. Crop yield is dependent on many factors. Some are controllable, others manageable to a degree, and some uncontrollable. Meteorological conditions are subject to change and the 1991-92 wheat year in Central China experienced some rather extreme ones. The drought was one of the harshest in 60 to 100 years and many days were uncharacteristically cloudy.

Results of a study conducted on a tree and wheat investigating the PAR and yield relationship indicated a significant reduction in yield under trees relative to a distance from the trees. However, no comparison could be made to open grown areas. The sheltering effect of the trees in this system which Zhu et al (1986) and Zhu (1990) document was not apparent due to generally cooler weather and partly cloudy days. Also irrigation reduced stress that would otherwise have shown the benefit of trees.

Paulownia root morphology did prove to be advantageous for agroforestry planting with winter wheat. Other crops with roots predominantly in the top 50 cm and those harvested in the early summer should also do well. During the first 3 to 4 years in a *Paulownia* rotation most crops are not seriously affected. Several examples are described in Zhu (1988) and

Jiang (1990). In later years (trees 5-10 years old) shading does create problems. This can be minimized by tree row orientation, spacing between tree rows, and basal pruning.

This research was on irrigated and fertilized wheat. China accrues more and more irrigated farm land each year, however, there is a substantial area that is still rainfed. In conditions of poor to moderate soils and limited water availability the *Paulownia*/crop intercropping system can significantly improve agricultural output as demonstrated in Henan Province.

Is this system exportable to other areas? The data suggests this possibility. *Paulownia* trees are found throughout much of China in both temperate and tropical areas. This wide range suggests that the tree is adaptable to other areas. The next question may be: Are other areas adaptable to the tree? Are local farming systems conducive to management practices that include trees in their system? Where possible the *Paulownia* and crop agroforestry system should be considered on a trial basis to see if local farmers would like to propagate this system.

While expansion of the system could begin, work on improving the tree and the tree/crop combination in its home environs should continue. The present research should be compared and contrasted to Zhu's (1990) work and to work being conducted at the *Paulownia* Center in *Zhengzhou*. One seasons results are seldom conclusive, especially under abnormal conditions. However, the depth of this work with scientific input form both East and West could be a valuable addition to *Paulownia* culture.

4.2. FUTURE DIRECTION

4.2.1. Experiments with Paulownia

It might prove beneficial to repeat this experiment with *Paulownia* and winter wheat in a more normal year to determine the effect of PAR on the different wheat yield components. The same might be attempted with other major crops. The shading effect on different crops could be established for critical growth periods. In order to make accurate comparisons of *Paulownia* intercropping systems from location to location it would be advisable to collect data that reports the amount of PAR available by development interval. It is difficult to determine how much PAR the plant actually used or how that compares to the same plant in other locations based only on percent of shade at a latitude and a certain time of year. To facilitate data collecting, an integrated sensor should be used to more accurately detect sunflecks under a tree canopy or partly cloudy conditions.

Along with the tree canopy factors that influence yield, further studies can be done with roots. Initially barriers can be employed to investigate other crop's root interactions with *Paulownia*. Technology has also been developed to study root growth using rhizotron techniques. Some work has been done with micro organisms and *Paulownia* trees (Zhu, 1990). However, little has been mentioned of *Mycorrhizae* with

Paulownia. The presence or lack of *Mycorrhizae* might help explain some of the phosphorus/tree interactions and general nutrient uptake as it affects the tree directly and the crop indirectly.

4.2.2. Standardizing Research Work

Anderson (1964), speaking of PAR studies, notes that much scientific data is of little use because photometric equipment was used. She attributes this to the accessibility of the equipment (cheaper) when measuring global solar radiation (direct and diffuse light). When planning and reporting results it would be helpful to the scientific community, and even the farmers in the long run, to use a standard system of weights and measures. International units (SI units) will eliminate much frustration and error when everyone learns to speak the same language especially when working with light. A suggestion might be to plan in SI units (distance, volume, weight, etc.), use equipment calibrated to SI units, and report in SI units with parenthetical information converted from SI to local units. If results are determined with local units (such as 3 gallons) and converted to SI units, the results may be reported in an awkward fashion (11.35 liters). In some cases an error may be introduced (converting lux to moles m^{-2}).

To assist fellow scientists, especially when working with the electromagnetic spectrum of light, it would be helpful to describe a site and data collected as thoroughly as possible. The site information would include latitude, longitude, time of season (in addition to months), solar noon (to overcome problems with countries that have large areas with 1 time zone), soil texture, soil horizons, soil samples for key nutrients, organic matter, pH, CEC, bulk density, tree measurements, rainfall and soil moisture. Economic constraints may limit collecting all of this data. However, while writing this dissertation all of these variables were sought for comparison studies.

For analysis and presentation of results, two articles were of great assistance in trying to understand analyses in the literature and how to interpret them -- 1) "Comparing Treatment Means Correctly and Appropriately" (Mize and Schultz, 1985) and 2) "On the Presentation of Statistical Analysis: Reason or Ritual" (Warren, 1986). These articles are particularly suited to forestry. However, they emphasize the importance of using solid statistical procedures to support the conclusions derived from the research and the inferences generated. Experimental results are much easier to interpret for individual use when results are presented so they are understandable to everyone.

Hangarter and Ries (1993) note the Analysis of Variance (ANOVA) is the most precise, flexible and readily useable method of analysis for field, green house or laboratory experiments. To use the ANOVA an appropriate experimental design must be developed before the experiment begins. This necessitates following three cardinal principles -- replication, randomization, and local control (Little and Hills, 1978). This will enable results to be reported as significant or not at some "p" value and not just as a percent increase. This gives much more credibility to the results. In addition Little and Hills (1978) mention the three "R,s" of experimentation -- replicate, randomize and request help. Requesting help illustrates the importance of cooperation and consultation.

