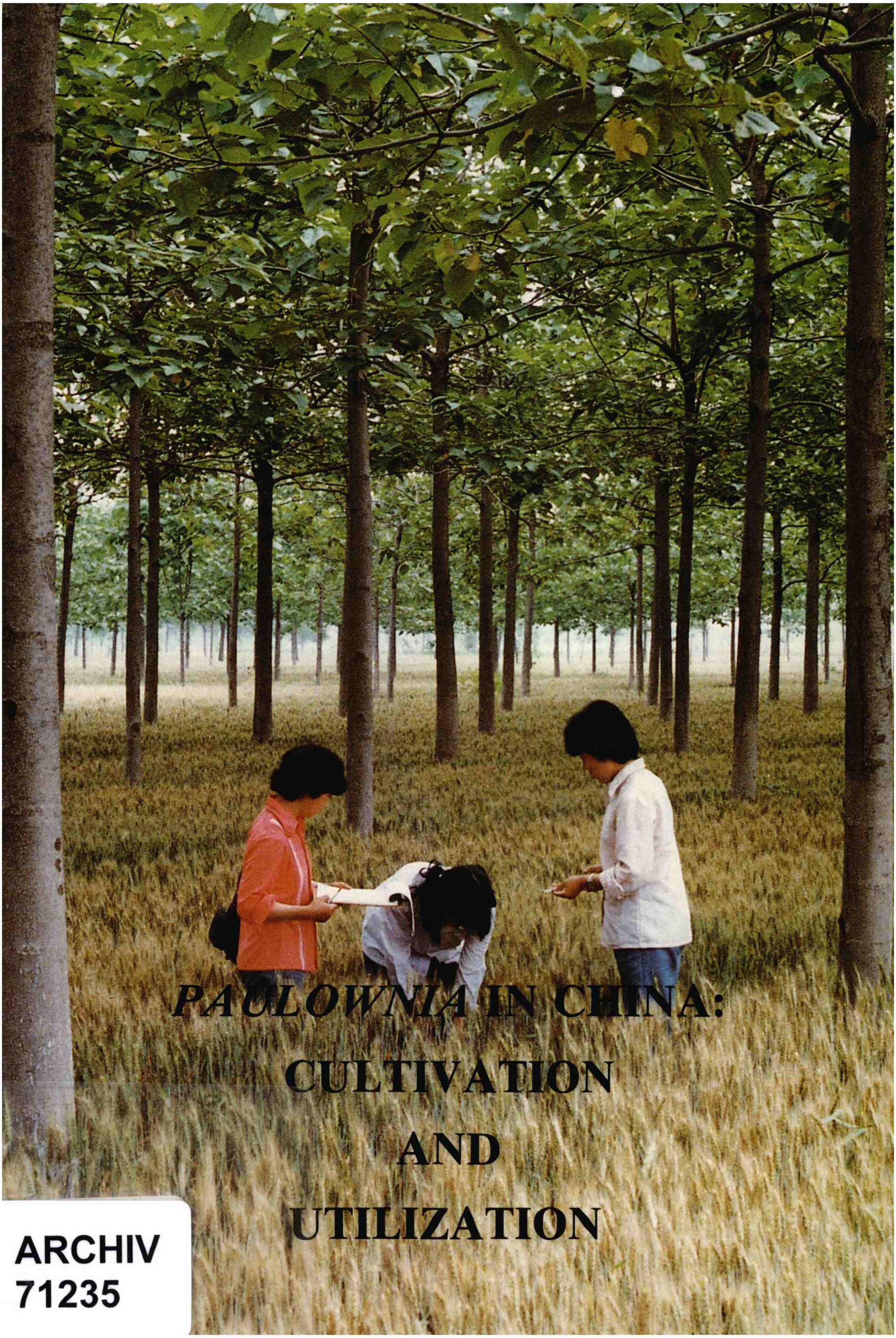

PAULOWNIA IN CHINA: CULTIVATION AND UTILIZATION

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BY

CHINESE ACADEMY OF FORESTRY STAFF

Published by

ASIAN NETWORK FOR BIOLOGICAL SCIENCES

and

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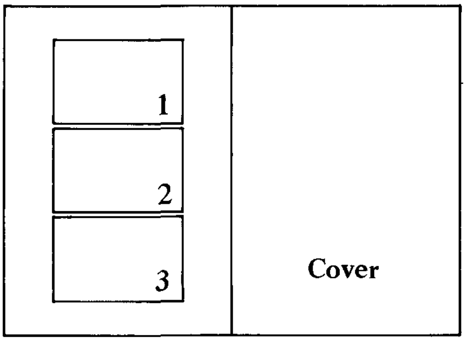

Front cover

Paulownia trees intercropping with wheat.

Back cover

1. *Paulownia* nursery, high ridges covered with plastic sheets.
2. *Paulownia* trees intercropping with rows of Crop plants.
3. Mature tea bushes in front, *Paulownia* trees in flowers at the back.

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FOREWORD

The depletion of the native forests of the tropics and sub-tropics is a cause for alarm, not only for conservationists, but also for all who live in and work for the development of the countries of the third world. The shrinking areas of native forests in turn result in the well known phenomena of increasing soil erosion, reduced soil moisture storage, and unreliable rainfall. These are problems familiar to the governments, scientists, and peoples of most developing countries.

At the same time the demand for timber, fuel, pulp and paper, and other wood based products continues to increase. Already in many developing countries there is a critical shortfall in the local supply of wood. Thus the attack on the resources of the native forests continues at an ever increasing rate. Add to this the equally increasing pressure to clear forest for agricultural/livestock production, and the urgent need for action becomes clear if calamity is to be averted.

The obvious answer is to plant more trees, both to reduce the pressure on the native forests, and to meet increasing demands for wood. However, large-scale afforestation programs are very expensive, and generally beyond the financial means of third world governments. Even when money is available, limited technical knowledge offen results in the failure of such schemes. Whilst large-scale afforestation undoubtedly can play some role in solving the wood supply/sort conservation problem, to hope that it can provide the complete answer is to delude ourselves.

An alternative strategy is to encourage the participation of the rural community in small-scale tree planting. Such a social forestry approach can take the form of village or individual woodlots, or the integration of trees in existing faming systems.

This book describes the successful Chinese experience in the use of one tree, Paulownia, in social forestry programs. Already Paulownia has been planted and incorporated into the system on over one million hectares of farmland in China. This planting has helped alleviate the chromic shortage of timber, fuelwood, and animal fodder, and at the same time served to increase agricultural production, and improve soil conservation.

Paulownia has been known to the Chinese people for several centuries but identification and selection of particular species and varieties to grow on different soils, terrains and micro-climates have only recently been studied. Dedicated research by scientists, and efficient application of the results by administrators has brought many benefits to the rural masses of China. Since 1983, the International Development Research Centre of Canada has supported a programme of research by the Chinese Academy of Forestry. This has resulted in many new developments in the breeding, propagation, cultivation and management of small plantations of the tree. Botanically, the genus offers a number of species, varieties and strains which are suited for cultivation under different soil, climatic, and cultural conditions. Researchers of the Chinese Academy of Forestry have taken advantage of the versatility of the genus to cultivate it extensively in a number of systems as an agricultural intercrop, in the rehabilitation of minedover areas, in village wood lots, in urban forestry, and for "four-sided" planting.

