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**PAULOWNIA AGROFORESTRY IN CHINA -
A CONTRIBUTION TO ADAPTIVE RESEARCH**

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ABSTRACT

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RESEARCH.

Nearly 2 million hectares of farmland have been intercropped with rows of paulownia (*Paulownia elongata*) trees in the North Central Plain of China. Paulownia provides an important timber source and long term income as a "saving bank". It is in harmony both ecologically and economically with the understorey winter wheat (*Triticum spp.*), the farmers' "survival food". Funded by ODA (Overseas Development Administration, UK), the present study investigates the role of the paulownia-crop intercropping (PCI) system in rural socio-economic development. It also identifies the socio-economic and technical factors that affect the promotion and success of PCI and examines the needs and problems encountered in the development of PCI under the present "Individual Responsibility System" (IRS). A socio-economic survey on PCI in Chengwu, Shandong Province, as a case study, shows that paulownia intercropping is an important component of socio-economic development in the poor areas.

Existing policy on paulownia intercropping and land distribution causes some problems for farmers, and technical guidance on optimum tree spacing, management and maximum production of PCI with emphasis on wheat yield is eagerly awaited.

An adaptive research approach to address the farmers' needs was applied in this study by interpreting scientific research to produce a useful, simple and practical model to optimise tree spacing for a range of scenarios.

Data used for analysis were collected during 1983 - 1992 from an experiment station at Dangshan, Anhui Province, on a project supported by The International Development Research Centre (IDRC) of Canada. The important components of the PCI system including tree growth, growth and yield of understorey crops, and light, as a key microclimate factor affecting understorey crops, were analysed to further understanding on the natural functioning of the PCI system. The denser the spacing, the earlier the fast-growth stage of the trees occurs. However, there was no significant difference among the spacings in any of the growth variables at the end of the study in the 10th intercropping year. There are always reductions in light transmissivity (LT) and Photosynthesis Active Radiation (PAR) and the proportion of PAR to total solar

radiation in the intercropped fields due to light interception by the trees. These effects are more apparent in areas near the trees, in denser spacings, in older paulownia, and when the paulownia have fully developed leaves. Intercropped wheat benefits from the modified microclimate, such as reduced temperature and increased soil water contents and relative humidity. Air temperature is the only microclimatic factor determining wheat leaf conductance, which gives a negative effect. Wheat yields start to decrease when LT is reduced to 81.8% as an average and about 10% higher for dense spacing and older trees and 10% lower for larger spacing and younger trees. Leaf conductance, biomass and yield of the intercropped wheat are slightly above those in open fields when the trees are young and widely spaced, but lower otherwise. The distribution of wheat yield across the alley in the intercropped field was similar to that of light, apart from in the dense spacing of older age trees where the competition of tree roots for nutrients probably also reduces yields near the tree rows. The reduction of leaf conductance and yield of summer crops by paulownia is greater than for the winter crop due to shading by the trees and different response of the crops. The yield reduction of cotton and maize is 15% at the edge of the tree canopy and as much as 50% near the tree rows.

Regression models were developed to express DBH (used as an index of tree growth) as a function of age; light transmissivity as a function of distance across the alley for different spacings and ages of trees; understorey wheat yield as a function of distance across the alley for different spacings and ages of trees; and understorey wheat yield as a function of light transmissivity. The models can yield information on rates of tree growth and changes in understorey wheat yield and LT, by inputting tree age, and distance from west row under a given tree spacing. The output will help farmers optimise the tree-row spacing depending on whether their objective is to maximise timber production, crop production or the economic return from both. The models could also provide useful and practical technical guidance to help decision-making and settle disputes among farmers and between farmers and the local authority.

Models were validated by the data collected during 1993 - 1994 from farmers' fields in Chengwu, Shandong Province. All the models perform well in these conditions and it is recommended that they be applied to PCI in all parts of North Central Plain of China due to the similarity of climate and soil conditions. Optimum tree spacings under different scenarios were also recommended.

The present study demonstrated the approach of adaptive research in PCI agroforestry by linking scientific findings to rural socio-economics and farmers' needs. It indicated the equal importance of three components: socio-economic survey, experimental data analysis and interpretation, and application of scientific findings. Socio-economic survey at the village or farm level is essential for identifying the needs of farmers from PCI under IRS conditions. Data analysis helps scientists and extension officers to understand and interpret the dynamic eco-biological interactions of PCI systems . Regression modelling is a practical, efficient, simple and easy way of interpreting and applying scientific findings to a realistic PCI system.

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observations related to August.

LIST OF SYMBOLS AND ABBREVIATIONS

<i>a</i>	Light transmissivity (fraction of incident radiation at a given wavelength that is transmitted by an object)
<i>r</i>	Light reflectivity (ratio of the incident flux to the reflected flux at the same wavelength)
<i>t</i>	Light absorptivity (fraction of incident radiant energy at a given wavelength that is absorbed by a object)
<i>C_s</i>	Leaf conductance ($\text{mmol m}^{-2} \text{s}^{-1}$)
<i>r_a</i>	Stomata resistance at the upper side of the leaf (cm s^{-1})
<i>r_b</i>	Stomata resistance at the lower side of the leaf (cm s^{-1})
<i>C_c</i>	Leaf conductance of cotton ($\text{mmol m}^{-2} \text{s}^{-1}$)
<i>C_{ew}</i>	Crown range at east-west direction (m)
<i>C_{sn}</i>	Crown range at south-north direction (m)
<i>C_w</i>	Leaf conductance of wheat ($\text{mmol m}^{-2} \text{s}^{-1}$)
DBH	Diameter at breast height of tree (cm)
H	Height of tree (m)
LAD	The integral area index with respect to time from ear development to maturity (also known as Watson's leaf area duration)
LAI	Leaf area index (plan area of leaves per unit ground of foliage)
LC	Leaf conductance ($\text{mmol m}^{-2} \text{s}^{-1}$)
LT	Light transmissivity (in this study, it is defined as the percentage of total solar radiation (SR) received at 10 cm height above the crop canopy compared with the amount received in a open field)
PAR	Photosynthesis Active Radiation (quantum flux density ($\text{mol m}^{-2} \text{s}^{-1}$ or $\text{mW cm}^{-2} \text{day}^{-1}$ ($\text{J cm}^{-2} \text{day}^{-1} = (\text{mW cm}^{-2} \text{day}^{-1})(3600/1000)$
R _r	Light reflectivity (ratio of the incident flux to the reflected flux at the same wavelength)
SR	Total solar radiation ($\text{J cm}^{-2} \text{day}^{-1}$)
<i>T_a</i>	Temperature ($^{\circ}\text{C}$)
TK	Trunk height under the first bottom branch (m)
VPD	Vapour pressure deficit (mb, the difference between the actual vapour pressure and the potential vapour pressure at saturation)
PCI	Paulownia-crop intercropping

IRS	Individual Responsibility System
CAF	The Chinese Academy of Forestry
ODA	The Overseas Development Administration of United Kingdom
IDRC	International Development Research Centre of Canada

TABLE OF UNIT

μm	= millimivron
cm	= centimetre
$^{\circ}\text{C}$	= degree Centigrade
d	= day
g	= gram
ha	= hectare
hr	= hour
mu	= 1/15 ha.
m	= meter
mb	= millibar
kg	= Kilogram
Joule	= watt sec = 0.239 Cal = 1×10^7 ergs
s	= Second

1. INTRODUCTION

China has a population of more than 1.2 billion people, with an annual natural growth rate of nearly 1.9%, in a land area of 9.6 million km². Arable land is only 10.4% of the total territory. Traditionally, the main economic base is agriculture. Some 80% of the population are farmers, though only an average of 0.1 hectare of arable land is available per capita compared with 0.18 ha in 1950. Most arable land is of poor soils, with degradation problems due to over-exploitation. There is tremendous demand for the very limited land available to meet the basic needs of food, fodder, fuelwood and construction materials. "No country in the world has ever encountered a need for afforestation as great as that which confronted China when the People's Republic was established in 1949. China's efforts since then to 'make green the motherland' eclipse by far the afforestation efforts of any other country in any time. The magnitude of the forestry problem which the new government faced stemmed not only from the sheer size of the country, with its extremes of climate. It was determined by the changes wrought in the landscape by continuous human occupation and cultivation over a longer period than anywhere else in the world" (Westoby, 1989). Chinese people consider every piece of their land as a precious resource to be diligently safeguarded and meticulously managed. It is in this context that an alternative land-use system, known as agroforestry has been extensively practised. Systems that today would be described as agroforestry were first recorded more than 2000 years ago in China (You, 1991). Lowdermilk (1932) discovered that "extensive farm woodlots of Simon's poplar (*Populus simonii*), etc. were cultivated for construction material on farmland" in the temperate regions, as cited by Richardson (1966). After a one month tour in 1974, Westoby (1989) concluded that "China has succeeded in something that very few other countries have achieved, in establishing a truly effective and fruitful integration between agriculture and forestry". Especially since policy reform in early 1980s, agroforestry has been accepted by the Government, local authorities and farmers as one of the most appropriate alternative technologies for promoting the integrated rural economic development in the poor areas. Agroforestry has become especially popular in the densely populated North Central Plain where, as indicated by Gold and Hanover (1987), the most extensive system of tree/crop admixtures is found throughout the northern provinces of China.

The North Central Plain is one of the country's major agricultural production centres. It accounts for two-thirds of the country's production of wheat, one of the Chinese staple foods. The agroforestry technology commonly practised in the area is mainly a form of agrisilviculture or more specifically alley farming, in which trees, rows of shrubs or

other woody perennials are intercropped with agricultural crops. The primary tree species for intercropping on the farm are timber trees such as paulownia (*Paulownia spp.*), nut trees e.g. Chinese date (*Ziziphus jujuba*), walnuts (*Juglans regia* L.), persimmon (*Diosphyros kaki* L.), shrubs e.g. Chinese ash (*Fraxinus chinensis*), *Amorpha fruticosa* L. (false indigo) and basket willow; and fruit trees, including apple (*Malus spp.*), peach (*Prunus persica*), pear (*Pyrus spp.*), grape (*Vitis spp.*), haw (*Crataegus laciniata*) and plum (*Prunus spp.*). Other timber trees such as poplars (*Populus spp.*), willow (*Salix spp.*) and black locust (*Robinia pseudoacacia*) are usually planted around farm boundaries and along roads and canals, to form shelterbelt grids. Paulownia is the tree most extensively planted by farmers in this region. To date, about 2 million hectares of farmland have been used for intercropping of paulownia with winter wheat (*Triticum spp.*), corn (*Zea mays*), cotton (*Gossypium spp.*), vegetables and medicinal crops (Plate 1.1).



Plate 1.1 Rows of paulownia (40 m apart) intercropped with winter wheat in the narrow strip lands managed by different individual families.

Paulownia is the only arborescent genus in the family **Scrophulariaceae**. There are nine species in this genus. Seven of them are naturally distributed only in China whereas white paulownia (*P. fortunei*) extends into Vietnam and Laos, and hairy paulownia or fox glove tree (*P. tomentosa*) into Korea and Japan. Paulownia grows in 23 provinces, municipalities and autonomous regions in China. Purple paulownia (*P. elongata*) (used as paulownia in this text) is the most widely planted on the farmlands. It is a very adaptable, extremely fast growing and multi-purpose species. Its rotation is normally 10 years with an average timber volume of 0.4-0.5 m³, a height of 12 m and an annual growth rate of 3-4 cm per year in diameter at breast height (DBH). Its wood does not crack and deform. It is light but strong and ideal for construction, the manufacture of furniture, plywood and musical instruments. Paulownia flowers are good sources of nectar and have medical value in curing bronchitis; the leaves are desirable fodder for livestock as they contain not only the eight essential amino acids but are also rich in protein and micro-elements. Paulownia is mainly cultivated in the form of intercropping and "four sides plantations" meaning the continuation of trees along side roads and water courses and around residential areas and villages. The tree's most important characteristics are its canopy and root system structures and its phenology that make it unique as a tree species for agroforestry. Paulownia's branches and leaf arrangement are sparse with late leaf emergence (end of April) and late leaf fall (end of October, by the first frost), which is different to the growing season of winter wheat (November-May). The sparse crown allows a large amount of light to penetrate through to understorey crops. The deep root system does not compete directly with crops for soil nutrients and water. Therefore, paulownia is considered the most promising multiple purpose agroforestry species (Zhu, 1986 and 1991; Wu and Dalmacio, 1991; Zhao and Lu, 1993 and Wu, 1993).

The massive paulownia-crop intercropping (PCI) systems were formed in China in the middle 1970s under collective ownership and attracted attention from many scientists and funding agencies. Chinese Governments (Central and local) have invested in PCI research since the early 1970s. The International Development Research Centre (IDRC) of Canada granted an integrated research project on PCI systems in the early 1980s for a decade. Numerous data on biological and ecological aspects of PCI were collected on controlled experimental sites during this period. It was reported that wheat yield was increased in the areas most distant from the trees in larger spacings (tree rows 30 - 50 m apart) and decreased under the tree and in the denser spacings (tree rows 6 - 10 m apart). Light is a key factor affecting yield (Zhu, 1986 and 1991; Wu and Dalmacio, 1991 and

Wu, 1993). However, only parts of the data were analysed. Most of the research results were presented as a strong scientific base for scientists to understand the bio-ecological interactions of the PCI system rather than for farmers to use to enhance their production. It is uncertain whether research results can be applied to the present PCI systems which, since the imposition of the Individual Responsibility System (IRS) in the early 1980s, are operated by individual farmers working small parcels of land. There have been arguments between foresters, agronomists and/or local authorities on proper paulownia spacing, and complaints among farmers about the present spacing policy. Farmers do not have enough information on dynamic management of the PCI system. Since it takes a long time and needs a large scale of experiment to obtain systematic data on PCI systems due to the nature of trees, the previous experimental data are regarded as very precious. Further analysis of the data and the development of models relevant to present PCI practice is considered an alternative way of addressing farmers' needs. However, the data closely reflect the production conditions and uniform management at commune or production brigade level under the previous collective system, when traditional cultivation methods were in practice. Under the present IRS regime, the traditional farming methods have been replaced by scientific cultivation using irrigation and fertilisation. It may be dangerous to apply research results from controlled experiments at research stations directly to farmers' fields under IRS without validation. As reported by Carter (1996), alley farming has lower-than-expected popularity because of poorer performance on farm than on station and some systems do not address farmers' particular needs. In practice, the author also found that farmers, as direct users of PCI technology in the present IRS system, have difficulties in accessing and interpreting the available findings. It was in this circumstance that the UK Overseas Development Administration (ODA) granted a 3-year adaptive research project, **"Farmer centred agroforestry research and development in Eastern China: methods for optimising tree spatial arrangements and fodder value"** in November 1992. Silsoe College, Cranfield University received the grant in co-operation with the Chinese Academy of Forestry (CAF).

The general aim of the project was the alleviation of poverty in rural areas through the improvement of food production and the provision of products from woody perennials. The improvement of food production through PCI is the main focus of the present study. However, the adoption and success of PCI are determined by many factors which may be broadly categorised into predominantly technical and predominantly socio-economic, although there are close links between these categories (Carter, 1996). The author has also observed that technical issues were more common under the uniform management

system, such as adopted on collectives and research stations, while today socio-economic issues and technical aspects are both important and closely linked to each other under the IRS. Certainly the development of agroforestry needs to embrace a combined technical and socio-economic approach from the very start; with the rural land user being intimately concerned with the available choices at every stage. The objectives, resources and socio-economic restraints underlying the adoption of tree-based farming systems will be more complex than in arable crop production systems. Even the techniques of tree production and distribution could be optimised through quite different pathways (Huxley, 1983). Farmers' needs from and perception of the PCI system should be determined before considering the optimal tree spatial arrangement. One could claim that the optimum tree spacing is required knowledge only if it addresses the farmers' particular needs in the realistic situation of farmers' fields and socio-economic conditions. Thus understanding the socio-economic background of farmers in PCI areas is one of the key components of the present study. How to interpret the scientific findings and apply or adapt them directly to the ultimate user - the farmers, is not clear to PCI scientists. Improving this situation by providing meaningful information to farmers is the second component of the present study.

The specific objectives of the research reported in this thesis are:

1. To investigate the general background, socio-economic roles, existing problems and potentials of PCI in present rural development under the IRS regime.
2. To understand farmers' needs from and perception of PCI systems
3. To further understanding of the physical aspects of the PCI system by analysing available data and developing a modelling approach so as to generalise and simplify the scientific findings towards farmers' needs for future improvement of PCI
4. To validate modelling results in farmers' fields.
5. To select the optimum paulownia tree spacing based on (2) and (4).

In order to achieve the above objectives the general approach used in this study is shown in Figure 1.1.

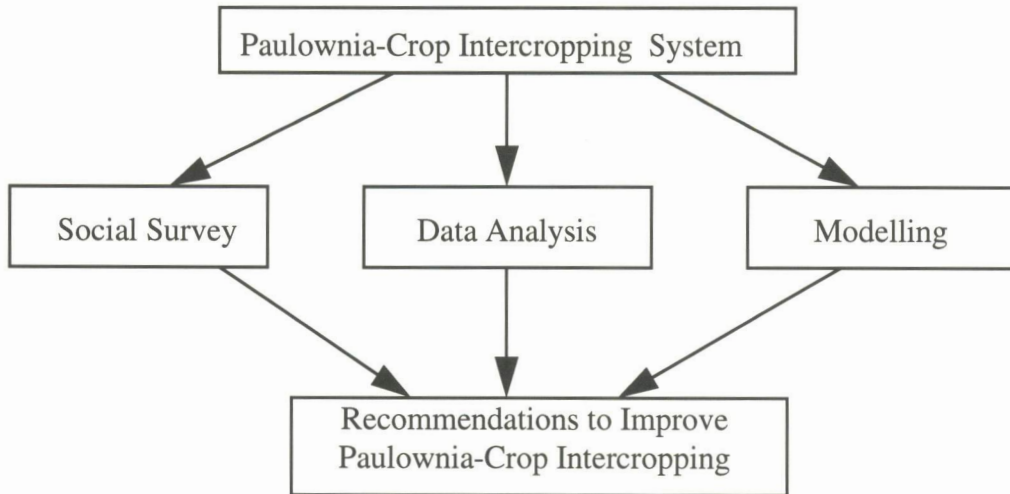


Figure 1.1 General approach of the research

2. AGROFORESTRY AND PAULOWNIA-CROP INTERCROPPING SYSTEM

2.1 General Background

The North Central Plain crossed by the Huang (Yellow), Huai and Hai Rivers is also called the Huang-Huai-Hai Plain. It constitutes about 10% of the country's total land area, covering 40 million hectares of farmland, and is inhabited by more than 350 million people. The maximum population density in the North Central China Plain is 552 persons per km. The climate is temperate monsoon. Mean annual rainfall varies from 400 mm in the north west to 1,000 mm in the south and south east, with 80 per cent falling from July to September. The mean annual temperature is 12-14°C. The soil is alluvial, characterised as sandy and saline-alkaline.

There are two crop seasons per year. Winter crops such as winter wheat, oil-seed rape and garlic, are sown in October and harvested at the end of May to early June of the following year. They are followed by summer crops such as maize, cotton, peanuts and soya bean, which are sown in early June, and harvested in September or October before the sowing of winter wheat. Winter wheat is the staple food and principal crop of the local farmers. Maize is usually for additional food for people and feeds for livestock, cotton is generally for cash and additional home weaving, and soya bean is for both additional protein and cash. Most villages in this region have access to electricity. Each household has its own pumping well for drinking water.

2.2 History of Agroforestry

There is a saying in China that "one inch land is worth of one inch of gold". With dense population, food crops have always had priority and been cultivated in every 'inch' of arable land. The enormous demands for fuelwood, construction materials and other necessities from the limited resources have led to over-exploitation and a vicious and fragile spiral of ecological degradation. Frequent natural disasters have occurred. People have suffered sandstorms, droughts, floods and starvation at intermittent periods. In order to diminish the above problems and ameliorate the degraded agriculture ecosystems, agroforestry as an alternative land use system, has been extensively practised in the North Central China Plain.

The present agroforestry systems in this region comprise "four sides plantations", farmland intercropping, shelterbelts and small woodlots (normally in the waste lands). The recent history of agroforestry development in the region can be divided into four

phases (Zhang et al., 1993). The first phase (1950-1957) was the sand- and wind-breaks stage. As soon as the Peoples' Republic of China was established, the Chinese Government realised that serious deforestation and over-exploitation of land had occurred due to the constant wars. Party activists mobilised the rural population to raise the production of staple grains and to carry out the related giant tasks of 'making green the Motherland' and taming the rivers. Within three years, large scale protection forests in the areas affected by sandstorms were developed by collective co-operation funded by state subsidies. For example, five dune fixation belts (each some 520 km in length and 1-2.5 km wide) were established in the east of Henan Province; and about 34,667 ha of sand- and wind-break forests and 1,390 km of river protection woodlots were set up in Hebei Province. In total 411,000 ha of farmland were protected. In 1956, the Central Government proposed that "trees should be planted in all possible places around residential areas and villages, and along with roads and water courses" and "who plant tree, who own the trees". Under the encouragement and support of the Government, "four sides plantations" started to take form with contributions of individuals and local governments. The second phase (1958-1966) was the farmland shelterbelts stage. In 1958 (the "Great Leap Forward"), most trees were cut down as fuel for massive steel making in small local factories and sources for small pulp and paper plants in each commune, which were newly established as a result of Party's unrealistic targets and confused objectives. Forest cover rate dropped to 1% in 1961 from 5% in 1955. The years 1959, 1960 and 1961 were excessively dry in China and this led to wide-spread famine. To offset the damage, the Central Government issued regulations in 1961 on governing, protection and development of forestry with emphasis on "four sides plantations". Local governments also set up regional relevant forestry policies for the protection of farmland. A few destroyed sand- and windbreaks were re-established and "four sides plantations" were extended to farmland. Small scale farmland shelterbelts and intercropping were established in a few places. Much progress of tree planting around the residential areas was also achieved. During the third phase (1967-1977), tree planting was considered a fundamental aspect of agriculture. However, there was not much progress at first due to the upheaval of the Cultural Revolution. In 1973, the national forestry development plan was drawn up. Tree planting in the residential areas was rapidly extended to the farmland. Shelterbelts and intercropping were taking shape in most areas as part of the "Farmland Fundamental Construction". Scientists started to do research again after it was almost banned during the ten years of Cultural Revolution. The fourth phase (1980-present) has seen major developments in multiple storey and more diverse agroforestry systems. Since 1980, the collective farming system has been replaced by one of individual responsibility. Agroforestry has been well developed and

favoured in most parts of the region in terms of its diversity, sustainability, productivity and protection. This was largely contributed by individual farmers due to the diversified management and practice of each individual and stable and preferential forestry policies. Today about 72% of farmland in this region is under protection of shelterbelts and intercropping (Song, 1991).

Most of trees around the "four sides" and in the farmland were fast growing species, which provided quick income for farmers. They encompassed not only timber and fuel trees but also orchard trees and economic crops. Peasants were not blind to the benefits of shelterbelts: they could see new land under crops after dune fixation, and could recognise the lower incidence of flood and erosion after protective afforestation (Westoby, 1989).

2.3 The Collective and Individual Responsibility System

The administrative regime was based on a collective ownership system before policy reform in 1978, and agricultural production and marketing were controlled by central planning. The People's Communes were the government institutions at the grassroots level in rural areas. Production was organised in a three-level administration by commune, production brigade and production teams. They wielded great power in government administration and economic planning and management. Farming was monitored by the production brigades and implemented by the production teams.

Usually the production team made decisions on production, based on the plan or task proposed by the commune. Production level very much depended on the knowledge of the team leaders. Farmers only did the field work as instructed by leaders, and they shared the products after their submission to the local government. The land was productive only in politician's reports, never in realistic production. The farmers were never self-motivated to work hard and never had enough food to eat.

The Individual Responsibility System (IRS) began in 1978, after the previous communes were replaced by the township or Xiang. The main role of Xiang is to promote social economic development and responsibility for administrative affairs such as family planning control. The ownership of land lies with the local government. Farmer households became the basic production unit. As a consequence, centralised management is integrated with decentralised management. The production plan issued by the central government is a guide for the grassroots production organisations linked

through the hierarchical administrative system as shown in Figure 2.1. Farmers take on the production decisions and management within their contract with the production team. They have to submit some amount of their produce to the local government for land tax and administration fees. Under the new system, farmers are given greater freedom to determine their own production, whilst being allowed to enter the free market to sell their surpluses. They are also given priorities for the development of rural commodity production, such as small scale enterprises, specialised in particular types of production. After the reform, all peasants became more industrious and the land became more productive.

The IRS was developed and completed during 1980 - 1982 in most areas of the North Central Plain. The land was divided equally among the members of the production team. Farm sizes are small. Their boundaries are dictated partly by the existence of roads and paths, and partly by the desire to allocate irrigatable and non-irrigatable land fairly. Finally, farmers prefer long strip fields because they are easier to plough. As a result, farms consist of long thin strips, 3-15 m wide.

The land is redistributed every 10 years. Minor additions for sons' brides and new-born babies, and subtractions for those who die or for out-marrying daughters, are carried out annually on designated "flexible land". This land area constitutes about 10% of the total. A 10-year contract is considered an appropriate time period - if it is longer the newly increased population would have no land; if it is shorter, farmers would not invest (e.g. in fertiliser) and land would be less productive. Most farming is done manually. Some small farm machines such as tractors (ploughing, harvesting and threshing) are commonly used for wheat farming.

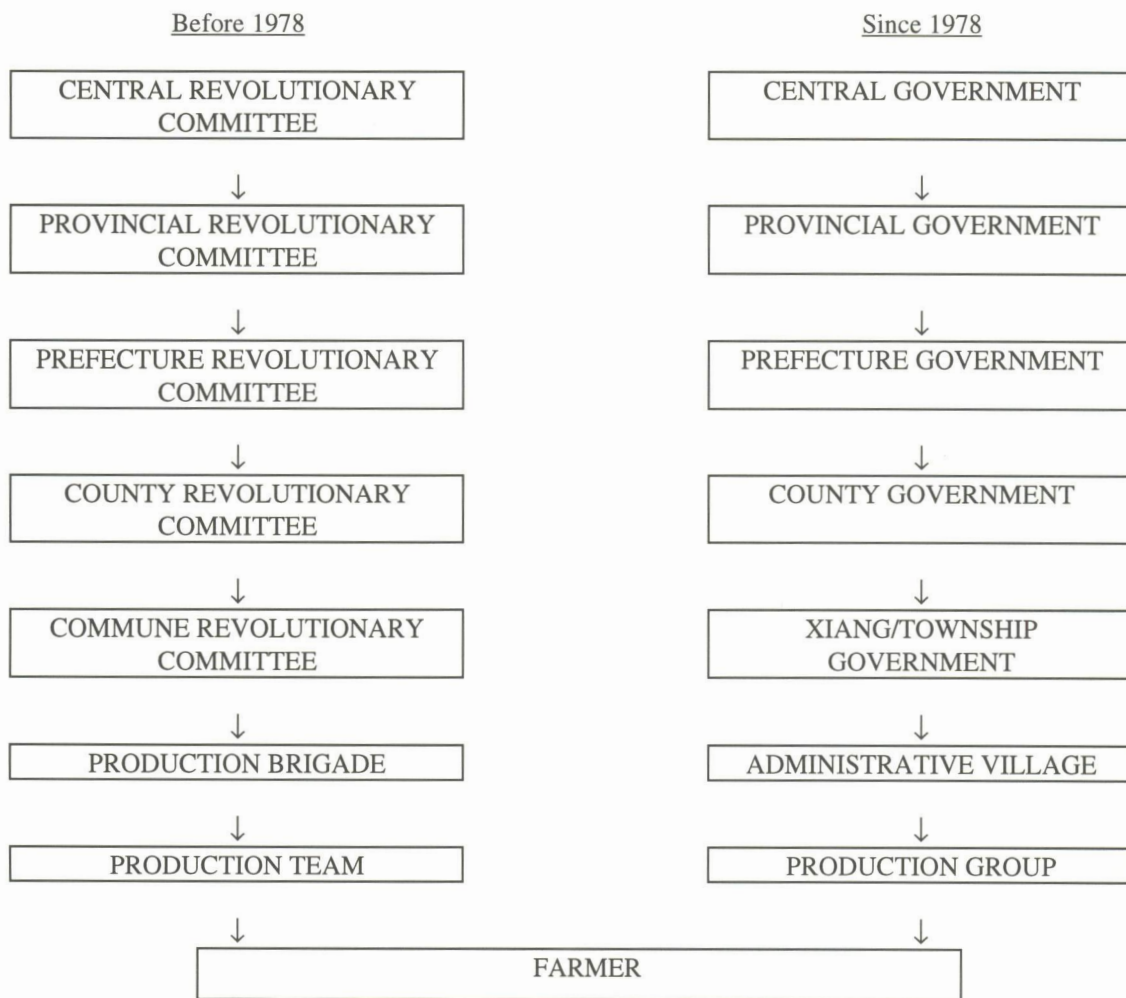


Figure 2.1. Chart showing hierarchical structure of authorities and their relationship to the farmer

2.4 Paulownia Agroforestry

Paulownia is one of the main timber species in the North Central Plain. It is called "Paotong" by local farmers which is the general Chinese name for all the species. Traditionally, paulownia was planted in the residential areas for timber. Paulownia-crop intercropping (PCI) was originally generated by farmers in Lankao County, Henan Province, one of the poorest counties in China, in the early 1960s. Therefore, the species used for intercropping, *Paulownia elongata*, is known as "Lankao Paotong" in Chinese. The General Secretary of the Communist Party of Lankao County, Jiao Yulu, realised that paulownia could be a promising resource to improve the poor condition. He encouraged his farmers innovatively to plant paulownia on their land. He devoted his life to the overall development of Lankou. In 1964 Jiao Yulu was set up as a good example of the Communist Party members, and is still regarded so today. His deeds were written in books and made into films. Lankao provided a good example of use of paulownia-crop intercropping to improve rural economic development. Immediately, PCI became well known nation-wide. The practical experience attracted many local authorities and scientists. In the middle of the 1960s, neighbouring counties such as Minquan, Shuixian, Luyi, Yuxian in Henan Province and counties in the neighbouring Provinces such as the southern counties of Hebei, the northern counties of Anhui and the south-west counties of Shandong Province, followed. Small plots of demonstration plantations were established in co-operation between the local government and farmers' collectives. In order to encourage farmers to adopt the new technology, local governments granted funds to the forestry bureaux. As a representative of the local government, the forestry bureau provided free saplings and technical services to the farmers. Farmers as a collective unit (a brigade or a village) had to follow the government's requirement to provide land and labour. When the trees were harvested, local governments shared 20% of the income for reinvestment and the rest of the income went to the farmers' collective. Many farmers did not like the idea of planting trees in the farm. However, as labourers on the farm, they had no choice but to obey the local authorities. Trees were planted in a general design at the village and/or commune level in collective ownership. Over several years, numerous villages followed the demonstration because the trees showed promising performance in terms of fast growth and harmony with crops. In the middle 1970s, the paulownia-crop intercropping technology rapidly extended across the region under the collective system. There were lessons to be learned, too, because in some places, paulownia was planted just for political reasons, ignoring land suitability. The first generation of paulownia was harvested during this period in a collective way. Most of the income from the farm was

used for welfare such as construction of irrigation systems, electricity, schools and hospitals (Wu, 1992a). After seeing the benefit from paulownia, farmers started to accept paulownia as a natural part of their farm. Since the land reform (1979-1982), trees have been planted by farmers themselves spontaneously on small pieces of land. Trees are planted in the middle of the land by each household or along the edge of two household's land with trees shared by two families. The spacing of paulownia varies more with the size of land parcels than was the case at the time of the collectives. On 27 February 1983, the Chinese reform pioneer, Deng Xiaoping especially requested to visit PCI fields in Yanzhou, Shandong Province during his journey to southern China. "I learnt from newspaper that *Paulownia* is a treasure, I should get off the train to have a look in the field" Deng said. During his 50-minute visit, Deng commented that "farmers, who are planting trees should look at the quality. Paulownia has good wood properties, high values and is fast growing. It should be extended in a large scale". Deng's visit and comments brought some inspiration to the local authorities and farmers. More paulownia trees were planted on the farms during 1984 and 1985.

Along with the extension and development of PCI, research work was also carried out. The research was divided into three phases (Zhu, 1991):

- 1). A learning and investigating period from 1973 to 1976, the beginning of the massive extension of PCI. The work focused on examining the existing PCI system established in the 1960s and investigating its adaptability and potential. A systematic research plan was worked out in 1973 by scientists from CAF in co-operation with scientists of Henan Agricultural University and Henan Agricultural Research Institute.
- 2). Primary study on species selection and cultivation of paulownia, microclimate and crop yield from 1976 to 1978. The studies were conducted with limited funds in the fields of the production brigades, where the traditional and simple way of cultivation was still in practice. This phase provided a strong base for future research. The primary findings were presented and awarded a second prize in the First National Scientific Conference in 1978 after the Cultural Revolution.
- 3). Comprehensive and in-depth research from 1983 to 1992. Since 1983, the International Development and Research Centre of Canada (IDRC) has offered great support to CAF in paulownia research. In addition, this research was listed as a key national project and received some funds from the Central Government. A PCI experimental station was established in Dangshan County, Anhui Province in early

1983. Integrated research was carried out at the station and demonstration plots were set up in Henan, Anhui and Shandong Provinces. The research emphasised the ecological parameters (microclimate, energy balance, water use, animal fauna, soil properties), ecophysiological parameters (transpiration, growth, biomass, grain quality and yields of under storey), cropping systems and patterns (understorey crop selection, intercropping patterns, spatial arrangement and management of trees), utilisation of trees (timber, fuel wood, fodder), and economic evaluation of PCI at the field level in controlled experimental conditions. In-depth and broad technical information on PCI obtained during this period has provided a strong scientific base for scientists to understand the natural functioning of the PCI system.

Nevertheless, the previous research on PCI was limited to scientific aspects of the system at the field level. The users of the scientific findings were scientists and extension officers. Farmers just followed passively. There were barriers or distances between scientists and farmers, and between research and applications. After several years of land reform, the food production increased tremendously especially after 1984 (Du, 1994). Farmers invested more, especially in irrigation, fertilisation and mechanisation. The agricultural system became more diverse to meet the multiple needs of each household from their small farm. The role of farmers, especially the head of each household, changed from labourer, into farm manager and decision-maker. Farmers now need to know how to plan and manage their farm for maximum production and marketing their surpluses. The new role for farmers brings about a new task for scientists. Scientists have to understand not only the physical aspects of the PCI system but also farmers' needs; they need to interpret the research results in a simple and practical way at the farm level. This new approach marks the start of a fourth phase of PCI research to which this thesis aims to make an initial contribution.

3. THE ROLE OF PAULOWNIA-BASED AGROFORESTRY IN RURAL ECONOMICS OF THE NORTH CENTRAL CHINA PLAIN - A CASE STUDY IN CHENGWU COUNTY

What is the status of a peasant's life or socio-economic background now? Do farmers still plant paulownia trees on their own initiative since the policy reform? Is agroforestry still playing an important role in their lives? What are farmers' needs from and perception of the PCI system? These questions are important to understanding the context within which any research on optimising the spatial configuration of trees would be applied. To address these issues of farmers, a case study was carried out in Chengwu County, Shandong Province, one of the poorest counties in the North Central China Plain but one where PCI is commonly practised.

3.1 History of Agroforestry Development in Chengwu County

Chengwu comprises 18 townships/communes (Xiang), 506 administrative villages and 1,313 natural villages, inhabited by 588,751 people of whom 93 per cent are farmers. The total arable land is 72,435.6 ha, with an average of 0.13 ha for each farmer. The economic base is agriculture. The total gross income in 1990 was 806.85 million ¥ (Yuan; £1 = ¥ 8-9 before 1993 and ¥ 13 in 1994), with 56.6% coming from agriculture. The forest income was 5.4% of the total agricultural income (Li, 1991).

There were only 0.7 ha of forest land and 431,000 trees sparsely planted around villages in the County in 1949. Forestry development was slow during the 1950s and 1960s. The major form of forestry was "four sides" plantations. Some forests were destroyed during the Cultural Revolution. In 1974, Chengwu County first introduced paulownia trees on to the farm land. Farmers were reluctant to accept the new agroforestry technology despite the free provision of saplings and advice. However, they had no right to refuse it due to the collective system.

Several years later, farmers realised that the trees have little effect on the crops, especially in the early 1980s when the first generation of trees was harvested. A lump sum of cash came from sale of the paulownia trees. Paulownia was considered one of the most profitable plant species to grow on the agricultural land.

The IRS was developed in Chengwu County during 1980 to 1982. The land was divided equally among the members of the production team. Farm sizes are small. Farm boundaries are dictated partly by the existence of roads. After the land was

distributed, most farmers were enthusiastic to plant paulownia trees on their small-holdings. Local authorities constantly encourage farmers to plant more trees. The former County Chief, Mr. Li Yucai (who was promoted as Director of Shandong Provincial Forestry Department and later became Director of the Planning Department and then Vice Minister of the Ministry of Forestry) especially realised that a significant change in farmers' lives could be brought about through planting more paulownia trees on their farms. By 1984, there was a total area of 3,093 ha of woodland, 30,923 ha of shelter belts and 10,644 ha of paulownia intercropping. Four sides planting on residential areas (Home Gardens) consisted of 437 million stems.

If all farmers wanted to plant paulownia trees on their small-holdings, tree spacing would be too dense to produce sufficient understorey food. Chengwu County government issued a paulownia-crop intercropping policy in 1984. All arable land which is suitable for paulownia should be planted, other areas should be planted with poplars as a shelter belt. Spacing of paulownia must be controlled with trees planted at 5 m intervals along the row and the rows between 20 and 40 m apart, i.e. 5x20-40 m spacing. Each village set up its own nursery through specialised farmers. Some 2,000 officials came to different villages to work for one month with the farmers planting paulownia trees in order to organise tree planting properly.