4.2.3. Research Cooperation

In order to accomplish this research, as with any research, many different organizations, departments and individuals contributed ideas and exerted time and effort. Most research in these "modern" times require interdepartmental and interdisciplinary cooperation. In addition this research required cooperation of farmers; technicians; researchers; academic institutions; local, county and national governments; and even hemispherical cooperation understanding and accommodating different cultures and customs.

4.2.3.1. Local level

Cooperation was necessary at all levels and began at the grassroots level with the farmers. The *Paulownia* trees were planted and maintained in a group supported effort before the researchers even arrived. This was the first generation of *Paulownia* trees in this area and the second generation will probably have a different layout. This next generation has been planted along the roads bordering the fields and not in the center of the fields. This will change the thickness of the shelterbelt (2 rows wide) and the spacing between tree rows. In turn this may alter the microclimate. There will be less porosity with 2 rows of trees and there will be more PAR to the fields due to wider tree row spacing. Depending on the sheltering effect, soil moisture in non-irrigated areas could become more critical at the center of the fields.

However, the important issue may be whether the trees survive at all. With the trees planted along the roads a different ownership pattern and maintenance regime arise. Trees along roads are not identified as one person or family's responsibility or possession. They are also much more accessible to mistreatment. The sticks (1- or 2-year-old nursery stock) along the roads showed signs of neglect and abuse. If lack of attention destroys the continuity of the *Paulownia* forest network the benefits of this agroforestry system may disappear.

A second stage of cooperation at the local level included County forestry officials, foresters, researchers, the local village government (*Shu Zhuang Cun*), the higher level village government (*Guan Ting Xiang*) and the county government (*Chang Ge County*). The constant consultation between all participants was a key factor towards project completion. In this case President Jiang's close working relationship over the years with the farmers and county forestry personnel enabled continuous progress once the site was selected.

4.2.3.2. Institutional level

At the University level both in China and America the necessity of interdepartmental cooperation was apparent. In this research wheat scientists, soil scientists, meteorological scientists, statisticians, experimental designers, tree breeders, and foresters, to name a few, were consulted. This required extra effort from the forestry departments on both sides of the Pacific Ocean which was readily forthcoming.

4.2.3.3. International level

Even at the international level there was a necessity to cooperate to produce a finished product. Travel permits were required at the national level at the start of this research for a foreigner to travel within China. Equipment was sent from America to China and had to clear customs. Visas and travel documents also were necessary which would have been difficult to obtain a few years prior.

4.2.4. Future Collaborative Research Efforts

From a scientific standpoint China has much to offer the scientific community, and with some nurturing from the West, can make even greater contributions. China brings a unique perspective to agriculture and agroforestry: 4000 years of sustainable agriculture (F.H.King, 1911). Jiang (1990) mentions several historical books that indicate the depth of agroforestry knowledge available in China:

Techniques All the People Should Know, Jia Simiao -- 6th century
Tree Crop Description and Classification -- 11th century
How to Plant Paulownia, Zhen Zhi -- 11th century
Planting Trees, Yu Zhong ben -- 14th century
The Book of Farming, Xiu Guangqi -- 15-16th century
Tree Crop Compilations, Li Shizhen -- 16-17th century
Three Agricultural Periods, -- 18th century

Of special interest is Chen Zi's *Paulownia Manual* in 1049 AD which summarized in detail the previous 900 years of cultivation techniques for fast growing *Paulownia* timber trees. Even today Jiang (1990) states, this book contributes to *Paulownia* scientific development.

Other strengths that China brings to the world agricultural community include their masses and their ability to reuse or recycle. Because of the land pressure in China, many items are recycled in some way for agricultural use. Compost is one example mentioned previously.

However, the Chinese countryside and agriculture production is changing rapidly. Today (1993) chemical fertilizer and pesticide use is on the rise. Mechanical equipment is also more and more prevalent. This means changes in ideas, management practices and even ways of living. There is a plethora of research literature on how agriculture development has failed since the industrial West began its development programs with lesser developed countries in the 1950's. Imposing Western ways and values on other cultures has not been effective. In fact some farmers in the West state that farming practices today have seriously degraded their land and its future production potential.

China, if it is cautious, has the ability to select those areas of agriculture development that are best suited to the strengths they possess and their long history of sustainable agriculture. If technologies are selected wisely sustainable agriculture will continue for more than a few centuries.

4.3. CONCLUDING REMARKS

In summary I would stress 2 points. First, as stated at the outset, this research was intended to contribute to the knowledge base of the *Paulownia* and wheat intercropping system. No claim can be made of any outstanding contribution attributed to this work, however, it is important to emphasize that none was ever anticipated. As with most research this was intended to add an incremental amount, albeit a small one, to that knowledge base. To that extent there has been a contribution.

Second, because of the support of Michigan State University and Henan Agricultural University the East and West have moved one step closer towards a mutual understanding. The fact that this was accomplished and continues to occur in many facets of science shows that scientists are entering a new stage of mutual cooperation and benefit that will surely take its place in a New World Order. If this research did nothing else, it helped cement a tiny brick into the bridge of mutual respect and common purpose towards the progress of humanity through scientific endeavor.

4.4. REFERENCES

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APPENDICES

APPENDIX A. ANOVA ASSUMPTIONS.

Table A.1. ANOVA Assumptions

EXPERIMENT	TEST OF	TEST FOR	TEST	TOT GRAIN WEIGHT (p)	1000-GRN WEIGHT (p)
DISTANCE & DIRECTION	Variable	Normality	Shapiro/ Wilks-S/W	.9601	.9467
	Residual	Normality	S/W	.9442	.9715
		Homogen-eity	Bartlett	.4743	.9818
		Additivit	Tukey	.2596	.1837
TEMPERATURE/ SHADE	Variable	Normality	S/W	.9615	.9887
	Residual	Normality	S/W	.9022	.9628
		Homogen	Bartlett	.5890	.7741
		Additivit	Tukey	.4142	.3153
SOILS	Variable	Normality	S/W	.9613	.9431
	Residual	Normality	S/W	.9097	.9283
		Homogen	Bartlett	.7286	.6441
		Additivit	Tukey	.2061	.1257
ROOT BARRIER	Variable	Normality	S/W	.9426	.9409
	Residual	Normality	S/W	.9431	.9727
		Homogen	Bartlett	.4757	.4751
		Additivit	Tukey	.8262	.6065
ORIENTATION	Variable	Normality	S/W	.9166	.9564
	Residual	Normality	S/W	.8459	.9722
		Homogen	Bartlett	.9004	.8404
		Additivit	Tukey	.7763	.7962

The assumptions of independent and random residuals was satisfied through random selections of plot positions. Error Tables were established as in Little and Hill (1978) in which independence and randomness were tested with no violations.