The successful development and use of *Paulownia* in China can be used to benefit many other countries which face similar problems of competing priorities between agricultural and wood production. This book documents the findings and experiences of the Chinese Academy of Forestry, and in doing so hopes to encourage the development of similar programmes in the other parts of the world. We believe that it will not only provide a guideline, but also the necessary impetus to those given the responsability of implementing the forestry programmes of their respective countries. We also hope the dissemination of the knowledge will ultimately benefit the countless millions of rural people all over the developing world.

In editing the book those concerned have made a conscientious effort to retain the Chinese character of the text as much as possible. The subject matter is presented in a logical order to include both the scientific detail of the *Paulownia* species as well as their relative merits and uses.

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I. INTRODUCTION

1. The significance of developing *Paulownia*

The genus *Paulownia* is represented by nine species of fast growing timber trees which are indigenous to China. It is very adaptable, widely distributed and extremely fast growing both in south and north China. Presently, the genus is either naturally distributed or cultivated in 23 provinces, municipalities and autonomous regions. It grows equally well on the plains as well as in mountainous regions up to 2,000 m high. Therefore, the genus provides a great potential for extensive cultivation all over China.

Under normal conditions, a 10-year old *Paulownia* tree can measure 30–40 cm diameter at breast height (dbh) and will have a timber volume of 0.3–0.5 m^3. However, under optimum conditions, they can produce useful timber within five to six years. For instance, in Yinjang County, Szechuan Province an 18-year old *P. fortunei* tree averages about 21.7 m high, has a dbh of 100.5 cm and has volume of 6.65 m^3 of timber, thereby having an annual increment of about 0.37 m^3. With this kind of high growth potential the cultivation of *Paulownia* should alleviate the problem of timber shortage in many of China's counties. For example, in Lankau County, Honan Province, *Paulownia* was planted over a large area from 1963 to 1965 the total area under mixed cultivation had already reached 20,000 hectares. Felling started in 1971 and it yielded almost 148,000 m^3 of timber by 1976 for the local people, effectively solving years of timber shortage.

Paulownia is very adaptable and extremely fast growing. Therefore, there is great potential to develop the trees of this genus in China.

The timber is light yet strong, dries easily, has a beautiful grain, does not warp or crack, or deform easily. The wood is easy to work with, and suitable for carving and has excellent insulation properties. It provides suitable wood for the manufacture of furniture, plywood and musical instruments. It also has many other uses.

Paulownia has late leaf emergence and leaf fall, and the root system is deep. The branching is sparse and so also the leaf arrangement. For these reasons *Paulownia* is an exceptionally good tree for intercropping. Intercropping of agricultural crops with *Paulownia* has thoroughly transformed the agricultural areas on the broad plains in north central China and the central plains into exemplary areas of agroforestry. Intercropping with *Paulownia* improves the microclimate for crop plants, and the yield increases considerably (Fig. 1).

Fig. 1. *Paulownia* trees as part of agroforestry system.

The leaves and flowers of *Paulownia* are rich in nitrogen and therefore serve as good fertilizer and fodder. They also possess many medicinal uses. The inflorescences of *Paulownia* are big and the flowers are a good source of honey. The flowers are colourful and beautiful in spring and the trees are green and shady in summer. *Paulownia* species are therefore very suitable for beautifying and enriching the environment and for afforestation purposes. They are also equally suitable for landscaping of urban and industrial areas. *Paulownia* can also be used for reclamation of mined areas. Like other forms, *Paulownia* is genetically variable and easy to propagate both vegetatively and sexually. These factors are very helpful for the rapid development of *Paulownia* silviculture.

2. The history of *Paulownia*

According to both legends and records, people in ancient times used *Paulownia* for various purposes and instruments. It is said that "When King Yui was buried on the hill, *Paulownia* timber of 3 cuen thick (1 cuen = 3 cm) was used to make a coffin for him". This shows that even 2,600 years ago, they were using *Paulownia* timber. In the work "Zhuang Tze" (400 B.C.) it is recorded "The Phoenix flew from the South Sea to the North Sea without perching on trees other than *Paulownia* and without eating anything but bamboo fruit". The Chinese people have been planting *Paulownia* trees for many centuries around their dwellings in order to bring good luck and to attract the phoenix.

Thus, *Paulownia* has a very long if not the longest history of cultivation in China. In the chapter "Yui Gong" of the book entitled "Shang Shu" (300 B.C.) (the Book of Documents) it is recorded "... the people in Shucho supplied the king with *Paulownia* . . .". This clearly shows that man-made plantations of *Paulownia* were already there in some areas at that time as centres of cultivation from where *Paulownia* timber was supplied. In a book entitled "Mencius" it is also recorded that all the people knew how to cultivate *Paulownia, Catalpa ovata* and other fine timber trees that were very big in diameter. One was not a good farmer if one did not plant *Paulownia* and *Catalpa*. This was during the period of the Warring States (475–211 B.C.). It is thus clear that the Chinese people had already gained considerable experience in the cultivation of *Paulownia* trees. In the book "On Qin Dynasty" (221–207 B.C.) it is recorded "Fu Jian Suei has planted thousands of *Paulownia* around the Arfang City" indicating the fact that *Paulownia* was already in cultivation on a very large scale. Among the many ancient or past records of *Paulownia* the particular work "A Monograph on*Paulownia*" written by Chen Chu (982–1061 B.C.) in the Northern Song Dynasty (960–1127) A.D.) is outstanding for many reasons.

"A Monograph of *Paulownia*" published in 1049 B.C., recorded the method of cultivation and the utilization of *Paulownia* timber. The historical data from before the Northern Song Dynasty was collected and sorted out. Many of the conclusions drawn are correct. The details regarding the taxonomy, morphology, seedling growth, afforestation, tending, management, wood properties and uses of *Paulownia* were discussed in detail and this information is still of great value for cultivation and scientific research on *Paulownia*.

In the 1960s, the people in Lankau County, Henan Province, summed up the precepts as follows: (a) If there are no forests on sandy land, the land cannot support the people; (b) Some of the adverse effects caused by natural calamities (wind and sand storm, drought and frost) therefore can be minimised by the intercropping of agricultural crops with *Paulownia* which was actively promoted.

At present, intercropping with *Paulownia* is being carried out on 1,300,000 hectares of cultivated land in the whole country. Many research institutions, colleges and universities have given priority to research projects on *Paulownia*. Some prefectures and counties have also established forestry research institutes and experimental stations to conduct research on *Paulownia*. They have made observations on the effects of intercropping, propagation, trunk and wood improvement, disease and insect pest control, selection and breeding. They have also carried out experiments on wood properties and utilization. Surveys have also been conducted on the resources and growth of *Paulownia*.

Since 1983, we have received financial and technical assistance from the International Development Research Centre (IDRC). The finances are used for research on *Paulownia* breeding and intercropping with other agricultural crops. This has played a major role in promoting research on *Paulownia* in China. We are now willing to share the knowledge and help in the development of *Paulownia* in other countries, especially in the developing countries of the world.