There were no more free saplings provided to individual households by the local government. Farmers who did not have nurseries and had no money to buy saplings could pay by wheat after the next harvest. This meant all households could have saplings to plant. Farmers were very enthusiastic to follow this policy. Some of them set up their own nurseries under the guidance of forestry technicians from the County Bureau or Xiang forestry stations. Since the land was divided into small portions for each household, not every household could plant trees on their farm as they wished. Some 2,000 county officials as well as local leaders from Xiang and administrative levels, monitored the planting - they decided which households should plant trees. Those who have a wide strip of land could plant trees in the middle of the strip, but if the strip is narrower than 6 m, trees should be planted at the edge of the land and shared with neighbours. Trees planted in 1985 covered a larger area than the total accumulated surviving forest area of previous years. Total woodland was 6,404 ha, nurseries 100 ha, paulownia-intercropping 28,950 ha, and shelter belts 29,333 ha.

By 1990 the forest cover reached 22.6 per cent of the land area from 10.1 per cent at the end of 1983. Some 39,519 ha had been intercropped with paulownia, which accounted

for 73.7 per cent of total land suitable for paulownia-crop intercropping. Paulownia intercropping and "four-sides planting" are the major components of the county's forest (Table 3.1).

Table 3.1 Forest component (ha) in Chengwu County, 1990.

Total area	Total forest area	% Forest area	Pure forestry		Trees in non-forest land		
			Woodland	Nursery	Shelter net	Paulownia inter-cropping	Home garden planting
98829	22303	22.6%	3781.5	3.7	4027.2	6639.6	7846.6

Adapted from Li, 1991.

Many trees were felled as farmers lost confidence in paulownia-crop intercropping systems during 1990-1992. Farmers had to fell their trees due to the second phase of land redistribution. Paulownia planted in previous years were still too dense to produce sufficient food for some farmers. International markets were banned following events in Beijing in 1989, and there were no local markets for paulownia due to timber surpluses after the extensive felling. Many farmers tried to plant more fruit trees in order to have a higher income. However, results were disappointing again, because fruit trees required greater husbandry skills and constant surveillance, since children started to pick fruits as they formed.

This background provided the starting point for the survey described in this chapter.

3.2 Methodology

3.2.1 Selection of village/production group

The survey was carried out in Goucun and Changqiao villages, Chengwu County (Figure 3.1), where the paulownia intercropping experimental sites of the ODA project are located. The time schedule of the project did not allow a large scale survey.

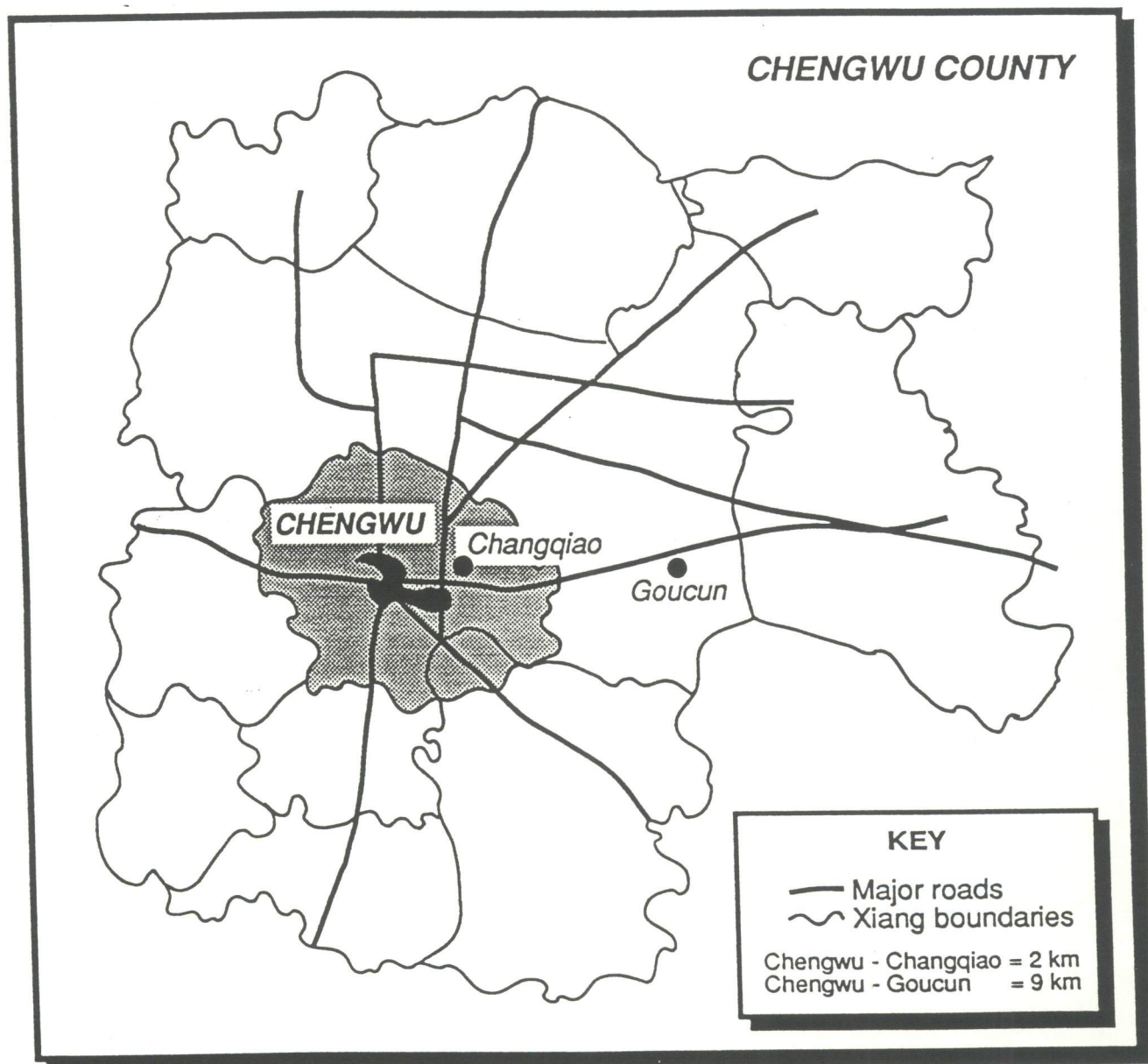


Figure 3.1 Location of Goucun and Changqiao.

Goucun is the capital of Goucun Xiang. It is 9 km from the County capital, Chengwu. There are 17 production groups, 1,000 households and a population of 4,000. The interview group is Production Group 7. There is a total of 65 households amounting to 285 people. Changqiao village is 1.5 km from Chengwu. It is a small village with 5 production groups and a total of 487 people. The interview group, Production Group 1, has 22 households and 99 people.

3.2.2 Selection of households

Location and layout of each household were first sketched by each village leader. The aim was to select 50 per cent of the households, sampling every alternate house from the sketch map for interview. However, only 29 households (44.6 per cent) were interviewed in Goucun.

3.2.3 Building trust and friendship with farmers

The accuracy of the study is dependent on farmer response. It was important to earn farmer trust to obtain accurate data.

Before the interviews were carried out, a meeting was held with representatives of the local authorities (including the leader of Xiang), administrative village, production group and farmers. The purpose of the meeting was to explain clearly the purpose of the survey and to outline the kind of questions to be asked. Some farmers do not usually like to answer questions to outsiders, such as what was their crop yield and how many children they have. They are afraid that they would be taxed or have family planning imposed.

There were no problems in obtaining the farmers' trust, because they had become acquainted with the ODA project which had been on-going here for a year.

3.2.4 Forming the interview group

Two forestry extension officers, who were well known to the local farmers and the village leaders, and one village leader, who was respected and familiar with all households, helped with the interview.

3.2.5 Making farmers feel at ease during the interview

May is the busiest season for most of the farmers; it is the peak time to prepare for harvesting wheat and sowing summer crops. Therefore farmers were interviewed during their breaks at dinner time and in the evenings, sometimes resulting in a 12-14 hour working day. Most farmers were very willing to be interviewed and even stopped their work. Being polite and respectful to all the farmers and able to speak their own language made everyone feel unexpectedly at ease and co-operative during the interviews.

During the interviews simple calculations were made of input cost and income from each crop for each household to provide a check the reliability of farmers' responses. Sometimes farmers realised for the first time that their net yields were lower or higher than they thought. The farmers then briefly explained why they have a high or low net income.

3.2.6 Data analysis

Computer software packages for social survey such as SPSS were not used in data analysis due to the small sets of data, time effectiveness and the purpose of the study which was intended to be informative and descriptive rather than a detailed socio-economic survey. Therefore, data were analysed by simple statistical methods and presented in average, total, ratio and percentage figures. The results of analysis are presented in under broad headings.

3.3 Human Resources

3.3.1 Gender and age distribution

In total 29 (44.6 per cent) and 11 (50 per cent) households were interviewed, composed of 136 and 52 people, in Goucun and Changqiao villages respectively.

Results showed that there are no big differences in gender among different age groups (Table 3.2). The population is mainly composed of children and young- to middle-aged adults. The smallest number is the age group between 50-60. This might be due to the low birth rate during the wars which caused hardship in China in the 1930-1940s.

Table 3.2 Age and gender distribution of the households interviewed in Goucun and Changqiao.

Age	Goucun			Changqiao		
	Total	Percentage	Man:Woman	Total	Percentage	Man:Woman
<18	54	39.7	1:1.16	20	37.2	1:0.9
18-49	58	42.6	1:1	28	54.9	1:1
50-60	2	1.5	1:1	1	2.0	0:1
>60	22	16.2	1:1.2	3	5.9	1:0.5
Total	136	100	1:1.09	52	100	1:0.96

Two children are allowed by policy in this area, especially when the first is a girl. Traditionally most people live in the same village for generations. There is only one care home in each township primarily for childless people. Older people who have children should be looked after by their children. Boys are always preferred by parents. It is perceived that the more boys they have, the stronger their power over their neighbours through more farm labour and greater security in old age. This perception is a key obstacle for family planning control in this area. Most couples still have 3-5 children even under the very strict family planning policy. Despite this, most people want to have as many children as possible.

3.3.2 Education Background

It is necessary to clarify the education system in China. Children receive education in Primary School from 7 to 12 years, Middle School from 13 to 15 years and High School from 16 to 18 years. The Chinese Government set up the Nine Years (Primary-Middle School) Compulsory Education Act after the Cultural Revolution. However, some farmers in this area neglect this law.

The early education of children is a low priority for parents and society in this area. There is a small nursery in Goucun for children aged 3-6 for pre-school education, but none of the children from this production group attend, although the fee is only ¥ 50

(about £4.00) per year. Most children do not have any education before the age of 7, even from their parents. Usually they cannot count until they start school.

The education rates of boys/girls within the 7-18 years age group are only 79/47 per cent and 86/50 per cent in Goucun and Changqiao, respectively (Table 3.3).

Parents always think that education of boys is more important than that of girls, due to their different roles within the family. The educational background of boys will be one of the main items considered by girls when they are looking for a husband. Girls normally leave their parents after they get married at the age of about 20. They are no longer considered a member of the family afterwards. There is a saying in China that "married daughters are like water drained from a basin". That is the major reason some parents do not want to invest money in the education of their daughters. The basic education of the boys is very important for them in finding a wife.

Some 22.5/59.5 per cent and 18.8/50.0 per cent of male/female adults in Goucun and Changqiao respectively are illiterate (Table 3.4).

Table 3.3 Gender and number of children aged eighteen and under in education in Goucun and Changqiao.

Age	Village	Boy		Girl	
		Total	School/ Nursery	Total	School/ Nursery
<7	Goucun	11	0	10	0
	Changqiao	4	0	3	0
7-18	Goucun	14	11	19	9
	Changqiao	7	6	6	3
Total	Goucun	25	11	29	9
	Changqiao	11	6	9	3

Table 3.4. Education background of the adults surveyed in Goucun and Changqiao.

Education level	Goucun			Changqiao		
	Male	Female	Total	Male	Female	Total
Illiterate	9	25	34	3	8	11
Primary school	5	11	16	5	5	10
Middle school	19	3	22	5	3	8
High school	5	3	8	3	3	6
Higher education	2		2			
Total	40	42	82	16	19	35

3.3.3 Manpower Resource in Farming

Most youngsters start to work on the farm full-time after they finish education (about 16 or 18 years of age). Because the education is quite poor in this area, most youngsters fail in the national higher education entrance examinations (which is the way to obtain city identification); only 2 boys are studying in college for their diploma in these two production groups (Table 3.4).

People aged 18-49 are the major manpower resource in farming. Some 36 and 27.5 per cent of farmers are working in the fields for more than 7 months in Goucun and Changqiao respectively (Table 3.5). In comparison, Goucun is more traditional and poorer than Changqiao. In Goucun, 53.7 per cent of people are not working at all. Most of them are children or elderly (Table 3.6). Some 19.9 per cent of women and 16.2 per cent of men are working in the fields for more than 7 months. Most of the women in this village are very submissive. Their labour is important in farming, but not their decision making. Women in this village could not answer most of the questions. Being close to the county capital, people in Changqiao, especially the men, have more opportunities to find a temporary job (most are in construction work) than in Goucun, and women are playing a very important role in farming. Some 21.2 per cent of women work in the field for more than 7 months, against only 5.8 per cent of men (Tables 3.5 and 3.6). Women were interviewed in 5 of the 11 households. In four, a woman was

the head of the household. Women's labour and decision-making are absolutely crucial to the agricultural production of those families.

Despite farming work, most farmers also spend much of their time on their routine life which is not counted as labour. This is especially true for women who, in addition to their role in agricultural production, are responsible for all household chores, feeding animals and looking after all members of the family. In fact they work much more than men.

Table 3.5 Manpower distribution in Goucun and Changqiao.

Working month	Goucun			Changqiao		
	No.	% total	Man:Woman	No.	% total	Man:Woman
0	73	53.7	1:1.09	24	46.2	1:0.67
1-3	7	5.15	1:0.75	11	21.1	1:0.375
4-6	7	5.15	1:0.75	3	5.8	1:2
7-9	29	21.3	1:3.83	13	25.0	1:5.5
>9	20	14.7	1:0.25	1	1.9	1:0
Total	136	100	1:1.09	52	100	1:0.96

3.4 Land Resources

All land is arranged in strips in this area. Land distribution methods are the same in both villages. General land distributions are usually carried out every ten years, with minor distributions annually. The more the population increases over the 10 years, the greater is the number of pieces of land that need to be distributed and thus, the smaller is the size of the land parcels. The small size of parcels has brought a lot of difficulties for farmers trying to manage the farm efficiently, and many problems for promoting agroforestry and land use productivity.

In Goucun, each household averages 4.4 pieces of land (in a range of 1-11 pieces) with a total of about 6 mu (Table 3.7; 15 mu = 1 ha). The "flexible lands"(refer to Section 2.3) are too small to re-allocate to the increased population. There are 70 people (about a quarter of total) who had no land at all in May 1994. If all the people were to attain their own land, the average area would be reduced to 1.28 mu compared with 1.7 mu in 1984. Normally only the first child gets land. The extra children can only get land in general distribution after the parents have been fined for contravening child-bearing

policy. For example, there are 3 couples, each with 4 children in Goucun; none of the younger 3 have land. In comparison, the average size of land in Changqiao is slightly larger with 1.55 mu for each person - about 7 mu for each household in 3.9 pieces. Land area per person is almost the same as 10 years ago.

Table 3.6. Distribution of sampled population by age, gender and working time in the fields in Goucun (G) and Changqiao (C).

Age	Gender	Number of months working in the fields												Total	
		0		1-3		4-6		7-9		>9		Sub-Total			
		G	C	G	C	G	C	G	C	G	C	G	C	G	C
<18	M	25	11									25	11	54	20
	F	29	9									29	9		
18-29	M	5	4	1	4	1	1	2	1	3		12	10	22	17
	F	3			1	1	1	6	5			10	7		
30-49	M	1		3	3	2		3		8	1	17	4	36	11
	F	1				2	1	12	6	4		19	7		
50-60	M									1		1		2	1
	F				1			1				1	1		
>60	M	4			1	1		1	1	4		10	2	22	3
	F	5		3	1			4				12	1		
Sub-Total	M	35	15	4	8	4	1	6	2	16	1	65	27		
	F	38	9	3	3	3	2	23	11	4		71	25		
Total		73	24	7	11	7	3	29	13	20	1	136	52	136	52

Table 3.7 Distribution of land resources in Goucun (G) and Changqiao (C).

Village	Production group total			Interviewed						
	Household	People	Land (mu)	Household	People	Pieces of land	Total arable land (mu)	Average area (mu per capita)	Average length (m)	Average width (m)
G	65	285	365	29	136	127	172.6	1.36	93.5 ±66.4	9.76 ±9.71
C	22	99	153	11	52	43	74.1	1.43	92.7 ±26.9	11.27 ±4.9

3.5 Annual Crop Production

The primary staple crop in this area is winter wheat, which, as already seen, is the "survival crop" for the rural farmers in the North Central Plain. During the collective system, the main staples in this area were sweet potatoes and sorghum. Farmers could only have wheat-flour steam-bun during Chinese Spring Festivals and on some special occasions. Nowadays it is the other way. However, the diet is still very low in protein.

Most peasant food production in these two villages is for survival. Some peasants produce small amounts of commercial products. Four main crops are grown in the two villages, namely winter wheat as a first crop, followed by maize, cotton or soya bean as the second crop of the year. Winter wheat is the survival food, maize is mainly used as animal feed or as a minor food supplement. Cotton is sold for cash, small quantities being used by farmers for home weaving. Soya bean is mainly for cash or as a protein supplement such as bean curd. Other cash crops include garlic, sweet potato, peanuts and medicinal herbs.

Self sufficiency in wheat is more important than anything else. Land tax (3 ¥ mu⁻¹) and other contractual submissions to government are calculated in wheat (Plate 3.1). Submission to the state is normally determined by the county administration based on its overall economic conditions. In Goucun each farmer who has land should submit ¥ 42.95 or 60 kg wheat per year for 1.7 mu per capita, which is equivalent to ¥12.63 per crop or a total 25.26 ¥ mu⁻¹ per annum. In Changqiao, general economic conditions are better than in Goucun, so submissions are higher; ¥100.8 per capita or 72 kg wheat for 1.5 mu per capita, which is equivalent to 33.6 ¥ mu⁻¹ for each crop or 67.2 ¥ mu⁻¹ per annum.

In addition to its importance to a peasant's life, wheat is also a more stable and profitable crop when compared to other crops in terms of yield. The total gross wheat yields are 258.5 kg mu⁻¹ (3878 kg ha⁻¹) and 257 kg mu⁻¹ (3855 kg ha⁻¹), giving a net income of 142.8 ¥ mu⁻¹ and 121.9 ¥ mu⁻¹, respectively in Goucun and Changqiao (Tables 3.8 and 3.9). Considering labour input, by converting net income into wages, maize is the most profitable crop. The most labour consuming and low profit crop is cotton. However, farmers would not worry too much, as long as there is enough wheat for one year's consumption. In terms of grain food only, considering wheat as the first crop, followed by maize or soya bean, one person can have 278.1 kg and 226 kg unmilled grain with 168.8 kg and 143 kg fine wheat grain per capita in Goucun and

Changqiao respectively, as shown in Table 3.10. The grain consumption per capita is slightly higher in Goucun and lower in Changqiao than the average national level. This was 257.16 kg total grain consumption of which 162.9 kg was fine-grain (wheat or rice) (Yu and Buckwell, 1991).

However, the farmers' lives are even more difficult in recent years than during the earlier reforming stage. The more grain they harvest, the lower profit the farmers achieve. This is because surplus grain leads to lower prices, and price increases in grain occur more slowly than those of the factors of production (Du, 1994).



Plate 3.1 Farmers are queuing to submit the contracted grains (wheat) to Xing Government in Goucun.

Table 3.8 Production of annual crops in Goucun (G) and Changqiao (C).

Crops	Working days	¥ day ⁻¹	Village	% Households growing crop	% of total land area under crop	Total area under crop (mu)	Yield (kg mu ⁻¹)
Wheat	33	4.3	G	100	94.2	155	258.5
		3.7	C	100	87.7	61.6	257.0
Maize	15	6.3	G	82.8	65.4	102.4	212.2
		6.0	C	100	48.4	32.1	236.2
Cotton	70	0.8	G	58.6	16.0	31.5	41.3
		0.4	C	63.6	13.9	109	62.4
Soya bean	12	0.59	G	69	13.3	22.2	50.6
		0.3	C	72.7	16.8	13.2	23.6
Others			G	13.8	4.3	1.7	297.7
			C	36.4	5.9	3.8	

Table 3.9 Cost and income associated with annual crops in Goucun (G) and Changqiao (C). IR = irrigation, SD = seed, FT = fertiliser, PS = pesticide spray, PL = ploughing, threshing. Tax = land tax at 3 ¥ mu⁻¹, contracted purchases of grain and administrative fee.

Crops	Village	Cost (¥ mu ⁻¹)							Income (¥ mu ⁻¹)	
		IR	SD	FT	PS	PL	Tax	Total	Gross	Net
Wheat	G	11.2	10	14.3	4.3	23.3	12.6	115.7	258.5	142.8
	C	15.3	10.6	53.3	2.1	20.2	33.6	137.9	257	121.9
Maize	G	10.9	5.7	16.9	3.9	0	12.6	50	143.9	93.9
	C	11.2	6.0	17.0	3.0	0	33.5	70.7	160.6	89.9
Cotton	G	4.5	0.89	22.0	54.8	0	14.1	96.3	153.5	57.2
	C	15	3.9	29.6	38.3	0	39.6	131.8	159.2	27.4
Soya bean	G	2.3	11.5	0	3.5	0	12.6	29.9	101.2	71.3
	C	0	9.2	0	0.9	0	33.5	43.6	47.1	3.5
Others	G							278.8	566.0	287.2
	C	5.3	7.9	39.4	4.5	0	54.1	111.2	443.2	332

Table 3.10 Total grain (unmilled) per capita among the interviewed households in Goucun (G) and Changqiao (C).

Crop	Price (¥ kg ⁻¹)	Village	Total area (mu)	Average area (mu per capita)	Total net income (¥ mu ⁻¹)	Total grain (kg per capita)
Wheat	1.0	G	155.6	1.14	142.8	168.8
		C	61.6	1.18	121.9	143.8
Maize	0.68	G	102.4	0.75	93.9	103.6
		C	32.1	0.62	89.7	81.8
Soya bean	2.0	G	22.2	0.16	71.3	5.7
		C	13.2	0.25	3.5	0.4
Total grain (kg per capita per annum)		G				278.1
		C				226.0

Wheat is the crop which farmers prefer to invest in. In this area soils are very poor and dry over the wheat growing season (October-May). Applying fertiliser and irrigation is crucial to final yields. Normally, home made composted organic matter (about 15 ton ha⁻¹) or residues of soya beans, cotton seed cake (if available) and 50 kg mu⁻¹ phosphate (0.46 ¥ mu⁻¹) and 10 kg mu⁻¹ nitrogen (1.2 ¥ mu⁻¹) fertiliser are applied before ploughing. Some 20-30 kg mu⁻¹ nitrogenous fertiliser are applied 2-3 times during the growing season. Irrigation is applied normally once in winter and 2-3 times in spring (20-25 ¥ mu⁻¹ at one time). Ploughing (25-20 ¥ mu⁻¹) and threshing (5 ¥ mu⁻¹) are all done by small machines (Plates 3.2 and 3.3). Fertiliser and irrigation are the major costs. Most of farmers like to invest money in fertilisers and irrigation if they can so as to achieve maximum wheat yield. In most cases, however, this investment gives minimal benefits due to the imbalance in price between fertiliser and fuel for irrigation and the final product, wheat grain (refer to Section 3.9). As a result, the cost-benefit ratios for wheat are 1:1.23 and 1:0.88 only in Goucun and Changqiao, respectively.

Maize is the second favourite crop for most farmers in this area, as it is less labour consuming. Drought during the sowing stage (late May and early June) is a limiting factor in maize production. As with wheat, irrigation and fertiliser application are key measures for maize production and major costs of investment.



Plate 3.2 Harvesting wheat by small tractor (1.5m width) is common in the North Central China Plain



Plate 3.3 All members of the family are threshing harvested wheat from paulownia intercropping fields, Goucun. Simple threshing machines are commonly used

Unlike the above two crops, cotton is potentially a valuable but labour intensive and risky crop. There are profit conflicts between state and individual. Farmers now have great freedom in growing most crops, with the exception of cotton. Farmers have to grow cotton as required by government. Some 60 per cent of arable land must produce cotton in Chengwu. Most cotton has to be sold to state markets as it is strictly controlled by the local government. The price of cotton is 6-10 ¥ kg⁻¹, varying with quality. The quality assessment mostly depends on the personal judgement of the state buyers. Nevertheless, cotton is a major source of revenue in a good year. It is however, risky for farmers to grow cotton due to the unpredictability of natural disasters and uncontrollable insects. Most farmers have to use pesticides every other day due to poor quality sprays and high resistance of insects. Many households had negative income from cotton in 1993. As shown in Table 3.9, average net income from cotton was only 57.2 and 27.4 ¥ mu⁻¹, the cost:income ratios were 1:0.59 and 1:0.21, and wages were equivalent to ¥0.8 and 0.4 per day in Goucun and Changqiao, respectively, which is similar to the wages before 1978 (¥0.4 per day). All farmers were disappointed with their cotton in this year.

The low income from cotton was explained by farmers as due to the very dry period during sowing. Some had no money to irrigate, and there were floods at the end of July and early August. The first frost occurred on 6th October, when cotton was not yet ripe, which was one month earlier than usual. Most farmers were upset about their cotton performance in 1993, except Zhao Qingmu and Wang Guilian, who unexpectedly benefited from our ODA project. Our wheat experiment required them to harvest their cotton before it was ripe, which they were very reluctant to do. They harvested cotton unwillingly, but ultimately achieved very good compensatory prices. Surprisingly, white cotton came out of its shell after being naturally dried before the first frost. They earned 120.4 ¥ mu⁻¹ from selling good quality cotton, which was double the average, plus additional compensation from the ODA project. During our interview, they told us they wished the ODA project experiment could be carried out on their land as long as possible!

As a cropping system, wheat-maize-wheat is better than wheat-cotton-wheat as it is some times too late to sow wheat after cotton has totally ripened.

There are more farmers growing cash crops in Changqiao than in Goucun. Several households grow medicinal herbs in Changqiao but none in Goucun. Most cash crops grown in Goucun are actually for self sufficiency. This might be due to the advantageous location of Changqiao in accessing technical assistance and marketing information.

3.6 Livestock

During the collective system, a small number of livestock (goats (*Capra spp.*), sheep (*Ovis spp.*), pigs (*Suidae spp.*) and chickens (*Galus galus*)) were the major income generators for individual households. All animals and even chicken eggs were for sale and provided the major source of cash. Farm animals such as cows, horses and donkeys were kept by production teams. After the individual responsibility system was implemented, the farm animals were sold to individual households. The farming activities were mainly done by farm animal power during the early 1980s. Farmers also started raising more livestock due to the surplus of grains and crops residues which could be used as animal feeds. Eggs and chickens were for both self use and sale. Other animals are all for sale. In recent years, most farmers think it is too risky to have more livestock due to serious disease problems. There are no special animal hospitals or qualified vets in this area. Vaccination and injections are very expensive for most farmers. The survival rates for most animals are very low; chickens only 20 per cent, goats 40 per cent and pigs 60 per cent as reported by local farmers. Most no longer raise farm animals for draft purposes because they can buy or rent a small machine for ploughing or other operations. Farmers like goats because they eat more grasses and tree leaves than pigs and they are less labour consuming and cheaper to buy. However, it is difficult to calculate the profit of raising different animals because feed costs, especially for pigs which need a lot of grain, were not surveyed. Table 3.11 summarises the numbers of animals, the present value and costs, excluding feed costs and labour.

3.7 Tree Resources

There is no pure woodland in these two villages. Trees are mainly planted in the residential areas and on the farm by intercropping.

Table 3.11 Livestock raised by the interviewed households in Goucun (G) and Changqiao (C) (values in ¥).

Animals	Village	Adults				Young			Total value net
		No.	Present value	Cost	Net value	No.	Present value	Cost	
Cow	G	0	0	0	0	0	0	0	0
	C	1	1200	700	500	0	0	0	500
Goats	G	48	2850	500	2350	2	20	20	2350
	C	14	960	150	810	0	0	0	810
Pigs	G	16	6277	2080	4197	16	1780	1780	4197
	C	10	4210	1300	2910	8	720	720	2910
Chicken	G	39	390	31	359	189	151.2	151.2	359
	C	23	230	18.4	211.6	103	101	101	211.6
Duck	G	4	40	5	35	4	10	10	35
Goose	C	6	60	7.2	52.8	8	20	20	52.8
Rabbits	G	3	30	10	20	0	0	0	20
	C	0	0	0	0	0	0	0	0
Total	G		9587	2626	6961	0	0	0	6961
	C		6660	2175.6	4484	0	0	0	4484

3.7.1 Tree resources in residential areas

Normally, each household has a 0.3-0.5 mu residential area. This area has always been a timber producing source for most farmers. Goucun is a very big village. Residential areas, however, appear smaller than those in Changqiao. Trees do not grow well in Goucun due to poor soils and low ground-water table. There are 5 households in the interviewed group which have no trees at all due to the bad soil conditions in Goucun.

There is a total of 189 trees in the residential area with a total value of ¥6650 (1994) in Goucun (Table 3.12). Of these, 62 stems are poplars with a net present value of ¥4700, 78 stems are black locust with a total value of ¥1076 and 9 are date trees (none of which bear fruits because of serious insects and disease). The others are mainly elm (*Ulmus pumila*) and tree of heaven (*Ailanthus altissima*). Most elm trees are dying from Dutch Elm Disease (*Ceratocystis ulmi*). In Changqiao, there is a total of 323 timber trees with a total net present value of ¥12384.5. Average households have 29.4 stems worth a total of ¥1125.9. There are 63 fruit trees, most of which are date and have no value. Mr. Chang Deyue's backyard contains a very complicated multi-storied agroforestry system. There are a total of 13 stems of locust and 20 poplars with a value of ¥1097. Some 50 maidenhair trees or ginkgo (*Ginkgo biloba*) grow very well; he can earn good money in several years because ginkgo seeds are very expensive herbs. He has planted roses (*Rosa spp.*), mini-cypress (*Cupressus dudouxiana*) and bodinier box (*Buxus boninier*). All this is market-oriented and worth ¥3317 in net value, which is more than his income from annual crops.

3.7.2 Tree resources on the farm

The farm is the major site for timber resources. Most trees are paulownia. All paulownia trees in the fields were planted in 1984-1986. They are now mature economically. Most spacings are 5x10, 5x15, 5x20, 5x30 and 5x40 m with south-north orientation. Generally, spacings are denser in Changqiao than in Goucun. This is because farmers in Changqiao prefer long-term cash to present-day food self-sufficiency. The common factor for the two villages is that all farmers consider paulownia as their "green capital". There are 7 households in Goucun and 1 household in Changqiao which have no trees on their farm. Most are newly married couples. Some of the land is given by their parents. They told us that their parents do not want to give their paulownia intercropping land to them. They cannot plant trees because their neighbours' trees are already very big. On average there are 17.2 stems with ¥1918 net

value per household and 25 stems with ¥2500.3 net value per household in Goucun and Changqiao respectively (Table 3.13). Assuming the average spacing is 5x20 m, 40.8 and 46.5 per cent of total land is intercropped with paulownia in Goucun and Changqiao, respectively.

Table 3.12 Present tree resources and their value in the residential areas (Present net values in ¥).

Village		Goucun	Changqiao
Number of Households		29	11
Total timber	Number	189	323
	Present net value	6650	12385
Poplar	Number	62	185
	Present net value	4700	5994
Locust	Number	78	88
	Present net value	1076	2365
Fruit trees	Number	9	63
	Present net value	0	240
Ornamental plants	Number	0	0
	Present net value	0	2040

Table 3.13 Current tree resources on the farms (values given in ¥).

Village	Total		Paulownia		Poplar		Others	
	No.	Value	No.	Value	No.	Value	No.	Value
Goucun	498	55631	469	52991	14	1370	15	1270
Changqiao	274	27503.5	230	26423	42	1064	2	16.5

Poplar and other trees are all planted along the roads to minimise their effect on the production of understorey crops. All trees are for timber or for cash, if there are surpluses from home use. The estimated value is based on present local timber prices. However, there are also high values to be obtained from other parts of the tree. Taking paulownia as an example, in addition to the main trunk, the tree normally develops a secondary trunk from the third or fourth year, which could be about 2-3 m long and 15-20 cm in diameter. The volume accounts for 29.1 per cent of the main trunk for a 10-year old tree. The secondary trunk and other big branches can be used for house

construction. One 8-year old tree can produce 14 kg of branches for fuel wood plus 30 kg a year of fresh leaves. Paulownia leaves contain nitrogen at 3.09 per cent and thus make excellent animal fodder and fertiliser (Hou, 1991). All these values are not counted in the economic analysis.

Paulownia is the most profitable and fast growing tree for farmers to plant. The only cost is for the sapling. It costs ¥1 for a paulownia sapling, ¥0.6-0.8 for poplar, and ¥0.3-0.5 for locust and other species. Irrigation, fertiliser and pesticides are not normally applied during tree growth. The only management is pruning. With ¥1 capital, paulownia can yield ¥200-300 return in 10 years for one tree. Trees account for the main cash income of most farmers (Table 3.14). Taking livestock and trees as standing assets, farm trees account for 80 per cent in Goucun and 17.6 per cent in Changqiao. Paulownia represents 95.3 per cent of these in Goucun and 96.1 per cent in Changqiao. In Table 3.14, the values for animals do not have feed costs deducted. The values of tree branches and leaves are not included. All labours for the two items are not deducted.

Table 3.14 Present value to farmers of livestock and trees (Value in ¥).

Village			Goucun	Changqiao
Households			29	11
People			136	52
Livestock		Value	6951	4484
		% total	10.1	2.9
Timber trees	Residence	Value	6650	123845
		% total	9.6	79.5
	Farm	Value	55631	27504
		% total	80.0	17.6
Cash and fruit trees		Value	0	2216
		% total	0	1.4
Total value			69242	155833

3.8 Roles of Paulownia in Farmers' Social Life

Farmers spend a lot of money on their social life, especially parents who have more sons. In fact, parents who have boys could have a difficult life in the future. This problem is more serious then ever before. It is a tradition that parents have to pay a lot

of money for finding a wife for their son. In most cases in this area, the marriage is still arranged by match-makers and parents. A boy's parents need to pay about ¥1,000-2,000 to the girl at their first blind date and provide a bicycle, sewing machine, watch and clothes (about 10 sets), totalling about ¥ 2,000-3,000, on the engagement day. Usually the poorer they are, the more money they need to spend. Parents also give ¥50-100 to the girl in each Chinese Spring Festival before their marriage. Parents must build a house for the new couple before the marriage, which costs about ¥6,000-10,000. It is unlikely that such money can come from annual crops. It is mostly from paulownia in this area. Farmers need paulownia wood for construction and cash (Plate 3.4). However, after the son gets married, the parents have to look after their grandchildren and do their own farming (Plate 3.5). The bride to be also needs paulownia trees, because her parents have to make paulownia furniture including chairs, table, desk, dressing cabinet, food cabinet etc. for the daughter (Plate 3.6). Children need a lot of money, not only until their engagement and marriage, but also for their schooling. Mr. Wang Baocheng has to sell at least 5 paulownia trees per year for his three children's education. It has become a tradition that most parents plant trees whenever they have a new baby.

The group leader of Goucun, Zhang Dehai, who is 64, told us that he works 365 days a year and every day he gets up at 4-5 o'clock to start work and continues until late in the evening. Excluding farming, he also sells clothing materials in open markets for 3-5 days per month. However, he still had ¥6,000 debt last year, because of the numbers of dependants in his family. He spent ¥3,000 for buying a "town identification" for his second son, giving citizenship and an official work permit for the town, the son thereby loses his right to farm land. The son is married and has 3 children, but still got a lot of money from his father to build his house. The father will need about ¥2,000 for the 3rd and 4th sons' education.

Old people need paulownia too, especially if they are unhealthy and older than 60. They will make a big (about 50-75 mm thick) board coffin. This would need two or three 10-year old paulownia trees. Mr. Zhang Jinlian who is 70, and his wife who is 66 (as shown in Plate 3.5), have four paulownia trees in their farm, which will be used for making their coffins.

Over the last 5 years, a total of 31 and 182 trees in Goucun were respectively used domestically and sold with a total net value of ¥21,864. Of this, 79.8 per cent of stems and 92.2 per cent of income were derived from paulownia. Over the same period, 38

trees were used domestically and 128 trees were sold by 10 of the 11 households interviewed in Changqiao, with a total net value of ¥14,386. This consisted of 109 stems of paulownia, 51 stems of poplar and 6 stems of locust, with average price of 106, 50 and 84 Yuan per stem for each species, respectively. In fact, for the last 5 years, the price of paulownia timber (about 250-350 ¥ m⁻³) was 3-4 times lower than currently.

Most paulownia now on the farms is 10-12 years old, and economically mature. In Goucun, paulownia trees on the farms measured an average 33.6 cm DBH (Diameter at Breast Height) and 13 m height, with a volume of about 0.45 m³ and a value of about ¥300. The biggest tree measured 43.2 cm DBH and 16.2 m in height. Most farmers do not want to cut their trees because paulownia prices are still increasing (Table 3.15). Most farmers said that they do not cut the trees until they really need money or timber, or when land distribution necessitates felling. Unfortunately, trees have to be cut this year in Goucun, due to the land redistribution.