APPENDIX B. MEANS AND STANDARD ERRORS.

Table B.1. Means--Distance Experiment--TGW, 1000-GW, Ears.

	EARS		TOTAL GRAIN WEIGHT		1000 GRAIN WEIGHT	
Block/ Treatment	Mean (no m^{-2})	Std error	Mean (g m^{-2})	Std error	Mean (g)	Std error
C1	669	15.6	646	20.2	36.5	.27
C2	520	10.4	570	11.1	34.7	.20
R1-4	466	6.4	424	7.3	32.1	.43
R1-4, 20m	467	20.5	478	11.4	33.6	.87
R1-4, 10m	463	8.4	449	12.2	33.1	1.12
R1-4, 5m	467	14.1	419	14.0	31.7	1.03
R1-4, 2.5m	473	22.3	393	15.1	30.9	.93
CT	482	6.7	497	15.8	34.9	.98
CT 20W	474	6.1	511	26.4	35.7	1.17
CT 2.5E	461	17.3	484	20.0	34.2	1.60
AS	489	9.7	436	30.2	30.4	.73

C1--Control 1
C2--Control 2
R1-4--Replications 1-4
CT--Cut tree area
AS--Artificial shade
TGW--Total Grain Weight
1000-GW--1000 Grain Weight
no--number

Table B.2. Means & Scheffe Test--Temperature/Shade Experiment --TGW, 1000-GW.

TOTAL GRAIN WEIGHT (TGW)		
Treatment	Mean (g/m^2)	Std. Error
Cut tree	511	26.4
Artificial shade	437	30.2
Tree reps (2.5E)	433	13.4

1000 GRAIN WEIGHT (1000-GW)

Treatment	Mean (g)	Std Error	Scheffe Test[a]
Cut tree	35.7	1.2	A
Tree reps (2.5E)	33.3	.8	A B
Artificial shade	30.4	.7	B

[a] Treatments followed by the same letter are not significantly different (α=.05).

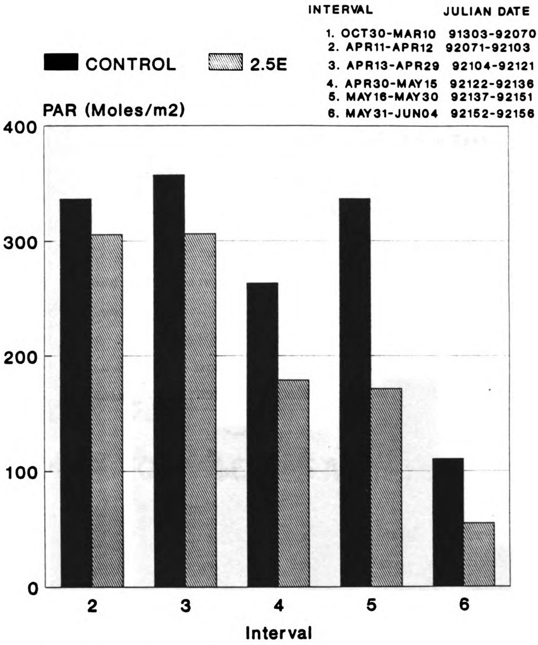
Table B.3. Means--Root Barrier Experiment--Ears, TGW, 1000-GW.

	EARS		TOTAL GRAIN WEIGHT (TGW)		1000 GRAIN WEIGHT (1000-GW)	
Treatment	Mean	Std.Error	Mean	Std.Error	Mean	Std.Error
BARRIER	473	25.8	402	16.2	31.6	1.02
NO BARRIER	456	13.2	409	13.1	31.9	1.08
2.5E	464	23.6	428	12.9	33.4	.59
2.5W	463	13.2	383	11.3	30.1	.71

Table B.4. Means--Orientation Experiment--Ears, TGW, 1000-GW.

	EARS		TOTAL GRAIN WEIGHT (TGW)		1000 GRAIN WEIGHT (1000-GW)	
Treatment	Mean	Std. Error	Mean	Std. Error	Mean	Std. Error
West	468	19.9	373	13.9	30.4	.90
North	473	20.3	369	11.0	30.5	.71
East	479	53.8	445	14.4	33.7	.63

APPENDIX C. PAR DATA.



Scheme I-Sensors record average of 2 5 minute readings for 2.5E and 10W at 10 minute intervals.

Figure C.1. Tree Shade (2.5E) vs Unshaded PAR--Scheme I.

APPENDIX D. AIR TEMPERATURE.

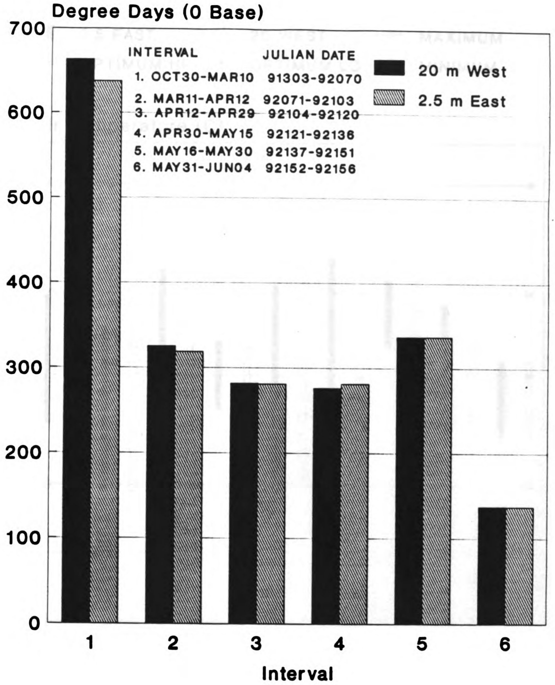


Figure D.1. Degree Days--20W vs 2.5E.