II. TAXONOMY AND DISTRIBUTION

It is noteworthy that *Paulownia* is the only arborescent genus in the family Scrophulariaceae which is primarily herbaceous. All nine species of this genus are confined to China except *P. fortunei* which extends into Vietnam and Laos, and *P. tomentosa* which also grows in Korea and Japan.

1. Taxonomic history

In "A Monograph on *Paulownia*" and in some other ancient books stated earlier, morphological characteristics of *Paulownia* were described in detail.

The Latin name *Paulownia* for this genus was given by the Swiss botanist Thunberg and details were published in "Japanese Flora" in 1781. He placed the genus in the Bignoniaceae and recognised one species *Bignonia tomentosa* which is the same as *Paulownia tomentosa.* In 1835, Dutch scholars. Zuccarini and Siebold transferred the genus to Scrophulariaceae after studying more details. From then on, Chinese and foreign scholars published new species based on good and fragmentary specimens available, recognising a total of 23 species, many of them are synonyms. Hu (1959) and others carried out further research on the genus and corrected some of the past confusion. They classified *Paulownia* into six species. Since 1973, Zhu Zhao Hua and other scientists of the *Paulownia* Research Group in the Chinese Academy of Forestry, have done a systematic survey of *Paulownia* resources and have accumulated many technical details which provide further information for the taxonomic revision of the genus and correct identification of species. However, the relationship of this genus is still argued. Some contend that the genus should be in the Bignoniaceae while others believe that *Paulownia* should be in a separate family, but most favour placing it in the Scrophulariaceae. Following the opinions of most taxonomists we consider *Paulownia* as a genus of the family Scrophulariaceae.

2. Morphology and taxonomy

(i) Morphological characters

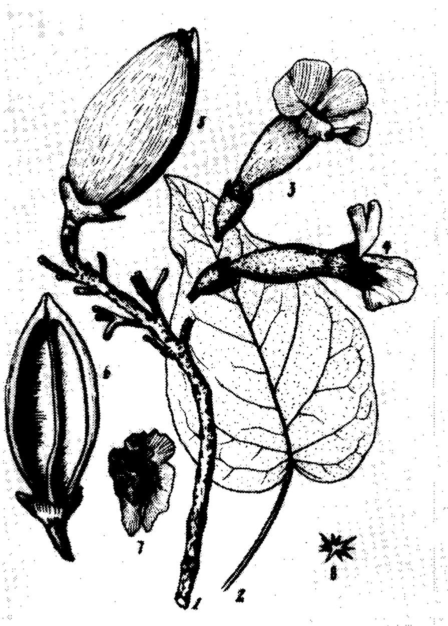
Paulownia species have grey, brown or black bark which is smooth but conspicuously lenticellate when it is young and gradually develops vertical cracks and tissues when it grows into a large tree (Figs. 2–5). The leaves are usually sparse and the crown is terete or umbrella-like (Fig. 2). Often, all the parts, except the old branches, are covered with mucilaginous glandular hairs, multiplenoded thick hairs, and dendritic or stellate hairs. Most *Paulownia* species have pseudo-dichotomous branches whose terminal buds dry up after winter. *P. fortunei* is exceptional in that the terminal buds sometimes grow into new branches. In young trees representing juvenile phase the leaves are large with long petioles, serrate margin, opposite and sometimes whorled in arrangement. The leaves on mature trees are smaller, entire with a smooth or wavy margin (Figs. 6–14). The inflorescence is a cyme of two to five flowers may be pedunculate or subsessile. They are produced in the axils of diminutive or smaller leaves in summer and autumn. Flowers are pedicellate and articulate at the apical end. The calyx is fleshy, campanulate and unequally five-lobed (Figs. 6–14). The lobes are triangular, with the upper middle lobe slightly larger, and usually densely covered with haris. In some species, the hairs fall at anthesis.

The corolla is big, purple to white, two-lipped with two lobes on the upper lip, and three elongated lobes on the lower lip. The campanulate corolla tube is usually curved forward 5 mm from the base, after which it enlarges gradually or abruptly. Near the limbs, the upper lip presses downwards and makes the corolla flat. Inside the corolla, there are often purple spots or stripes and yellow wrinkles (Figs. 6–19).

The stamens are didynamous, about half as long as the corolla.

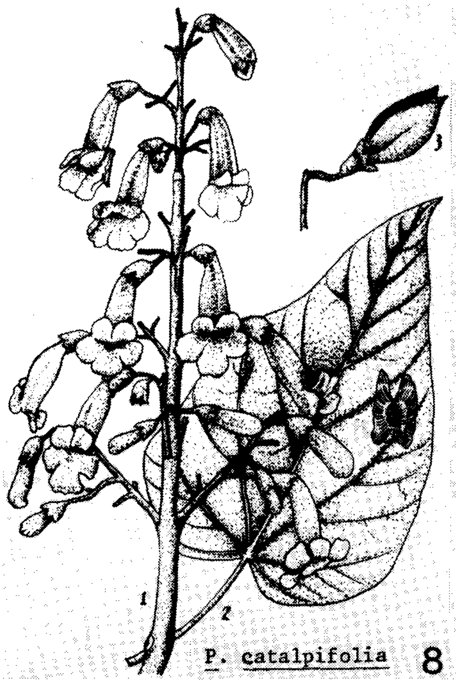
The pistil is about as long or longer than the stamens. The ovary is bilocular. The fruits are loculicidal capsules, ovoid, ovate or ellipsoid in shape (Fig. 19).

Figs. 2–5. 2. *P. fortunei* in De Jiang County, Kweichow Province, 80-year old, 202 cm breast diameter, 49.5 m tall, 34 m^3 in timber volume. 3. *P. fortunei* in Yan He County, Kweichow Province, 90-year old, 224 cm breast diameter, 44 m^3 in timber volume. 4. *P. elongata* in Min Chuan County, Henan Province, 13-year old, 73 cm breast diameter, 17.5 m tall, 2.5 m^3 in timber volume. 5. *P. fortunei* in Gei Lin Municipality, Kwangsi Chuang Autonomous Region, 11-year old, 75.1 cm breast diameter, 22 m tall, 3.69 m^3 in timber volume.