Plate 3.4 Mr Wang Baojin and his wife Li Qinlian, Goucun, are sawing locust and paulownia logs to prepare to build a house for their first son Wang Pin who is only 12 (not shown in this picture). They have to work hard because their second son is 8.



Plate 3.5 Mr. Zhang Jinlian (70), and his wife (66) are harvesting their wheat from the ODA experimental site in Goucun. They cannot get help from their 3 married sons, because of all of them have to harvest their own wheat



Plate 3.6 These two trees were 10 years old when felled. They will be used for furniture making for the girl (left of the photo) for her wedding, Changqiao

Table 3.15. Prices for 2-m long paulownia logs in Chengwu County local market (May 1994). (*) and (**) represent prices for first class wood of 800 ¥ m^{-3} and 1000 ¥ m^{-3} respectively in Shangqiu Paulownia Wood Processing Factory which is 70 km from Chengwu.

Age (years)	Diameter in small end (cm)	Price (¥ m^{-3})
5	16-18	380
6	20	460
7	24	480
8	26	560
9-10	28	600 (*)
>10	30	660 (**)

3.9 The Future of Chinese Agriculture and Rural Development in Chengwu

The rural development of Chengwu greatly depends on national policies and macro-economic reforms. Since more than 80 per cent of China's population of 1.2 billion are farmers, developments in rural socio-economics determine greatly the overall economic development of the whole country (Du, 1994).

"Why is China poor"? Some Chinese officials simply answer "Because of too many people". Wang Gengjin, the Director of the Chinese Academy of Social Sciences Institute of Rural Development, said this answer is nonsensical, because human beings are producers as well as consumers. Wang further explained that the population density of The Netherlands or Japan is twice as great as China's. China lags behind them in terms of efficiency not because its land is "overloaded" with people, but because its agricultural policy is not stable enough. His evidence is the widening price gap between industrial and farm products, the low quality of farm production materials, the heavy cost of farm operations and the reckless bureaucratic levies and regulations imposed on farmers (Zhang, 1993). Zhang compared the situation in 1990, when the Chinese population was less than double its size in 1952, but its grain output was more than two and half times the 1952 level and meat production had increased more than seven times. Zhang then concluded that this was not attributable to any major increase in the Chinese arable land area, but more to the farmers' enthusiasm for the reformed system, along with new techniques and materials. Provided with enough incentives, Chinese farmers can raise their output per unit area still further.

The survey shows that the present IRS has been playing very important roles in rural socio-economic development, but it might not be the right system for long-term development. It has disadvantages. It limits the farm production to a traditional small scale, thus restricting the application of machinery and technology, and results in difficulties in investment, management, and low profits.

The Chinese Communist Party and Government have been attempting to find the right strategy for promoting agricultural production and improving rural socio-economical development. However, it is difficult for the Chinese due to their particular situation in agricultural production (Du, 1994). Agriculture is a low profit estate due to small scale production in household units and high capital investments. High risks in production arise both through nature and marketing. Farming products cannot be treated as 100 per cent commercial because they not only meet peoples' needs but also are crucial to social stability and security. Governments have to control or balance the price between farmers' profit and the acceptance of society. The Chinese Government cannot provide subsidies to offset lower prices as a protective measure for agricultural production because of the large population of farmers.

What is the future for Chinese agriculture? Du (1994) pointed out the following two aspects:

1. Further reforms are needed at the rural level clarifying the rights and benefits between farmers and the state, avoiding the collective system, and transferring the surplus farmer work force to small industry and enterprise.
2. The Government should set up an overall control system and provide better conditions for rural economics. These include setting up policies and laws to protect farmers' rights and benefits, reducing risks by providing insurance and investment services, and strengthening agricultural research and extension services. Du further declared that this has been appreciated by most people and accepted by the highest decision makers.

In some areas, especially the better developed regions, co-operative contract systems are more practised recently. They divide a third of the total land as survival land equally to each person, which is tax free. The remaining two thirds of the land is managed by a contract system to one or several farmers. The remaining manpower can be transferred

to small scale industry enterprises or hired by the contract farmers. This system works well in more developed areas and it could especially solve the present problems in IRS. However, one policy cannot be applied throughout China because of the extensive variation in conditions. The author believes the co-operative contract system is not suitable for Chengwu County. This is because Chengwu's economic conditions are too under-developed to invest for more enterprise, transportation and access to outside markets are rather backward, and most farmers have no alternative skills. It is difficult for them to learn such skills due to their low educational background. Here the IRS would still be the main system for the next decade.

Most regions actually have specific rules in their particular area under the guidance of Central Reform Policy. In Chengwu, the authorities and farmers agree that IRS is still considered the appropriate system, and agroforestry will be the most appropriate farming practice for promoting socio-economic development and sustainable agriculture.

Mr. Zhaofu Shong, Director of Chengwu Agriculture Committee explained their following plans:

1. Consolidation of all land of each household to 2-3 fields with redistribution every 30-years for ease of management and increased tree planting. All suitable land should be intercropped with paulownia. In order to increase diversity of species, all roads and canals should be planted with Chinese white poplar (*Populus tomentosa*), black locust and other species. This will lead to both increased forest area and livestock numbers.
2. Adjustment of agricultural structure, based on market demands and benefits, by increasing grain crop yields per unit area and cash crop growing area, mainly with cotton. Some 60 per cent of the total arable land of the county must be planted with cotton. State markets and higher prices will always be guaranteed. Such strict law guarantees a certain amount of cotton storage and employment of textile workers. In addition, 250,000 mu will be grown with vegetables in the specialised areas near the county capital. About 30,000 mu will be planted with mulberry (*Morus alba*) for silk worms (*Bombyx mori*).
3. Motivation of technology extension and establishment of a well organised service network, by implementing individual responsibility contracts to extension officers.

4. Strengthening of basic farmland construction by establishing more irrigation and drainage systems.

The survey asked farmers: "Do you intend to plant more trees in the future?" In Goucun three farmers answered no; one who has 4 children said because of food shortages and less land, and two said that they are too old. In Changqiao, only one farmer, Yen Xianqin (who was bought by her husband from Guizhou Province), said no - because she did not have enough food, and was the poorest of the interviewed group in terms of housing and social standing.

A total of 3 households (the above 3 farmers) in Goucun and 4 households in Changqiao will not plant trees in the next three years. In Changqiao, two such responses were due to insufficient food, and the other two said that all their land was already intercropped with trees so they can only plant more trees after the present ones have been felled. A total of 160 paulownia, 64 poplar and 180 apple or peach trees will be planted within the next three years. In Goucun, 26 households will plant 30-50 paulownia trees along their strip land (about 150-200 m long). Only one farmer planned to plant some apple trees. The land will be redistributed in October 1994. All people will get their share, but much less than before. However, land redistribution also means tree regeneration. Several young couples in Goucun told us that they want land redistributed as soon as possible so that they can plant trees.

Do farmers inform the neighbours when they plant trees on their narrow land strips? All answered no in Changqiao. The reason is that Chengwu Forestry Bureau set up a rule in 1990 that all can plant their own trees as long as they give a 3 m wide edge to their neighbours. All farmers said they will plant poplars along the road and one row of paulownia in the middle of their land, or two rows if the land is wider than 20 m. All farmers who have less land strongly argued that this rule is unfair to small households and irrational in practice. Government should change this policy. The proposed research on modelling within this project would help resolve this argument by indicating how close tree rows can be spaced without reduction of understorey wheat yield. In Goucun, farmers are more co-operative than those in Changqiao. All farmers said that if their land is wide enough, they will plant one row in the middle or plant along the edge by sharing with neighbours.

Why do farmers want to plant more paulownia trees? Most of the farmers said for timber and cash, some of them said because it produces high profit and low risk. Some said that it is for their children, whilst others explain that there are no effects on understorey crops during the first 7 years, followed then by a small reduction in the yield of summer crops. However, the reductions of cash crop are much less than the gains from paulownia.

3.10 Summary of Findings

From this survey we can conclude that:

1. Paulownia intercropping is still considered by local farmers and the authorities as the most appropriate system for promoting rural socio-economic development in the poor areas, like Chengwu County. Paulownia trees are more important as timber and cash source in the less commercial and remote village of Goucun because it is cheap to invest in them. Other trees are also important in Changqiao, where skills, investments and markets are available.
2. All annual crops give very low profits due to the big gap and imbalance of prices between industrial products and agricultural products. Wheat is a "survival food" and is relatively a more stable and profitable crop than the summer crops. Its yield is an important component that concerns farmers in the PCI system. The present common summer crops (maize, cotton and soya bean) give very low profits.
3. The existing policy based on the 3 m edge rule (refer to Section 3.9) on paulownia intercropping causes some arguments among farmers and between farmers and local authorities. This policy should be abandoned. Technical guidance from models, which could predict when, where and how wheat yield reduction starts as a result of tree growth, could be useful for solving the problems and also for optimising the management system.
4. Population is increasing rapidly against decreasing arable land resources. Education rates, especially amongst females, are low.
5. Small pieces of land make farms more difficult to manage and do not encourage investment. This is related to population increase. But, providing information and

guidance on efficient land use systems and proper natural resources management may help farmers alleviate these problems.

6. The traditional farming methods under the collective regime have been replaced by scientific cultivation using irrigation and fertilisation by individual farmers under IRS regime. The role of farmers, especially the head of each household, has changed from labourer into farm manager and decision-maker. Women play an important role in rural development and decision-making.

7. Farmers need to have knowledge in planning and managing their farm for maximum production and marketing their surpluses. However, they have difficulties to translate the scientific findings directly to their needs due to their lower education. To fill the gap, a bridge should be built between scientists and farmers through which scientific findings are turned into practical technical guides or tools to address farmers' needs and those of extension officers transferring the knowledge to farmers. A contribution to this need is presented in Chapters 4 and 5.

4. TREE GROWTH, LIGHT TRANSMISSIVITY AND UNDERSTOREY CROP YIELD IN PAULOWNIA INTERCROPPING SYSTEMS: DATA ANALYSIS AND DISCUSSION

The information presented in this Chapter is aimed at furthering understanding of the ecophysiological interactions of the PCI system by analysing tree growth and quantifying the microclimatic effects and their influence on understorey crop growth and yield over time. Data collected by the author at Dangshan, Anhui Province, during 1983-1992 on a project funded by International Development Research Centre of Canada (IDRC), which were not yet fully analysed, were used for the study, along with data from Chengwu, Shandong Province, also collected by the author in 1993 and 1994 as part of the present ODA project.

4.1 Experimental Sites

Dangshan is located between 116°09' and 116°38' E and between 34°16' and 34°39' N, in the north west of Anhui Province. The temperate monsoon climate has a mean annual rainfall of 773 mm with almost 80 per cent occurring during the rainy season from July to September. The mean daily air temperature is 14.0°C. Annual sunlight is 2,480 hours. The soils, typical of the North Central Plain (Section 2.1), are alluvial in origin, sandy, alkaline and poor in organic matter, phosphorus and nitrogen.

Chengwu is located between 115°44' and 116°11' E and between 34°39' and 35°10' N, in the south west of Shandong Province. The temperate monsoon climate has a mean annual rainfall of 611 mm with 15.5, 59.8, 20.4 and 4.3 per cent falling respectively in spring, summer, autumn and winter. The mean daily air temperature is 13.9°C. Annual sunlight is 2,377 hours. The soil conditions in Chengwu are slightly poorer than those in Dangshan.

The underground water table in these areas is below a depth of 2 to 4 m. Late spring and early summer often have hot and dry winds (speeds $> 3 \text{ m s}^{-1}$) with temperatures over 30°C and a relative humidity of less than 30 per cent. These conditions are extremely harmful to agricultural crops, especially wheat, and result in yield losses of up to 20 to 40 per cent. Drought in late spring and floods in summer are common natural calamities.

The effect of shelter on climate is best evaluated by comparing the sheltered conditions with those in open, unprotected fields and making observations of microclimatic variation within the sheltered areas over time (Rosenberg et al, 1983). Therefore, experimental sites were established for both paulownia-wheat intercropping and for open field (crop only) conditions.

The trees in both experimental sites were *Paulownia elongata*. The study conducted in the Dangshan Paulownia Research Station was based on a controlled experimental site, which was set up by Prof. Zhu Zhaohua of CAF, as part of the IDRC project. About 25 ha of farm were rented from a state farm for the experiment. Due to its complexity in nature, measurement in environmental interactions must be done against a wide-ranging set of spatial and temporal possibilities (Huxley, 1990). Five different spacings of paulownia tree rows with wheat intercropping were studied, with rows at 6, 10, 20, 40 and 50 m apart respectively. The tree spacing within the rows was 5 m. The spacing of 5x6 m was representative of a pure paulownia plantation. It is too dense for use in a PCI system. The experiments were started with 1-year-old saplings in 1983. All rows were north-south oriented. A Randomised Complete Block Design (RCBD) with three blocks (replicates) was used for each spacing treatment. The trees in the 6 and 10 m spacings were thinned in the 8th year of intercropping to 30m spacing.

Annual crops were sown every year between the trees. Winter wheat was always the first crop (from October to end of next May) and cotton, maize or soya bean the second crop (from early June to September or October). The control treatment consisted of a plot of the same crop species grown simultaneously in a nearby open field. Crops were managed by individual farmers (farm workers). An area of 15x16 m was selected from each block for crop experiments. The crop sampling area and the trees were managed by technicians of the Station. All crops and trees received the same management. Plots did not receive any irrigation during the growing season. All plots received a normal level of fertiliser prior to the sowing of wheat (150-250 kg ha⁻¹ of NP-fertiliser applied broadcast). The areas close to the trees received less fertiliser because the trees and the crop land were under different ownership.

In Chengwu, the data were collected from farmers' fields from two villages selected by the author. Spacings of 5x10, 15 and 20 m, covering four rows of paulownia in the 8th year of intercropping were selected from farms in Changqiao (Plate 4.1). The fields including the control were managed by four individual families. Spacings of 5x15, 20, 30 and 40 m including six rows of paulownia trees in the 9th year of intercropping were

selected from 16 rows of intercropped fields in Goucun (Plate 4.2). Crops within the six tree rows and control were managed by seventeen families. Different wheat varieties were sown in the sites because some of the farmers did not follow instructions. In 1993, the experiment was not controlled at all because it started in May when the wheat was about to be harvested. Wheat normally receives irrigation and pesticide spray once or twice during the growing season. About 1,500-2,000 kg ha⁻¹ of NP-fertiliser and 20 t ha⁻¹ of organic compost were applied prior to the sowing of wheat and 150 kg ha⁻¹ of nitrogen fertiliser during the growing season.

4.2 Data Collection

The data collection in both sites was organised by the author, in Dangshan, with assistance of two MSc students from Nanjing Meteorology Institute, Xiong Qixue (1989), Jing Yunshu (1992), two technicians Cao Xiaozen and Yang Suqiou and five technical workers (1983-1992) from the Station; and in Chengwu, with assistance of Li Yongchun and Song Lijin of the Chengwu Forestry Bureau, Lu Qi, PhD student of the Natural Resources Integrated Survey Commission of the Chinese Academy of Sciences, Jing Yuanshu, lecturer from Nanjing Meteorological Institute, local village leaders and farmers (1993-1994).

Detailed data collection and layout were reported by Wu and Dalmacio (1991) and Wu (1993).

4.2.1 Microclimatic factors

Data on microclimate (including total solar radiation, wet and dry bulb temperatures, soil moisture) were collected for the 5th, 7th and 10th years of intercropping in Dangshan at booting and grain filling stage of wheat and flowering stage and during seed filling of summer crops. Measurements were recorded hourly over periods of 3 or 4 days for each collection. The instruments were installed in the centre of the control plot and at three positions in the intercropped plots, namely under the trees, at the edge of tree crown and in middle of the alley (Wu and Dalmacio, 1991).



Plate 4.1 5x10 m paulownia-wheat intercropping at the 9th year in Changqiao site. The owner, Mr. Chang Deyue is very happy that it is again a bumper harvest from his PCI



Plate 4.2 5x30 m paulownia-wheat intercropping at the 9th year in Goucun site. Wheat is in the grain filling stage, 10 days before harvest.

The incoming (S_r) and reflected (R_r) solar radiation over each plot were measured as hourly integrated values using an Automatic Recording Station (CIMEL Electronique, 13 Rd, Rochechouart, Paris 9, France) at 10 cm above the crop canopy (Plate 4.3). R_r was measured for the 7th intercropping year only. Total solar radiation at different heights above ground was measured in May and August of the 10th intercropping year. The heights chosen were 1 m (crop canopy), 4 m (under the tree crown) and 6 m (in the middle of tree crown) on the intercropped plots; measurements at 1 m height in the middle of the alley in the 5x40 m spacing were considered as representative of the controlled conditions. Dry and wet bulb temperatures were collected using Ventilating Wet-Dry thermometers at 10 cm above the crop canopy. In 1993 (the 11th intercropping year), only SR and Photosynthesis Active Radiation (PAR) were measured at Dangshan (Plate 4.3). PAR was measured as daily integrated values using a PAR Didcot DRI-02 (Abingdon Instrument Co. Ltd. United Kingdom), operating simultaneously with the Automatic Recording Station.

The soil moisture content was determined gravimetrically using samples taken at 10 cm increments from 0 to 40 cm below the soil surface.

In Chengwu, only SR and PAR were measured, using the methods and instruments described above, in 1993 and 1994 (the 8th and 9th intercropping year in Changqiao and the 9th and 10th year in Goucun).

4.2.2 Crop data

In Dangshan, yields of wheat and summer crops were collected using RCBD with three replicates in each sample strip at a standard distance from the paulownia trees. Three to fifteen samples of wheat were taken from the control field. The collection was made each year over the experimental period (1983-1992).

Several types of data that relate to water use and photosynthesis were collected from 1986 to 1992 in Dangshan for study of the ecophysiological response of understorey crops. The ecophysiological measurements were taken from five plants in the middle replicate only. Measurements were made on flag leaf of wheat and leaves in the upper one third of the canopy of summer crops. In wheat, measurements were conducted at booting (ear swells the upper stem) and flowering, and grain filling stages, and in cotton, maize and soya bean at flowering and during seed filling. Data collected were

leaf temperature, transpiration and stomata resistance of both sides of the leaf and PAR at the top of the crop canopy by a portable gas exchange measuring device (Li-1600 Stable Poremeter, Li-Cor Inc., 4421 Superior Street, P.O. Box 4425, Lincoln, Nebraska, 68504 USA) (Plate 4.5). All data were measured either hourly or two-hourly, at different distances from the tree rows and in the open field. Total transpiration is the sum of the values for both leaf sides (Liu et al, 1987); leaf temperature is the mean of the values for both sides of the leaf. Leaf conductance (C_s) as reverse of resistance was calculated from Equation 1:

$$C_s = \frac{r_a + r_b}{r_a \times r_b} \quad (4.1)$$

where r_a and r_b are resistance ($s\ cm^{-1}$) of the upper side and lower side of the leaf, respectively.

Leaf Area Index (LAI, plan area of leaves per unit ground of foliage), 1000-grain weight (natural dry weight with 14 per cent moisture content), above ground biomass (total dry weight of stems, leaves, ears per plants) and other growth parameters of wheat were also measured during the same period.

4.2.3 Tree data

All individual trees in the experimental sites were measured each year (1983-1992) in winter when growth had stopped. Data were obtained on DBH, H (height), Cew (crown range at east-west direction), Csn (crown range in south-north direction) and TK (Trunk height under the first bottom branch).

All data were analysed by Statgraphics and Microsoft Excel 4.0a. Results of data analysis are presented under broad headings.



Plate 4.3. Automatic Radiation Station in use along a transect with Digital PAR integrator (right hand side) in 5x30 m paulownia-wheat intercropping field at Dangshan, Anhui Province, China 1993.

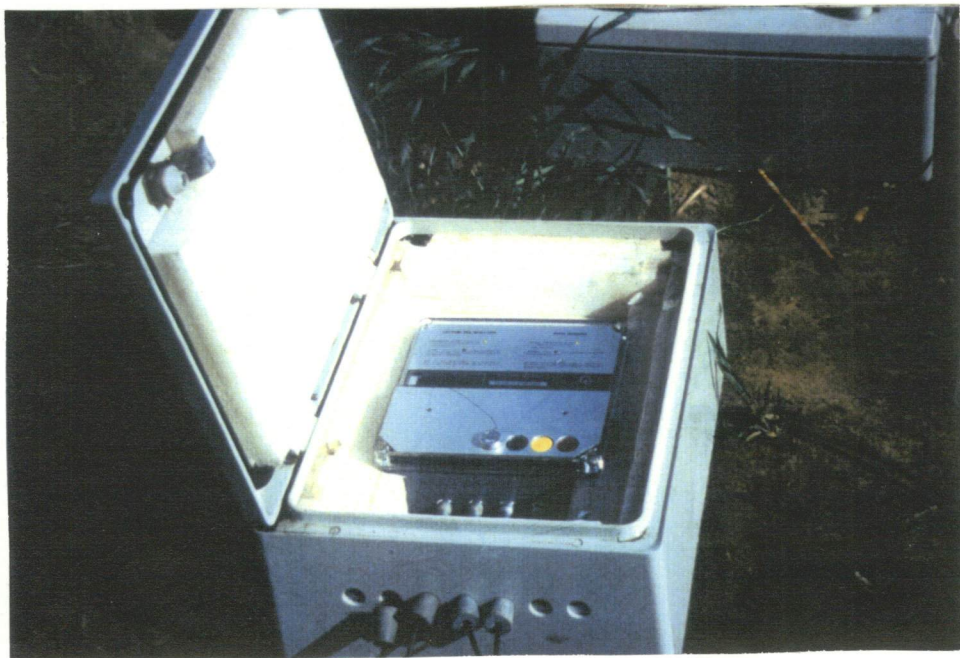


Plate 4.4 Automatic Radiation Recording Station which is connected with solarimeter sensors (see Plate 4.3) by wire for measuring total solar radiation.



Plate 4.5 LI - 1600 stable porometer used in paulownia - cotton field which was also used in measuring the physiological variables of winter wheat and other summer crops.

4.3 Tree Growth

Paulownia grows better under intercropping conditions due to benefits arising from the intensive management of crops, such as ploughing and the application of irrigation and fertilisers. Studies at Dangshan showed that trees have different growth patterns in relation to inter-row spacing. Following transplanting, the trees grew very slowly in the first year due to the root system being incompletely developed. In subsequent years, growth was fastest for the denser spacings and DBH responded more rapidly than height (Figures 4.1 and 4.2). For the first five years after transplanting, the trees in 5x6 m spacing grew the fastest. In the 6th year (1988), the growth in the 5x6 m spacing slowed, when DBH was 23.4 cm only, and the trees in the 5x10 m spacing grew faster than those in any other spacing until DBH reached 30 cm at the 8th intercropping year (1990), when the trees in the 5x20 m spacing started to have fastest DBH growth. Despite these observed trends, there was no significant difference between the spacings in any of the growth variables at the end of the study in the 10th intercropping year. However, average DBH was significantly affected by age ($p < 0.0001$) (Table 4.1).

In terms of height, the 4th to 6th intercropping years were period of fastest growth. There were no significant differences in height from the 7th to the 10th intercropping year.

DBH, height and trunk form (average coefficient is 0.42 for paulownia) are the main factors that determine the timber volume, which is the key index for commercial use. Table 4.2 shows that in the first 5 years of intercropping, 5x6 m had always the highest single tree timber volume. At the 8th year of the intercropping, timber volume in 5x10 m became the highest and followed by 5x20 m, whereas timber volume in 5x50 and 5x6 m were the lowest. At the 10th intercropping year (after 5x6 and 5x10 m were cut), timber volume in 5x20 m (0.6905 m^3) became the highest at 31.65 and 49.4 per cent higher than that in 5x40 and 5x50 m respectively.

Significant differences between each of the first three years were found in the tree canopy range in the east-west direction but then no significant differences were observed between the 5th, 6th and 7th years. The east-west canopy range in the 5th year was significantly greater than that in the 4th year and that in the 7th year was significantly smaller than that in the 8th year. From the 8th year to 10th year, annual differences in the east-west canopy range were not significantly different. The canopy range in the south-north direction grew fastest in the first 5 years, at the end of which

the canopy range reached 5.5 m. There were no significant differences in the range between years until the 9th intercropping year. This was because the canopies of neighbouring trees (intra-row spacing of 5 m) had overlapped by the 5th year.

Annual growth rates of DBH and height were always positive, while changes in crown range could be negative due to pruning. When there were high growth rates of canopy range, the trees tended to have higher rates of DBH growth in the same or the following year (Figures 4.1 and 4.2). DBH was significantly affected by canopy range ($p < 0.0001$) (Table 4.1). When the canopy range in the east-west direction occupied 42 per cent of the alley width, tree growth became rapid; when the canopies overlapped along the rows and the canopy range reached 76 per cent of the alley width, tree growth started to slow. For instance, trees in the 5x6 m spacing attained their highest growth when the canopy range was 2.8 x 2.8 m in the 2nd intercropping year and growth slowed when the canopy range reached 6.6 x 6.0 m in the 5th year. Trees in the 5x10 m spacing grew fastest when the canopy range reached 4.2 x 4.0 m in the 3rd intercropping year and slowed when the canopy range reached 7.9 x 6.6 m in the 6th year. The trees in the 5x20 m spacing grew fastest when the canopy range reached 8.6 x 6.4 m in the 8th intercropping year (Figures 4.1 and 4.2). Therefore, tree pruning and/or thinning should be implemented to increase tree growth rates when the tree canopies overlap. The larger the spacing, the later is the stage of fastest growth. For spacings larger than 5x20 m, the cutting rotation could be longer than 10 years. In practice, farmers usually cut trees about 10-12 years old. From Table 3.15, it can be concluded that economic maturity of the trees as defined by local market prices, occurs when diameter of the tree at the small (top) end exceeds 20 cm. It follows that a 5x6 m spacing is too dense for paulownia tree growth because the repaid growth period stops before economic maturity is reached and, in some cases, the latter is not attained before the end of the 10-12 year rotation. The 5x10 m spacing could be considered the best for tree growth followed by the 5x20 m because the period of the fast growth stops after economic maturity is reached and this occurs close to the end of the rotation period. Spacings of 5x40 and 5x50 m are not economical because the period of fast growth starts after the end of the 10-12 year rotation. However, these large spacings would be economical if farmers want to obtain larger timber board in a longer rotation.

Figures 4.1 and 4.2 also indicate that, in most cases, DBH growth slowed down whenever the canopy range was reduced by pruning. It can be concluded that pruning in the early stages could reduce DBH growth because it takes away leaves, leading to a reduction in photosynthesis.

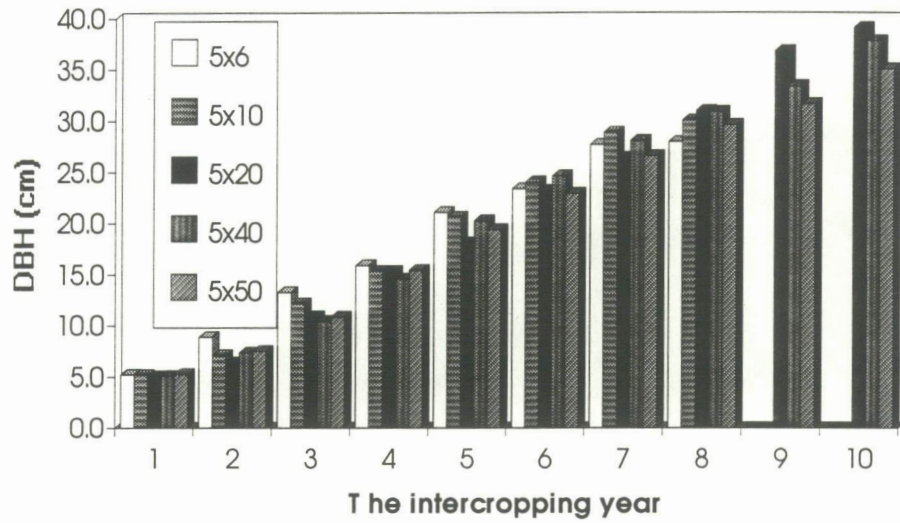
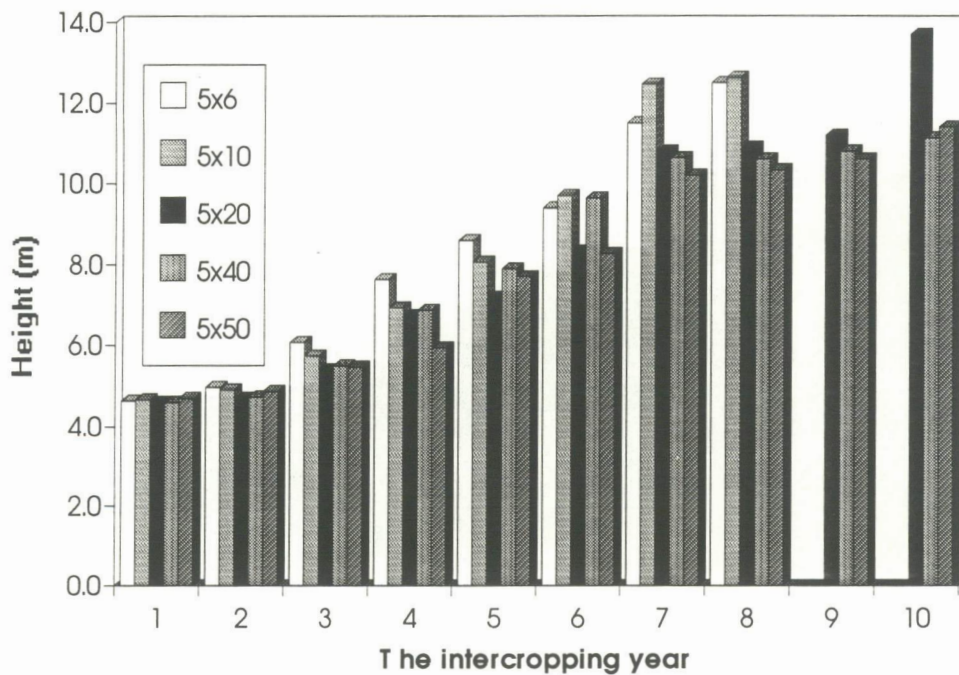


Figure 4.1 Diameter at Breast Height (DBH) and height of paulownia trees for different intercropping years and different spacings.

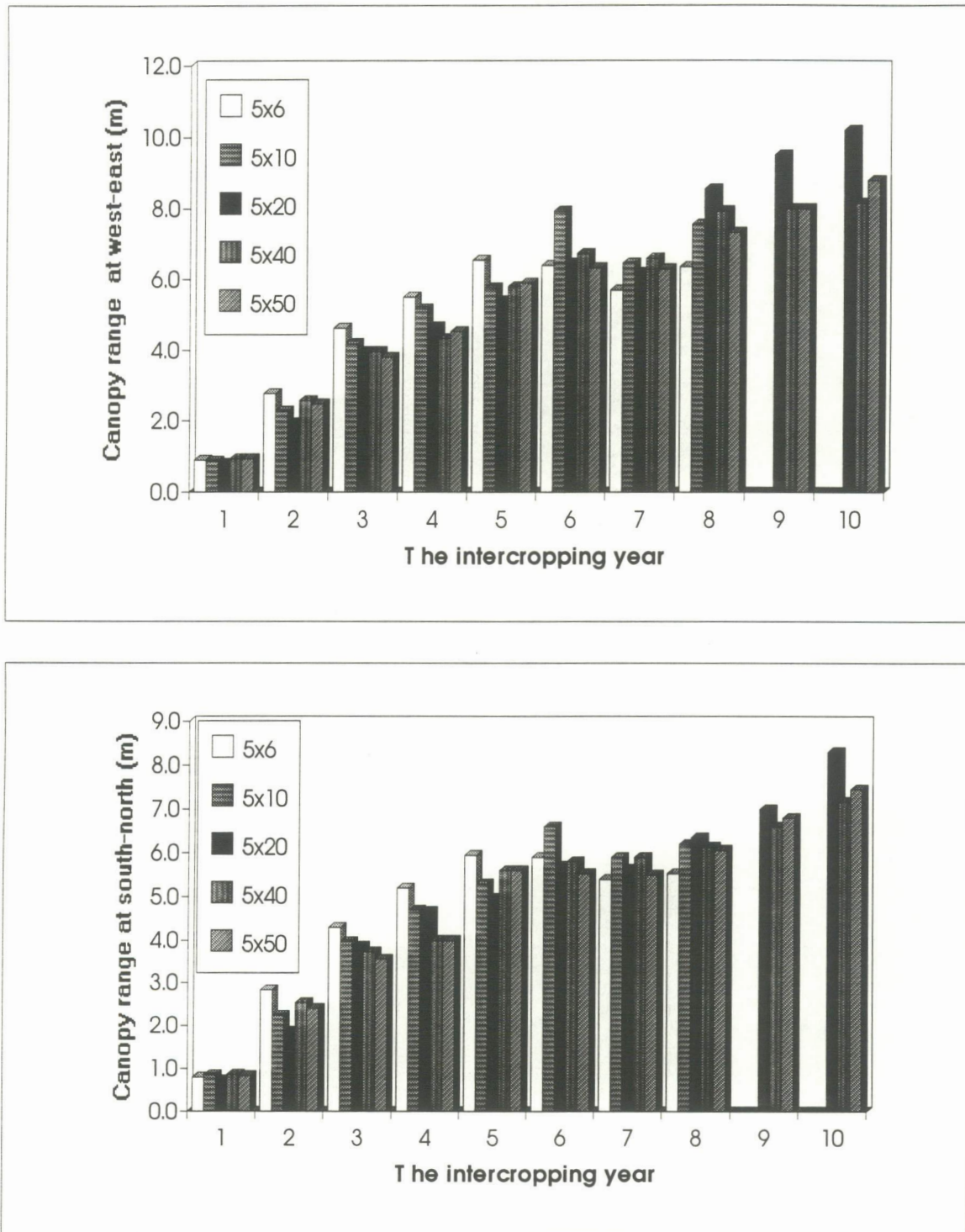


Figure 4.2 Canopy ranges (West-East and South-North) for paulownia trees in different intercropping years and at different spacings.

Table 4.1. Summary ANOVA Table for analysis (at 95% confidence level) of tree growth parameters. DBH = diameter at breast height; CEW = crown range in east-west direction; CSN = crown range in south-north direction; D.f. = degrees of freedom.

	Source of Variation	Sum of Squares	D. f.	Mean Square	F-ratio	Sig. Level
DBH by Age	Between groups	12545.2	9	1393.9	299.3	< 0.0001
	Winthin groups	577.6	124	4.7		
	Total (corrected)	13122.8	133			
Height by Age	Between groups	907.3	9	100.8	126.2	< 0.0001
	Winthin groups	99.1	124	0.8		
	Total (corrected)	1006.4	133			
CEW by Age	Between groups	602.5	9	66.9	67.8	< 0.0001
	Winthin groups	116.5	118	0.98		
	Total (corrected)	719	127			
CSN by Age	Between groups	444.7	9	49.4	116.1	< 0.0001
	Winthin groups	50.2	118	0.43		
	Total (corrected)	494.9	127			
BDH by EW	Between groups	11131.1	66	168.7	11.9	< 0.0001
	Winthin groups	863.4	61	14.2		
	Total (corrected)	11994.5	127			

Table 4. 2 Indices of single tree growth for different spacings. DBH = diameter at breast height (cm), H = height (m), Timber volume (m³ per tree), $V = \pi (DBH/2)^2 \times H \times 0.42$, where 0.42 is a trunk form coefficient.

Spacing (m)	Growth variables	Age									
		1	2	3	4	5	6	7	8	9	10
5x6	DBH	5.20	8.87	13.27	15.90	21.05	23.37	27.65	27.93		
	H	4.63	4.97	6.07	7.63	8.60	9.40	11.50	12.50		
	V	0.0041	0.0129	0.0352	0.0636	0.1256	0.1692	0.2899	0.3216		
5x10	DBH	5.17	7.07	12.13	15.30	20.57	24.03	28.85	30.03		
	H	4.67	4.90	5.73	6.93	8.07	9.70	12.47	12.63		
	V	0.0041	0.0081	0.0278	0.0535	0.1125	0.1847	0.3421	0.3757		
5x20	DBH	5.03	6.37	10.87	15.30	18.07	23.17	26.37	30.95	36.80	39.10
	H	4.60	4.70	5.40	6.73	7.20	8.33	10.80	10.90	11.20	13.70
	V	0.0038	0.0063	0.0210	0.0520	0.0775	0.1475	0.2475	0.3442	0.5001	0.6905
5x40	DBH	5.07	7.33	10.40	14.55	20.23	24.60	28.03	30.87	33.37	37.80
	H	4.60	4.73	5.50	6.87	7.90	9.63	10.63	10.60	10.80	11.13
	V	0.0039	0.0084	0.0196	0.0479	0.1066	0.1922	0.2755	0.3330	0.3964	0.5245
5x50	DBH	5.27	7.50	10.83	15.40	19.37	22.90	26.53	29.57	31.63	35.07
	H	4.70	4.87	5.47	5.93	7.70	8.27	10.20	10.33	10.60	11.40
	V	0.0043	0.0090	0.0212	0.0464	0.0952	0.1429	0.2368	0.2978	0.3497	0.4622
AVERAGE	DBH	5.2	8.7	13.3	15.9	21.1	23.4	25.9	27.9	33.1	36.0
	H	4.7	4.9	5.7	6.9	8.1	9.7	12.5	12.6	11.1	11.4
	V	0.0042	0.0122	0.0332	0.0575	0.1189	0.1751	0.2765	0.3234	0.4010	0.4871

4. 4. Light Climate

Tree-rows in an agroforestry system modify the microclimate of the sheltered area by shading. Solar and net radiation may be significantly reduced. Shading depends on the latitude, season and time of day and on the orientation, age and height of the tree rows (Zhu and Xiong, 1978; Rosenberg et al, 1983 and Wu, 1993). A detailed study on the microclimatic effects of a paulownia-based intercropping system has been reported by Wu (1993).