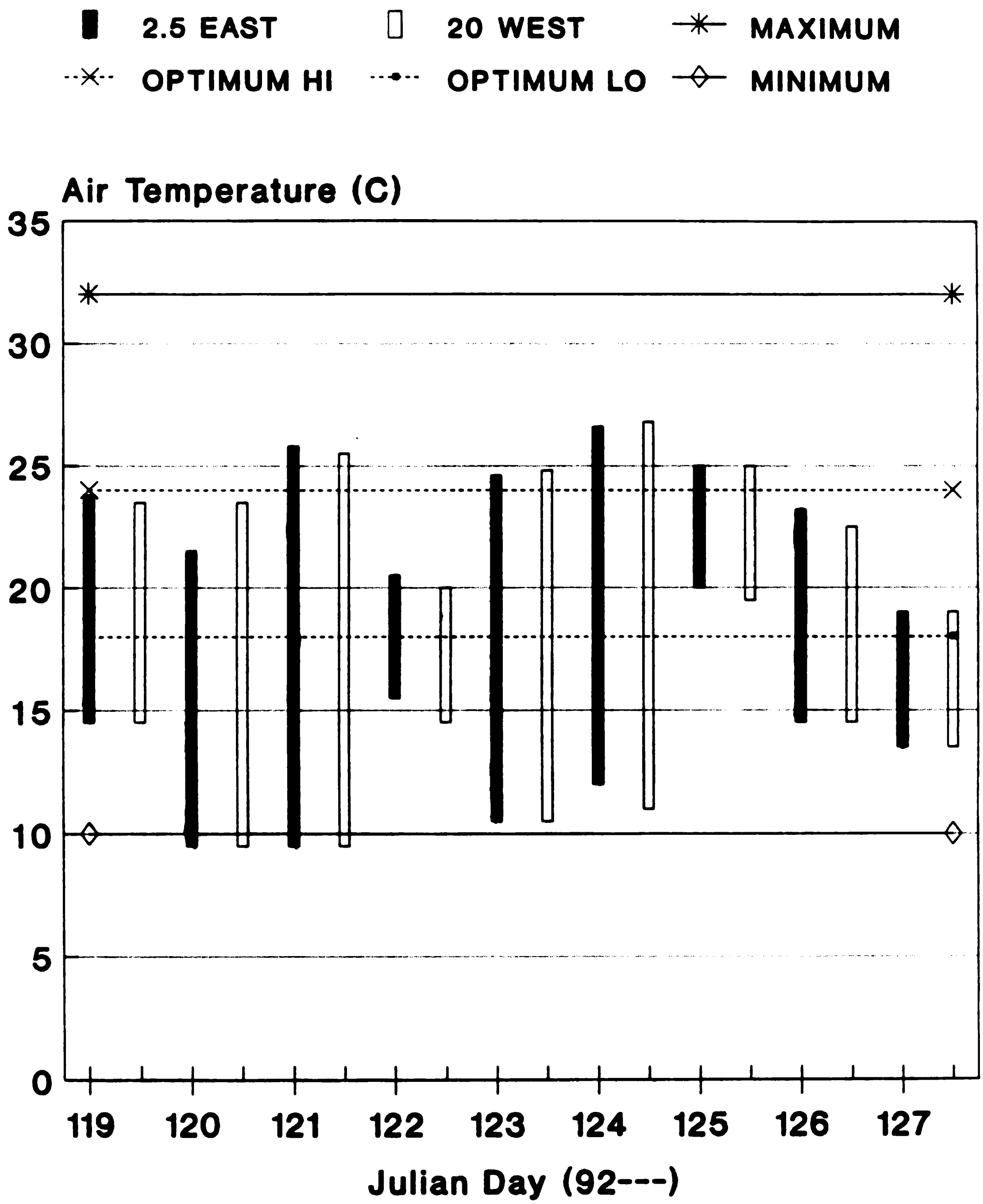


Figure D.2. Daily High/Low Temperatures After Anthesis.