P. fortunei 6

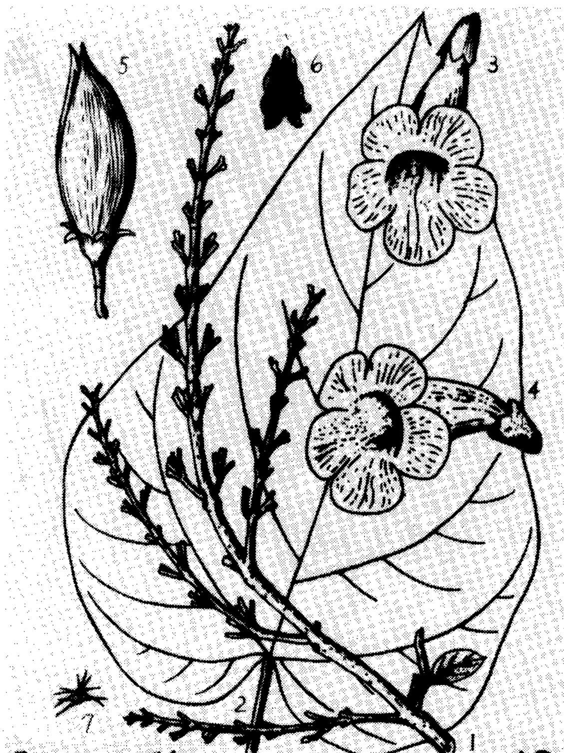
P. albiphloea 7



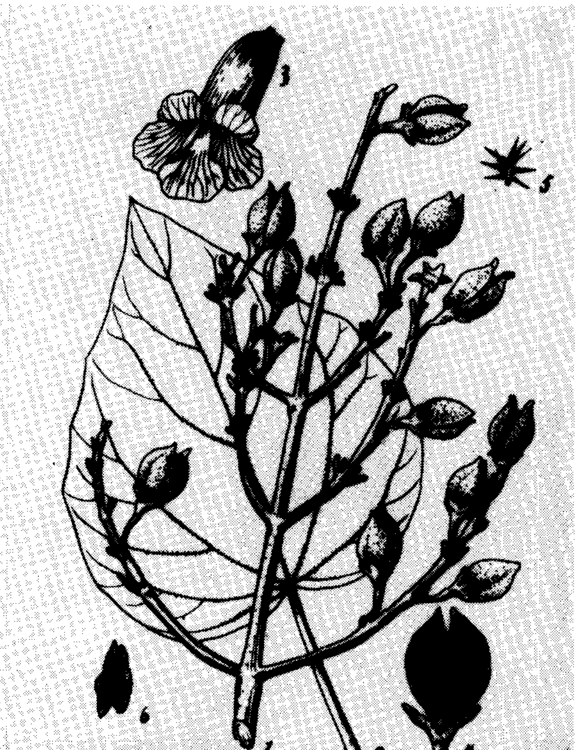
P. catalpifolia 8

P. elongata 9

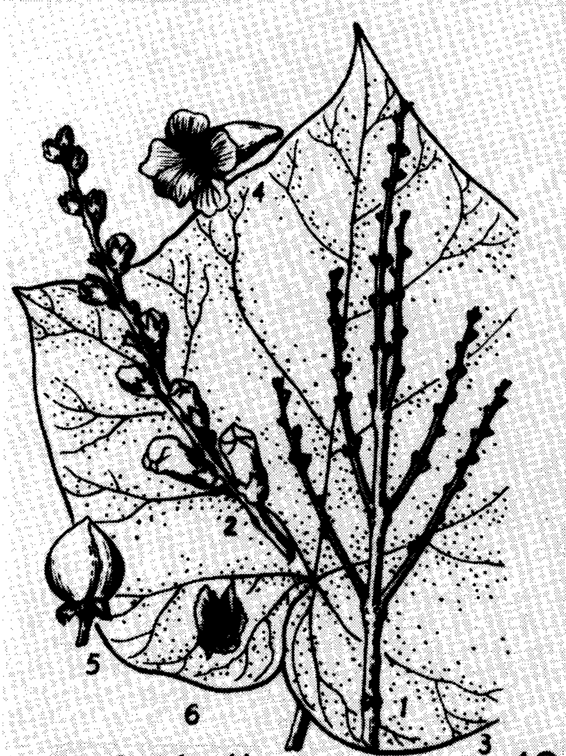
Figs. 6–19. 6. *P. fortunei.* (1) Fruit branch; (2) Leaf; (3, 4) Top and side view of the flower; (5) Fruit; (6) Pericarp; (7) Seed; (8) Hairs. 7. *P. albiphloea.* (1) Flowering branch; (2–3) The front and back of leaf; (4) Flower; (5) Flower buds; (6) Fruit; (7) Seed (enlarged). 8. *P. catalpifolia.* (1) Flowering branch; (2) The front of leaf; (3) Fruit; (4) Seed. 9. *P. elongata.* (1) Flowering branch; (2) The front of leaf; (3) Fruit; (4) Seed (enlarged). 10. *P. australis.* (1) Flowering branch; (2) Leaf; (3, 4) Two views of the flower; (5) Fruit; (6) Seed; (7) Hairs. 11. *P. fargesii.* (1) Fruiting branch; (2) Leaf; (3) Flower; (4) Pericarp (vertical section); (5) Hairs; (6) Seed. 12. *P. kawakamii.* (1) Flowering branch; (2) A part of inflorescence; (3) Leaf; (4) Corolla; (5) Fruit; (6) Seed. 13. *P. tomentosa.* (1) Part of inflorescence; (2) Leaf; (3) Fruit; (4) Hairs. 14. *P. taiwaniana.* (1) Flowering branch; (2, 3) The front and back of the leaf; (4) Fruit; (5) Seed (enlarged); (6) Whole flower; (7) Part of the flower showing anthers and style. 15–18. Inflorescences of 15. *P. tomentosa;* 16. *P. elongata;* 17. *P. kawakamii;* and 18. *P. fortunei* respectively. 19. A comparison of the main morphological characteristics of various *Paulownia* species.