Solar radiation is one of the most important environmental factors for plant growth (Rosenberg et al, 1983; Monteith and Unsworth, 1990; Jones 1992). Particularly in agroforestry systems, the amount and quality of light intercepted by the understorey crop determine its productivity (Jackson, 1983). Besides the physical factors such as solar declination, elevation and latitude, the solar radiation environment in an intercropping system is related to three properties of the upper storeys (covering) of the trees, namely transmissivity (α), reflectivity (ρ) and absorptivity (τ). The sum of $\alpha + \rho + \tau$ at any radiation wavelength equals 1. Radiation is decreased by reflectivity and absorptivity as it travels through the tree canopy and the amount of solar radiation transmitted into the covered area is less than that outside (Takakura, 1993). Therefore, the properties of trees are important factors to be considered in the system.

Monteith and Unsworth (1990) showed that the fractions of incident solar radiation reflected and transmitted by a dense stand of vegetation depend on two main factors: the fraction intercepted by foliage and the scattering properties of the foliage. These, in turn, depend mainly on the area of foliage specified as a Leaf Area Index (LAI) and the spatial distribution of foliage with respect to the direction of radiation. Rosenberg et al (1983) also noted that the penetration of net radiation into plant canopies is a function of depth into the canopy expressed in terms of cumulative LAI. The penetration of light (quantitative and qualitative) is of considerable ecological significance. The leaf angle and orientation affect light penetration.

The unique structure and phonology of paulownia make the light properties in farmers' fields enclosed by trees in a paulownia intercropping system distinguishable from those of other agroforestry systems.

4.4.1 Light transmissivity

Light transmissivity (LT) is defined as the fraction of incident radiation at a given wavelength that is transmitted by an object (Jones 1992). In this context transmissivity was calculated as the percentage of total solar radiation (SR) received at 10 cm height above the crop canopy compared with the amount received in an open field. It was found that the crop layer in the intercropped plots received less radiation than the crop in the open field. Reduction of solar radiation depended on paulownia spacing, distance from the tree, and the age and growth stage of the tree. Greater reduction of solar radiation occurred in denser tree spacings, closer to the trees, when the trees were older and after the paulownia leaves were fully developed.

Over the growing season of the understorey wheat crop, there was less light reduction from sowing (October) to booting stage (April) when trees were in dormancy and flowering stage. Most radiation reduction occurred during the grain filling stage (May), especially in the dense spacing and in areas near to the trees (Figure 4.3). Patterns of seasonal variation in LT vary with different spacings as shown by data for the 7th intercropping year (1989). LT in 5x40 m was at its seasonal highest in the middle of the alley (Figure 4.3) but at its seasonal minimum under the trees in October when tree leaves had nearly fallen. The seasonal minimum value of LT in the middle of the alley was observed in July-August, whereas under the trees the LT in August was higher than in May. The latter might be due to the higher solar declination in August causing shorter hours of shading and therefore more light being received. This might compensate for the higher light interception by the trees in full leaf which lowers the LT received by the understorey. However, this may not be adequate to derive a conclusion because LT is also determined by solar elevation angle and cloudiness during the day. Thus, cloudy conditions in the early morning and late afternoon when the area was not shaded could lower the LT under the trees. In 5x20 m, LT was not measured in October, but it was at its seasonal highest at all locations across the alley in April. The seasonal low in the middle of the alley occurs in August, similar to the situation in the 5x40 m spacing. In contrast to the latter, however, the seasonal low under the trees in the 5x20 m spacing also occurs in August when there is a dramatic fall in LT from the middle of the alley to the edge of the canopy. This maybe due to the larger canopy area of the trees in the 5x20 m spacing (as shown in Figure 4.2) leading to higher light interception by the tree leaves and longer shading hours especially in the middle of the day (Wu, 1993).

In the 7th intercropping year, average daily LT in the middle of alley was 75.6, 79.8 and 97.1 per cent of that in open field during April in the 5x10, 5x20 and 5x50 m spacing respectively. There were significant reductions of light in 5x6 and 5x10 m, but not in spacings larger than 5x20 m. It was observed that LT was 18.1, 35.0, 76.3, 92.3 and 95.8 per cent during May in the 5x6, 5x10, 5x20, 5x40 and 5x50 m spacings, respectively.

LT decreased with greater tree age and denser spacing (Figures 4.4 and 4.5). As shown in Figure 4.4, in the 5x20 m spacing, very high LT values (95.9 per cent) were still observed in the 4th intercropping year with little variation with distance across the alley. In the 5th year, LT was significantly lower under the trees and by the 7th year reductions were observed across the whole width of the alley. In 5x40 m, significant reduction of LT under the trees started in the 7th intercropping year which was two year later than in 5x20 m. The decrease can be minimised by pruning as shown by data for the 10th year. After pruning in the 10th intercropping year, LT was 97.2 per cent in April in the middle of alley for 5x30 m spacing, and 85.4, 90.8 and 94.2 per cent in the middle of alley in May for the 5x20, 5x30 and 5x40 m spacings respectively. Thus LT was higher in the 10th intercropping year than in the 7th, especially under the trees, which were taller but with relatively smaller canopies after pruning (Figure 4.4 and 4.5). Figure 4.5 also showed that there was not much difference in LT among different spacings at the 10th intercropping year after pruning.

Considering the vertical distribution of solar radiation within the tree row, the lowest light levels were found inside the tree crown. Average percentage LT at 1 m (above crop canopy), 4 m (under tree crown) and 6 m (middle of tree crown) heights above the ground were respectively 39.9, 45.8 and 33.7 per cent in May and 31.2, 27.6 and 30.3 per cent in August. LT at any height from above crop canopy to inside the tree crown was higher in May than in August. In the middle of the alley, the position 2 m above ground received $2154 \text{ J cm}^{-2} \text{ day}^{-1}$ which was $32.9 \text{ J cm}^{-2} \text{ day}^{-1}$ higher than the amount received at 1 m above the ground. However, solar radiation at 1 m above ground was up to $81 \text{ J cm}^{-2} \text{ day}^{-1}$ higher than that at 2 m before 08.00 hours and after 15.00 hours because the lower angle of the sun avoided the block of tree canopy.

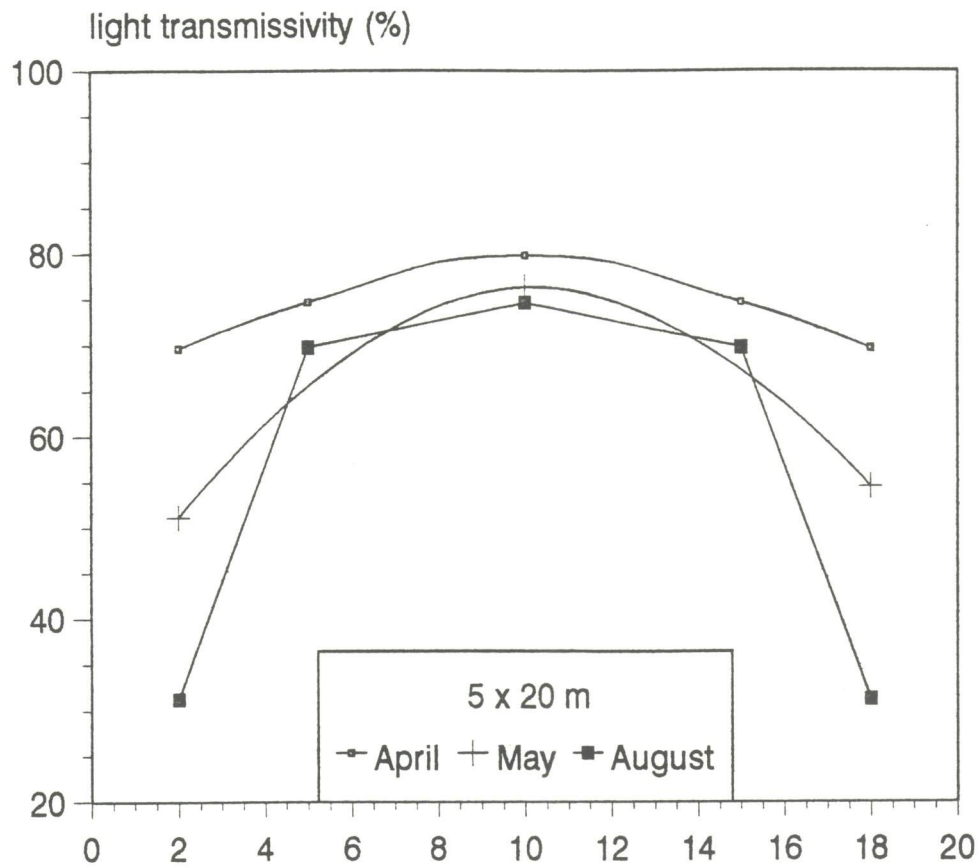
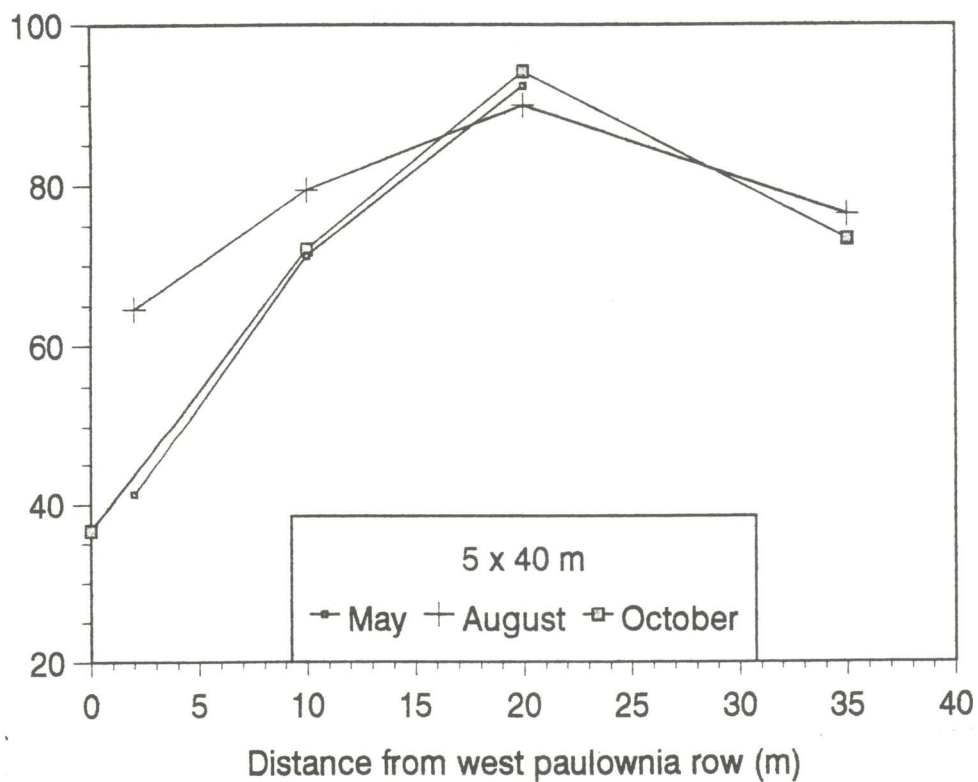


Figure 4.3 Seasonal distribution of light transmissivity (percentage of control) for the 5x20 and 5x40 m tree-row spacings for 1989.

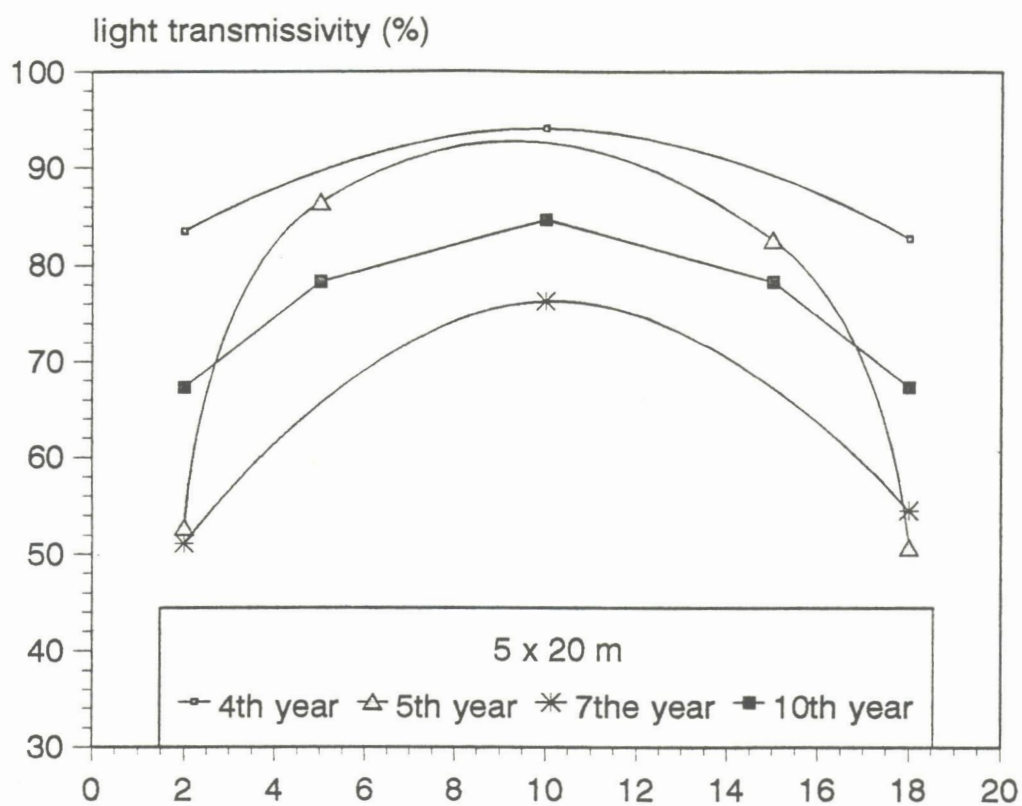
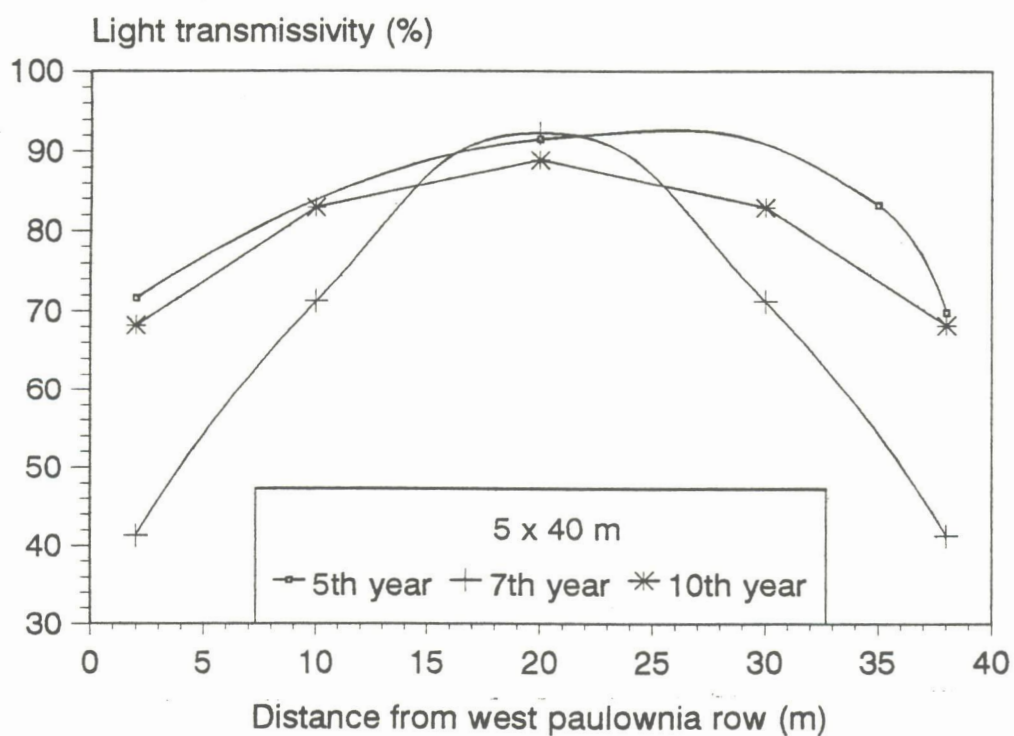


Figure 4.4 Distribution of light transmissivity (percentage of control) across the alley in the 5x20 and 5x40 m tree-row spacings during May for different intercropping years.

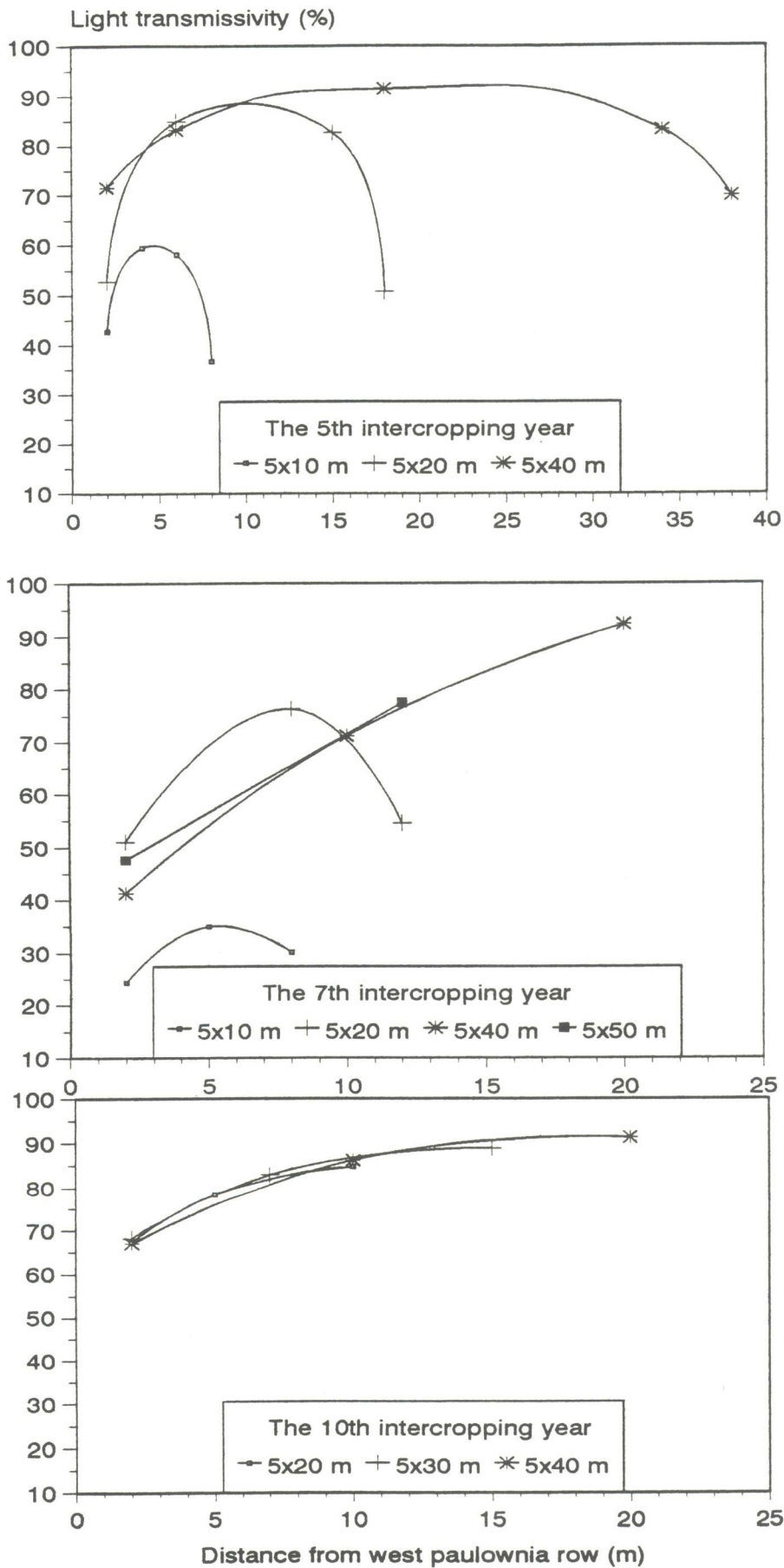


Figure 4.5 Distribution of light transmissivity (percentage of control) across the alley in May for different tree-row spacings and different intercropping years.

The hourly horizontal distribution of solar radiation in the middle of the alley in 5x20 m spacing is almost the same as that in the control plots (Figure 4.6). The peak solar radiation appeared between the rows at the same time as that in the control and the radiation difference was less between 10.00 and 15.00 hours than at any other time due to the shading effects before and after these times. Radiation received at 2 m and 18 m from west tree rows showed peaks at both the early morning and late afternoon when there was no shading from the low-angled sun.

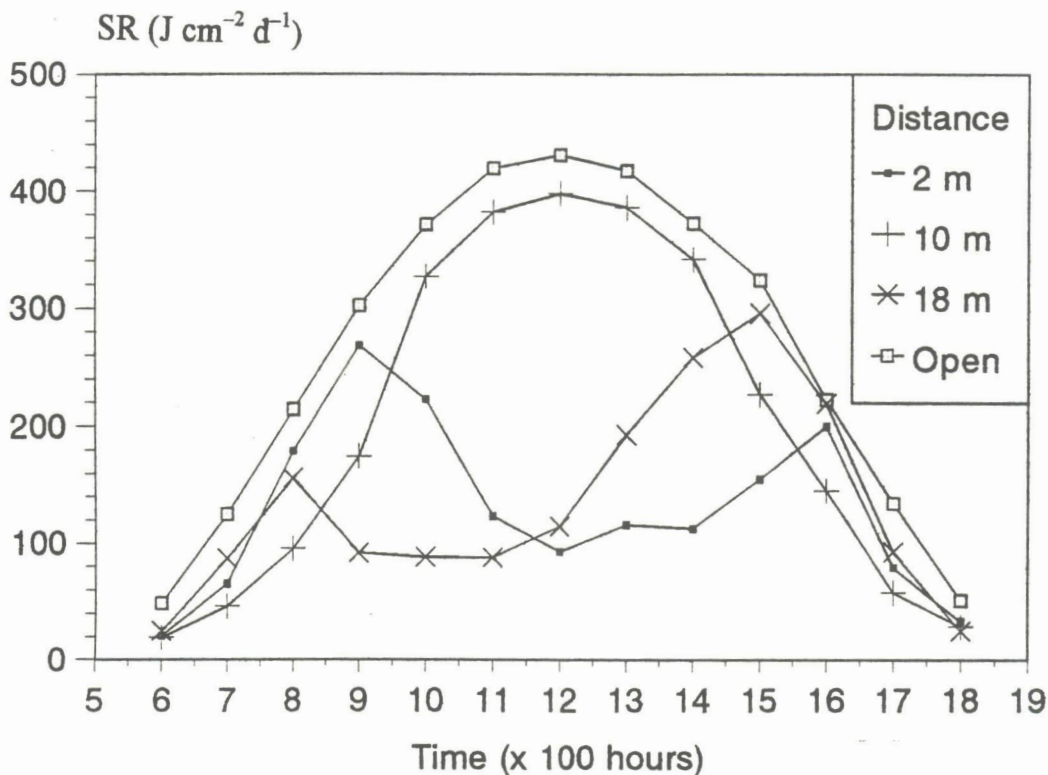


Figure 4.6 Hourly distribution of solar radiation with distance across the alley on a clear day for the 5x20 m tree-row spacing and control in the 7th intercropping year (measured on 17 May 1989).

4.4.2 Reflectivity

The reflectivity (R_r) of a surface is defined as the ratio of the incident flux to the reflected flux at the same wavelength (Jones 1982). Average values of R_r (in percentage reflected radiation over SR) in the intercropped plots of 5x10 and 5x20 m spacings and under the trees in the 5x40 and 5x50 m spacings in May ranged from 17.5

to 21.4 per cent, which were 20 to 47 per cent higher than those in the open field (%Rr/C). In contrast, for the wide spacings, the Rr in the middle of 5x40 and 5x50 m alleys was respectively 17.8 and 2.1 per cent lower than that in the open field in May (Table 4.3). This agrees with the conclusion of Rosenberg et al (1983) that reflectivity is negatively related to air temperature and conforms to the findings of Wu (1993) who showed that in dense spacing (denser than 5x20 m) air temperature during the day in the middle of the alley was 0.4-2.3°C lower than in the control, whereas in the wider spacings (5x40 m) air temperature was 0.4°C higher or was no different from that of the control (5x50 m).

However, the absolute amount of radiation reflected (TRr) was still much lower in the intercropping systems than in the control because the total amount of radiation received was less. As shown in Table 4.3, in comparison with control, total amount of radiation reflected (%C) in May was only 36.2-43.7 per cent in 5x10 m, and 51.6-94.3 per cent in 5x20 to 5x50 m.

4.4.3 Photosynthesis active radiation

Most measurements of solar energy at the ground are confined to the visible (400-700 µm) and near-infra-red (700-1500 µm) wavebands which in fractions of the Solar Constant constitute 39.8 per cent and 38.8 per cent, respectively. The visible waveband is sensitive to the human eye and ranges from blue (400 µm) through green (550 µm) to red (700 µm); since it stimulates photosynthesis, it is referred to as Photosynthesis Active Radiation (PAR).

Following the spatial distribution of total solar radiation, the greater the distance from the trees and the larger the spacing, the higher is the PAR received by the understorey (Figure 4.7). However, there is almost no difference in the distribution pattern of PAR transmissivity across the alley between clear days and cloudy days, though the actual amount of PAR received is very different (Figure 4.8).

PAR received under trees can be about 40 per cent lower with fully developed leaves (May-September) than in the flowering and dormancy season (April and February) due to PAR interception by tree leaves during the former period; the reduction is higher when the trees are older. However, there are no seasonal differences for the area between the crown edge and the middle of the alley (Figure 4.9). Therefore serious crop yield reduction caused by the depression of PAR only occurs under the trees.

Table 4.3 Radiation reflectivity (Rr, percentage of reflected radiation over total solar radiation), total amount of radiation reflected (TRr, $\text{J cm}^{-2} \text{ day}^{-1}$) in intercropped systems compared with that in control in percentage (%C) and comparison of reflectivity (Rr) in the intercropped as percentage of that in control (%Rr/C) in the 7th intercropping year for different seasons. D = distance from western tree-row (m).

Spacing (m)	D (m)	April		May			
		TRr	Rr	TRr	%C	Rr	%Rr/C
5x10	2	286	19.8	154.3	36.2	21.4	147.6
	5	326	21.5	181.3	42.6	17.5	120.7
	8	382	28.8	186.0	43.7	21.0	144.8
	Open			426.0		14.5	
5x20	2	316	20.9	336.7	71.5	21.1	139.7
	5	318	19.7				
	10	330	18.3	362.7	77.1	18.3	121.2
	18			313.7	66.6	18.8	124.5
	Open			470.7		15.1	
5x40	2			242.7	51.6	21.2	145.2
	10			269.3	57.3	12.4	84.9
	20			373.0	79.3	12.0	82.2
	Open			470.3		14.6	
5x50	2			212.7	60.3	18.7	128.1
	12			288.0	81.6	15.3	104.8
	25			333.0	94.3	14.3	97.9
	Open			353.0		14.6	

Hourly PAR transmissivity at all distances were lower before 10:00 AM than at any other times because the whole alley was in shadow due to the lower angle of the sun. Similar to the pattern for total solar radiation, hourly PAR interception was not symmetrical across the alley due to shading movement (Wu, 1993). PAR was higher at 2 m from the east row (28 m from the west row) than at 2 m from the west row in the 5x30 m spacing, but not so in the denser spacings because of shading overlap between the rows (Figure 4.10).

The proportion of PAR to total SR was slightly lower in the intercropping than in the control. The nearer to the trees the lower is the percentage (Table 4.4). This might be due to PAR consumption by tree leaves.

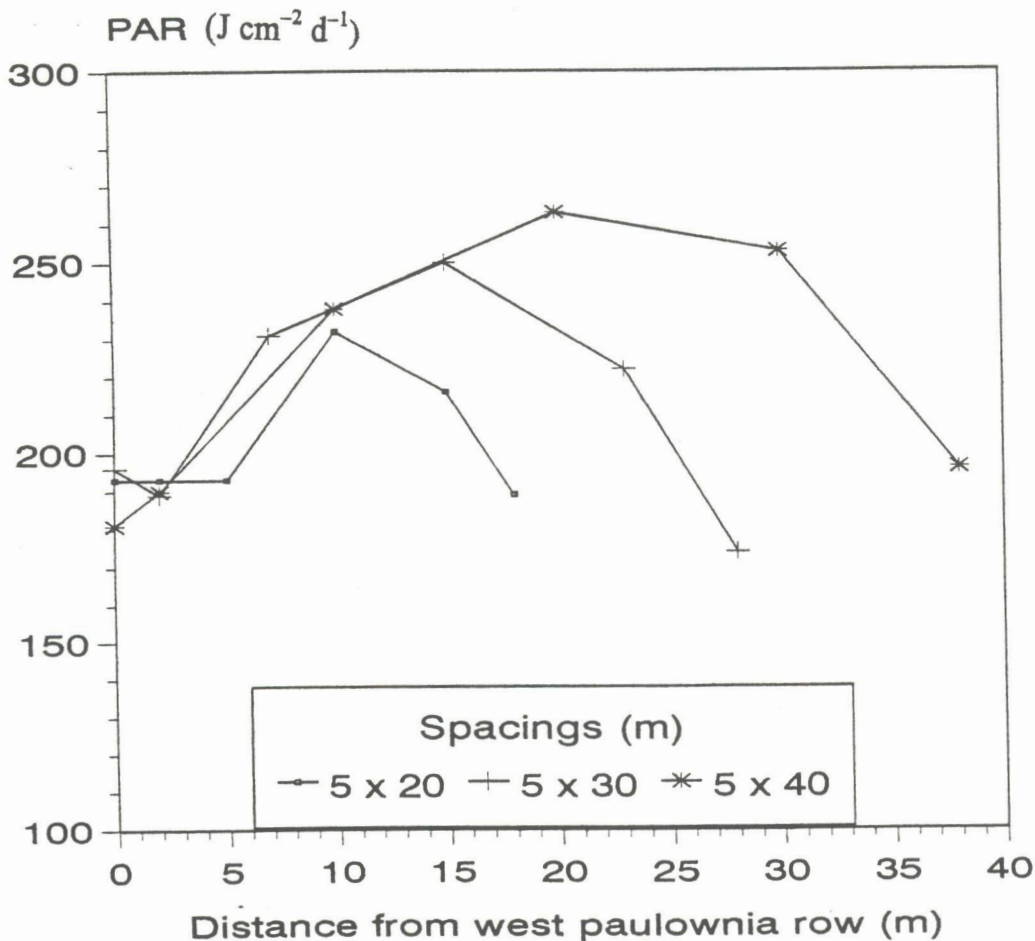


Figure 4.7 Distribution of Photosynthesis Active Radiation (PAR) across the alley on clear days in May for different tree-row spacings in the 11th intercropping year.

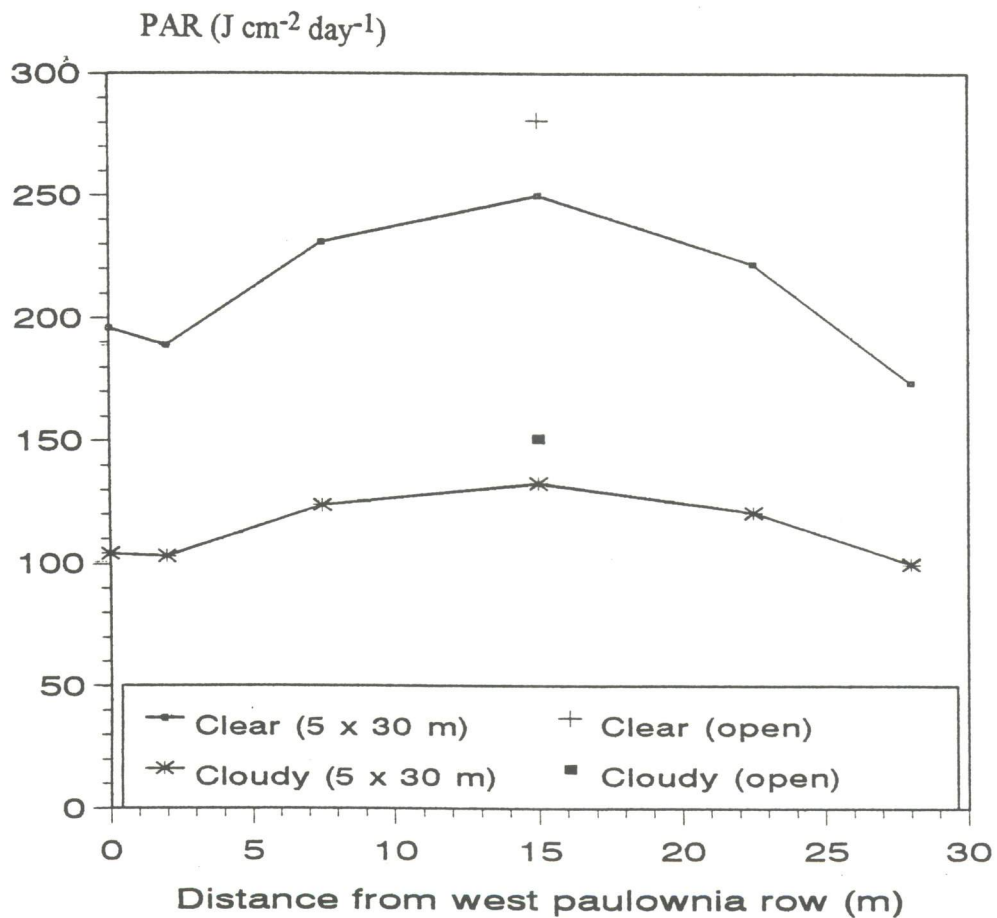
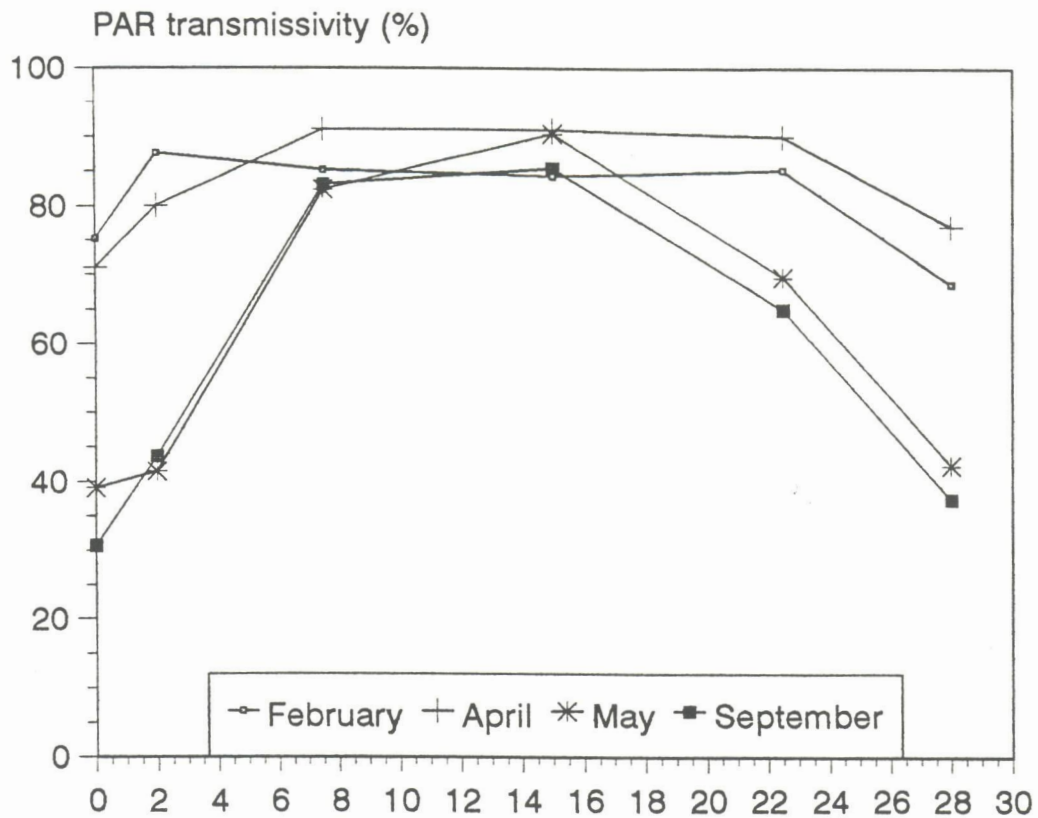
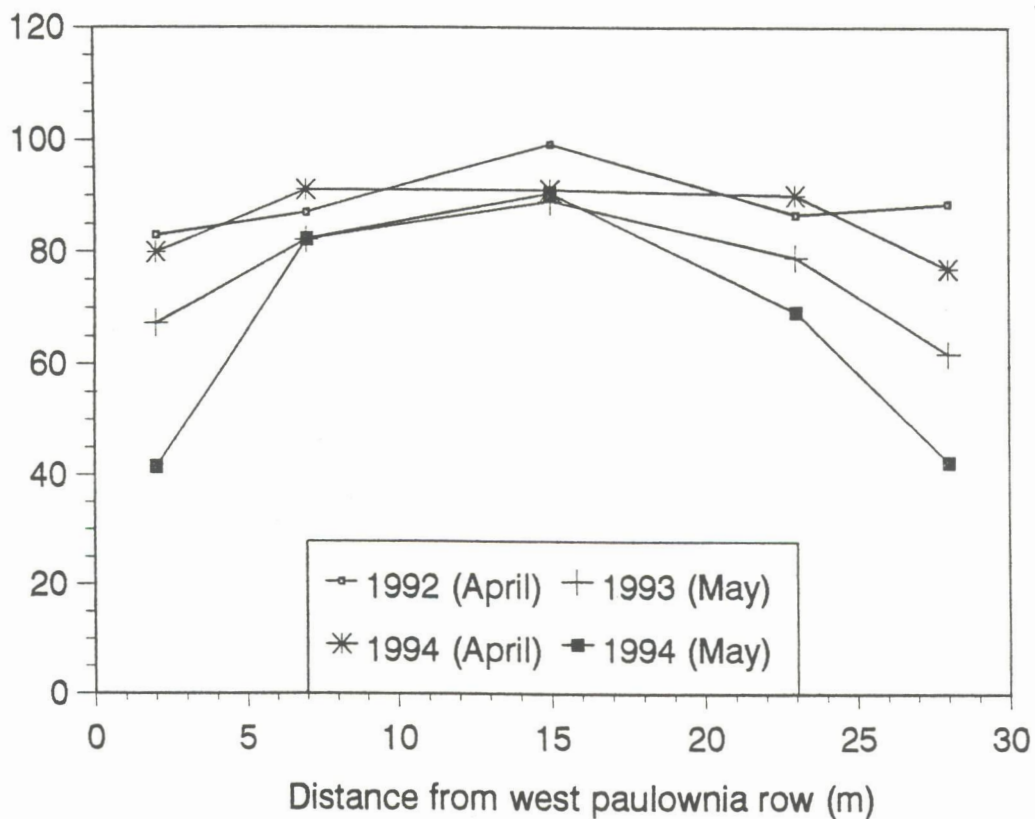


Figure 4.8 Distribution of Photosynthesis Active Radiation (PAR) across the alley for clear and cloudy days in 5x30 m tree-row spacing in May in the 11th intercropping year compared with an open field.