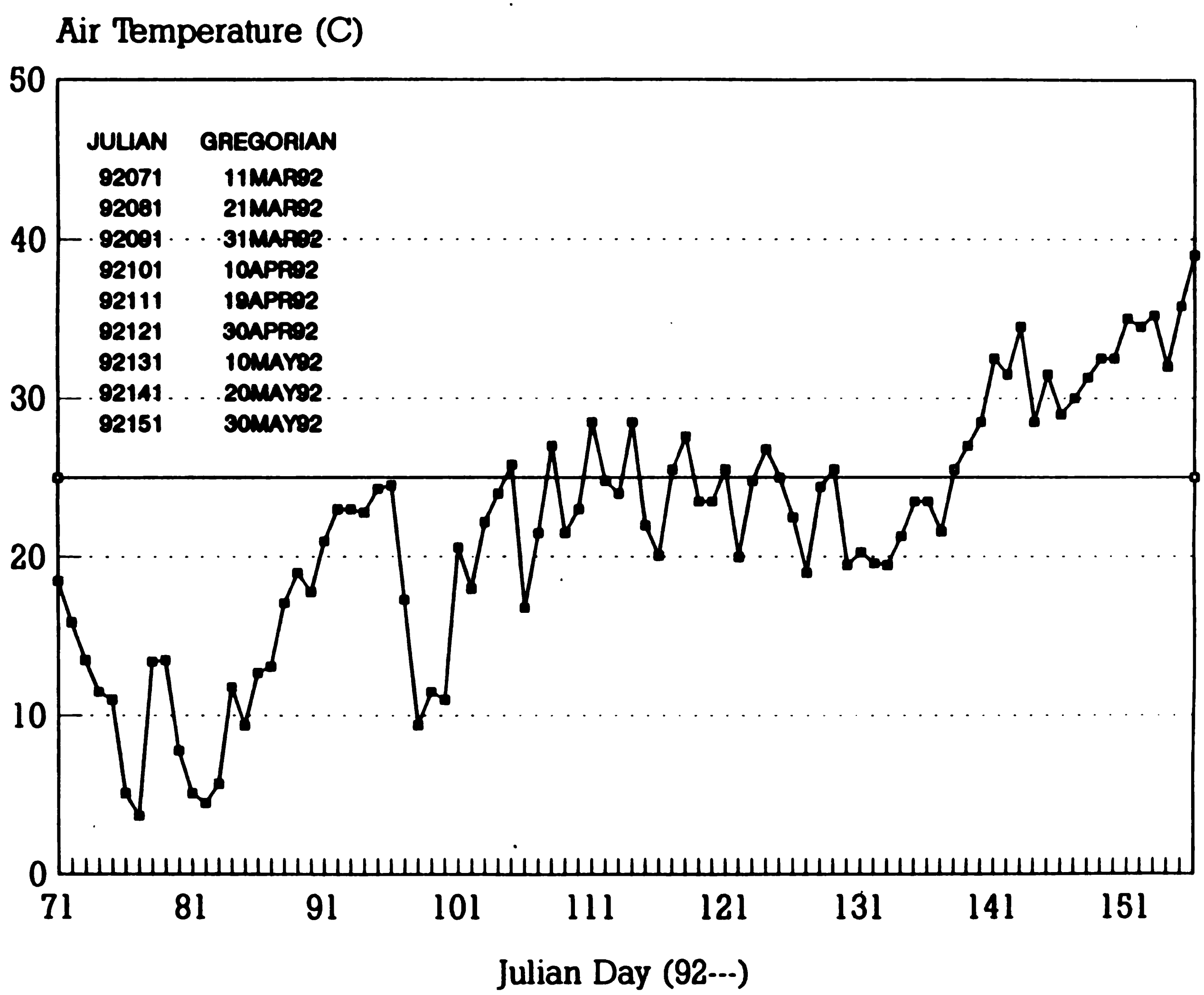


Figure D.3. Daily High Temperature--March 11th to June 4th.

APPENDIX E. HAUN SCALE READINGS.

Table E.1. Haun Rating by Block.

	BLOCKS							
Date	1	2	3	4	5	6	7	8
92085	--	4.5	--	--	--	4.4	4.5	--
92086	--	4.4	--	--	4.0	5.1	--	--
92093	5.8	5.5	5.6	5.5	5.8	6.3	5.5	--
92101	7.5	6.7	7.3	6.9	7.3	7.3	7.1	7.3
92108	18.7	18.4	18.6	18.5	18.5	28.0	18.8	18.5
92115	38.3	38.0	38.2	38.2	38.1	38.2	38.0	38.2
92118	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Block
1-4 Trees
5 Cut tree
6,7 Controls
8 Artificial Shade

Haun Rating
8 Flag leaf
18 Enlargement
28 Emergence
38 Elongation
100 Anthesis

Dates
92085--Mar 25, 1992
92086--Mar 26, 1992
92093--Apr 02, 1992
92101--Apr 10, 1992
92108--Apr 17, 1992
92115--Apr 24, 1992
92118--Apr 27, 1992

Table E.2. Haun Rating by Yield Position.

TREATMENT (DISTANCE/DIRECTION)										
Date	No.	20W	10W	5W	2.5W	2.5N	2.5E	5E	10E	20E
92086	1	4.9	5.0	4.1	4.8	4.5	4.5	4.7	3.7	3.5
92093	4	5.7	5.6	5.5	5.5	5.5	5.4	5.7	5.8	5.8
92101	4	7.1	7.2	7.1	7.1	7.1	7.1	7.3	7.0	7.2
92108	5	18.5	18.7	18.6	18.5	18.5	18.5	18.6	18.6	18.5
92115	5	38.1	38.2	38.1	38.2	38.1	38.3	38.2	38.4	38.1
92118	5	100	100	100	100	100	100	100	100	100

Dates

92085--Mar 25, 1992
92086--Mar 26, 1992
92093--Apr 02, 1992
92101--Apr 10, 1992
92108--Apr 17, 1992
92115--Apr 24, 1992
92118--Apr 27, 1992

Haun Rating

8 Flag leaf
18 Enlargement
28 Emergence
38 Elongation
100 Anthesis

APPENDIX F. WIND SPEED AND DIRECTION.

Table F.1. Average Wind Speed--Feb 23-Jun 7.

	INT 2		INT 3		INT 4		INT 5		INT 6		INT 7		
	NO. DAYS	AVE WSP m/s	NO. DAYS	AVE WSP m/s	NO. DAYS	AVE WSP m/s	NO. DAYS	AVE WSP m/s	NO. DAYS	AVE WSP m/s	NO. DAYS	AVE WSP m/s	TOT DAYS
NW	2	2.4	0	0	0	0	0	0	0	0	0	0	2
N	18	4.0	5	3.9	7	2.5	4	1.8	0	0	1	2.8	35
NE	2	2.9	0	0	0	0	0	0	0	0	0	0	2
E	2	2.8	3	2.4	5	1.3	2	2.3	0	0	0	0	12
SE	1	2.0	0	0	2	2.3	0	0	2	1.8	0	0	5
S	21	1.7	5	2.3	2	1.7	6	1.2	2	1.4	1	3.5	37
SW	1	2.5	4	2.5	0	0	2	1.9	0	0	0	0	7
W	3	2.5	0	0	0	0	1	1.3	1	2.0	1	2.0	6

INT--INTERVAL
NO.--NUMBER
AVE
WSP--AVERAGE WINDSPEED
m/s--METERS/SECOND
NW --NORTHWEST
N --NORTH
NE --NORTHEAST
E --EAST
SE --SOUTHEAST
S --SOUTH
SW --SOUTHWEST
W --WEST

INT 2--FEB23-APR12
INT 3--APR13-APR29
INT 4--APR30-MAY15
INT 5--MAY16-MAY30
INT 6--MAY31-JUN04
INT 7--JUN05-JUN07

APPENDIX G. SOIL MOISTURE, RAINFALL, IRRIGATION

Table G.1. Percent Soil Moisture, Irrigation and Precipitation.