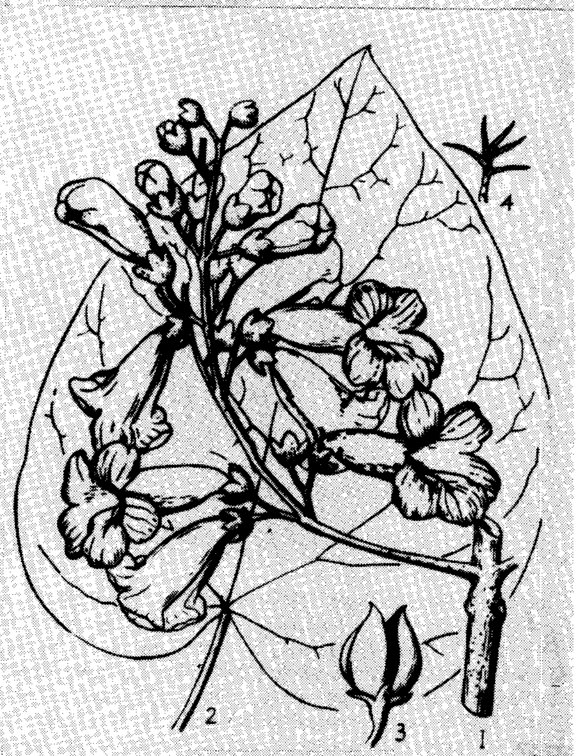
P. australis 10



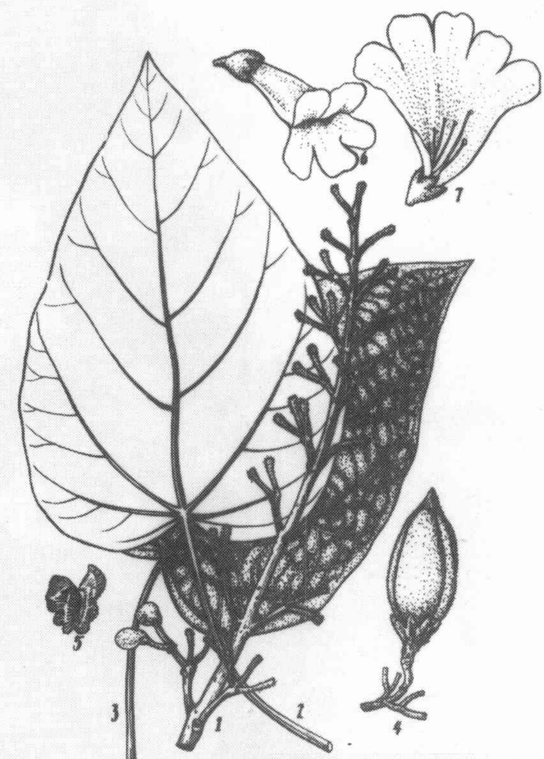
P. fargesii 11



P. kawakamii 12

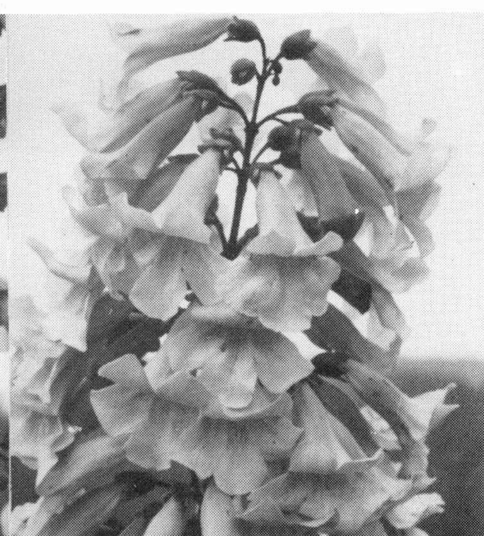


P. tomentosa 13

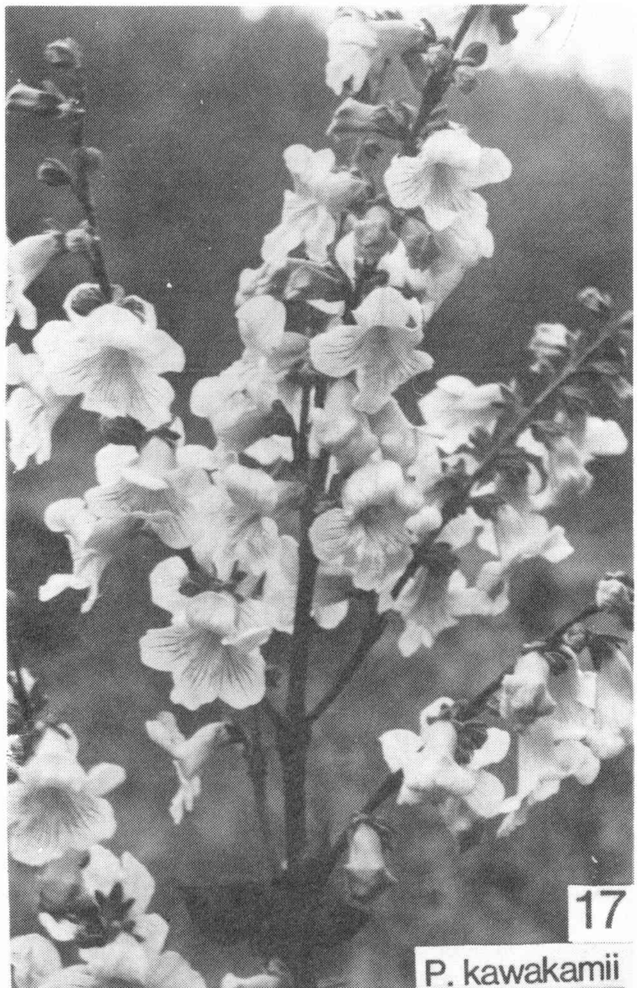


P. taiwaniana 14

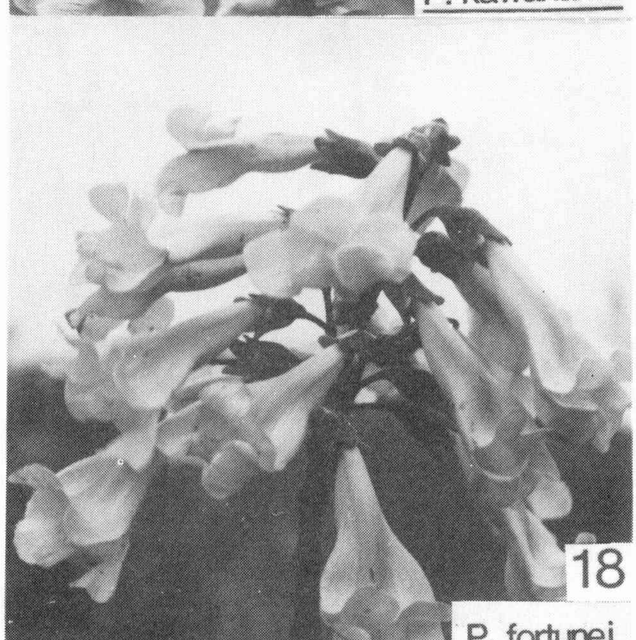
15
P. tomentosa



16
P. elongata

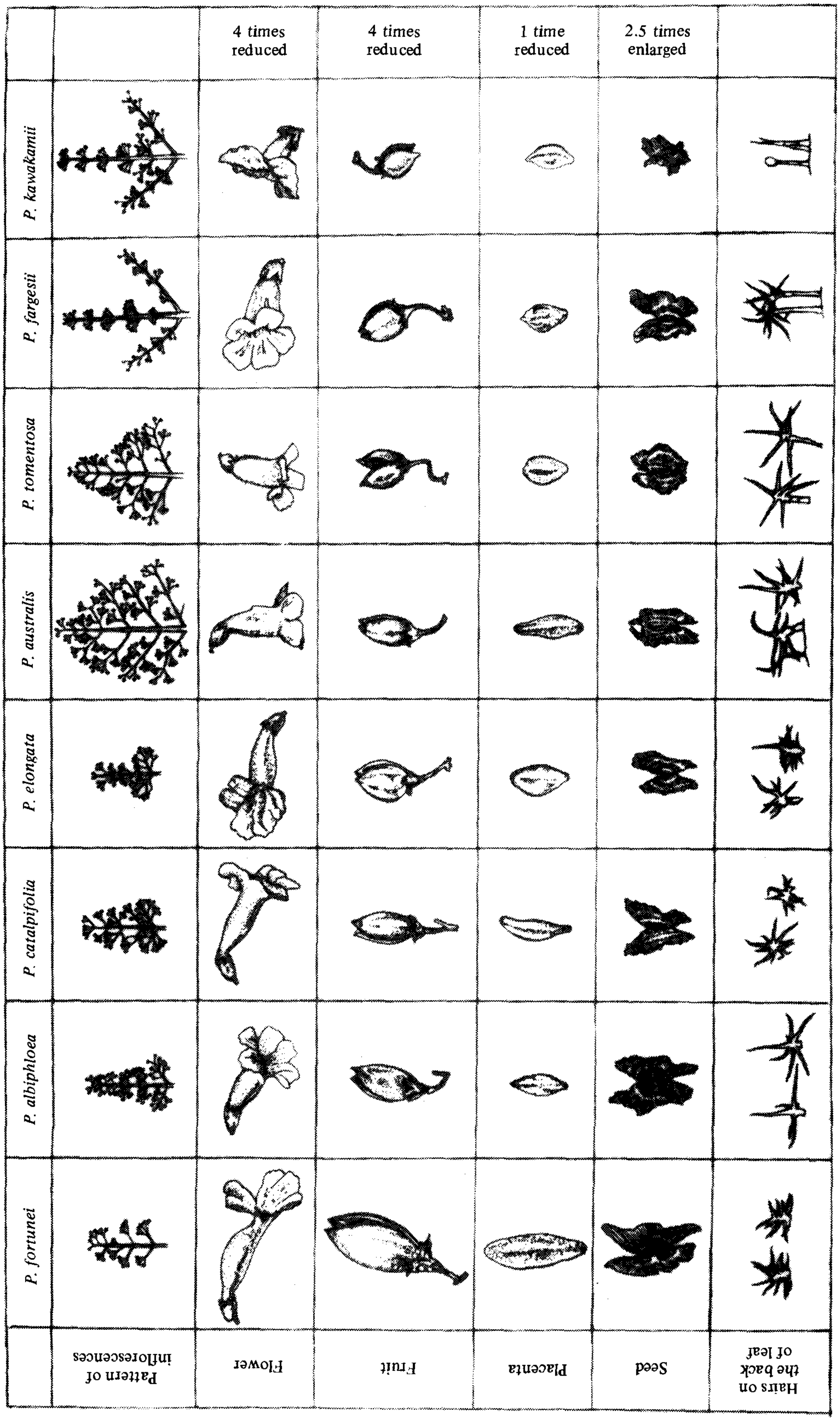


17
P. kawakamii



18
P. fortunei

19


4 times reduced
4 times reduced
1 time reduced
2.5 times enlarged
P. kawakamii
P. fargesii
P. tomentosa
P. australis
P. elongata
P. catalpifolia
P. albiphloea
P. fortunei
Pattern of inflorescences
Flower
Fruit
Placenta
Seed
Hairs on the back of leaf

The pericarp varies from thin to thick, sometimes woody. The inner surface of the pericarp is either smooth or rough. The placentae are fleshy, rugose and variable in shape. The numerous seeds are ellipsoid, very small, membranaceous and with striate wings (Fig. 19). The seed coat consists of two layers of cells, an inner layer of thick-walled lignified cells and an outer transparent layer which is expanded into wing-like outgrowths (Fig. 19). The seed is endospermous.

(ii) Taxonomic characters

In this genus, the length of the cymes, with or without peduncles, the depth of the calyx lobe, the shape of the corolla and capsule, the thickness of the pericarp and the shape of placenta are comparatively stable characters and can be used as the principal basis for classification of species (Figs. 6–19). The size of the fruit and corolla, the shape and size of the paniculate inflorescence and the shape of the mature leaves on large trees are also somewhat comparatively stable characteristics but they should be used with caution. The type of hair cover on the leaf blade and sepal varies with the species and is valuable in classification but the type of hair cover on the leaf blade varies with the age of the tree (Fig. 19). Therefore special care should be taken while using this character. The type of hair cover on seedling leaves, young leaves and mature leaves on large trees on the upper or lower leaves or the branch vary greatly. But the type of hair cover on the mature leaves at the central upper position of twigs on large trees is mostly stable (Fig. 19). The size of the leaves, the density of hair cover and the colour of the flowers do vary greatly, therefore, they are used as the principal characteristics for species classification and identification (Figs. 6–15).

3. Key to the *Paulownia* species

The following key is presented which is helpful for species identification.

1. Cymes peduncled, the peduncles as long as or longer than the pedicels, growing on the main axis and branches of the paniculate inflorescence.

   2. Calyx deeply lobed, the lobes as long as or longer than the tube — *P. tomentosa* (Figs. 13, 15)

   2. Calyx shallowly lobed, the lobes shorter than the tube

      3. Capsules oblong, 6–11 cm long,

         4. Corolla 8–10 cm long; inflorescence cylindric-ovoid — *P. fortunei* (Figs. 6, 18)

         4. Corolla 6–7 cm long; inflorescence pyramidal — *P. taiwaniana* (Fig. 14)

      3. Capsule ellipsoid, ovoid or subglobose, usually less than 6 cm long,

         5. Cymes with longer peduncles, usually as long as the pedicels or nearly so; corolla 7.5–9 cm long,