(a)



(b)

Figure 4.9 Distribution of Photosynthesis Active Radiation (PAR) transmissivity (percentage of control) across the alley in 5x30 m tree-row spacing for (a) different seasons at the 10th intercropping year and (b) different (8th, 9th and 10th) intercropping years.

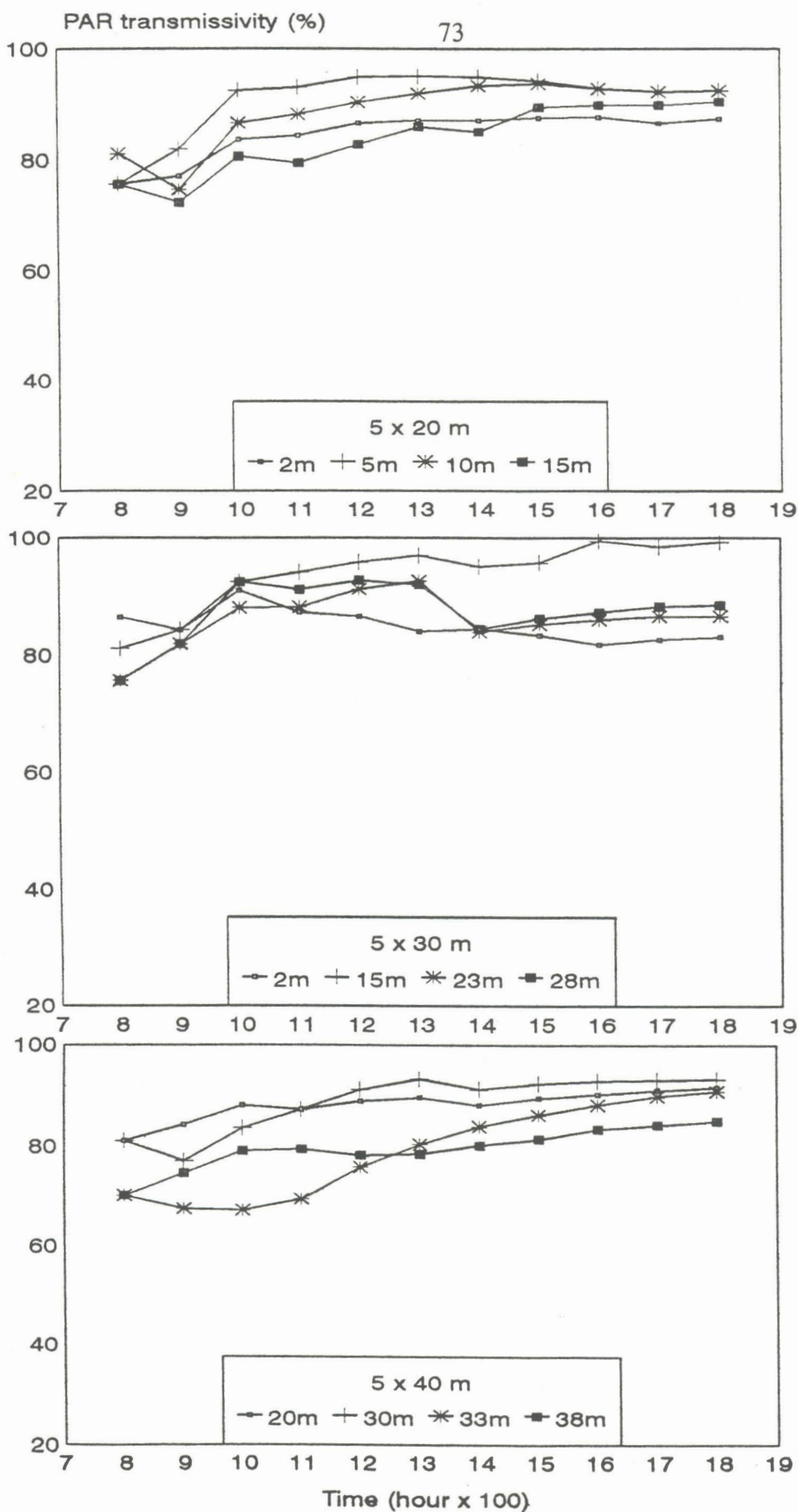


Figure 4.10 Changes in hourly PAR transmissivity (percentage of control) across the alley for different tree-row spacings in the 10th intercropping year.

Table 4.4 Solar radiation (SR, in $\text{J cm}^{-2} \text{ d}^{-1}$) and Photosynthesis Active Radiation (PAR, in $\text{J cm}^{-2} \text{ d}^{-1}$) in 5x30 m tree-row spacing at the 10th intercropping year in Goucun, May 1993. PAR was measured in $\text{mW cm}^{-2} \text{ day}^{-1}$ and converted into $\text{J cm}^{-2} \text{ day}^{-1}$ ($\text{J cm}^{-2} \text{ day}^{-1} = (\text{mW cm}^{-2} \text{ day}^{-1}) * 3600/1000$). %PS = proportion of PAR to SR expressed in percentage. %C = values received in the intercropped systems compared with control expressed in percentage.

Date	Light	Distance from the east tree-row (m)						
		2		7		15		Control
		Total value	%C	Total value	%C	Total value	%C	Total value
27 May	SR	901.8	59.6	1267.8	83.8			1513.2
	PAR	338.4	51.4	514.8	78.1			658.8
	%PS	37.5		40.6				43.5
28 May	SR	1327.6	50.0	2338.5	88.1	2318.4	87.4	2653.7
	PAR	532.8	50.2	820.8	77.3	903.6	85.1	1062.0
	%PS	40.1		35.1		39.0		40.0
29 May	SR	1418.5	63.4	1769.7	79.1			2236.6
	PAR	500.4	57.9	662.4	76.7			864.0
	%PS	35.3		37.4				38.6

4.5 Understorey Crops

The microclimatic changes in the intercropped fields may be expected to affect crop growth and yield. Trees can be both advantageous and disadvantageous to crop production. The beneficial effects of trees include reduction in plant damage due to wind, higher air and soil temperature, decreased soil erosion, low evaporation rate, and increased carbon dioxide concentration in the sheltered zone. The deleterious effects include shading, root competition, slow crop ripening and drying, and delayed harvesting. The trees may shade the nearby crops sufficiently to affect their production. Severe shading may suppress photosynthesis and dry matter production but the effect can be offset by reduced evapotranspiration in the shaded zone (Marshall, 1967; Huxley, 1983; Rosenberg et al 1983; MacDicken and Vergara, 1990 and Sanchez, 1995). Moreover, beyond a distance of 1H or 2H from the tree row (where H is the height of the tree row), the energetic effect of shading is probably unimportant and despite the reduction in yield near the belt, the overall yield per unit of land can exceed that of the unsheltered fields (Rosenberg et al., 1983). The penetration and greater assimilation of

photosynthetic active radiation under the sheltered canopy may actually contribute to a greater photosynthetic rate in the sheltered crops (Ogbuehi and Brandle, 1981). For further understanding of how trees affect understorey crop, it is necessary to explore the ecophysiological response and yield of both the main winter crop, grown in the dry season when paulownia has few leaves, and summer crops grown in the rainy season when paulownia carries leaves and provides shade.

4.5.1 Intercropped wheat

Leaf conductance

For the management of plantations in agriculture and forestry, where the target is the greatest possible productivity, it is important to know the relationship between water consumption and productivity (Larcher, 1983). Measurements of leaf transpiration and calculations of leaf conductance to water vapour are important in almost all investigations of plant water relations. Conductance of the leaf to water vapour loss is usually presented rather than its inverse, a resistance, since conductance is proportional to the flux and it expresses the regulatory control exerted by the stomata on transpiration rates. Changes in conductance translate into changes in transpiration, photosynthesis and hence in water use efficiency (Percy et al. 1993).

Leaf conductance (LC) changes during the day. In unstressed conditions, changes are in response to light level. Water stress suppresses this response. Meyer and Anderson (1952) reported that when the soil water supply is inadequate, the water content of the leaf is so low that opening is seldom complete even though light favours stomata opening, especially on clear days. This is because the effect of water usually predominates over that of light under such conditions. Ma and Lu (1990) discovered that leaf conductance in wheat near poplar trees was higher than that in the open field, and attributed this to differences in the soil water content. Wu and Dalmacio (1991) reported that both actual evapotranspiration and potential evapotranspiration decreased in cropped alleys between tree rows of any spacing on clear days because shading reduced the driving force for evapotranspiration and leaf conductance. In turn, such changes reduce evaporation from soil and transpiration from plants. Therefore the water deficit was less in intercropped conditions than in the control. It was also reported by Wu (1993) that the average water content in the soil layer 0-40 cm below the surface is 16-32 per cent higher in the intercropped field than in the open field; the difference is most pronounced in the dry season and in the denser spacings. The

increased soil moisture is beneficial to the wheat crop that absorbs 50-60 per cent of its water from 0-30 cm depth (Doorenbos and Kassam, 1979). The water contents measured in the field in the upper 60 cm of soil in April and May showed the same trend, but variability of the data does not permit any firm conclusions to be drawn. The response to light at the very end of wheat growing season suggests that while plants in the control plot suffer from a degree of water stress, plants between the trees respond to changes in light level and appear to suffer less water stress. It was observed that LC was higher in the intercropped fields than in the control and its distribution across the alley was similar to that of light. The further from the trees, the higher was the LC. Also LC in the intercropped fields was higher than in the control (Figure 4.11). The higher LC means lower stomata resistance to carbon dioxide which leads to longer duration of photosynthetic process in the shelter of the trees (Rosenberg et al, 1967 and Brown and Rosenberg, 1972).

Wheat is sensitive to high temperature, especially during grain filling. The optimum temperature for flowering is 18-20°C (Van Keulen and Seligman, 1989); fertilisation is hampered at temperatures above 30°C and lower grain numbers may reduce yield drastically. During grain filling, the optimum temperature is 20-22°C; higher temperatures accelerate phenological development and thus shorten the period in which carbohydrates can accumulate (Yang and Yu, 1988). The optimum temperature for photosynthesis is 10-25°C (Van Keulen and Seligman, 1989). As leaf temperature increases, metabolic activity in the guard cells and the leaf as a whole increases, reaches an optimum and then decreases. Leaf conductance follows this response (Willmer, 1983).

Wu (1993) reported from Dangshan that trees in the intercropped field have a barrier effect, which obstructs the heat transfer and reduces air mixing and evaporation, thus leading to increased air temperature, whilst the shading effect of the trees decreases the air temperature. As a result, air temperatures in the dense spacings (5x6 and 5x10 m) were 0.79-0.12°C higher than in the control during the early years of tree growth but started to decrease from the 7th intercropping year due to closure of the tree canopies. The air temperature in the day during booting and grain filling stages of wheat at the 7th intercropping year was 0.6-0.3, 0.2-1.5 and 0.4°C lower than in the open in the 5 x 6, 5x 10 and 5x20 m spacings respectively, but 0.4°C higher in the middle of the alley in the 5x40 m spacing.

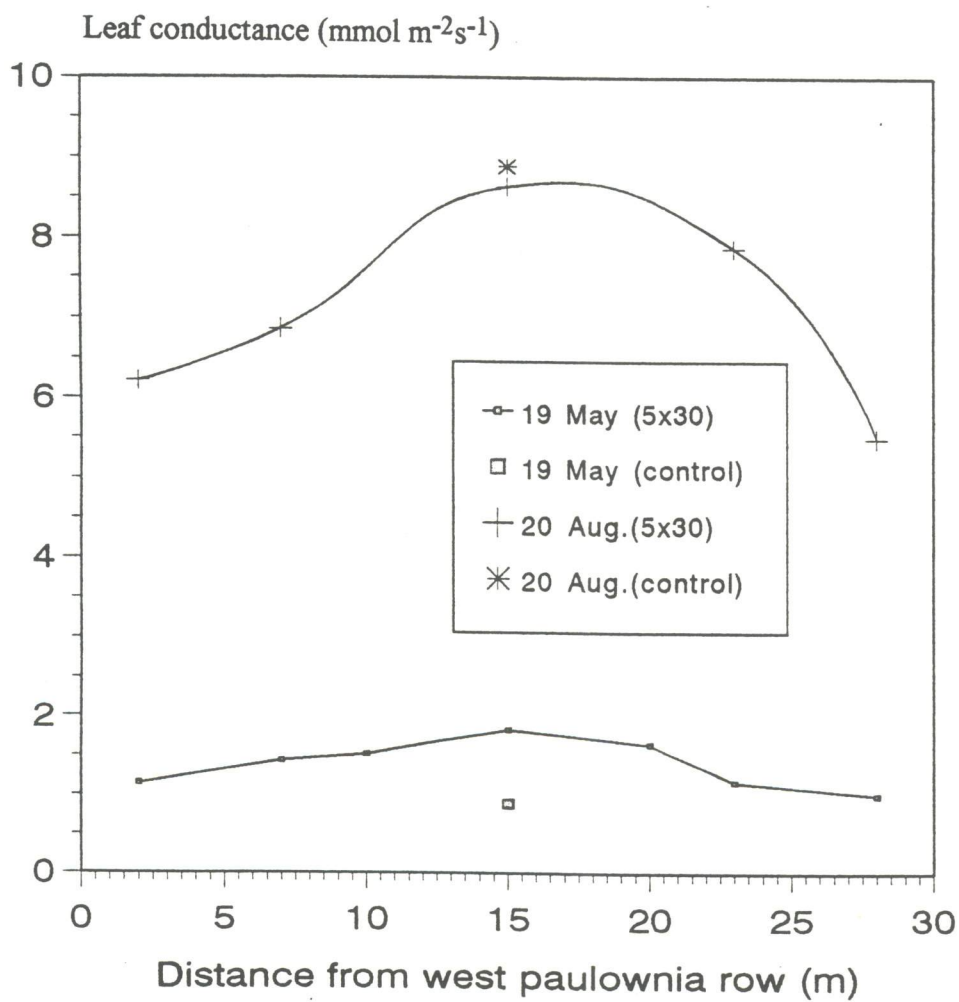


Figure 4.11 Daily average leaf conductance of wheat (19 May) and cotton (20 August) at different distances across the alley in the 5 x 30 m tree-row spacing in the 11th intercropping year.

To determine whether leaf conductance (C_s , $\text{mmol m}^{-2} \text{s}^{-1}$) was related to light, temperature and other climatic factors in the intercropped conditions, measurements were made of its value and the principal microclimatic factors that affect it. The response of wheat in the Dangshan experimental plantation (10th intercropping year, 5x40 m spacing) was analysed, using regressions of leaf conductance against controlling factors. For the wheat crop, temperature (T_a , $^{\circ}\text{C}$) appeared to be the only variable that explained a large fraction of the variation in leaf conductance of wheat (C_w):

$C_w = -0.0867T_a + 3.5119$	under trees	
	($r = 0.64$, $n = 48$)	(4.2)
$C_w = -0.2017T_a + 7.4084$	at the edge of the trees	
	($r = 0.76^*$, $n = 48$)	(4.3)
$C_w = -0.1070T_a + 3.9774$	in the middle of the alley	
	($r = 0.66^*$, $n = 48$)	(4.4)
$C_w = -1.0796T_a + 4.1145$	control	
	($r = 0.76^*$, $n = 48$)	(4.5)

where (*) denotes significant at $p < 0.05$.

Paulownia provides little shade during the booting and early grain filling stages of wheat in 5x40 m intercropped spacing in the 10th intercropping year (Section 4.4.1) because at the times the tree is flowering or at an early leaf expansion stage. The absence of an effect of light level in Equations 4.2 to 4.5 was therefore expected. The negative correlation with temperature agrees with the observation that paulownia prevents hot winds which can cause great loss of wheat yield, as observed in the open field (Zhu, 1986).

Growth and development

Leaf development rate depends on environmental factors such as temperature, water use efficiency, and nutrient supply (Penning de Vries and Van Laar, 1982). The trees exerted positive effects through increased air and soil temperature and soil moisture (Wu, 1993) on wheat growth from the sowing to the flowering stage which coincided with the dormancy period of paulownia. It was found that germination, tillering, stem elongation and booting of wheat were 2-4 days earlier in the paulownia-wheat

intercropped field than in the control. The denser the spacing, the earlier is the start of the development stage of wheat.

The higher leaf conductance in intercropped fields with wide tree spacings led to more robustness in metabolism. The relatively longer period of photosynthesis led to a higher growth rate and finally higher yield. Depending on tree spacing and location in the intercropped field, the leaf area index (LAI) of wheat could increase up to 36 per cent in the booting stage and up to 53-229 per cent in the grain filling stage in comparison with the LAI of wheat in the control field (Table 4.5). Under the trees, the LAI was lower than in the control during booting at all spacings, and during grain filling at the dense spacing of 5x20 m. This general beneficial effect of intercropping on LAI was because wheat in the control sometimes suffered from hot and dry winds during the grain filling stage, which caused the leaves to wither and die before maturity. It was also observed that leaves of intercropped wheat die more slowly than those in the control, giving the intercrop a 2-5 days longer growing season. The higher LAI and longer growth period might result in higher wheat yield. The delay and prevention of wilting in shelter also suggest that greater photosynthetic opportunity accounts for greater yield production (Rosenberg, 1979). As reported by Puckridge (1971) in more arid environments, LAI reached its peak well before anthesis and fell progressively as water stress increased. Consequently, the LAI was less than 4, and light interception less than complete, throughout most of the grain filling period. Under these circumstances, yield is likely to bear a close relation to LAD (the integral area index with respect to time from ear development to maturity, also known as Watson's leaf area duration). Of the variation in yield not accounted for by differences in LAD, most can be ascribed to differences in incoming radiation during grain filling. Welbank et al (1968) found that the ratio of grain yield to LAD increased linearly with increase in daily radiation during grain filling. Grain yield itself did not do so, however, tending to plateau at high radiation levels. The reason for this is presumably that the duration of grain filling is shorter at higher radiation levels, cancelling any effect of greater photosynthesis.

Wheat productive development was more affected than the vegetative growth in the intercropped field due to the later stage of grain filling coinciding with full leaf development of the paulownia trees. The light reduction under the trees and in the dense spacing may hamper the inflorescence development and number of spikelets. As reported by Friend (1965) the rate of inflorescence development is usually faster the higher the light intensity, the longer the day-length and the higher the temperature. The number of spikelets formed is higher when light intensity is higher. It was found that

the number of spikelets per unit was lower in the paulownia-wheat intercropped fields than in the control. The denser the spacing the lower was the spikelet rate. The trends were more apparent when the trees were older. Evans et al. (1980) stated that the storage capacity of a wheat crop depends on the number of ears per unit area, the number of spikelets per ear and grains per spikelet, and on individual grain size. The relative magnitudes of these yield components vary substantially with the sequence of growing conditions, with features of agronomic practice such as sowing density and fertiliser application, and with the cultivar used. These yield components are determined sequentially during the development of the crop, both ear and spikelet number before anthesis, grain number around anthesis, and grain size between anthesis and maturity. Thus, the storage capacity of a wheat crop can respond to environmental conditions almost until maturity. Radiation and nutrient level during inflorescence growth, as well as temperature and day-length, influence spikelet number, while grain set is particularly influenced by light intensity and water supply just before and at anthesis. In the following weeks these factors also exert a marked influence on ultimate grain size, as does temperature throughout the grain filling period. Consequently, the relation between grain yield and particular yield components varies greatly depending on the sequence of environmental conditions at the various stages in the development of the crop.

Table 4.5 Wheat leaf area index at booting and grain filling stages in the 10th year of intercropping.

Spacing (m)	Booting Stage			Grain Filling Stage		
	Under canopy	Canopy edge	Middle of alley	Under canopy	Canopy edge	Middle of alley
5x20	3.2	4.3	4.9	0.13	0.26	0.28
5x30	3.2	3.5	3.6	1.13	0.73	1.52
5x40	2.7	3.9	3.7	1.11	0.81	1.20
5x50				1.08	1.57	0.93
Control	3.6			0.48		

Due to the modified micro-environmental conditions, wheat grain quality, measured as 1000 grain weight and grain quality were changed (Tables 4.6 and 4.7). In comparison with control, at the 7th intercropping year, the 1000 grain weight was 10.6-25.6 per cent lower in the 5x6 and 5x10 m intercropped fields, but was 1.0-3.9 per cent higher in the 5x20 m spacing. In spite of a 2.8 per cent increase under the canopy, there was not much difference in 1000 grain weight between 5x40 m and control. Table 4.6 also

indicated that the nearer to the trees, the higher was the 1000 grain weight in the spacings of 5x6 to 5x20 m. An explanation might be that under the dense spacing, where the understorey is fully covered by paulownia canopy in 5x6 m and most portions are covered in 5x10 m, the greatly reduced light led to a lower rate of photosynthesis during the day causing lower carbohydrate accumulation than in the control. Another, possibly negative, effect might be caused by stronger competition between trees and crops for water and nutrients. In contrast, in the 5x40 m spacing, the nearer to the trees, the higher was the 1000 grain weight. The reasons for this could be that, with the larger spacings, the slightly reduced radiation has less effect on photosynthesis, and the decreased temperature, particularly maximum temperature, has led to a longer grain filling stage. As Evans et al. (1980) reported, it is temperature not radiation that has the predominant effect on duration of grain filling. The lower the temperature, the longer grain filling continues, resulting in greater final grain weight. Asana and Sahay (1965) stated that the main effect was due to day temperature, grain size being reduced 16 per cent with a rise from 25°C to 31°C. A marked reduction in the duration of grain filling was found with an increase in incident radiation for crops in the field (Evans et al. 1980). Low light intensity for 7-10 days after anthesis reduced endosperm cell numbers, and also final grain weight, especially at high temperature (Wardlaw, 1970). The negative effect from competition between trees and crops for water and nutrients could be very small because of the lower number of trees.

Table 4.6 Comparison of 1000 grain weight (g) in intercropped wheat in 7th and 10th intercropping years with that of the control.

Spacing (m)	Under canopy	Edge of canopy	Middle of alley	Year
5x6	28.9		30.1	1989
5x10	29.4		35.3	
5x20	39.9	40.1	41.1	
5x40	40.6	39.9	39.6	
Control	39.5			
5x20	34.4	30.5	37.7	1992
5x30	37.8	34.4	33.8	
5x40	39.7	37.5	34.7	
5x50	39.8	36.1	33.8	
Control	33.8			

It is the characteristics of the glens that are so important in bread making (Evans, 1980). However, glens were not measured due to lack of facilities and funds, but

coarse protein and other variables were analysed in this study. Table 4.8 indicated that wheat protein contents were increased in most locations in the intercropped areas. Especially in the 7th intercropping year, coarse protein content of the crop from under the trees to the edge of the tree canopy in all spacings was 21.37 to 24.66 per cent, which was 27.7 per cent higher than that for the crop in the middle of the alley and 68.3 to 94 per cent higher than that for the crop in the control. The highest protein contents were for the crop under the trees to edge of the canopy in the 5x20 m spacings which averaged 24.4 per cent, 92 per cent higher than that for the crop in the control. In the 10th intercropping year, the highest coarse protein contents were observed at the edge of canopy (16.25 per cent) and in the middle of the alley (15.15 percent) in the 5x20 m spacing and at the edge of canopy in the 5x40 m spacing (15.14 per cent), which were 41.7, 32.1 and 32.0 per cent higher than in the control, respectively. There are four possible explanations for the greater protein contents of the crop in the intercropped fields. First, it could result from more extensive mobilisation of leaf nitrogen due to shading of leaves as stated by Neales et al. (1963). Second, Johnson et al. (1967) reported that high nitrogen levels in grain will tend to be associated with low nitrogen levels in leaves during grain filling. Third, Mikesell and Paulsen (1971) found high protein lines to have a higher nitrogen content in their lower leaves at anthesis, though not at maturity. Fourth, Bremner (1972) claimed that high grain nitrogen may also be associated with greater uptake rather than more mobilisation, in which case leaf and grain nitrogen contents may be positively correlated. A longer period of development before flowering, for example, is usually associated with greater uptake and content of nitrogen in the grain.

Coarse fat content of wheat in the intercropped fields for the 7th intercropping year was 3.8 to 62.8 per cent higher than that of wheat in the control, apart from in the 5x6 m spacing where it was 11.6 per cent lower. However, in the 10th intercropping year, the coarse fat contents decreased in the intercropped fields, apart from that of the crop in the middle of alley in the 5x40 m spacing. Starch contents in the 7th intercropping year were up to 6.8 per cent higher at the edge of the canopy and the middle of alley in the 5x40 m spacing than in the control, but up to 19.7 per cent lower at other spacings. In the 10th intercropping year they were up to 60.1 per cent higher in the 5x40 m and up to 7.8 per cent lower in the 5x20 m spacing. This agrees with observations that higher temperatures increase the rate of starch deposition (Jenner, 1968 and Wu 1993).

Yield

Evans et al. (1980) describe the major factors determining wheat yield as photosynthesis, translocation and storage. The relative impact of these varies with the cultivar and growing conditions, and especially with the sequence of conditions during inflorescence, development and grain filling. The duration of grain growth is a more powerful determinant of yield in wheat than is the rate of grain growth. Under most circumstances, 90-95 per cent of the carbohydrate in grain is derived from carbon dioxide fixation after anthesis. Grain yield bears a close relation to the duration and rate of photosynthesis after anthesis, but photosynthesis before anthesis, and particularly during ear development, profoundly influences yield through effects on the components of storage capacity.

Table 4.7 Comparison of wheat grain contents (%) in the 7th (1989) and 10th (1992) intercropping years with those of the control. D = distance from west row.

Spacing (m)	D (m)	Water	Coarse fat	Coarse protein	Coarse fibre	Ash	Starch	Year
5x6	3	14.4	1.64	23.27	3.03	1.25	78.0	1989
5x10	2	14.05	2.29	23.05	3.06	1.32	69.04	
5x10	7	13.75	1.91	23.57	4.03	1.11	71.71	
5x20	2	13.74	2.42	24.66	3.42	0.97	74.22	
5x20	7	13.28	2.11	24.14	3.0	1.02	79.61	
5x20	10	13.69	1.90	15.76	2.6	0.86	70.62	
5x40	2	13.30	2.98	21.37	3.40	0.91	79.80	
5x40	7	13.47	2.14	22.87	2.83	1.14	88.71	
5x40	20	13.42	2.75	15.72	3.62	0.68	84.43	
Control		13.69	1.83	12.70	3.37	0.81	83.1	
5x20	2	9.72	1.25	12.01	4.56	1.74	53.77	1992
5x20	7	9.42	1.62	16.25	3.73	2.06	45.39	
5x20	10	10.28	0.94	15.152	3.91	2.30	46.99	
5x40	2	8.20	2.60	14.724	3.25	1.78	81.08	
5x40	7	8.45	2.45	15.135	3.14	1.87	58.17	
5x40	20	8.34	2.77	12.163	3.20	1.85	70.40	
Control		7.92	2.76	11.469	3.20	1.67	50.65	

The versatile influence of microclimate on wheat growth and development resulted in lower yield and final biomass in the dense spacing, but higher in the large spacing. At the larger spacing, 30-50 m, total above ground wheat biomass at grain filling was higher than in the control field. In the 10th year of intercropping, total wheat biomass at

grain filling increased by 0, 4.6, 27.9 and 26.9 per cent, and ear weight by 0.5, 4.6, 3.8 and 0.05 per cent at 20, 30, 40 and 50 m spacing respectively over that of the control (Table 4.8).

Table 4.8 Comparison of above ground dry matter weight (g per plant) at different growth stages of wheat in the 10th intercropping year.

Spacing	Booting stage				Filling stage			
	Total weight	%ear	%stem	%leaf	Total weight	%ear	%stem	%leaf
5x20	11.48	27.35	56.07	16.58	12.4	66.48	27.64	5.88
5x30	9.91	26.79	54.29	18.91	12.98	69.20	25.54	5.26
5x40	10.79	28.37	55.57	16.07	15.86	68.65	26.21	5.14
5x50	12.35	23.31	60.69	16.31	15.73	66.16	26.30	7.53
Control	11.94	28.33	53.33	18.33	12.4	66.13	29.57	4.3

Wheat yield in Dangshan open fields varied from 2,904 kg ha⁻¹ to 4731 kg ha⁻¹ during the experiment years with an average of 3,605 kg ha⁻¹. This variation of yield was mainly determined by climate, pests, and wheat cultivars. Therefore, the intercropped yield was standardised as percentage of the yield in the control. Wheat yield in response to tree age and spacing provides an interesting pattern. In the first two years, trees do not appear to affect the yield. After the 3rd year, yield in the narrow spacing (6 m) declines and is only about 50 per cent of that of the control in the 7th intercropping year and 45 per cent in the 8th intercropping year. The process of decline starts later for the next wider spacing. The yield of 5x10 m remained quite stable at about 65 per cent of the control under the trees in most years, but in the middle of the alley yields ranged from 104 to 61 per cent of control in the 6th and the 7th intercropping year before increasing again in the 8th year after pruning. The yield with 20 m spacing remained almost constant, especially under the trees, in the first 9 years. Yield was reduced, especially in the middle of alley, to about 80 per cent of control in the 10th intercropping year. For the 40 m spacing, the yield from the edge of tree crown to the middle of the alley was always just above or around that of the control. The yield averaged 88.5 per cent of that of the control under the trees in all years (Figure 4.12).

When incident radiation is reduced by shading, without marked change in temperature, grain yield is usually reduced (Pendleton and Weibel, 1965; Willey and Holliday, 1971). The level of shading can be translated directly into an expected level of yield loss by assuming a constant light use efficiency (Monteith, 1975, Van Keulen and

Seligman, 1989). However, this yield reduction occurred only in the wet years, when light was limiting but water was not; in dry years shading had little effect on yield. Such interactions between radiation, temperature and water supply probably account for the absence of any clear relation between radiation and grain yield in wheat in the experiments of Sibma (1970). In the PCI system, wheat yield was closely related to LT. The relation is stronger in the larger spacings than the narrower spacings (Figure 4.13). In average of all spacings over years, wheat yield only reduced when LT was lower than 81.8 per cent which means that 81.8 per cent is the threshold level of LT in the intercropped fields below which a reduction in crop yield occurs. There is variability but the effect on yield is such that the average threshold can be used for practical purposes. The larger the spacing and the older the trees, the higher was the LT threshold. For instance in the 7th intercropping year, the maximum LT was 79.8 per cent whereas the yield was 98 per cent of the control in the 5x20 m spacing. Yield started to decrease when LT was about 70 per cent in the 5x40 m and 75 per cent in the 5x50 m spacings respectively. In the 10th intercropping year, the LT threshold was 86 per cent in the 5x40 m spacing. Figure 4.13 also indicates that for the denser spacings, the younger the tree age, the stronger is the correlation of percentage yield and LT. With the older trees, the determining role of light on yield declined and other factors, perhaps competition of water and nutrients between trees and wheat, became more dominant since no application of irrigation and fertiliser was made during the growth stage of wheat.

4.5.2 Cotton and other summer crops

Leaf conductance

In August, paulownia leaves are fully expanded, and the leaf area index is much higher than in May. Light transmission was much lower with daily total of 54, 74 and 84 per cent of the control total under the tree canopy, at the edge of the tree and in the middle of the alley, respectively. The responses of cotton are similar to those of wheat in the same intercropping field (the 10th intercropping year, 40 m spacing). Flowering cotton plants photosynthesise actively and clearly respond to light level. A statistical analysis of the conductance of cotton leaves (C_c) and principal climatic factors yielded the following results:

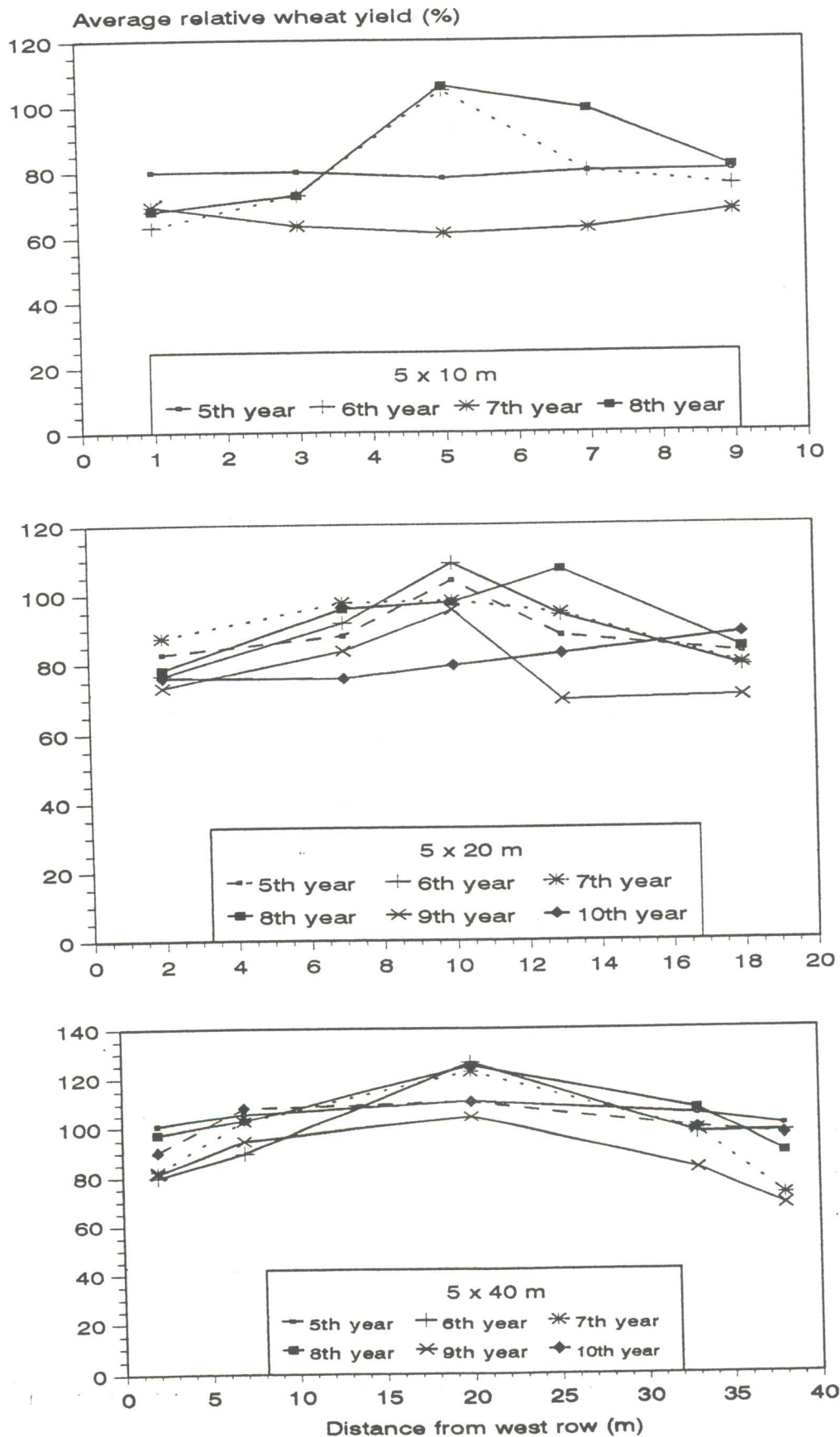


Figure 4.12 Average relative wheat yield (% of control) across the alley for different tree-row spacings and different intercropping years.