	PERCENT	SOIL	MOISTURE	IRRIGA		PRECIP
	REP1-4	REP 5	REP 6,7	REP	DURATION	(mm)
91289				1-5,8-10	2	
91295-365						22.32
92001-045						0.92
92045				1-5,8-10	4	
92058				6	1	
92059				7	1	
92046-060						8.0
92061						13.3
92071	21.2	20.4	21.6			
92085	18.1	17.5	18.5			
92093	12.4	14.2	12.7			
92062-099						36.3
92100						12.8
92101	15.3	15.2	15.2			
92107	10.8	8.8	8.9			
92101-114						.03
92115	5.0	4.9	4.0	1-10	5	
92125	19.7	20.2	12.8			
92115-125						12.3
92126						30.2
92130	18.7	19.0	15.7			
92135	16.6	17.2	12.0			
92141	13.6	15.0	8.4			
92147				6,7	1	
92148	9.8	10.4	5.3			
92121-151						10.14
92154	6.8	6.0	4.1			
92152-155						1.81

Table G.1 (cont'd)

REP1-4--TREE AREA	91289 --JULIAN DATE (YEAR-1991, DAY-289)		
REP5 --CUT TREE	IRRIGA --IRRIGATION		
REP6,7--CONTROLS	REP --REPLICATIONS	.01mm --TRACE PRECIPITATION	
mm --MILLIMETERS	PRECIP --PRECIPITATION		

Table G.2. Soil Moisture (%)--Distance and Direction.

	20 m		10 m		5 m		2.5 m			
JD	W	E	W	E	W	E	W	E	W	E
071	21.2	21.3	21.8	21.1	21.1	20.9	20.8	21.0	21.2	21.1
085	21.0	18.5	16.8	17.5	17.6	17.5	18.3	17.6	18.4	17.8
093	13.1	13.4	12.2	11.4	11.7	12.4	13.2	11.9	12.6	12.3
101	16.2	14.7	16.0	14.3	15.0	15.4	15.4	15.0	15.7	14.9
107	11.0	10.0	11.9	10.5	11.6	9.8	10.8	10.8	11.3	10.3
115	5.0	5.1	4.8	5.5	5.1	4.5	5.1	4.3	5.0	4.9
125	20.3	19.0	19.7	19.3	19.9	19.7	19.7	19.7	19.9	19.4
130	19.1	18.7	18.7	18.1	18.8	18.4	18.5	18.3	18.8	18.4
135	17.0	15.2	16.7	16.3	17.4	16.2	16.9	16.7	17.0	16.1
141	13.4	13.7	13.4	13.1	14.0	12.4	14.4	13.3	13.8	13.2
148	9.6	8.9	9.6	9.1	10.6	9.6	10.5	9.7	10.1	9.3
154	7.8	6.4	5.9	6.2	7.3	6.1	7.4	6.3	7.1	6.2

JD - Julian Date
m - meter
W - west
E - east

Table G.3. ANOVA--Soil Moisture--Distance and Direction (92115)

Source	df	SS	MS	F	p	Signif
Block	3	3.79				
Direction	1	.20	.203	.94	.4029	NS
error a	3	.65	.215			
Distance	3	1.01	.337	.97	.4292	NS
Direction x Distance	3	2.74	.912	2.62	.0821	NS
error b	18	6.26	.348			
Total	31	14.64				

Table G.4. ANOVA and Mean % Soil Moisture by Direction (Blocks 1-4).

	DIRECTION				
DATE	2.5W	2.5E	2.5N	ANOVA(p)	SIGNIF
92071	20.82	20.98	21.37	-	-
92085	18.3	17.60	18.30	-	-
92093	13.25	11.95	12.05	-	-
92101	15.45	15.05	15.10	.6935	NS
92107	10.85	10.83	10.90	.9957	NS
92115	5.10	4.33	5.11	.0248	*
92125	19.71	19.70	20.10	.2732	NS
92130	18.48	18.33	19.23	.1769	NS
92135	16.89	16.70	17.14	.4691	NS
92141	14.40	13.35	14.30	.4082	NS
92148	10.49	9.73	10.96	.0784	NS
92154	7.40	6.31	7.90	.1244	NS

Table G.5. ANOVA--Soil Moisture (92115).

SOURCE	df	SS	MS	F	p	SIGNIF
Block	3	3.539				
Direction	2	1.628	.8140	7.28	.0248	*
error	6	.670	.1117			
Total	11	5.837				

Table G.6. Scheffe Test--Soil Moisture (92115).

	MEANS	SCHEFFE[a]	STD ERROR
North	5.11	A	.379
West	5.10	A	.418
East	4.33	B	.180

[a] Treatments followed by the same letter are not significantly different (α=.05). Minimum significant difference = .7581.

APPENDIX H. SOIL SAMPLES.

Table H.1. Soil Analysis--Means for Blocks 1-4 on 92057[a]--and ANOVA--Distance and Direction.