            6. Capsules broadly ovoid, central-lower portion the broadest, the width more than half of the length; leaves usually ovate-cordate — *P. elongata* (Figs. 9, 16)

            6. Capsules cylindric-ellipsoid, central portion the broadest, the width less than half of the length

               7. Hairs covering capsules and their stalks persistent; leaves ovate-cordate — *P. albiphloea* (Fig. 7)

7. Hairs covering capsules and their stalks deciduous; leaves lanceolate to ovate-cordate

P. catalpifolia (Fig. 8)

5. Cymes with short peduncles (less than 6 mm long); corolla 6–7 cm long

P. tomentosa (Figs. 13, 15)

1. Cymes sessile or nearly so, directly growing on the main axis or branches of the inflorescence,

8. Calyx shallowly lobed, the lobes shorter than the tube; capsules oblong-ellipsoid; pericarp thick (1.2–2 mm in thickness)

P. australis (Fig. 10)

8. Calyx deeply lobed, the lobes longer than the tube; capsules ovoid; pericarp thin (less than 1 mm)

9. Leaves covered with unbranched hairs, some glandulate; calyx-lobes usually reflexed; corolla small (3.5–5 cm long)

P. kawakamii (Figs. 12, 17)

9. Leaves covered with branched hairs, not glandulate; calyx-lobes straight, not reflexed; corolla larger (5.5–7 cm long)

P. fargesii (Fig. 11)

The ability to distinguish different species even in their seedling stage is very important both for cultivation and further scientific research. However, the morphology of *Paulownia* seedlings changes rapidly since they are fast growing.

Different provenances of the same species vary in morphology. *Paulownia* is an entomophilous, cross-pollinated plant. It is easy to obtain interspecific hybrids resulting in viable seedlings of diverse morphology. Despite this wide morphological variability it is still possible to recognise and key them to particular species.

4. Distribution

Paulownia has a very wide range of distribution in China. Its northern limit is approximately at southern Liaoning, Beijing, Taiyuan, Yianan and the Pinglian area (Fig. 20). It extends into Kwangtung and Kwangsi in the south, into Taiwan in the east, and into eastern Gansu, Szechuan and most areas of Yunnan in the southwest. In southern China and on the mountains in the southwest, *Paulownia* can be found up to and around 2,400 m in altitude, both on hills and in valleys. In western Honan it reaches up to 1900 m. The distribution ranges of most species overlap in the middle and dowstream valleys of the Yangtze River (Fig. 20). For instance, *P. fortunei, P. australis, P. elongata, P. tomentosa, P. kawakamii, P. fargesii* and *P. albiphloea* are found in the western Hupeh Province and the three-gorge areas of eastern Szechuan. Only *P. catalpifolia* and *P. taiwaniana* have not yet been found in this area. It is very likely that this area is the centre of origin for this genus because many intermediate types (or natural hybrids) exist there which are intermediate forms and some-what difficult to identify. They grow in association with *Metasequoia glyptostroboides* (Hu et Cheng), a plant with a long lineage and survived the glacial (Quarternary) period. Therefore, it is inferred that this area might also be the remnant centre of the genus *Paulownia* from which the species spread in different directions.