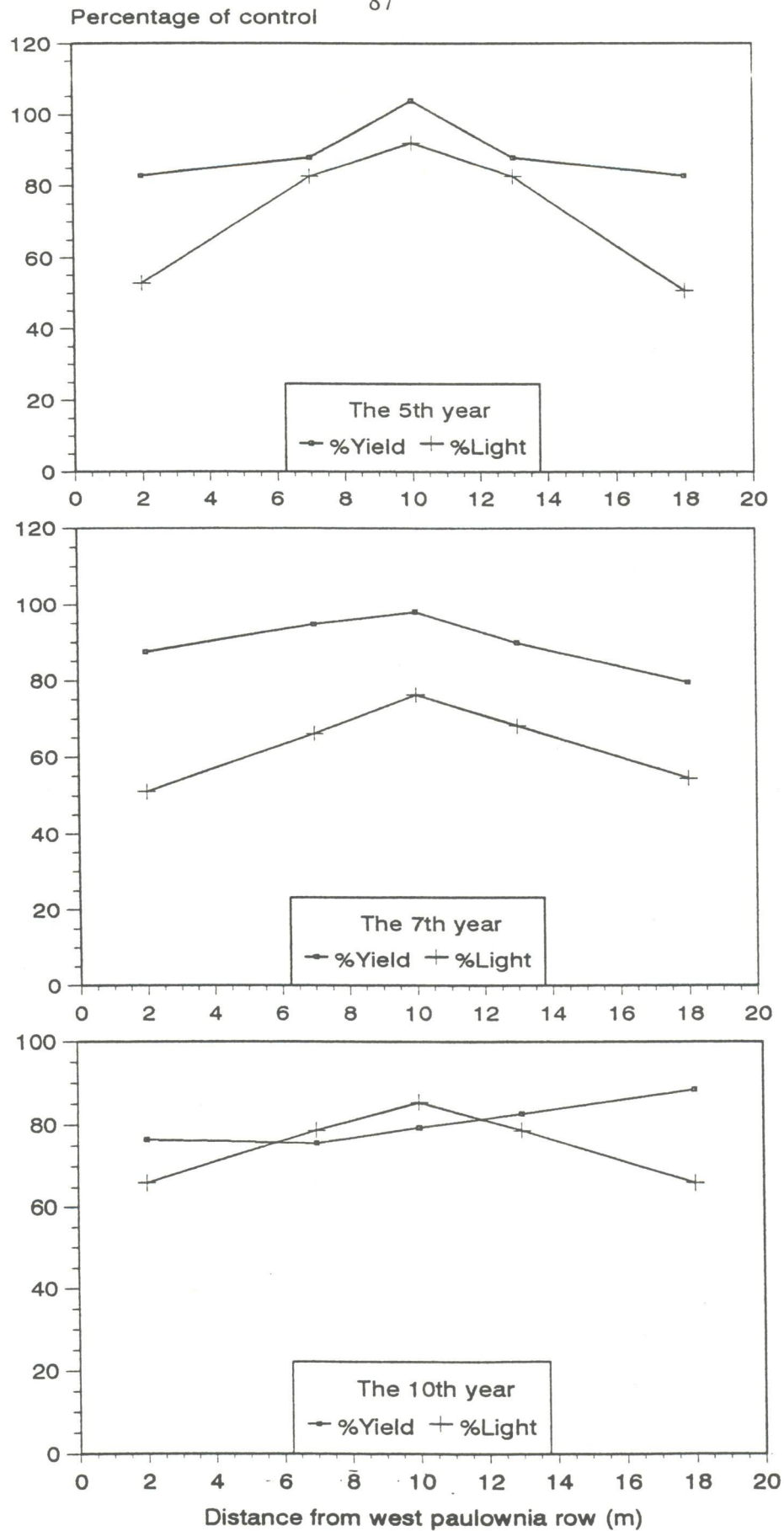


Figure 4.13(a). Relative wheat yield (% of control) and light transmissivity across the alley in different intercropping years for the 5x20 m tree-row spacing.

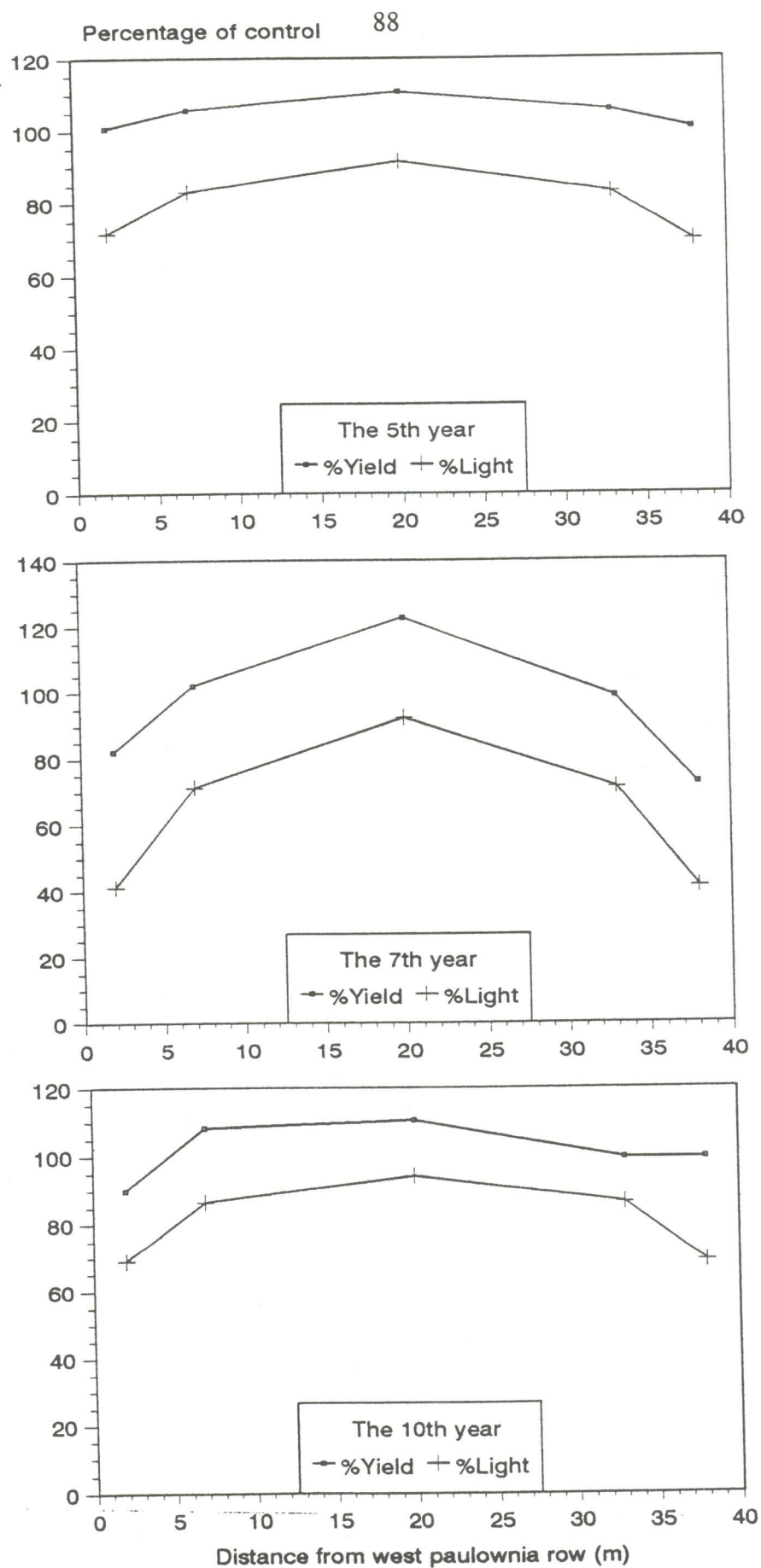


Figure 4.13(b). Relative wheat yield (% of control) and light transmissivity across the alley in different intercropping years for the 5x40 m tree-row spacing.

$Cc = 0.0160PAR/Ta + 1.5161$	under trees	
	($r = 0.62$, $n = 40$)	(4.6)
$Cc = 0.0453PAR/VPD + 1.0847$	at the edge of the trees	
	($r = 0.83^*$, $n = 40$)	(4.7)
$Cc = 0.0025PAR - 0.2631Ta + 8.3599$	in the middle of the alley	
	($r = 0.79^*$, $n = 40$)	(4.8)
$Cc = 0.0067PAR/VPD + 0.2689VPD + 0.1668$	control	
	($r = 0.81^*$, $n = 40$)	(4.9)

where PAR is the quantum flux density ($\mu\text{mol m}^{-2} \text{s}^{-1}$), VPD is the vapour pressure deficit (mb, the difference between the actual vapour pressure and the potential vapour pressure at saturation), Ta is temperature ($^{\circ}\text{C}$) and (*) denotes significant at $p < 0.05$.

Much of the variation in leaf conductance of cotton is explained by variation in light level (Monteith, 1975). The results imply a considerable reduction of intercropped cotton yield in comparison with the control. Equations 4.6 to 4.9 also indicate that conductance responds to other factors, depending on the distance from the tree. Air temperature is moderately correlated with conductance in a negative way in two equations, and vapour pressure deficit has a small effect. These equations suggest that for cotton in the rainy season, light is the limiting factor on growth and not water.

For the other summer crops (soya bean and maize) conductance under the tree canopy (average $2.0 \mu\text{mol m}^{-2} \text{s}^{-1}$, standard deviation 1.7) was always lower than at 20 m distance from the trees (average $3.2 \mu\text{mol m}^{-2} \text{s}^{-1}$, standard deviation 3.0) or in the open field (average 3.1, standard deviation 2.5).

Yield

The relative yield of cotton (dry cotton bolls) decreased slowly from the level of the control at 25 m distance from the trees to 80 per cent at 5 m, and 50 per cent near the trees (Figure 4.14). The variability of the observations is relatively large (standard deviation 20 per cent), possibly due to differences between individual plants or between locations where they grow. Yet the trend is clear and corresponds well with the trend in light transmission reduction. Thus, most of the decrease in cotton yield can be explained by the reduction in light level.

For maize, the same observation was made about its yield (dry grains only, no cob spill or husk; Figure 4.14), albeit that the variability of the observations was less (standard deviation 10 per cent). Thus, the response of maize yield to distance from the trees is also dominated by the effect of shading. The slightly different responses of average yield of maize and cotton to distance from the tree rows could not be statistically proven, as was to be expected since the limiting factor for production is the same in both cases.

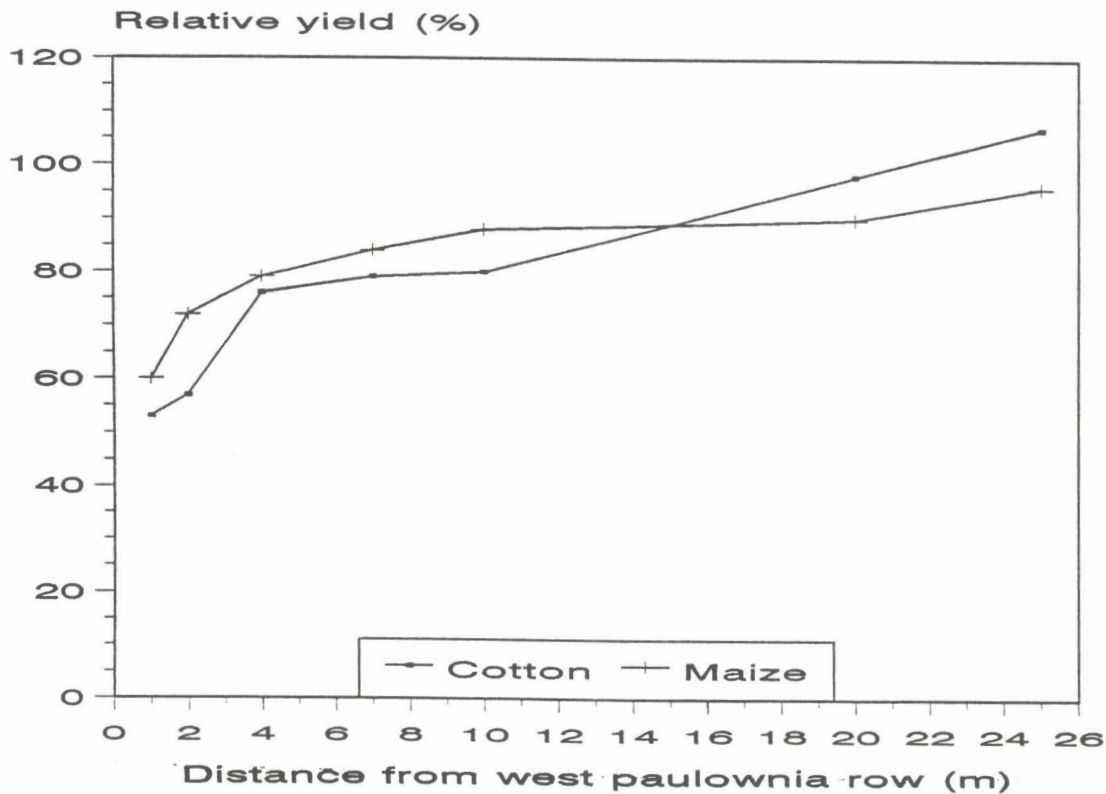


Figure 4.14 Average relative yield (percentage of control) of cotton and maize across the alley in the intercropped field.

4.6 Summary of Findings

Studies at Dangshan showed that trees had different growth patterns in relation to inter-row spacing. Following transplanting, the trees grew very slowly in the first year due to the root system being incompletely developed. In subsequent years, growth was fastest for the denser spacings and DBH responded more rapidly than height. The denser the spacing, the earlier the fast-growing stage occurs. However, there was no significant difference between the spacings in any of the growth variables at the end of the study in the 10th intercropping year. Average DBH was significantly affected by age and closely related to canopy ranges. Tree growth could be manipulated by management such as pruning and thinning. The 5x6 m spacing is too dense for paulownia because the fast growth stops before its economical maturity is reached and, in some cases, the latter is not attained before the end of the 10-12 year rotation. The 5x10 m could be considered the best spacing and then the 5x20 m because their fast growth period ends after their economical maturity and close to the end of the rotation period the farmers are practising. For tree spacings of 5x40 and 5x50 m, the tree rotation would need to be longer than 10 years because no fast growth was recorded in the ten-year period of study.

There are always reductions in light in the intercropped fields and the effects of paulownia on light were more apparent during clear days, in areas near the trees, with older trees, and when the trees had fully developed their leaves. The average reflective radiation (R_r) was found to increase in the 5x6-20 m spacings but to decrease in the 5x40 and 5x50 m spacings. Following the spatial distribution of total solar radiation, the greater the distance from the trees and the larger the spacing, the higher is the PAR received by the understorey. The proportion of PAR to total SR was slightly lower under intercropping than in the control conditions. The nearer to the trees, the lower is the percentage of PAR to total SR.

The winter crop, wheat, benefits from the modified microclimate. The negative effect of shading is small with large tree spacings but higher in the denser spacings and in the later growing stages of wheat. However, the modified microclimate environment such as increased soil water and decreased maximum air temperature is favourable to wheat growth; as a result, leaf conductance, biomass and yield of the intercropped wheat are slightly above those in open fields when the trees are young and widely spaced, but lower otherwise. The closer plants are to trees, the denser the spacing and the older the trees, the more is the reduction of leaf conductance and yield, but the higher is the leaf

area index and the number of growing days. Wheat grain quality increased in the denser spacing with medium age of trees and under the canopy of large spacing with older trees.

Wheat yield was reduced significantly in relation to light reduction when LT below an average of 81.8 per cent which may be considered a threshold value. The threshold is about 10 per cent lower in the larger spacings and 10 per cent higher in the denser spacings. The reduction of leaf conductance and yield of summer crops by paulownia is greater than is the case for the winter crop due to shading by the trees and different response of crops. The yield reduction of cotton and maize is 15 per cent at the edge of the tree canopy and as much as 50 per cent near the tree rows. The degree of reduction can be explained by the absorption of light by the tree foliage.

5. REGRESSION MODELS: DEVELOPMENT AND VALIDATION

Agricultural research findings are of little use if they are not adopted by farmers. Unfortunately, the only effect of much research is to produce an interesting article in a scientific journal or a report which lodges on library shelves. Fruitful agriculture research requires scientists to be oriented towards farmers and their problems, and to be interested in co-operating with extension officers (Van Den Ban and Hawkins, 1992). Extension officers act as a bridge providing the practical experience of taking the research results from scientists and delivering them to the users, namely farmers (Wu, 1992b).

Forestry research, extension and production are the remits of separate organisations in China, but close collaboration occurs between them (Wu and Zhu, 1996). In this present study, scientists, extension officers and farmers co-operated with each other in planning the research and conducting on-farm verification trials to present the findings. Being aware of farmers' problems through interviews with farmers, collaboration with extension officers and observation, scientists were responsible for doing research on the research station and in farmer's fields and for providing solution packages or guide tools to solve farmers' problems. Provision of a linkage between farmers' problems and research institutes, which requires two-way communication, was a major task of the extension officers. Realistic recommendations were developed for the situations of different groups of farmers. In most cases, farmers lack adequate knowledge and insight to recognise their problem or to think of a possible solution. Extension officers have to help farmers to identify their problems. The research-extension linkage for this study is illustrated in Figure 5.1. It is clear that the status or conditions of the package of research results, and the degree of knowledge intake and interpretation by extension officers determine the success of technology transfer. Appropriate readable material for a non-professional audience must be produced from research findings for easy and efficient dissemination to the users, either extension officers or, directly, the farmers.

As reported in Chapter 3, the major requirement from farmers is advice on the optimum spacing of trees with emphasis on sustainable maximum wheat yield and essential income from trees in their narrow strip holdings. Obviously, the outcome of the data analysis presented in Chapter 4 is not ready to be delivered to extension officers or farmers, because it only provides scientific information for understanding the natural function of PCI systems; it does not provide solutions for farmers' problems. It is difficult and time consuming for extension officers and farmers to derive useful

information from consideration of factors individually. To address farmers' needs and transfer the knowledge more efficiently and accurately, alternative options or solutions must be presented in simple and ready-to-use form which addresses the diversified objectives or needs of individual households. It was thought that modelling would be a useful way to achieve this. Modelling involves representing the theoretical behaviour of real phenomena as mathematical expressions and formalises approximation, through existing knowledge, to the reality of the system under study (Spilsbury, 1993). Models are particularly useful in cases where real time is inconvenient for practical experimentation or measurement, and in cases where forecasting is desirable. Penning de Vries et al. (1989) also noted that models give quick answers to many 'what if?' questions. Progress with models can be much faster than with experimental research alone, even though it is still necessary to evaluate key simulation results with field observations. Therefore, this chapter is aimed at developing some useful problem-oriented models based on the research results from Chapters 3 and 4, verifying the models with current farm practices, and finally providing alternative options or solutions for farmers' problems under realistic circumstances.

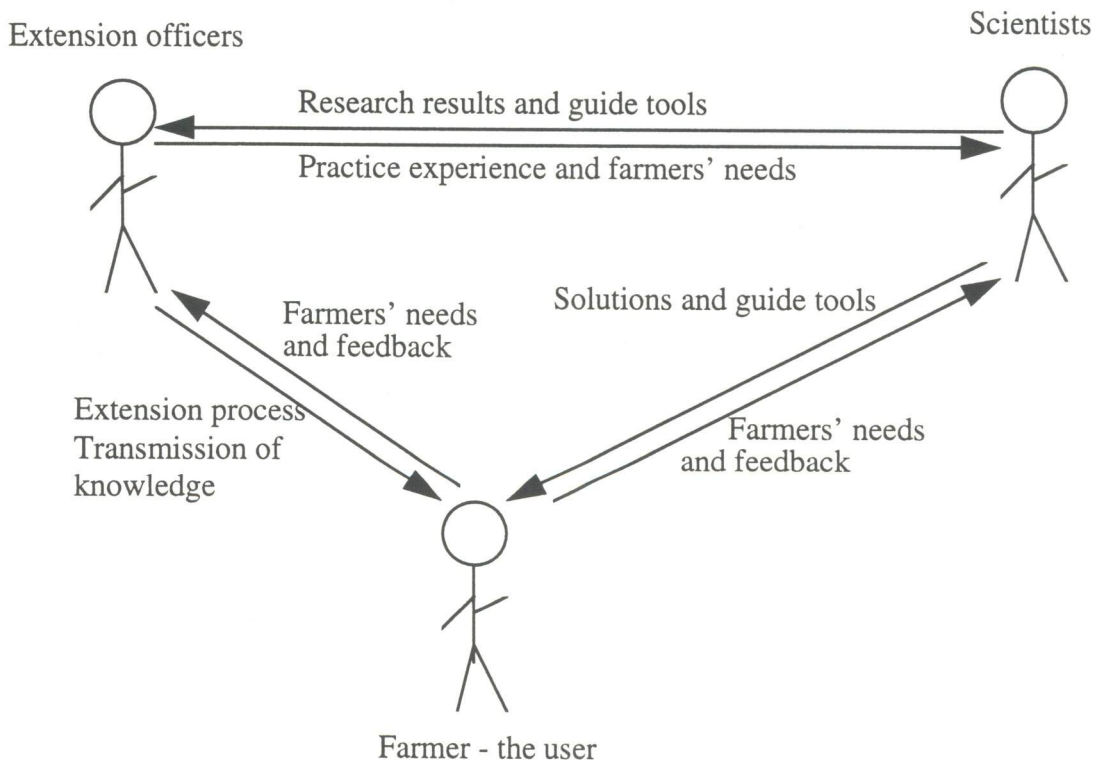


Figure 5.1 The research - extension linkage

5.1 Modelling Strategy

As reported in the above chapters, tree growth, wheat yield and light transmissivity are important factors in the PCI system. Tree growth prediction is important because paulownia is a major source of timber and long-term cash income; tree spacing and growth can significantly affect food production and economic return from the farming system. Wheat is the most important food crop and prediction of its yield could provide basic information affecting farmers' awareness of food security and tree management. Light is the key and stable ecological factor affecting wheat yield. Therefore, modelling of the above three components in a PCI system is the focus of this study.

For light modelling, geometric type models like SOLID (Jackson and Palmer, 1972 and Palmer, 1977), in which tree rows are conceived as being a simple geometric, non-transmitting and non-reflecting solid with given dimensions, are not readily applicable to tall, sparsely arranged broad-leaved species such as paulownia where reflectivity and transmission of light cannot be ignored. The model developed by Norman and Welles (1983), which describes individual plants growing singly or in groups, such as widely spaced trees in an orchard or plants in a row (assumed as an array of ellipsoid sub-canopies (trees)), seems to offer the greatest potential for simulating the PCI system, but it demands strong computing power (Spilsbury 1993). This is still a major limitation for transfer to China as a basis for farm management and extension work. A physical light interception model was first developed by Liu and Xiong (1991) for the PCI system, based on assumptions that all leaves are horizontally distributed in an ellipsoid canopy with two different layers of leaf density and that the reflectivity of paulownia leaves has no seasonal changes but varies between 17.4 - 25.2 per cent depending on elevation angle during the day. The model is not entirely successful as a prediction tool because the authors were not able to obtain an acceptable level of validation when comparing the simulated values with measured total radiation. The authors claimed that there is a significant linear relationship between the simulated and the accumulated values of measured instant radiation at hourly intervals at different locations. This claim cannot prove that the model is reliable. Ecophysiological models such as MAESTRO enable a large array of individual trees to be specified, with each tree represented geometrically in three-dimensional space as an ellipsoid containing leaves (Wang and Jarvis 1990). Irradiance is considered as beam and diffuse, with complete angular distributions of these components. MAESTRO evaluates the irradiance at a series of points inside each one of the tree canopies, by taking into account the attenuation of light at all elevations and azimuths. Thus, the shading of one tree by its

neighbours may be properly simulated. However, the model demands many parameter values, including six coefficients to describe the leaf area density distribution, and information about the inclination, transmittance and reflectance of foliage. It is thus not easy to use in practice.

Crop simulation models are useful tools to examine the feasibility of agricultural management systems and can be used to examine the effect of trees within cropping systems (Huda and Ong, 1989). Adaptation of a crop ecophysiological model developed by Penning de Vries et al (1989) to predict wheat growth and yield gives a good result for the PCI system (Wu, 1990a). However, it requires a lot of crop physiological parameters and weather data on a daily basis, a requirement which cannot be satisfied within this project.

All the above models are considered unsuitable for an adaptive research project, because some of their outputs are more complicated than the project requires and some of the models cannot satisfy the requirements of the project since they demand too much data and computing power to be used in China. In fact, computers are not available at all to extension officers and farmers in the PCI region, so it is impossible for them to use these models. A statistically based approach was therefore used as an alternative.

As regard to tree growth models, there are three different general approaches of tree growth modelling including whole stand models, stand class models and individual tree models as reviewed by Spilisbury (1993). These approaches differ from each other in many aspects, but one thing in common is that all predictions are the results of regression equations. Regression models were also thought more suitable for tree growth in this study due to the availability of adequate data (Chapter 4).

The data collected at Dangshan (Chapter 4) were analysed to determine the main trends in tree growth, understorey crop yield and light transmissivity over time. Regression relationships were developed to explain the variations in tree growth, light transmissivity and wheat yield. These regression equations were combined within an overall model structure as shown in Figure 5.2. Modelling the relationship between light and wheat yield is intended to help clarify the effect of management of the trees on the crop and thereby aid farmers and local authorities to understand how much yield could be lost or gained from a given spacing and age of paulownia tree rows. Knowing the spacing, age and management regime of the trees, the model predicts the variability

in understorey wheat yield at different distances from the western tree row as a percentage of the yield in an open-field (control). The output of the model is therefore intended to help farmers who wish to optimise the spacing of paulownia trees on their small holdings, and to guide local authorities in their general land use and production planning, involving balancing the local agro-ecosystem and economics.

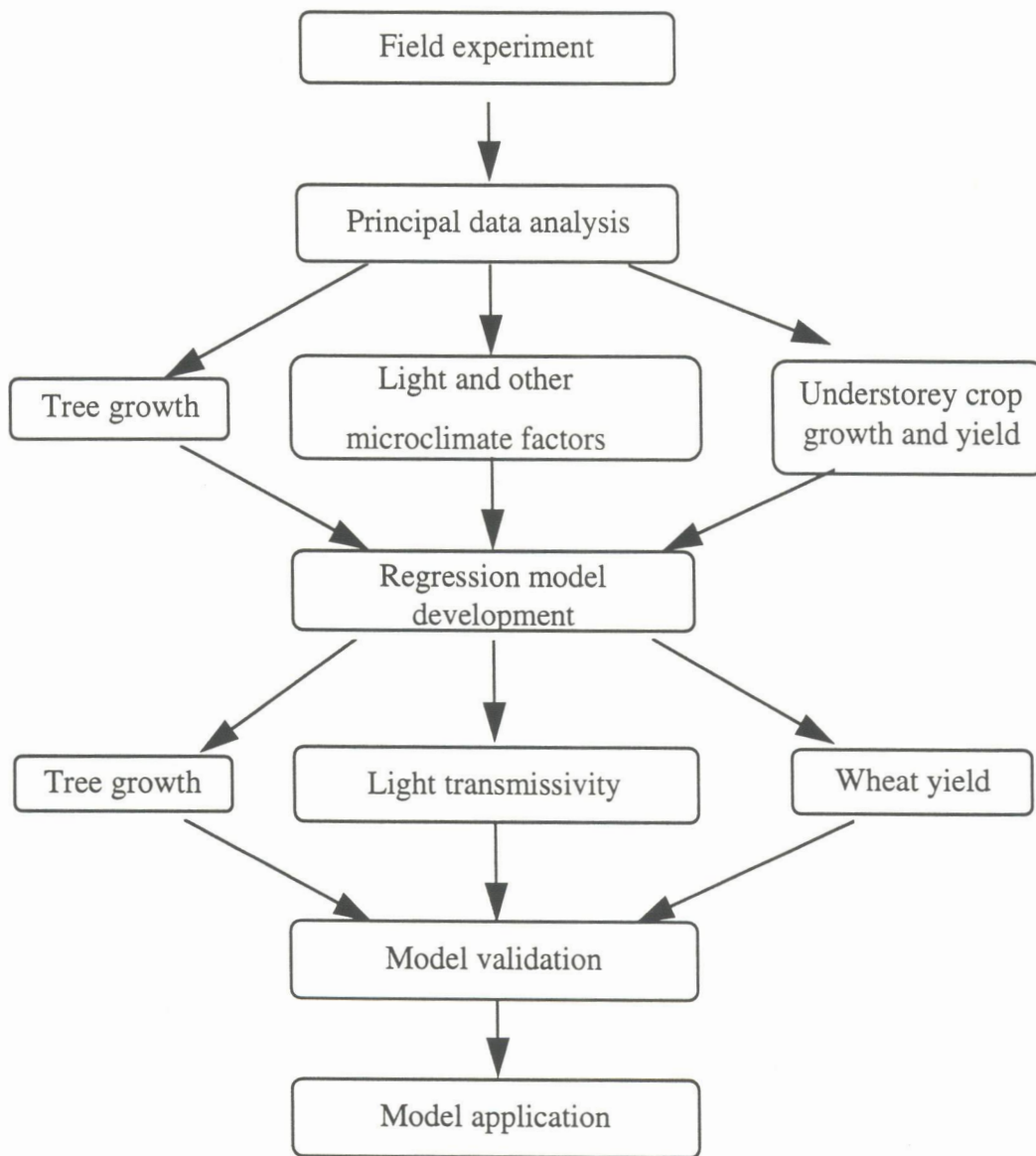


Figure 5.2 Procedure for development of the paulownia-wheat intercropping agroforestry model.

5.2 Regression Model

In order to operate the model structure shown in Figure 5.2, regression equations were developed to express DBH (used as an index of tree growth) as a function of age; light transmissivity as a function of distance across the alley for different spacings and ages of trees; understorey wheat yield as a function of distance across the alley for different spacings and ages of trees; and understorey wheat yield as a function of light transmissivity.

5.2.1 Tree growth

Among all parameters of tree growth, age and DBH are very important since they are easier to measure than other growth parameters and highly correlated with them (Table 5.1). The regression models expressing DBH for each spacing as a function of age all have coefficients of determination greater than 87 per cent, apart from the 5x6 m spacing which should not be practised in PCI because it is too dense for both tree growth and understorey crops (Table 5.2 and Chapter 4). Tree trunk height under the first bottom branch and canopy range have less close relationships with DBH because they are determined by pruning as well.

Comparing the original planting spacing of 5x30 m in the 10th intercropping year with a 5x30 m spacing of the same age obtained after thinning the 5x6 and 5x10 m spacings in the 8th intercropping year, tree growth is slightly different. Figure 5.3 indicates that the growth rate is higher in the non-thinned spacing than in the modified spacing, especially for DBH and crown range. This is because of limited space and resources in the years prior to thinning. As a result, the single tree timber volume in the 8th intercropping year for the original 5x30 m spacing ($V = 0.3361 \text{ m}^3$) was higher than that of the modified 5x30 m, from 5x6 m, but lower than that from 5x10 m, respectively (Table 4.2). Total timber values, however, were higher for the modified spacing because 80 per cent of trees (266 trees per hectare) from the 5x6 m spacing and 67 per cent of trees (133 trees per hectare) from the 5x10 m were removed in the 8th intercropping year, which provided yields of timber of $85.66 \text{ m}^3 \text{ ha}^{-1}$ and $50.34 \text{ m}^3 \text{ ha}^{-1}$ respectively (Table 5.3). Therefore, in terms of total timber volume per unit area, the denser the spacing, the higher timber value obtained. However, 5x6 m is not economically sound as discussed in earlier (Section 4.3). The 5x10 m could be the most profitable spacing because it could provide a high total metric timber volume per unit area within a short term rotation. The 5x50 m spacing is the most uneconomical spacing of because its low

growth rate and timber volume both in single tree and per unit area and less protective effects on understorey crops (Chapter 4). Such information is important for future economic studies and precise farm management. However, the economic value of each system is not evaluated in this project.

5.2.2 Light transmissivity

Since light transmissivity (LT) was significantly correlated with distance from the trees, regression models of changes in LT with distance across alley were established for different spacings (Table 5.4). From these, we can calculate that, even with the 5x10 m spacing, LT under the trees was still as high as 96 per cent in the 3rd intercropping year (1985) and only in the 4th intercropping year did it start to decrease. Models were also developed to express LT under the canopy, at the edge of the canopy and in the middle of the alley against alley width, as a function of spacing or alley width (Table 5.5). The effect of pruning on the light transmissivity in these different locations was allowed for using regression equations based on the observations for the 5x10, 20 and 40 m spacings (Table 5.6). LT after pruning could be 33.6 per cent and 26.2 per cent higher than before pruning in the 10th intercropping year under the canopy and in the middle of the alley respectively.

From the equations for the 5x10 m spacing, it is clear that LT changes with age in a multiplicative relation. However, we do not have enough years of data to establish the relationship without pruning for the 5x20 and 40 m spacings. For these spacings, using data for 1987 and 1989 only, linear relationships are obtained (Table 5.6).

5.2.3 Wheat yield

Since wheat yield varies from year to year due to the planting of different varieties, climatic factors and pests, modelling was based on the intercropped yield expressed as a percentage of the yield in the control. Variations in the percentage yield across the alley were expressed as a function of distance from the western tree row for different years and spacings (Table 5.7). The relationship between percentage yield and percentage LT, which is a very stable microclimate factor, was also investigated in order to minimise the effect of different management measures (Table 5.8).

The parameters of the best-fit quadratic equations for 5x20, 40 and 50 m spacings were plotted against intercropping age (Figure 5.4). No clear trends in the parameter values emerge. However, P1, consistently in the range of 70 to 100 per cent, can be interpreted as expressing the percentage yield under the trees. It is significantly lower in the 5x20 m (71.8 per cent average) than in wider spacings (80.8 - 81.7 per cent) (Figure 5.4a). Figure 5.4b and c show that the denser the spacing, the higher are the values of P2 and P3. These parameters control the degree of curvature of the relationship. The higher the parameter value, the greater is the gradient of the curvature and the higher the decline in yield from the middle of alley to the area close to the trees. Therefore, in the denser spacing, when inter-row canopy overlaps, the yield across alley becomes more constant and may even be lower in the middle of the alley than under the trees, as with the 5x20 m spacing in the 10th year and the 5 x 10 m spacing in the 7th year.

5.3 Model Validation

Validation is necessary for any model that is to be applied in the real world. Model validation is the comparison of its behaviour with that of the real world in a similar situation (Penning de Vries et al, 1989). There are two main forms of validation, as described by Mitchell and Sheehy (1995). Conceptual validation is concerned with the way that the model represents the real system and the meaning of the parameters. This is more usually applied to conceptual models. Empirical validation is the comparison of model predictions with observations and the assessment of whether the model is adequate for its purpose. This is used for applied models. The observations may be experimental results or measurements from the real system. What is regarded as adequate depends on what the model is for. The distinction between calibration and validation is important. Calibration is the estimation of values for parameters or variables using information from the real system. The crudest but most effective method is to make an empirical adjustment to parameter values to obtain the best-fit between model predictions and observed data. The calibrated model should then be validated against an independent data set derived from the same kinds of conditions for which the model was calibrated.

Table 5.1 Correlation between tree growth parameters (each correlation is based on 461-575 observations). DBH = diameter at breast height (cm); H = height; TK = trunk height under first bottom branch; CEW = crown range in east-west direction; CSN = crown range in south-north direction.

SPACING (m)		AGE	DBH	H	TK	CEW	CSN
All	DBH	0.99					
	H	0.94	0.95				
	TK	0.89	0.89	0.90			
	CEW	0.94	0.96	0.89	0.85		
	CSN	0.93	0.95	0.88	0.85	0.98	
5x6	DBH	0.85					
	H	0.82	0.92				
	TK	0.60	0.69	0.73			
	CEW	0.65	0.78	0.67	0.51		
	CSN	0.60	0.75	0.62	0.49	0.90	
5x10	DBH	0.93					
	H	0.91	0.92				
	TK	0.55	0.59	0.61			
	CEW	0.83	0.88	0.79	0.46		
	CSN	0.76	0.79	0.70	0.35	0.86	
5x20	DBH	0.94					
	H	0.90	0.93				
	TK	0.53	0.54	0.59			
	CEW	0.93	0.95	0.88	0.49		
	CSN	0.89	0.91	0.83	0.43	0.95	
5x30	DBH	0.99					
	H	0.91	0.94				
	TK	0.99	0.99	0.99			
	CEW	0.97	0.97	0.96	0.99		
	CSN	0.95	0.95	0.93	0.96	0.99	
5x40	DBH	0.95					
	H	0.88	0.91				
	TK	0.63	0.63	0.63			
	CEW	0.88	0.91	0.85	0.53		
	CSN	0.84	0.88	0.80	0.49	0.92	
5x50	DBH	0.94					
	H	0.88	0.92				
	TK	0.66	0.65	0.67			
	CEW	0.88	0.92	0.83	0.52		
	CSN	0.83	0.88	0.77	0.47	0.93	

Table 5.2 Regression equations used to model tree growth as a function of intercropping age (A; years) and diameter at breast height (DBH; cm). H = height; TK = trunk height under first bottom branch; CEW = crown range in east-west direction; CSN = crown range in south-north direction (all in m).