	DEPTH	2.5 m	5 m	10 m	20 m	DISTANCE p	WEST	EAST	DIRECTION p
Nitrogen	0-20	92.6	97.8	95.6	97.7	.5201	91.5	100.3	.0611
(mg kg^{-1})	21-40	90.0	86.9	90.2	97.4	.4590	92.0	90.2	.8015
Phosphorus	0-20	7.5	9.6	5.9	5.6	.0069**	8.3	6.0	.1659
(mg kg^{-1})	21-40	3.9	2.2	2.3	2.4	.1678	2.6	2.9	.7293
Organic	0-20	1.99	2.00	1.77	1.95	.2518	1.98	1.87	.6842
Matter (%)	21-40	1.58	1.49	1.68	1.44	.6539	1.57	1.53	.8352
pH	0-20	8.4	8.4	8.4	8.5	.6959	8.6	8.3	.0313*
	21-40	8.4	8.3	8.4	8.3	.2996	8.4	8.3	.1354

[a] February 26, 1992.

Table H.2. Phosphorus--ANOVA--Distance and Direction (92057)[a].

SOURCE	df	SS	MS	F	p	SIGNIF
Block	3	55.6				
Direction	1	42.8	42.8	3.32	.1659	NS
error a	3	38.6	12.9			
Distance	3	78.9	26.3	5.58	.0069	**
Dist x Dir	3	17.6	5.9	1.25	.3225	NS
error b	18	84.8	4.7			
Total	31	318.4				

[a] Phosphorus at 0-20 cm on February 26, 1992.

Table H.3. Scheffe Test[b] for Phosphorus on 92057.

TREATMENT	MEAN	SIGNIFICANCE[c]	STD. ERROR
5 m	9.6	A	1.6
2.5 m	7.5	A B	1.1
10 m	5.9	B	.6
20 m	5.6	B	.5

[b] Treatments followed by the same letter are not significantly different (α=.05).

[c] Minimum Significant difference = 4.12.

Table H.4. Phosphorus Levels (mg kg^{-1}) on 92057[a] by Block.

	2.5 m		5 m		10 m		20 m	
	WEST	EAST	WEST	EAST	WEST	EAST	WEST	EAST
Block 1	11.6	5.4	14.7	12.7	9.8	5.0	7.2	7.2
Block 2	6.3	4.0	5.2	5.9	5.8	6.1	6.5	6.2
Block 3	11.9	4.5	16.2	5.4	6.7	4.6	5.6	4.0
Block 4	9.4	6.6	6.9	9.7	4.5	4.8	4.6	3.8
Block 5	7.7	5.4	--	--	--	--	5.6	7.2

[a] February 26, 1992.

Table H.5. pH[a]--ANOVA--Distance and Direction on 92057[b].

SOURCE	df	SS	MS	F	p	SIGNIF
Block	3	.511	.170			
Direction	1	.845	.845	14.70	.0313	*
error a	3	.172	.057			
Distance	3	.004	.001	.49	.6959	NS
Dist x Dir	3	.020	.007	2.59	.0843	NS
error b	18	.046	.003			
Total	31	1.60				

Table H.6. pH[a]--Means--Direction on 92057[b].

DIRECTION	MEAN	STANDARD ERROR
West	8.6	.02
East	8.3	.05

[a] for 0-20 cm

[b] February 26, 1992

Table H.7. Soil Test Results--Orientation Experiment on 92057.

	DEPTH (cm)	WEST	EAST	NORTH	ANOVA p
N (mg kg^{-1})	0-20	88.3	96.9	96.2	.2454
	21-40	88.3	91.6	88.8	.9714
P (mg kg^{-1})	0-20	9.8	5.1	7.7	.0218*
	21-40	3.5	4.4	1.7	.4440
Organic Matter (%)	0-20	2.2	1.8	2.1	.5021
	21-40	1.5	1.7	1.5	.5732
pH	0-20	8.6	8.3	8.5	.0209*
	21-40	8.4	8.3	8.5	.2618

Table H.8. pH--ANOVA--Orientation Experiment on 92057.

SOURCE	df	SS	MS	F	p	SIGNIF
Block	3	.377				
Direction	2	.285	.143	7.89	.0209	*
error	6	.108	.018			
Total	11	.770				

Table H.9. pH--Scheffe Test--Orientation Experiment on 92057.

TREATMENT	MEANS	SCHEFFE[a]	STD ERROR
West	8.62	A	.048
North	8.47	A B	.131
East	8.25	B	.144

[a] Treatments followed by the same letter are not significantly different (α=.05). Minimum significant difference = .305.

Table H.10. Phosphorus ANOVA--Orientation Experiment on 92057.

SOURCE	df	SS	MS	F	p	SIGNIF
Block	3	30.6				
Direction	2	43.8	21.92	7.74	.0218	*
error	6	17.0	2.83			
Total	11	91.4				

Table H.11. Phosphorus--Scheffe Test--Orientation on 92057.

TREATMENT	MEANS	SCHEFFE[a]	STD ERROR
West	9.80	A	1.29
North	7.67	A B	1.40
East	5.12	B	.57

Table H.12. Phosphorus Means(mg kg^{-1})--Orientation experiment by Block.

	DEPTH (cm)	WEST	EAST	NORTH
Block 1	0-20	11.6	5.4	10.9
Block 2	0-20	6.3	4.0	4.9
Block 3	0-20	11.9	4.5	9.1
Block 4	0-20	9.4	6.6	5.8

[a] Treatments followed by the same letter are not significantly different (α=.05). Minimum significant difference = 3.815.

APPENDIX I. TREE MEASUREMENTS.

Table I.1. Average Tree Measurements by Block.

	TOTAL HEIGHT (m)	DIAMETER AT 1.5 m (cm)	BOLE LENGTH (m)	CROWN DIAMETER (m)
BLOCK 1	13.2	31.4	5.7	9.0
BLOCK 2	13.1	33.5	5.3	8.9
BLOCK 3	12.5	32.9	5.9	9.9
BLOCK 4	12.5	30.2	7.0	9.1

Table I.2. Tree Measurements--Overall Means.