It should also be pointed out that this might not be the only centre of variation. Some species can produce a series of variations during the process of range expansion because of adaptation to the complex site and environmental conditions. Thus, they form secondary centre of origin for some species. For instance, in Sheng Long Jia mountainous region, Hupeh Province, the variation of *Paulownia tomentosa* is quite complex. This might be considered as another centre for this species. Similar situations exist in other mountain areas. The general tendency is, however, that the variation decreases with distance from the distribution centre of the genus *Paulownia*, namely, the middle and downstream valley areas of the Yangtze River (Fig. 20).

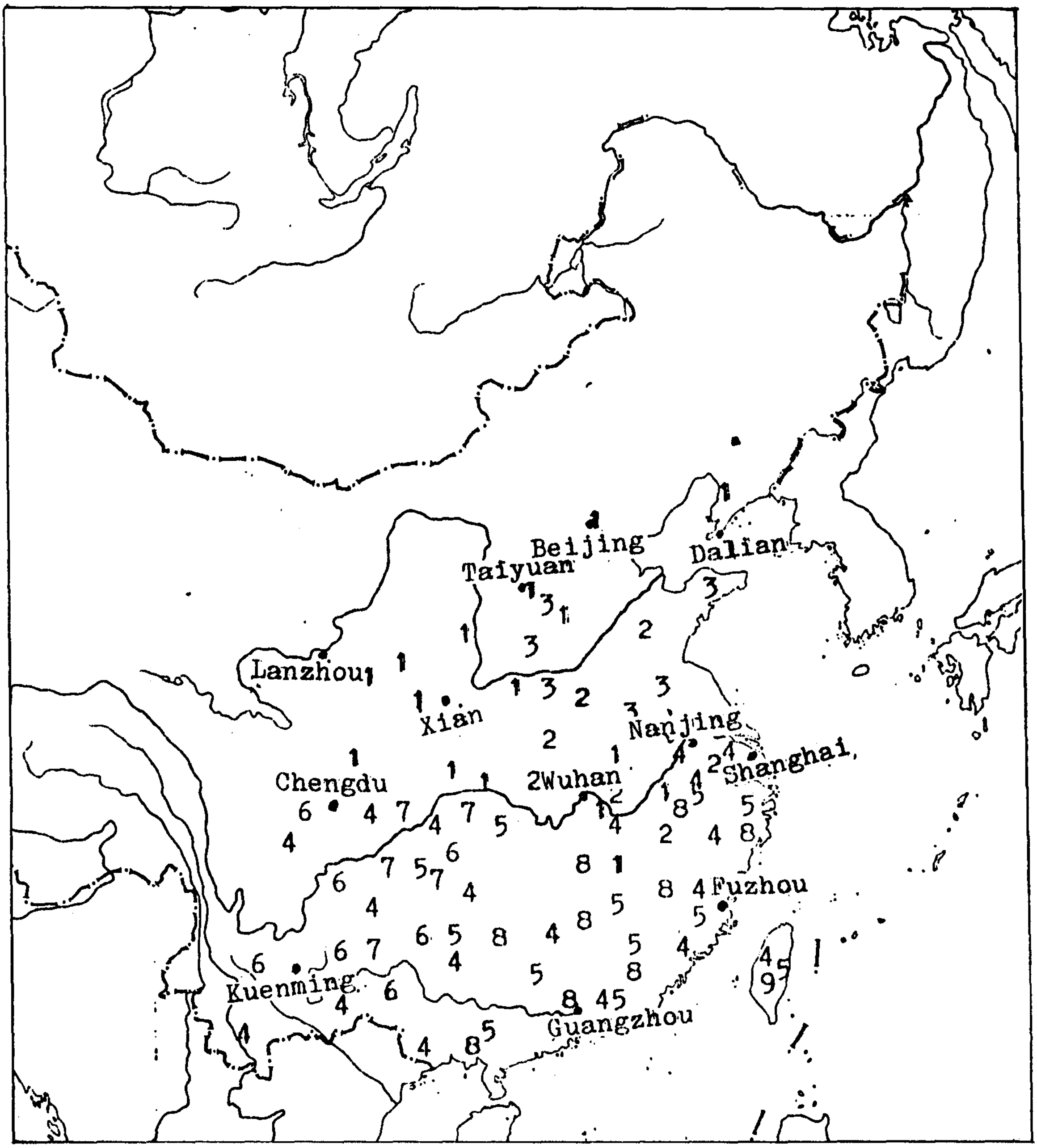


Fig. 20. Distribution of various *Paulownia* species. (1) *P. tomentosa;* (2) *P. elongata;* (3) *P. catalpifolia;* (4) *P. fortunei;* (5) *P. kawakamii;* (6) *P. fargesii;* (7) *P. albiphloea;* (8) *P. australis;* (9) *P. taiwaniana.*

Some of the morphological variations of the genus *Paulownia* are quite interesting. For example, the inflorescence development may prolong for almost one year. The development begins in late summer lasts through autumn, usually overwinters and finally blossoms in the following spring. The juvenile leaves both on seedlings and immature branchlets are large and occasionally exceed 1 m in length. At times *Paulownia* is evergreen in subtropical and tropical areas or in the greenhouse. In May 1976, it was recorded that the *P. tomentosa* introduced into Nanning, Kwangsi Autonomous region, was not completely deciduous during the winter. The distribution ranges of all the *Paulownia* species except *P. catalpifolia* reach the subtropical area to the south of Yangtze River; three species – *P. fortunei, P. kawakamii* and *P. australis* reach or almost reach the tropical zone.

Some species, such as *Paulownia elongata* which is mostly present in the north of the Yangtze River, grows very well, bears more fruits and tends to exceed those growing in Honan Province. Trees in Szechuan Basin from Lankau County, show similar variations. On the basis of the above mentioned characteristics, Zhu Zhao Hua (1980) suggested that *Paulownia* has some characteristics of subtropical and tropical plants species.

III. GROWTH CHARACTERISTICS AND ECOLOGY

1. Fast growth

Fast growth is an outstanding characteristic of *Paulownia* species. Under good management useful timber trees can be obtained in five to six years. As the Chinese say, "It looks like a pole in one year, an umbrella in three years and can be sawn into boards in five years". The dimensions of better grown *Paulownia* individuals in various places are shown in Table 1. In eastern Honan, under normal conditions, the annual average breast diameter increment of *P. elongata* can be 3–4 cm, with a maximum of 8–9 cm in some years with the annual average increment of timber volume of 0.05–0.06 m^3.

Table 1. Details of some better grown *Paulownia* trees.