Spacing	Age Range (Year)	Equations	R ² (adj.)	Number of observations
All	1-10	$H=3.02+0.26D$	0.92	46
		$TK=2.1+0.1D$	0.84	46
		$Cew=0.72+0.23D$	0.92	46
		$Csn=1.10+0.18D$	0.88	46
		$D=0.85+3.69A$	0.99	46
		$H=3.26+0.95A$	0.90	46
	2-10	$TK=2.17+0.22A$	0.84	46
		$Cew=1.49+0.78A$	0.89	41
		$Csn=1.99+0.57A$	0.86	41
		$V=-0.13+0.06A$	0.88	46
		$V=-0.147+0.0159D$	0.89	46
		$V=-0.302+0.0576H$	0.85	46
5x6	1-9	$D=3.61+3.23A$	0.76	421
		$H=2.11+0.34D$	0.81	421
		$TK=2.13+0.07D$	0.47	395
		$Cew=1.99+0.18D$	0.61	395
		$Csn=2.09+0.15D$	0.56	395
5x10	1-9	$D=1.22+3.7A$	0.87	498
		$H=2.73+0.29D$	0.84	485
		$TK=2.46+0.05D$	0.35	485
		$Cew=0.53+0.26D$	0.77	485
		$Csn=1+0.2D$	0.63	485
		$H=2.78+1.14A$	0.82	498
		$TK=2.52+0.18A$	0.3	485
		$Cew=0.81+0.97A$	0.68	485
		$Csn=1.18+0.75$	0.57	485
5x20	1-11	$D=-0.03+3.83A$	0.88	490
		$H=2.93+0.25D$	0.86	490
		$TK=2.48+0.04D$	0.29	462
		$Cew=0.64+0.25D$	0.90	462
		$Csn=1.07+0.19D$	0.83	462
		$H=2.78+0.98A$	0.81	490
		$TK=2.46+0.15A$	0.28	462
		$Cew=0.38+1.01A$	0.86	462
		$Csn=0.89+0.76A$	0.79	462
5x30	1-9	$D=-0.06+3.89A$	0.98	28

		$H=3.11+0.97A$	0.77	28
		$TK=2.43+0.19A$	0.76	18
		$Cew=1.02+0.73A$	0.78	18
		$Csn=1.9+0.58A$	0.75	18
		$H=3.04+0.25D$	0.82	28
		$TK=2.4+0.05D$	0.77	28
		$Cew=0.75+0.24D$	0.89	16
		$Csn=1.74+0.16D$	0.87	16
5x40	1-11	$D=1.26+3.6A$	0.90	597
		$H=3.53+0.22D$	0.83	597
		$TK=2.56+0.04D$	0.39	575
		$Cew=1.16+0.21D$	0.83	575
		$Csn=1.41+0.17D$	0.77	575
		$H=3.7+0.81A$	0.78	597
		$TK=2.6+0.17A$	0.4	575
		$Cew=0.60+0.77A$	0.77	575
		$Csn=1.63+0.61A$	0.7	575
5x50	1-11	$D=0.91+3.6A$	0.89	562
		$H=3.14+0.24D$	0.87	562
		$TK=2.46+0.04D$	0.42	547
		$Cew=0.86+0.22D$	0.85	547
		$Csn=1.06+0.18D$	0.78	547
		$H=3.2+0.89A$	0.78	547
		$TK=2.43+0.17A$	0.44	547
		$Cew=1.01+0.83A$	0.78	547
		$Csn=1.23+0.66A$	0.69	547

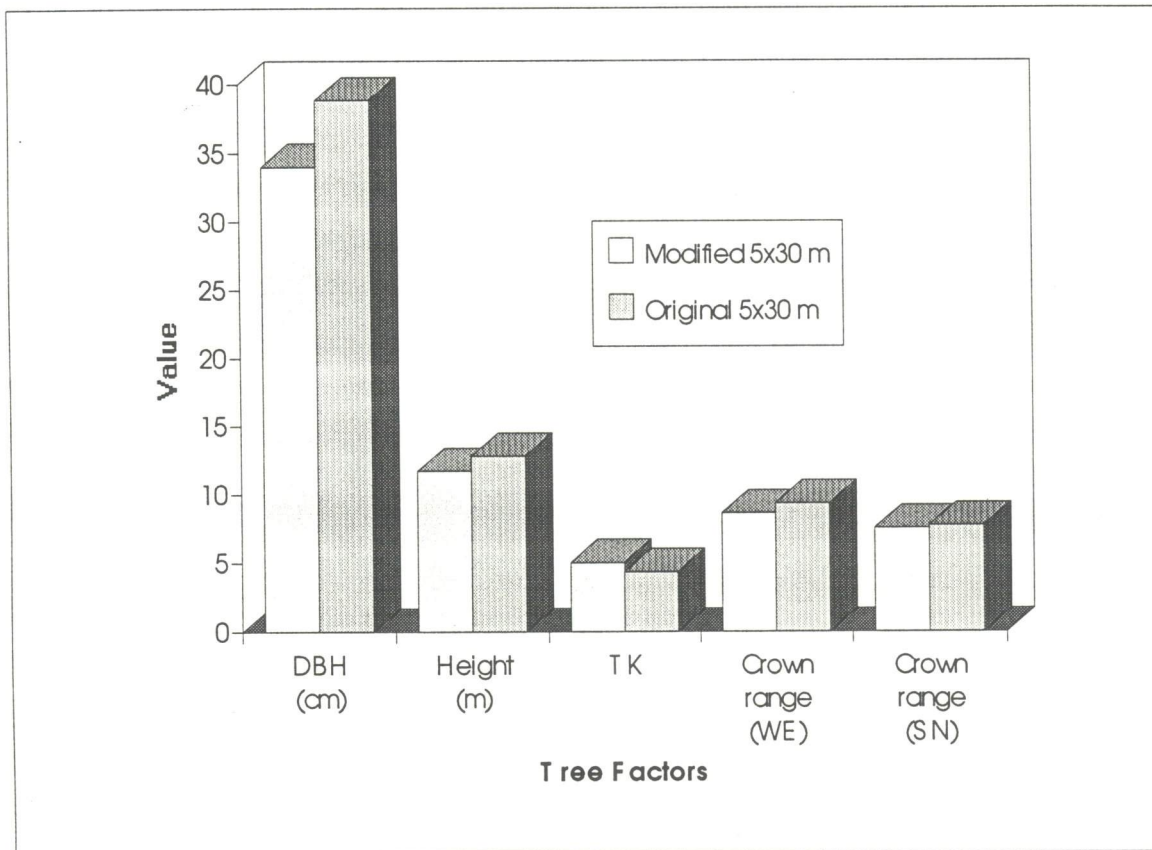


Figure 5.3 Effect of initial dense spacing on tree growth at the 10th intercropping year (3 years after thinning). The initial spacings for the modified 5x30 m treatment were 5x6 and 5x10 m. TK = trunk height under first bottom branch (m).

Table 5.3 Growth in total timber volume ($\text{m}^3 \text{ ha}^{-1}$) for different tree spacings in paulownia-wheat intercropping systems.

Age (Year)	Spacing (m) and Trees per Hectare						AVERAGE
	5x6 333	5x10 200	5x20 100	5x30 67	5x40 50	5x50 40	
1	1.38	0.82	0.38	0.27	0.19	0.17	0.54
2	4.29	1.61	0.63	0.51	0.42	0.36	1.30
3	11.72	5.57	2.10	1.49	0.98	0.85	3.79
4	21.19	10.70	5.20	2.45	2.40	1.86	7.30
5	41.84	22.50	7.75	6.52	5.33	3.81	14.62
6	56.35	36.94	14.75	11.12	9.61	5.72	22.41
7	96.53	68.42	24.75	23.28	13.78	9.47	39.37
8	107.08	75.14	34.42	22.51	16.65	11.91	44.62
9			50.01	25.77	19.82	13.99	27.40
10			69.05	37.21	26.22	18.49	37.74

Table 5.4 Regression equations used to model percentage light transmissivity (%LT) as a function of distance from the western tree row (D, expressed in m) for different tree spacings. a = simulated from other spacings. Significance levels: ** = $p < 0.01$; * = $p < 0.05$. N = number of observations in sample used to derive equations.

Spacing (m)	Year	Month	Equation	Adjusted R^2	N
5x10	1986	Sept.	%LT = $12.6 + 28.9 D - 2.84D^2$	0.95**	11
			%LT = $e^{3.73291 D^{0.464498}}$	0.94**	11
	1987	May	%LT = $19.61 + 15.23D - 1.48D^2$	0.76*	8
			%LT = $e^{3.63203 D^{0.2715}}$	0.81**	8
	1989	April	%LT = $52.1 + 10.5D - 1.17D^2$	0.86**	9
			%LT = $e^{4.06512 D^{0.155891}}$	0.67**	9
		May	%LT = $8.58 + 9.58D - 0.86D^2$	0.65*	9
			%LT = $e^{3.07361 D^{0.31303}}$	0.48*	9
5x20	1986	May	%LT = $81.1 + 1.93D - 0.1D^2$	0.36	10
			%LT = $e^{4.30131 D^{0.110131}}$	0.95**	9
	1987	May	%LT = $29.52 + 12.63D - 0.63D^2$	0.91**	8
			%LT = $e^{3.8036 D^{0.32585}}$	0.91**	8
		Aug	%LT = $17.4 + 13.04D - 0.62D^2$	0.92**	20
			%LT = $e^{3.55176 D^{0.405364}}$	0.91**	20
	1989	April	%LT = $63.39 + 3.16D - 0.16D^2$	0.82**	15
			%LT = $e^{4.18088 D^{0.0851273}}$	0.85**	15
		May	%LT = $37.4 + 7.57D - 0.368D^2$	0.65*	9
			%LT = $e^{3.78509 D^{0.247084}}$	0.74**	9
		Aug	%LT = $9.04 + 15.13D - 0.76D^2$	0.85**	21
			%LT = $e^{3.28032 D^{0.511021}}$	0.83**	14
	1992	May	%LT = $59.2 + 5.32D - 0.27D^2$	0.97**	27
			%LT = $e^{4.17172 D^{0.135}}$	0.96**	18
5x30	1987 ^a	May	%LT = $54.3 + 5D - 0.17D^2$	0.95**	5
			%LT = $e^{4.0221 D^{0.1868}}$	0.97**	5
	1989 ^a	May	%LT = $30 + 6.4D - 0.21D^2$	0.999**	5
			%LT = $e^{3.5227 D^{0.31835}}$	0.99**	5
	1992 ^a	May	%LT = $57 + 4.7D - 0.17D^2$	0.95**	5
			%LT = $e^{4.06549 D^{0.17257}}$	0.97**	5
	1992	May	%LT = $53.12 + 5.38D - 0.18D^2$	0.90**	15
			%LT = $e^{4.01315 D^{0.193037}}$	0.90**	9
	1993	May	%LT = $76.1 + 2.47D - 0.08D^2$	0.76**	15
			%LT = $e^{4.337 D^{0.0779345}}$	0.79**	12
5x40	1987	May	%LT = $66.23 + 2.65D - 0.066D^2$	0.97**	12
			%LT = $e^{4.18644 D^{0.114769}}$	0.97**	4
	1989	May	%LT = $28.2 + 6.04D - 0.15D^2$	0.98**	15
			%LT = $e^{3.4773 D^{0.347059}}$	0.996**	9
		Aug	%LT = $47 + 4.16D - 0.1D^2$	0.92**	25
			%LT = $e^{3.85773 D^{0.214252}}$	0.96**	15
		Oct	%LT = $41.34 + 5.5D - 0.14D^2$	0.87**	17

			$\%LT = e^{3.93608} D^{0.202189}$	0.98**	10
	1992	May	$\%LT = 63.4 + 2.95D - 0.07D^2$	0.92**	25
			$\%LT = e^{4.14513} D^{0.129751}$	0.92**	15
5x50	1989	April	$\%LT = 64.4 + 2.18D - 0.044D^2$	0.70**	15
			$\%LT = e^{4.14095} D^{0.121781}$	0.79**	9
		May	$\%LT = 46.6 + 2.65D - 0.053D^2$	0.85**	15
			$\%LT = e^{3.65892} D^{0.279844}$	0.93**	9

Table 5.5 Regression equations used to model light transmissivity (percentage of control, %LT) in May at different positions in relation to the tree canopy as a function of alley width (W in m). For the position under the canopy in 1992, it was not possible to fit an equation and average values for 5x20, 5x30 and 5x40 m spacing are given. Significance levels: ** = $p < 0.01$; * = $p < 0.05$. N = number of observations in sample used to derive equations.

Year	Position	Equation	Adjusted R^2	N
1992	Under	mean transmissivity = 62.4, 68.6 and 68.9%		
	Edge	$\%LT = e^{4.05391W^{0.110362}}$	0.58*	14
	Middle	$\%LT = e^{4.08239W^{0.121957}}$	0.75*	15
1989	Under	$\%LT = e^{2.59065W^{0.33599}}$	0.49*	12
	Edge	$\%LT = 45.8 + 0.633W$	0.94**	6
	Middle	$\%LT = e^{2.28274W^{0.607889}}$	0.87**	12
1987	Under	$\%LT = e^{2.9031W^{0.36375}}$	0.98**	6
	Edge	$\%LT = e^{3.39428W^{0.300445}}$	0.84**	7
	Middle	$\%LT = e^{3.5256W^{0.28361}}$	0.84**	6

Table 5.6 Regression equations used to model percentage light transmissivity (%LT) at different positions under the tree canopy and for different management regimes as a function of intercropping year (A; expressed as an integer value from 5 = 1987 to 10 = 1992). Significance levels: ** $p < 0.01$; * = $p < 0.05$. N = number of observations from which equations were derived. Data are for 5x10, 5x20 and 5x40 m spacings.

Spacing (m)	Position	Management	Equations	Corrl. Coef.	Adjusted R^2	N
5x10	under	no prune	$\%LT = e^{6.33447A^{-1.61443}}$	-0.98	0.96**	9
	middle	no prune	$\%LT = e^{6.6967A^{-1.61822}}$	-0.995	0.99**	9
5x20	under	no prune	$\%LT = e^{5.58462A^{-0.877051}}$	-0.89	0.80**	10
		pruning	$\%LT = 211.2 - 44.9A + 3.1A^2$		0.84**	15
	middle	no prune	$\%LT = 115.73 - 5.57A$	-0.88	0.77**	9
		pruning	$\%LT = 151.5 - 19.6A + 1.3A^2$		0.69**	15
5x40	under	no prune	$\%LT = 145.63 - 14.9A$	-0.998	0.995**	6
		pruning	$\%LT = 314.49 - 72.8A + 4.8A^2$		0.95**	11
	edge	no prune	$\%LT = 123.38 - 7.46A$	-0.991	0.98**	6
		pruning	$\%LT = 209.7 - 37.1A + 2.47A^2$		0.95**	11
	middle	no prune	$\%LT = 93.99 - 0.24A$	-0.57	0.32	6
		pruning	not fit in model, avg.92%			

Table 5.7 Regression equations used to model intercrop yield in percentage of the control (%Y) as a function of distance across the alley from the western tree row (D). Significance levels: ** = $p < 0.01$; * = $p < 0.05$.

Year	Spacings (m)	Equations	Adjusted R ²	Corr. Coefficient
1987	5x10	%Y=80.8-0.75D+0.075D ²	0.11	-0.85
	5x20	%Y=74.8+4.03D-0.2D ²	0.11	0.88
	5x40	%Y=98.4+1.24D-0.03D ²	0.999**	0.99
	5x50	%Y=80.2+1.85D-0.04D ²	0.99**	0.92
1988	5x10	%Y=45.5+16.7D-1.5D ²	0.28	0.87
	5x20	%Y=62.1+7.6D-0.37D ²	0.28	0.98
	5x40	%Y=68.13+4.6D-0.1D ²	0.65	0.90
	5x50	%Y=91.6+2.14D-0.04D ²	0.57	0.85
1989	5x10	%Y=74.5D+0.48D ²	0.84*	-0.94
	5x20	%Y=80.3+4.0D-0.23D ²	0.91**	0.90
	5x40	%Y=72.3+5.2D-0.13D ²	0.83*	0.97
	5x50	%Y=89.5+2.56D-0.05D ²	0.90**	0.96
1990	5x10	%Y=49.1+15.5D-1.29D ²	0.52	0.77
	5x20	%Y=66+6.4D-0.3D ²	0.87*	0.83
	5x40	%Y=86.8+3.7D-0.09D ²	0.86**	0.97
	5x50	%Y=72.3+4D-0.08D ²	0.86*	0.98
1991	5x20	%Y=72+3.32D-0.21D ²	0.29	0.64
	5x30	%Y=100.7+3.4D-0.13D ²	0.4	0.76
	5x40	%Y=75.4+3.2D-0.08D ²	0.95**	0.82
	5x50	%Y=73.+2.6D-0.05D ²	0.79*	0.81
1992	5x20	%Y=75.7-0.19D+0.05D ²	0.95**	-0.28
	5x30	%Y=64.6+5.9D-0.17D ²	0.74*	0.83
	5x40	%Y=89.7+2.2D-0.05D ²	0.54	0.80
	5x50	%Y=78.2+2.4D-0.04D ²	0.66	0.92

Table 5.8 Regression equations used to model intercrop yield in percentage of control (%Y) as a function of percentage light transmissivity (L).

Year	Spacing (m)	Equations	Adjusted R ²	Corr. Coefficient
1987	5x10	%Y=81.88-0.045L	0.03	-0.52
	5x20	%Y=62.77+0.36L	0.53	0.81
	5x40	%Y=68.14+0.46L	0.97**	0.99
	5x10-20	%Y=63.2+0.34L	0.61**	0.81
	5x10-40	%Y=54.07+0.55L	0.63**	0.81
1989	5x10	%Y=89.1-0.77L	0.71	-0.92
	5x20	%Y=54.6+0.56L	0.55*	0.81
	5x40	%Y=-15.9+1.76L	0.85**	0.94
	5x50	%Y=71.3+0.49L	0.88**	0.95
	5x6-50	%Y=44.15+0.80L	0.86**	0.93
	5x6-20	%Y=44.44+0.71L	0.87**	0.94
	5x40-50	%Y=53.6+0.71L	0.84**	0.92
1992	5x20	%Y=93.9-0.18L	-0.22	-0.29
	5x30	%Y=41.05+0.71L	0.25	0.66
	5x40	%Y=47.5+0.66L	0.72*	0.89
	5x20-40	%Y=40.5+0.67L	0.25*	0.55
	5x30-40	%Y=42.28+0.71L	0.50**	0.74
All	All	%Y=50.9+0.6L	0.61**	0.78

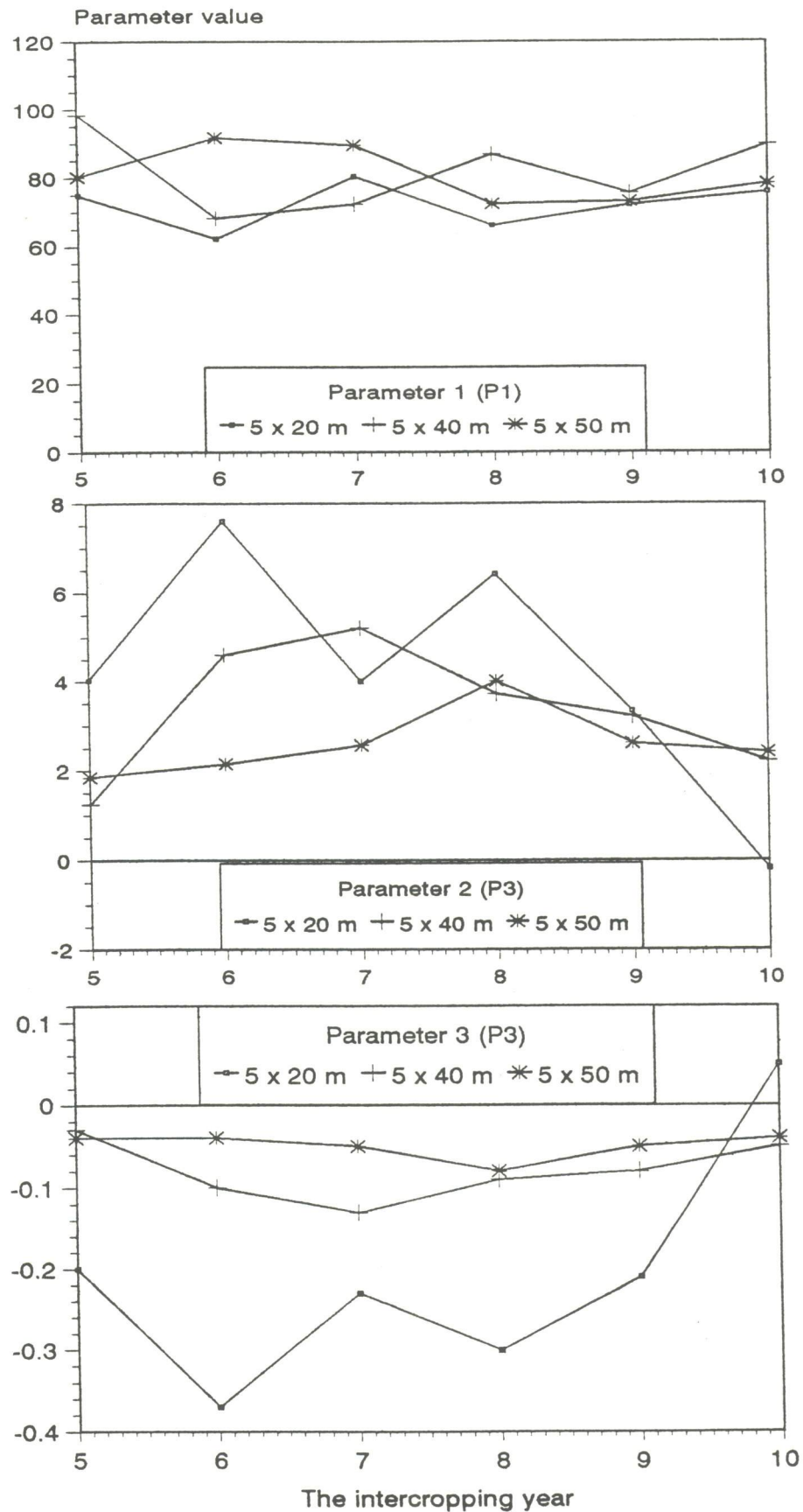


Figure 5.4 Changes in parameter values with intercropping age and spacing in the relationship $\% \text{Yield} = P_1 + P_2 D + P_3 D^2$ where D = distance from the western tree-row (m).

The most commonly used procedure in model validation is to plot the observations against the predictions in a scatter graph and to compute the line of best-fit using linear regression. This approach suffers from several logical flaws since a significant regression is often an inevitable and trivial result. Even a test that the slope of the line does not differ from 1.0 can give ambiguous results. This is because the fitted line is an abstraction not related to model performance but only to the particular sample of pairs of prediction and observation. The fitted line is neither part of the model nor its output. As an alternative approach, the modeller should consider, quantitatively, the bias and repeatability that are required, with reference to the application of the model. This is aided by plotting the deviations (prediction minus observation) with an envelope of acceptable error. The envelope and the proportion of points (usually 95 per cent) that lie within it are defined by the modeller in advance with reference to the application of the model. In this way some rigour and objectivity are brought to empirical validation and the misuse of statistics is avoided (Mitchell and Sheehy, 1995).

For this study, the similarity in trend of the predicted values with the observed values is more important than the actual values. This is because the trends reflect the physical influences of the environment on the agroforestry system, while the fluctuations in value are mostly due to management. For instance, tree pruning will increase light transmissivity but will not alter much the pattern of light distribution across the alley, whereas wheat yield and tree growth could be increased if intensive management such as fertiliser, irrigation and pesticide spray were applied. Therefore, two validation criteria were used to determine whether the output of the model was acceptable. One is that 95 per cent of the observed values should lie within a range of one standard deviation of the predicted value. The other is that the observed and predicted values should have a 1:1 relationship and therefore show similar spatial trends. Model validation was based on a year-by-year comparison of predicted and observed data. Where no suitable regression equation existed in the model for a given year, one for a comparable year was substituted.

Model validation in this study was based on data from Chengwu, Shandong Province, collected in 1993 and 1994 as part of the present project, and also from Yanzhou, Shandong Province, and Luyi, Henan Province, during the IDRC project. The climate and soils in Yanzhou and Luyi are similar to those in Dangshan. Data on wheat yield, tree growth and light were measured at these sites, using the same methods and instruments as in Dangshan (Section 4.2).

One problem that arose was that the data used for the validation were collected under less controlled conditions than those used to develop the model. As seen in Section 4.1.2, the data in Dangshan were collected as part of a well-managed experiment in which crop management was uniform across all the tree spacings. The data from Chengwu were obtained from individual farmers' fields after major changes in land tenure. The land was managed in small units with each unit being typically a 3 to 15 m wide and 50 to 200 m long strip. Thus the land with tree-row spacings of 5x20 to 5x40 m could be managed by several families with no conformity on the dates of sowing, application of irrigation and fertiliser or use of pesticides. Also, tree ownership in the system is now complex and varies from a single row to two rows per family. Under these circumstances, it is difficult to separate the spatial variations in yield due to the effect of trees from those resulting from differences in management.

5.3.1 Light transmissivity

Equations for the 10th intercropping year were chosen for validation because data for validation were collected for that year. The results showed that all percentage LT models gave good predictions of trends and mean values for the 5x30 and 40 m spacings (Table 5.9; Figure 5.5). For the 5x20 m spacing, there was a 14.4 per cent difference between the predicted and observed mean values but the trends in percentage LT across the alley were well simulated (Figure 5.6) with very high correlation ($r = 0.93$). The difference between the observed and predicted values might due to the heavier pruning of the trees in Dangshan.

Table 5.9 Comparison of predicted and measured light transmissivity (percentage of control, %LT) for the 10th intercropping year. * = based on calculating %LT from % PAR ($\%LT = 11.94 + 0.93 \%PAR$). ** = predictions %LT related to May whereas observations related to August.

Year	Spacing (m)	Predicted Mean	Measured Mean	Correlation Coefficient
1992	5x20	73.0	58.6	0.93
	5x30	69.8	70.1	0.99
	5x40	82.5	81.2	0.88
	5x30*	76	72	0.999
	5x30**	78.4	71.5	0.99

From the results of the validation exercise it was found that the equations expressing percentage LT in May could be used to simulate conditions at other times in the same year. Thus, the relationship for May for the 5x30 m spacing in the 10th intercropping year gives very good predictions of percentage LT in August from the edge of tree canopy to the middle of the alley; the percentage LT under the trees was, however, over predicted by 26 per cent because the greater growth of the trees in August led to higher light interception compared to May.

Figure 5.7 shows how well percentage LT values for the 5x10 m spacing are predicted for the 6th intercropping year using, in this instance, a relationship developed for the 5th intercropping year. Since the predicted percentage LT values for the 6th year were only slightly lower than and not significantly different from those of the 5th year, the relationship for the latter could be used to predict the conditions in both years. It could not be used, however, to predict the conditions in the 4th year; the predicted percentage LT in the middle of the alley was 26.3 per cent lower than that observed in the 4th year. Significant differences were found between the 4th and 5th year in both the percentage LT values and the trends across the alley. These might due to the significant increase in canopy range in the 5th intercropping year (Section 4.3). The validation results thereby confirm the dramatic reduction in LT that occurs in the 5x10 m spacing from the 4th to the 5th intercropping year.

Relationships of percentage LT as a function of percentage PAR developed from data for the 10th intercropping year at Chengwu were validated using data for the 11th intercropping year at Yanzhou in 1986. The measured values closely fitted the predicted ones except under the trees (Figure 5.8).

5.3.2 Wheat yield

Two types of predicted yield models were established. One was based on yield as a function of distance from the western tree row and the other was based on percentage LT. Results showed that the larger the spacing, the more accurate were the predictions of both models. For alley widths less than 5x20 m and also for locations near to the trees in the wider spacings, the predicted values for the 10th intercropping year were always irregular in pattern across the alley and lower than those observed in Chengwu.

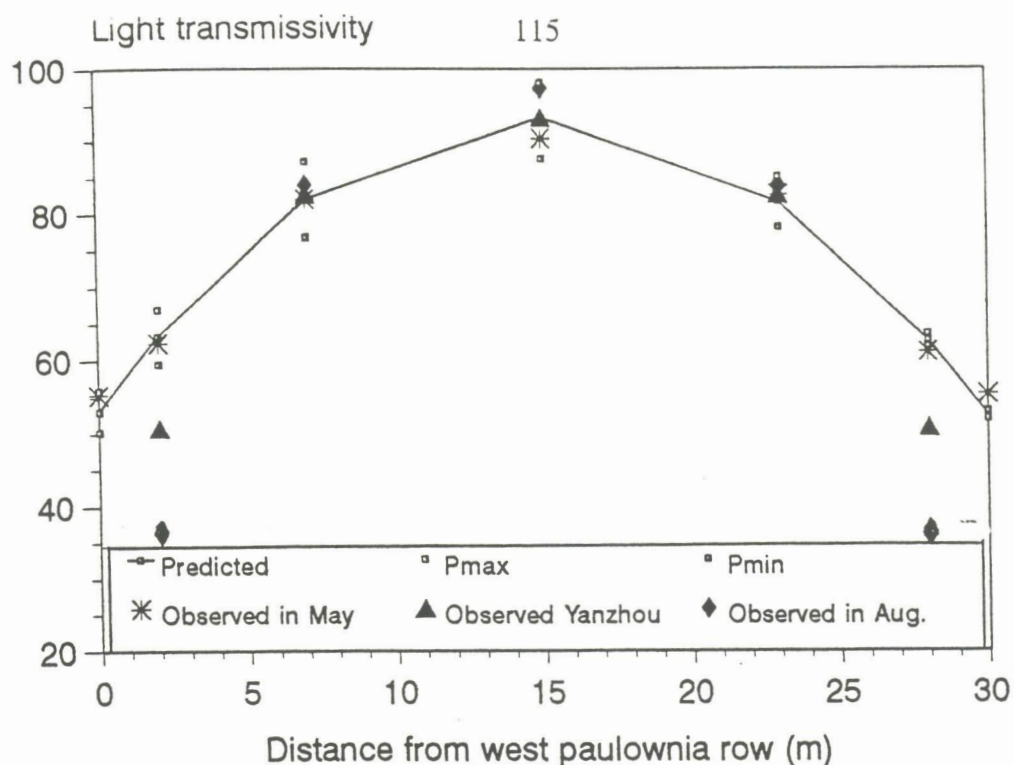


Figure 5.5 Comparison of predicted light transmissivity (percentage of control, %LT) across the alley in 5x30 m tree-row spacing with measured values in the 10th year of intercropping at Chengwu (May and August) and Yanzhou (May). The prediction equation used is $\%LT = 53.12 + 5.38D - 0.18D^2$ where D = distance from the western tree-row (m).

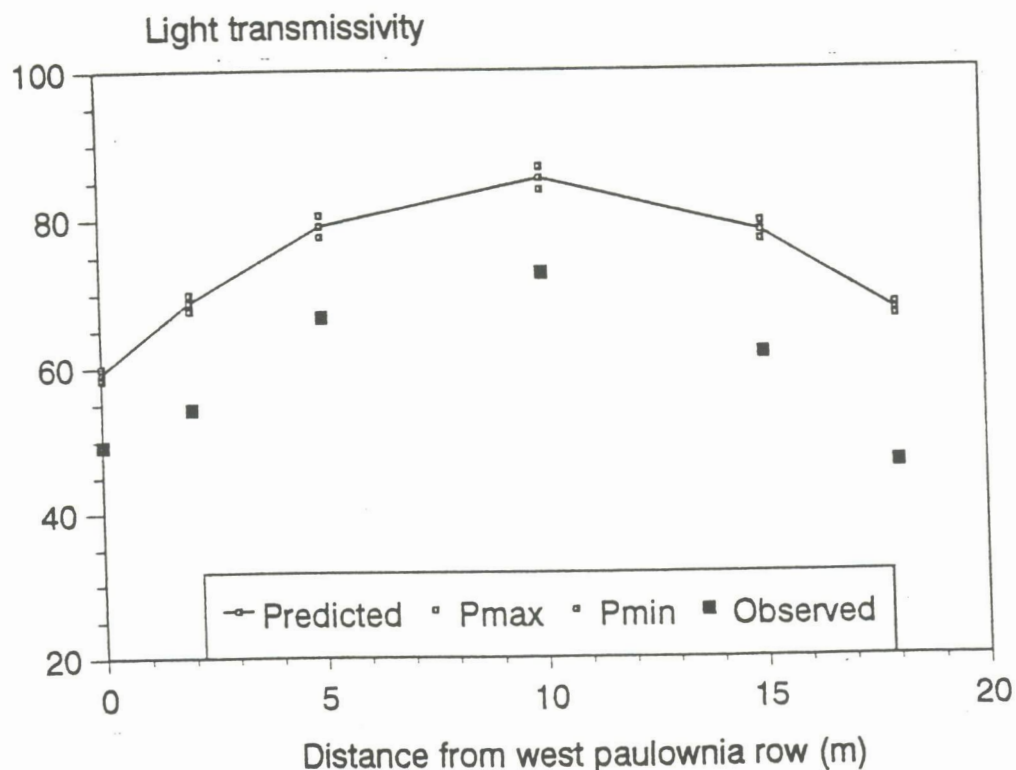


Figure 5.6 Comparison of predicted light transmissivity (percentage of control, %LT) across the alley in 5x20 m tree-row spacing with measured values in the 10th year of intercropping at Chengwu. The prediction equation used is $\%LT = 59.2 + 5.32D - 0.27D^2$ where D = distance from the western tree-row.

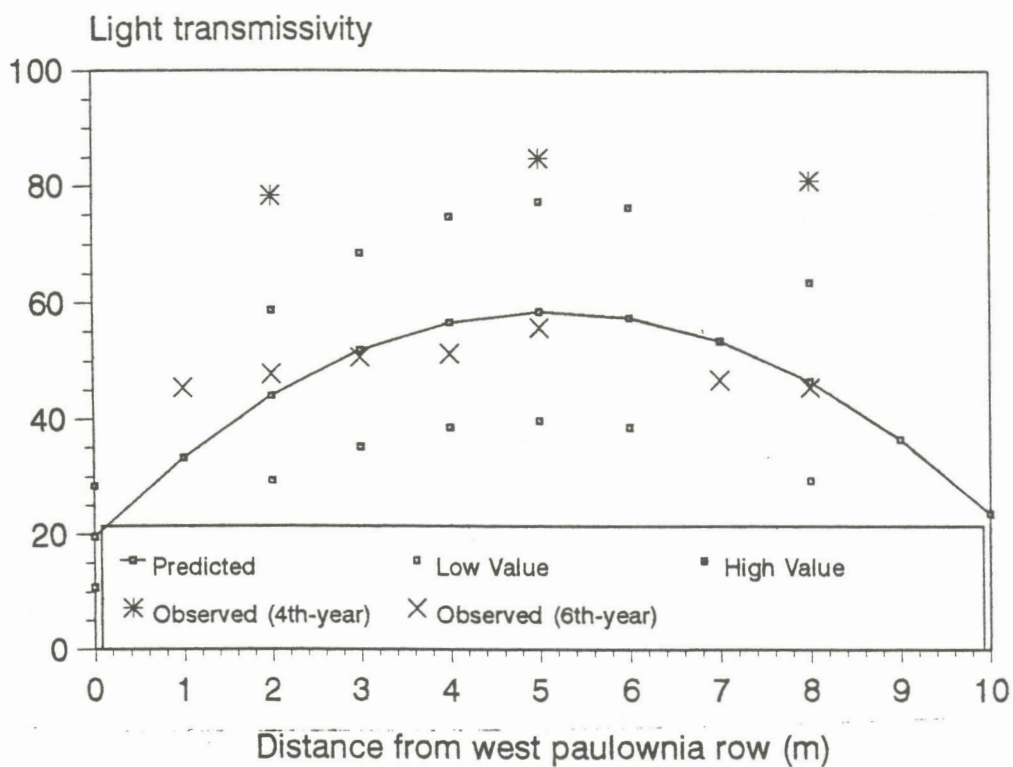


Figure 5.7 Comparison of predicted light transmissivity (percentage of control, %LT) across the alley in 5x10 m tree-row spacing with measured values in the 4th year of intercropping at Luyi and the 6th intercropping year at Yanzhou. The regression equation used is that developed for the 5th intercropping year: $\%LT = 19.6 + 15.23D - 1.48D^2$ where D is the distance from the western tree-row.

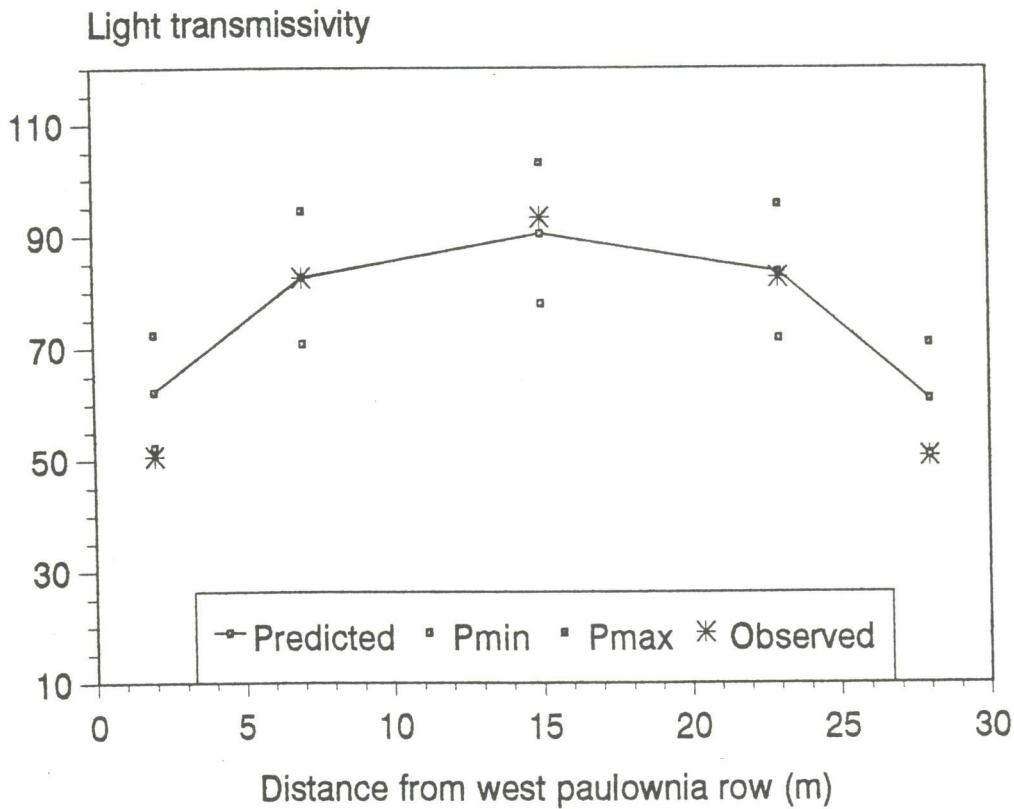


Figure 5.8 Light transmissivity (percentage of control, %LT) across the alley in 5x30 m tree-row spacing, predicted as a function of Photosynthesis Active Radiation transmissivity (percentage of control, %PAR), compared with measured values in the 10th year of intercropping at Yanzhou. The regression equation used, based on data in the 10th year of intercropping at Chengwu was: $\%LT = 11.94 + 0.93 \%PAR$.