	COUNT	MEAN	STDERR	MINIMUM	MAXIMUM
TOTAL HEIGHT (m)	48	12.8	.122	11.7	14.4
DIAMETER (cm)	32	32.0	.858	22.0	39.9
BOLE LENGTH (m)	32	5.9	.262	2.7	8.3
CROWN DIAMETER (m)	32	9.2	.202	7.6	12.9

APPENDIX J. SOIL TEMPERATURE.

Table J.1. Soil Temperature Differences--2.5E, 2.5W, 2.5N (92114[a]-92148[b]).

1992	JUL	SURFACE			5 cm			10 cm			DAILY MAX
		MAX	TEMP	DIFF	MAX	TEMP	DIFF	MAX	TEMP	DIFF	AIR
DATE	DATE	BETWEEN	C	TIME[c]	BETWEEN	C	TIME	BETWEEN	C	TIME	TEMP C
Apr 23	92114	N-W	3.5	12:00	N-W	1.8	11:00	N-W	.9	12:00	28.5
		N-E	3.3	15:00	N-E	1.5	16:00	N-E	.5	17:00	
Apr 29	92120	N-W	2.0	12:00	N-W	1.0	12:00	E-W	.5	14:00	23.5
		N-E	2.8	14:00	N-E	2.0	16:00	E&N-W	1.0	17:00	
May 8	92129	N-W	1.5	12:00	N-W	.8	10:00	E-W	.5	11:00	25.5
		W-E	3.0	14:00	W	1.8	15:00	W-E	.5	14:00	
May 14	92135	N-E	1.0	11:00	N-W&E	.5	12:00	N&E-W	.3	11:00	23.5
		W-E	1.5	14:00	W	1.0	15:00	N&W-E	.6	18:00	
May 20	92141	N-W	2.5	11:00	N-W	2.1	11:00	N-W	.7	14:00	32.5
		W-E	3.8	14:00	W	2.0	15:00	W	1.0	18:00	
May 27	92148	E-W	3.3	10:00	N-E&W	2.0	09:00	E	.8	12:00	31.3
		W-E	5.0	16:00	W	3.0	16:00	W	1.0	17:00	

[a] April 23, 1992
[b] May 27, 1992
[c] Solar noon--12:20.

APPENDIX K. JULIAN DATE vs GREGORIAN DATE.

Table K.1. Julian vs Gregorian Calendar Dates--1991-1992.

30-09	91273	15-11	91319	11-12	91345	06-01	92006
01-10	91274	16-11	320	12-12	346	07-01	007
22-10	91295	17-11	321	13-12	347	08-01	008
23-10	91296	18-11	322	14-12	348	09-01	009
24-10	91297	19-11	323	15-12	349	10-01	92010
25-10	91298	20-11	324	16-12	91350	11-01	011
26-10	91299	21-11	325	17-12	351	12-01	012
27-10	91300	22-11	326	18-12	352	13-01	013
28-10	301	23-11	327	19-12	353	14-01	014
29-10	302	24-11	328	20-12	354	15-01	015
30-10	303	25-11	329	21-12	355	16-01	016
31-10	304	26-11	91330	22-12	356	17-01	017
01-11	305	27-11	331	23-12	357	18-01	018
02-11	306	28-11	332	24-12	358	19-01	019
03-11	307	29-11	333	25-12	359	20-01	92020
04-11	308	30-11	334	26-12	91360	21-01	021
05-11	309	01-12	335	27-12	361	22-01	022
06-11	91310	02-12	336	28-12	362	23-01	023
07-11	311	03-12	337	29-12	363	24-01	024
08-11	312	04-12	338	30-12	364	25-01	025
09-11	313	05-12	339	31-12	365	26-01	026
10-11	314	06-12	91340	01-01	92001	27-01	027
11-11	315	07-12	341	02-01	92002	28-01	028
12-11	316	08-12	342	03-01	92003	29-01	029
13-11	317	09-12	343	04-01	92004	30-01	92030
14-11	91318	10-12	91344	05-01	92005	31-01	92031

Table K.1. (cont'd)

01-02	92032	29-02	92060	28-03	92088	25-04	92116
02-02	033	01-03	061	29-03	089	26-04	117
03-02	034	02-03	062	30-03	92090	27-04	118
04-02	035	03-03	063	31-03	091	28-04	119
05-02	036	04-03	064	01-04	092	29-04	92120
06-02	037	05-03	065	02-04	093	30-04	121
07-02	038	06-03	066	03-04	094	01-05	122
08-02	039	07-03	067	04-04	095	02-05	123
09-02	92040	08-03	068	05-04	096	03-05	124
10-02	041	09-03	069	06-04	097	04-05	125
11-02	042	10-03	92070	07-04	098	05-05	126
12-02	043	11-03	071	08-04	099	06-05	127
13-02	044	12-03	072	09-04	92100	07-05	128
14-02	045	13-03	073	10-04	101	08-05	129
15-02	046	14-03	074	11-04	102	09-05	92130
16-02	047	15-03	075	12-04	103	10-05	131
17-02	048	16-03	076	13-04	104	11-05	132
18-02	049	17-03	077	14-04	105	12-05	133
19-02	92050	18-03	078	15-04	106	13-05	134
20-02	051	19-03	079	16-04	107	14-05	135
21-02	052	20-03	92080	17-04	108	15-05	136
22-02	053	21-03	081	18-04	109	16-05	137
23-02	054	22-03	082	19-04	92110	17-05	138
24-02	055	23-03	083	20-04	111	18-05	139
25-02	056	24-03	084	21-04	112	19-05	92140
26-02	057	25-03	085	22-04	113	20-05	141
27-02	058	26-03	086	23-04	114	21-05	142
28-02	92059	27-03	92087	24-04	92115	22-05	92143

Table K.1. (cont'd)

23-05	92144
24-05	145
25-05	146
26-05	147
27-05	148
28-05	149
29-05	92150
30-05	151
31-05	152
01-06	153
02-06	154
03-06	155
04-06	156
05-06	157
06-06	158
07-06	159
08-06	92160
09-06	161
10-06	92162