For the 5x20 m spacing, the relationships for the 8th and 9th intercropping year were found to predict well the conditions in the 10th intercropping year at Chengwu. The results showed that the 9th year relationship gave similar trends but lower yield values than those measured, while the 8th year relationship gave both values and trends which were very close to those observed (Figure 5.9). This might be because as the trees became older, light was no longer a key factor affecting yield in proximity to the tree row. Competition for nutrients and water between trees and crops may have led to a greater reduction in crop yield near the trees in the experimental sites. This was supported by results from the 5x30 and 5x40 m spacings in the farmers' fields in Chengwu. The observed yields close to the trees were higher than predicted in both cases with the trend being slightly better for the wider spacing. Again applications of fertiliser, irrigation and pesticides may have served to minimise the competition and yield reduction (Figure 5.10). It can be concluded that by application of fertiliser and irrigation, farmers can delay any yield reduction due to competition for nutrients and water by up to two years.

Yields predicted by the model in terms of percentage LT have very high deviation. As a result, 100 per cent of the observed values fitted within the prediction for all models and were not significantly different from the predicted values. However, this result may reflect in part the large variability in the data used for model establishment which, in turn, allows the user a high variability in predicted values whilst still maintaining model validity. Yields predicted for the denser spacings and also nearer to the trees in the wider spacings were generally lower than those measured in the farmers' fields, most likely reflecting intensive management by farmers designed to minimise the yield reduction but which cannot be accounted for by the model.

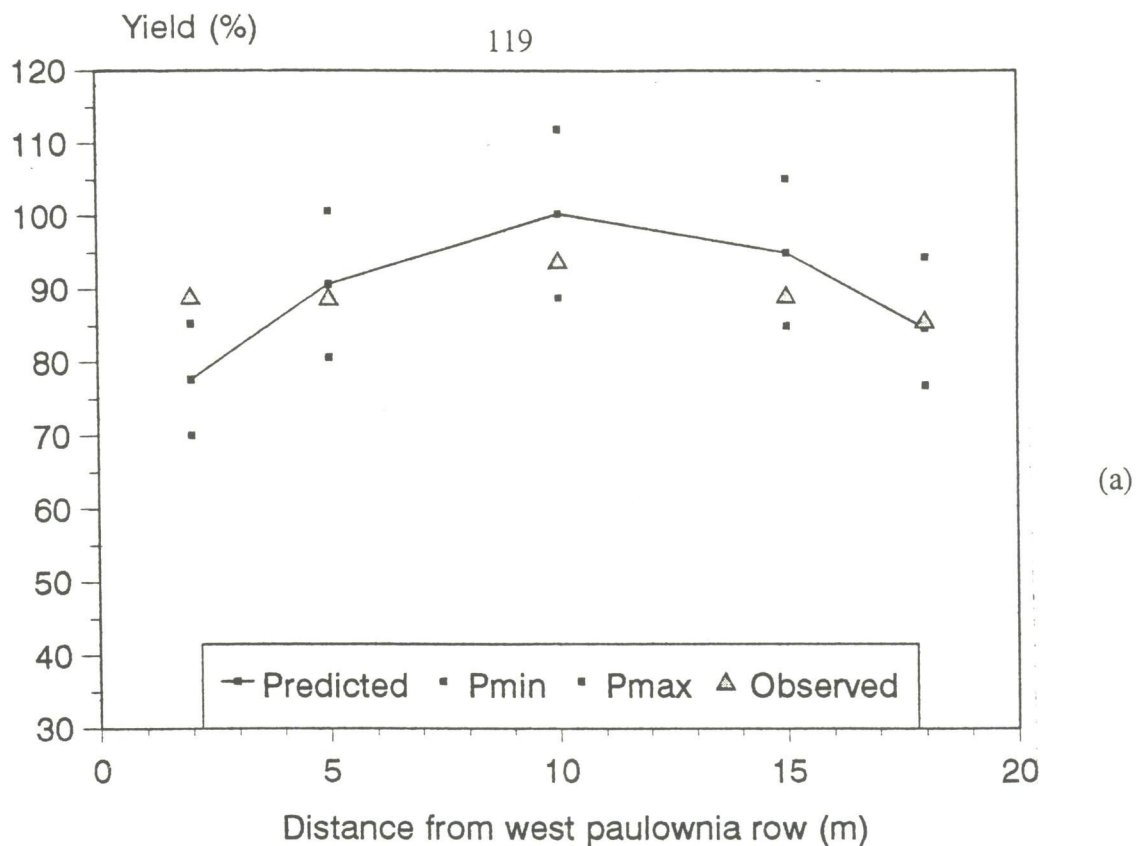
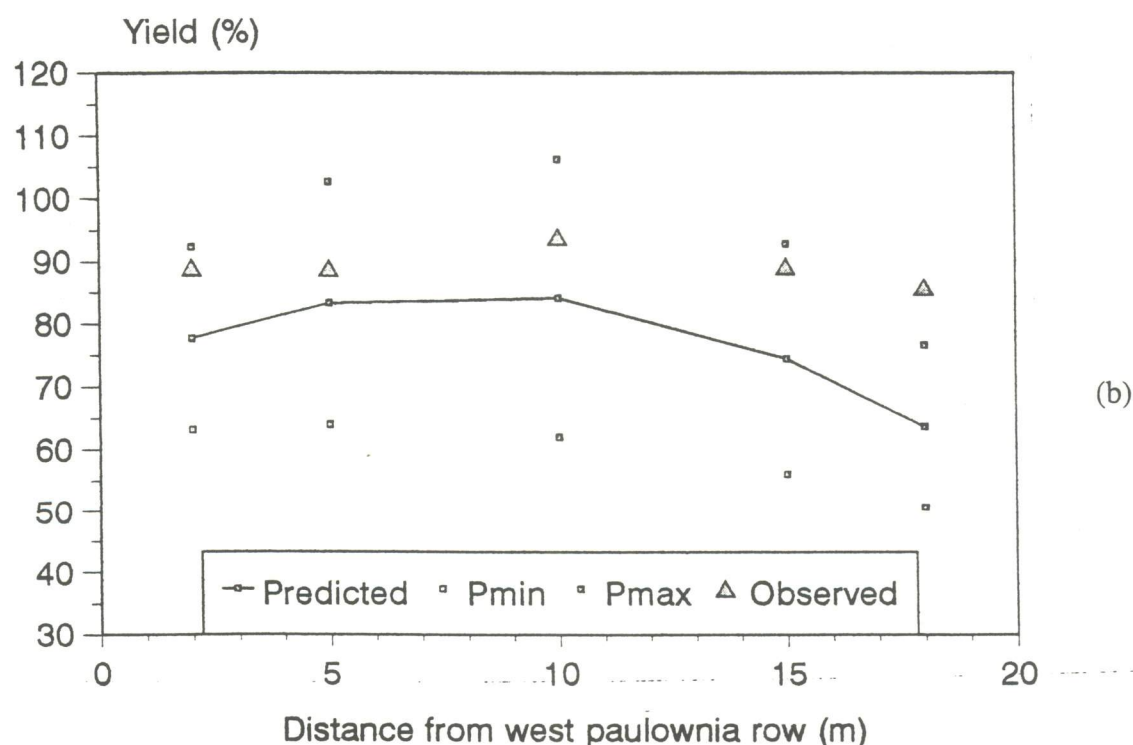


Figure 5.9 Comparison of relative wheat yield predictions in percentage of control (%Y) in 5x20 m tree-row spacing with measured values in the 10th intercropping year at Chengwu. The regression equations used are: (a) $\%Y = 66 + 6.4D - 0.3D^2$, derived for the 8th intercropping year, and (b) $\%Y = 72 + 3.32D - 0.21D^2$, derived for the 9th intercropping year, where D = distance from the western tree row.

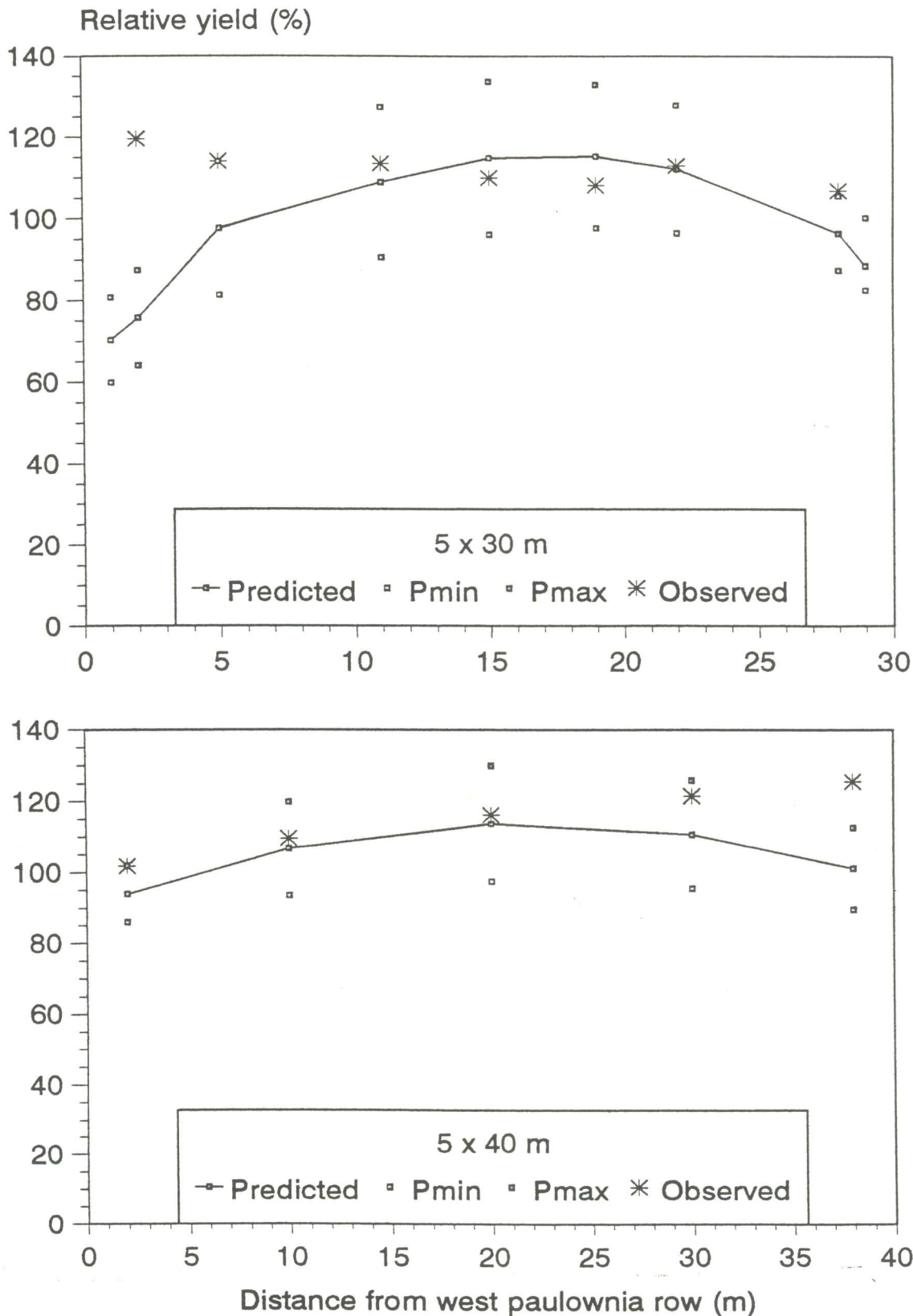


Figure 5.10 Comparison of predicted relative wheat yield in percentage of control (%Y) in (a) 5x30 m spacing and (b) 5x40 m spacing with measured values in the 10th year of intercropping at Chengwu. Regression equations used were: (a) $\%Y = 64.6 + 5.9D - 0.017 D^2$ and (b) $\%Y = 89.7 + 2.2D - 0.05D^2$ where D = distance from the western tree row.

5.3.3 Tree growth

Data for validation of the tree growth component of the model were restricted to two years of information from Chengwu and one year each from Yanzhou and Luyi. Further, since trees were described by single values representing the state of growth for a given year, the total quantity of data was very limited. This contrasted with the situation for LT and understorey wheat yield which were described by many values representing the situation at different distances from the tree rows for different spacings and for different years. Since the data were insufficient for validating separate tree-growth models for each spacing, the relationships combining all spacings were tested, expressing DBH as a function of age. The average DBH for all the spacings, as measured at Chengwu in May of a given year, provided the data for validation. The results were somewhat disappointing with only 45 per cent of the observed values falling within a range of plus or minus one standard deviation of the predicted values; some 25 per cent of the values lying outside this range were higher and 30 per cent were lower. Thus the tree growth relationships could not be properly validated.

5.4 Optimising of Paulownia Spacing and Implementation

The extension or adoption of PCI mainly depends on socio-economic and technical factors. In most cases, the former determine the latter ones. The technical aspects such as tree site suitability and spacing, crop selection and management, could normally be easily followed by farmers. The socio-economic factors, however, are more complex and include land tenure, land parcel size, labour, income, food and financial demand and supply, markets, neighbourhood co-operation and local policies.

As wheat is the most important production from the farm for most of the farmers in the PCI areas, consideration of understorey wheat yield becomes a priority factor in the optimisation of tree spacing. From the above model predictions, it could be concluded that the following spacings are optimal under different scenarios:

1. Should one desire to achieve stable and maximal wheat yields and at the same time want to grow more trees, the spacing range of 5x30-40 m is considered suitable. Tree spacing should not be wider than 5x40 m because the trees then have a low growth rate, low timber volume both in single tree and per unit area, and less protective effects on understorey crops.

2. If one wants to have reasonable wheat yield and good tree growth, 5x20-30 m are more suitable, and more practical for those who have narrow strips of land parcels.
3. Tree row spacings could be flexible between 20 and 40 m by adjusting land strip width so as to compromise the conflict between land parcel width and optimum spacing. A 5x10-20 m is the most ideal spacing for farmers who want to have maximum income from trees, whilst minimising loss of wheat yield.
4. If both adjacent neighbours expect more trees than food from their farm, they could plant trees in the middle of their land strip, but give at least a 5 m width edge allowance to each other so that two tree rows could be kept at least 10 m apart. Otherwise they would have to plant their trees at the edge of the farm along the shared boundary.
5. The 3 m wide edge rule, which was set up in 1990 in Chengwu should be banned because the resulting tree rows are too dense for both tree growth and understorey crops.
6. Constant pruning should be done from the 5th year in order to minimise the shade effect of trees on crops under the tree canopy.
7. One spacing should be applied outright from tree planting to harvest. It is impractical to plant trees with initial dense spacing such as 5x10 m and then thin them into large spacing as suggested by Wu (1990b) under the uniform management conditions. As most of farmers in practice do not want to cut their trees at all until their economical maturity, they will not cut their trees for the benefit of their neighbours' crops.

In practice, to plant trees with large spacing or optimum spacing is not as simple as just looking at the physical arrangement of trees. Many farmers have strip parcels narrower than 10 m. This means that if the planting spacing is controlled at 5x30 - 40 m or even 5x20 m, there are some families who cannot plant trees at all. To implement optimum tree spacing, the above social factors should not be neglected. Security of land tenure is almost invariably necessary for farmers to establish a PCI system. It is proven that farmers have trusted the present land reform policy after more than a decade and feel secure in adopting PCI under the 10-year tenureship. The proper local policy, central control and regulating roles of local authority are very important at land distribution and tree planting stages. Therefore, the following suggestions should be considered for a suitable paulownia-wheat intercropping under the IRS:

1. Before land redistribution, village leaders and farmers should classify their land as tree planting fields and non-tree fields and the population as tree planting and non-tree planting households for the duration of one land tenureship period.

2. In the field which is suitable for paulownia, each land parcel of each household should be controlled to at least 10 m in width. For small households who want to plant trees, their land should be consolidated to one parcel so that their holdings will be wide enough for them to plant trees. Those who do not want to plant trees on their land should be allocated non-tree fields only so that they would not complain of suffering crop loss from their neighbours' trees.

5.5 Summary of Findings

The regression-based model developed in this study provides a useful, easy and practical tool for giving guidance to farmers, local extension officers, local authorities and scientists in decision- and policy-making on paulownia agroforestry systems. It could be easily used with a calculator. The information it can give on rates of tree growth and changes in understorey wheat yield in relation to management, will help farmers to optimise the tree-row spacing depending on whether their objective is to maximise timber production, crop production or the economic return from both. Such information will also help resolve disputes among land holding neighbours and between the local authority and farmers.

As shown by the results of validation trials, the model generally performs well, giving acceptable levels of prediction measured against the criteria described in Section 5.6.2. The model can be applied to paulownia agroforestry in most areas in the North Central China Plain because of the similarity in climate, soil conditions and production practices within this region.

Optimal tree spacings were derived under different scenarios: 5x10-20 m is ideal for farmers who want to have maximum income from trees; 5x20-30 m is more suitable for farmers who want to have reasonable wheat yield and good tree growth, and more practical for those who have narrow strips of land parcels. The spacing range of 5x30-40 m is considered suitable for farmers who desire to achieve stable and maximal wheat yields and at the same time want to grow more trees. Constant pruning should be applied from the 5th intercropping year to minimise reduction of light and understorey yield.

However, the model is only applicable within a certain range of tree spacing (5x10 to 5x50 m) and age (the 1st to the 10th intercropping year). The understorey crop yield prediction is applicable to wheat only, and not to summer crops.

Step by step procedure describing the model operation is presented in Appendix I.

6. CONCLUSION AND RECOMMENDATIONS

6.1 Achievements

The study has made the following major contributions to research on Paulownia-crop Intercropping system:

1. It marks the start of a fourth phase of PCI research, namely that of "adaptive research" in which the scientist links directly with the ultimate users - extension officers and farmers. Scientific findings are interpreted in the context of farmers' needs with emphasis on changed socio-economic conditions under the present Individual Responsibility System (IRS) regime. The study demonstrates the importance of PCI scientists (normally foresters) acquiring interdisciplinary knowledge including silviculture, agro-meteorology, agronomy, crop ecophysiology, socio-economics, extension and rural development.
2. It indicates that socio-economic survey is very important for understanding farmers' needs from PCI. Before undertaking the survey, it was thought that farmers might have replaced most of their paulownia trees by high value fruit trees due to the recent economic development and policy reform, and the freedom of farmers to grow crops and market their products under IRS; even though farmers might be very experienced in PCI after nearly two decades of practice. It was discovered that paulownia is still viewed by farmers as being extremely important under IRS for it is a stable and profitable tree. Farmers failed to grow fruit trees because they need complicated husbandry skills in management and post harvest operations and require constant surveillance. Farmers urgently need technical guidance in manipulating optimum tree spacing of paulownia with emphasis on both maximum understorey wheat yield and income from trees in their narrow strip land under the present IRS regime.
3. Value has been added to data collected over a ten year period on tree growth and understorey crop yield under constant uniform management. Without this study, this valuable data would have remained untouched due to the limitation of the project duration.
4. Experiment and principal data analysis are necessary for scientists and extension officers to understand the natural function of PCI systems and establish models. The regression-based model developed in this study provides a useful, easy and practical

tool for giving guidance to farmers, local extension officers and authorities and scientists in decision- and policy-making on paulownia agroforestry systems. It could be easily applied by using a calculator and inputting simple and easily measured parameters such as tree age or DBH and distance from tree rows. The outputs on rates of tree growth and changes in understorey wheat yield in relation to management will help farmers to optimise the tree-row spacing, depending on whether their objective is to maximise timber production, crop production or the economic return from both. Outputs of the models will also help resolve disputes among farmers and between the local authority and farmers. It is particularly practical for farmers and extension officers in the North Central China Plain, where computers are not available.

6.2. Main Findings of the Study

This study has produced the following information not previously reported elsewhere:

6.2.1 Social economic and paulownia agroforestry

1. Paulownia intercropping is still considered by local farmers and the authorities as the most appropriate system for promoting rural socio-economic development in the poor areas of the north China Plain, like Chengwu County. Paulownia trees are more important as timber and cash sources in the less commercial and remote village of Goucun because farmers only have limited resources to grow the trees and crops successfully. Other trees are also important in the more cash-oriented settlement of Changqiao, where skills, investments and markets are available.
2. All annual crops give very low profits due to the big gap and imbalance between industrial and agricultural products. Wheat is a "survival food" and is relatively a more stable and profitable crop than the summer crops. Its yield is an important concern of farmers in the PCI system. The present common summer crops (maize, cotton and soya bean) give very low profits, some even give negative net income.
3. The traditional farming methods under the collective regime have been replaced by scientific cultivation using irrigation, fertilisation and pesticide spray by individual farmers under the IRS regime. The role of farmers, especially the head of each household, has changed from labourer into farm manager and decision-maker as well as labourer. Women play an important role in rural development and in decision-making. Farmers have need of knowledge in planning and managing their farm for maximum

production and marketing their surpluses. However, they have difficulties in gaining access to scientific findings and translating the scientific findings directly to their needs due to their lower education.

4. The existing policy of allowing a 3 m "edge-allocation" (Section 3.9) on paulownia intercropping causes some arguments among farmers and between farmers and local authorities. This policy should be abandoned.

5. Adaptive research requires scientists to interpret their findings to address the farmers' needs and those of extension officers transferring the knowledge to farmers. A technical guide based on a regression model output, which can predict when, where and how wheat yield reduction starts as a result of tree growth, will help farmers to solve problems and to optimise their management system.

6. Population is increasing rapidly against the decreasing arable land resources. Education rates, especially amongst females, are low.

7. Small pieces of land make farms more difficult to manage and do not encourage investment. This is related to population increase. Points 6 and 7 are associated with the present social regime, an analysis of which is beyond the scope of this study. However, results from the present study will provide farmers with some useful information and technical guidance in efficient land use systems and natural resources management so as to ameliorate the problems.

6.2.2 Tree growth

8. Trees have different growth patterns in relation to inter-row spacing. During the first 5-6 years, growth was fastest for the denser spacings (5x6 - 10 m) and DBH responded more rapidly than height. The denser the spacing, the earlier the fast-growing stage occurs. After the 8th year of intercropping, trees in 5x20 m spacing had the fastest growth rate and the tree growth, particularly DBH, in the denser spacings slowed down. Average DBH was significantly affected by age and so closely related to other variables that it could be used as an index of tree growth.

9. There was no significant difference between the spacings in average values of any of the growth variables by the 10th intercropping year.

10. The 5x6 m spacing is too dense for paulownia because the fast growth stopped before its economical maturity. The 5x50 m spacing is too wide because it has very low growth rate and timber volume and provides no protective effects on understorey crops. The 5x10-20 m are the optimum spacings for tree growth because their fast growth stops after or near to their economical maturity and close to the length of rotation practised by the farmers. For the tree spacing of 5x40, the tree rotation could be longer than 10 years because there was no apparent fast growing stage for the trees in these spacings before the end of the 10th intercropping year.

6.2.3 Light climate

11. Following the spatial distribution of total solar radiation (SR), the greater the distance from the trees and the larger the spacing, the higher is the Photosynthesis Active radiation (PAR) received by the understorey. The proportion of PAR to total SR was slightly lower in the intercropping than in the controlled conditions. The nearer to the trees, the lower is the percentage of PAR to total SR. It was found in this study that the significant light reduction only occurs within 5 m distance of the trees.

6.2.4 Understorey crops

12. Leaf conductivity of the understorey crops in 5x30-40 m spacing of paulownia is higher than that in control plots. But the closer plants are to trees, the denser the spacing and the older the trees, the more is the reduction of leaf conductivity. Shading and increased soil water content minimise the reduction of the physiological process of crops at noon time compared to that in the control and prolong the wheat grain filling stage. Air temperature is the only microclimatic factor significantly related to wheat leaf conductivity, which is negatively affected. The reduction of leaf conductivity of summer crops by paulownia is greater than that of winter crops because in summer the tree leaves are fully developed and light is a key determining factor.

13. The winter crop, wheat, benefits from the modified microclimate. The negative effect of shading is small with large tree spacings but higher in the denser spacings and in the later growing stages of wheat. In the dry, hot and windy season (May), trees create a micro-environment in which the soil water content is a little above that in the

control plots and maximum air temperature and wind velocity are lower than that in the control. These have a positive effect on leaf conductivity, photosynthesis and ultimately on wheat production. In the wet season, this effect is absent. The closer plants are to trees, the denser the spacing and the older the trees, the more is the reduction of leaf conductance and yield, but the higher is the leaf area index and the number of growing days. Wheat grain quality increased in the denser spacing with medium age of trees and under the canopy of large spacing with older trees.

14. The modification of wheat yield is shown to be the balance of three components: a positive effect as described in point 13, the negative one of shading on reduction of photosynthesis, and a third factor, which might be caused by a lower rate of application of fertiliser, or by competition of tree and crop roots for nutrients and water. With application of fertiliser and irrigation in farmer's fields, wheat yield reduction under trees could be postponed for 2 years.

15. The reduction of yield in the summer crops (cotton and maize) is caused by shading, and is 15% at the edge of the tree canopy and as much as 50% near the stems. This degree of reduction can be explained by the absorption of light by the tree foliage.

16. Wheat yield starts to decrease when Light Transmissivity (LT) is reduced to 81.8% as an average and about 10% higher for dense spacing (5x10) and older trees and 10% lower for larger spacing (5x30-50) and younger trees. When LT falls below this point, wheat yield decreases linearly with reduction of light.

6.2.5 Model development and validation

17. As shown by the results of validation trials, the regression model developed in this study generally performs well, giving acceptable levels of prediction of light, wheat yield and trends in both across the alley as measured against the criteria described in Section 5.6.2. The model can be applied to paulownia agroforestry in most areas in the North Central China Plain because of the similarity in climate, soil conditions and production practices within this region.

6.2.6 Optimisation of tree spacing

18. One spacing should be applied outright from tree planting to harvest. It is impractical to plant trees with initial dense spacing such as 5x6 and 5x10 m then thin them into large spacing because farmers do not want to cut their trees before their economical maturity. Constant pruning should be done from the 5th year in order to minimise the shade effect of trees on crops under the tree canopy and keep the tree trunk in good form.

19. For obtaining sustainable maximum understorey crop yield and essential income from trees, a tree spacing range of 5x30-40 m is considered suitable. If one wants to have good tree growth and reasonable wheat yields, 5x20-30 m are more suitable, and more practical for those who have narrow strips of land. Tree row spacing could be flexible between 20 and 40 m by adjusting land strip width so as to reduce the conflict between the narrow land parcel width and optimum spacing. The 5x10-20 m spacing is ideal for farmers who want to have maximum income from trees. If farmers want to plant trees in the middle of their land, they should give at least 5 m width edge allowance to their neighbours.

20. It is essential that land should be consolidated so that the holdings will be wide enough for households to plant trees. Central control by local authorities with technical assistance of extension officers and co-operation among farmers are still important in the planning and initial manipulation of PCI and land distribution under IRS.

The study also confirms the previous findings by Wu (1993) and Wu and Dalmacio (1991) that:

21. There are always reductions in light in the intercropped fields and the effects of paulownia on light are more apparent and significant on clear days, in areas near the paulownia trees, with older paulownia, and when the paulownia has fully developed leaves.

22. The average reflective radiation (R_r) was higher than that in the control in the 5x6-20 m spacings but lower in the 5x40 and 5x50 m paulownia spacings. R_r is negatively related with air temperature.

6.3 Limitation of the Study

The present findings have limitations in applications. Will the results of the study help farmers to decide whether to plant more paulownia or grow more wheat and other summer crops when their socio-economic conditions change? Could the farmers apply results to other agroforestry systems such as fruit tree intercropping? Could farmers learn and interpret the results and apply them to their PCI management properly? The answers are unknown. Specifically, this present study has the following limitations:

1. The regression models developed in this study are only applicable within certain ranges of tree spacing (5x10-50 m) and age (1-10 year old).
2. The regression models are presented in tables and figures only, which cannot be easily understood by farmers and extension officers.
3. The crop yield predictions can be applied to wheat only, and not to summer crops.
4. The study dealt with the growth and production of trees and crops only. Therefore, it could not provide further information to local authorities on long term local planning of the economy for which a more detailed integrated socio-economic study at farm, village or regional level is required.

6.4 Recommendations for future work

Socio-economic and technical factors are equally important in promoting the PCI system. Proper technical guidance can help local authorities in their policy- and decision-making and solve arguments among farmers. In return, the preferential policy on land tenure and parcel size, on marketing and prices of the products and on tree policy, will determine the investment of farmers and the success or failure in the take-up of the PCI system. Technical guidance can also help farmers to achieve dynamic optimum spacing and cropping patterns and finally maximise the production of the PCI system, as they are not only the labourer in their farm, but also the farm managers and decision makers under the IRS regime. Scientists are important because they can provide an in-depth understanding of the present social regime and its economic conditions, including farmers' needs from and perception of the PCI system; they must,

however, transform their findings into a practical tool to address farmers' needs in the realistic world. Extension officers are important to transfer the technology to farmers and local authorities. They build the bridge between scientists and farmers.

The following work should be carried out in order to help farmers further to manage their PCI and promote their socio-economic conditions:

1. A simple manual should be prepared presenting examples of model output in tables and diagrams with text explanations so that extension workers and farmers can understand and use the results of the research more efficiently and easily.
2. Feedback on application of the model should be obtained from farmers and extension officers by questionnaires and interviews so as to refine and improve the model.
3. In order to help scientists and technicians use the model and update the new findings more efficiently and easily, a Regression Model Based Management (RMBM) system should be developed which allows all the required relationships to be placed in one system. With an RMBM system, the user will be able to input and change the set of variables, the set of templates and the regression models to the model base (Edit), generate a standard report (Retrieval), run the stored models to calculate the prediction values (Utilise) and search the relations between two defined variables (Deduce or Develop). The users will also be able to analyse relationships which are not included in the individual regression equations, for example changes in wheat yield as a function of tree growth.
4. Scientists should help farmers to select shade tolerant cash crops such as ginger and medicinal herbs in paulownia intercropping for sustainable understorey crop production and maximum economic returns.
5. Further study on cost-benefit analysis including the prices of timber and crops, labour costs and investment should be made so as to develop an economic model which could be linked to the present model. Together, the two models would provide a foundation for a systems approach to optimising the production and thereby help farmers to maximise food supply and short term and long term income, and to minimise risks and also help local authorities to implement long term local economy planning.

Nonetheless, it could be concluded from this study that paulownia crop intercropping is considered by local farmers and the authorities as the most appropriate system for promoting rural socio-economic development in the poor areas of North Central China Plain. The reason that farmers like to plant paulownia in their narrow strips of land is that it provides an important timber source and long term income as a "saving bank" and has nearly no effect on their "survival food" (wheat) when the tree rows are arranged in an optimum spacing, apart from a small loss of yield near to the trees. The present study lays the foundation for "adaptive research" aimed at improving policy and management of the PCI.

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Appendix I

MODEL OPERATION

Model is operated in the following step by step procedure:

Tree Growth:

For commercial purposes, tree growth is represented by DBH (D in cm), Height (H, in m) and Timber Volume (V, in m³, $V = \pi(D^2/2) \times H \times 0.42$, unit of D in cm should be converted to m by multiplying 0.01).

Step 1: Identify tree age (A), for example age 5 years

Step 2: Choose tree spacings either (a) any spacing between 5x10 to 5x50 m or (b) one specific spacing (for example: 5x20 m)

Step 3: Select equations from Table 5.2:

(a) For any spacing between 5x10 to 5x50, the equations are:

$$D = 0.85 + 3.69A$$

$$H = 3.26 + 0.95A$$

(b) For spacing of 5x20 m, the equations are:

$$D = -0.03 + 3.83A$$

$$H = 2.78 + 0.98A$$

Step 4: Replace A in above equations with age of 5, we could have results of:

$$a) D = 0.85 + 3.69 \times 5 = 20.65 \text{ (cm)}$$

$$H = 3.26 + 0.95 \times 5 = 8.06 \text{ (m)}$$

Thus, for a single tree timber volume:

$$V = \pi((20.65 \times 0.01)/2)^2 \times 8.06 \times 0.42 = 0.1134 \text{ (m}^3\text{)}$$

If timber volume per hectare is needed, then multiply a single tree timber volume (0.1134 m³) by tree numbers per hectare, based on the tree spacing, for example, standing timber volume per hectare for 5x20 m (total 100 trees) would be 113.4 m³ per hectare.

$$(b) D = -0.03 + 3.83 \times 5 = 19.12 \text{ (cm)}$$

$$H = 2.78 + 0.98 \times 5 = 7.86 \text{ (m)}$$

Here:

$V = \pi((19.12 \times 0.01)/2)^2 \times 7.86 \times 0.42 = 0.0948 \text{ (m}^3\text{)}$ per single tree, standing timber volume per hectare for 5x20 m (total 100 trees) would be 9.48 m³ per hectare.

Light Transmissivity:

Light transmissivity could be predicted from models in Table 5.4. The models apply for the 5th, 7th and 10th intercropping year but the results can be used as references for other intercropping years. Prediction of LT before the 5th year is unnecessary because there is less reduction in LT.

Step 1: Identify spacing and intercropping year, for example spacing 5x20 at the 5th intercropping year

Step 2: Select equations from Table 5.4 (e.g. for May): $\%LT = 29.52 + 12.63D - 0.63D^2$

Step 3: For a given distance from west tree-row, e.g. $D = 10 \text{ m}$ from west tree-row, percentage LT the 5x20 m spacing in the 5th intercropping year is: $\%LT = 29.52 + 12.63 \times 10 - 0.63 \times 10^2 = 92.82\%$

Step 4: Calculate average LT:

From equation $Y = a + bx + cx^2$, we could derive an equation for calculating average value: $Y = a + (b/2)x + (c/3)x^2$ where x is alley width, say $x = 20 \text{ m}$. Therefore, the average LT in 5x20 m at the 5th intercropping year is:

$$\%LT = 29.52 + (12.63/2)(20) + (-0.63/3)(20^2) = 71.82\%$$

For equations of $Y = e^ax^b$ (where x is the distance from west tree-row), the equation for calculating average is: $Y = (e^a/(b+1))x^b$, where x = alley width (m).

Wheat Yield

- 1). Relative wheat yield (in percentage of control) can be predicted using models in Table 5.7 for a given distance from west tree-row and average relative yield in a given spacing at a given year.

Step 1: Identify tree spacing, age and distance, for example, to predict relative wheat yield at 10 m from west tree-row and average relative yield across alley width for spacing of 5x20 m in the 5th intercropping year

Step 2: Select equation from Table 5.7 for above conditions:

$$\%Y = 74.8 + 4.03D - 0.2D^2$$

Step 3: Replace D with 10 m, thus the relative yield at the 10 m from west tree-row are:

$$\%Y = 74.8 + 4.03 \times 10 - 0.2 \times 10^2 = 95.1\%$$

Step 4: Calculate average relative wheat yield across alley, use equation

$$Y = a + (b/2)x + (c/3)x^2 \text{ as above where } x \text{ is alley width, in this exercise } x = 20 \text{ m}$$

thus: $\%Y = 74.8 + (4.03/2)(20) + (-0.2/3)(20^2) = 88.4\%$

- 2). Relative wheat yield could be also predicted using models in Table 5.8 for a given light transmissivity in a given spacing at a given year. For example, for the 5x20 m at the 5th intercropping years:

Step 1: Calculate LT, e.g. from above LT at 10 m ($\%LT = 92.82\%$) and average LT across the alley ($\%LT = 71.82\%$).

Step 2: Select equation from Table 5.8, $\%Y = 62.77 + 0.36L$ where $L = \%LT$

Step 3: Replace L with above value, we could have

$$\%Y \text{ at 10 m: } \%Y = 62.77 + 0.36 \times 92.82\% = 92.47\%$$

$$\%Y \text{ average across the alley: } \%Y = 62.77 + 0.36 \times 71.82\% = 88.63\%$$

From above exercises, for the 5x20 m spacing in the 5th year of intercropping, we predict a tree growth of DBH = 20.65 cm, H = 8.06 m, V = 0.1134 (m³), total timber volume V = 9.48 m³ per hectare, average wheat yield across the alley as 88.4 per cent of that in the open field and wheat yield at the middle of the alley as 95.1 per cent of that in the open field.

Assuming the timber price is ¥400 per m³ (Table 3.15), we will have 3792 Yuan income per hectare from trees. Assuming wheat yield in the open field is 3,500 kg per hectare (Section 4.5.1) and market price is ¥1.0 per kg (Table 3.10), the average yield of 5x20 m will be $Y = 3,500 \times (100 - 88.63)\% = 3102$ kg or ¥3102 per hectare. Thus for trees at 5x20 m spacing in the 5th intercropping year, the income gained from trees will be ¥3792 per hectare and the wheat yield loss will be 398 ¥ per hectare only.