Paulownia species	Locations	Age of the tree (year)	d.b.h. (cm)	Tree height (m)	Timber volume (m^3)	Lat. N	Long. E
P. elongata	Lan-Kau County, Honan Province	19	104	17.1	4.81	34°51'	115°50'
P. elongata	Minchuan County, Honan Province	13	73	17.5	2.50	34°50'	115°55'
P. fortunei	Yu Yang County, Szechuan Province	75	134.4	44.0	22.48	28°06'	108°54'
P. fortunei	Yeng Jang County, Szechuan Province	31	100.5	21.7	6.65	28°06'	108°55'
P. fortunei	Gui Lin City, Kwangsi Province	11	75.1	22.0	3.69	25°00'	109°50'
P. fortunei	De Jiang County, Kweichow Province	80	202	49.5	34.0	26°13'	108°45'

The following examples illustrate the rapid growth of *Paulownia* in Honan Province.

i. In the spring of 1969 avenue trees were planted from Lankau County, Honan Province to He Tse County of Shantung Province. There were two rows on each side, 4 m apart and 500 trees per km. In October 1977, the average breast diameter and volume were 29.8 cm and 0.362 m^3 respectively. Nearly 92% or about 467 trees survived per km with a total timber volume of 169 m^3.

ii. *Paulownia* was planted in the agricultural fields as an intercrop in Kuong Yang Village, Lankau County, Honan Province, in the spring of 1967. The area was 2.67 hectare and the spacing of trees was 6 x 18 m with 93 trees per hectare. In October 1977, the trees on an average had 50.1 cm dbh, 1.10 m^3 in average standing timber volume, and 102.3 m^3 of total timber volume per hectare.

iii. Plantations were started in Yi Wang village forestry farm, Yu County, in February 1964, with 5 x 5 m in spacing. By 1974, the trees had grown with average dbh of 30.1 cm, 13.5 m height, 0.3927 m^3 individual timber volume with 400 trees per hectare totalling 153.2 m^3/timber volume/hectare.

In southern China, *P. fortunei* grows even faster. For instance, in Yin Jiang County and Yin Yang

County, Szechuan Province, 43 trees of *P. fortunei* on calcareous soil reached an average of 34.2 cm in dbh, 16.6 m height and 0.805 m^3 individual timber volume when they were ten years old.

2. Relative growth rates of different species

The differences in growth rate between four *Paulownia* species under similar site conditions in Wu Gueng County, Shensi Province and Juan Cheng County, Shantung Province are shown in Tables 2 and 3.

Both in the plains and high areas, the fastest growing species order based on Tables 2 and 3 are: *P. elongata, fortunei; catalpifolia;* and *tomentosa. P. tomentosa* var. *tsinlingensis* is the slowest. Both *P. tomentosa* and *P. catalpifolia* grow very fast on the high mountainous regions of north central China. *P. fortunei* grows best near the buildings, around the villages, along the roads and canals. These four different sites are usually referred as planting "on four sides". *P. fortunei* adapts well both at low and high altitudes.

Table 2. Growth of four *Paulownia* species (5-year old) in Wu Gueng (Lat. N 34°26' Long. E 107°42').

Species	d.b.h. (cm)		Height (m)		Timber volume		Percentage disease affected (%)	
	Average	Annual increment	Average	Annual increment	Average (m^3)	Increase (%) Index (*P. glabrata* = 100)	Witches' broom disease	Sunscald
P. elongata	18.0	3.6	11.1	2.2	0.1191	275	10	0
P. tomentosa	15.3	3.0	9.5	1.9	0.0716	165	30	10
P. fortunei	14.7	2.9	9.3	1.9	0.0696	161	0	0
P. glabrata	12.9	2.6	7.9	1.6	0.0433	100	50	40

Table 3. Tree growth of different species of *Paulownia* (10-year old, Juan Cheng).

Species	d.b.h. (cm)		Height (m)		Timber volume	
	Average	Annual Increment	Average	Annual Increment	Average (m^3)	Increase (%) Index (*P. glabrata* = 100)
P. elongata	39.6	4.0	13.2	1.3	0.6232	306
P. catalpifolia	25.0	2.5	11.5	1.2	0.2996	148
P. tomentosa	28.1	2.8	10.2	1.0	0.2426	120
P. glabrata	27.3	2.7	9.9	1.0	0.2020	100

Under the same growing conditions at the Xiao Pu Forestry Farm, Chang Xing County, Chekiang Province, the trunk of 4-year old *P. fortunei* was 7 m high and 21 cm dbh, while the trunk of *P. kawakamii* was 2 m high and 10 cm dbh. At an altitude of 600 m in En Shi County, Hupeh Province, under the same site conditions, 6-year old *P. fortunei* was 11 m high and 22 cm dbh with a trunk height of 7 m but *P. fargesii* of the same age was 6 m high and 18 cm dbh with a trunk height of only 2.5 cm. However, at altitudes above 800 m, *P. fargesii* grows better; its annual average diameter increment can reach 3–4 cm. In the south, *P. kawakamii* grows more slowly than the other species.

3. Root growth

Paulownia is a deep rooted tree with well developed root system. The upper roots are thin, sharp, dichotomously branched and grow very densely. The absorptive roots are long, usually 1–5 mm in thickness and can extend to more than 60 cm. The root hairs are like cotton fibres. The development and distribution of the root system is greatly influenced by the underground water level, the physical characteristics of the soil and the nutrition available. *Paulownia* is most suited to loose sandy soils with good drainage. Usually there are several strong and large clawshaped lateral roots growing downwards.

In the plain area of eastern Honan, the root system of *P. elongata* usually grows in the upper and lower soil layers, the depth in between varies from 0.8–1.0 m. The roots spread in the upper layer are small and 98% of the absorptive roots are thin, non lignified and occur in a radius of 0–4 m. The roots in the lower layer usually grow one metre deep with a very large root spread. For example, in Yui Xiang village, Suei County, Honan Province, the spread of roots in one tree was 29.5 m by 28.1 m wide, about 2.8 times larger when compared with the crown spread.

Almost 70–85% of the absorptive roots of *P. elongata* are spread in a radius of 40–100 cm (see Table 4). This type of root spread is helpful and provides very suitable conditions for intercropping.

Table 4. Root distribution in *P. elongata* trees of different ages.

Soil depth (cm)	Tree #1 (11-year old)		Tree #2 (12-year old)		Tree #3 (9-year old)	
	Average weight of absorbing roots (g)	% of Total	Average weight of absorbing roots (g)	% of Total	Average weight of absorbing roots (g)	% of Total
0– 20	10.6	2.0	26.1	3.7	0.5	0.1
20– 40	63.1	12.0	130.7	18.6	163.9	8.0
40– 60	287.6	54.4	301.8	43.0	393.7	19.2
60– 80	105.6	20.0	71.2	10.1	497.7	24.3
80–100	50.3	9.5	110.8	15.8	653.7	32.0
100–120	11.1	2.1	3.0	0.4	231.6	11.3
120–140	–	–	9.4	1.3	105.1	5.1
140–160	–	–	0.2	0.1	–	–
160–180	–	–	20.8	3.0	–	–
180–200	–	–	28.1	4.0	–	–
Total	528.3	100	702.1	100	2046.2	100

4. Crown growth

The growth of the crown is an accumulation and continuation of the branches produced every year. The apical as well as the second to third pairs of axillary buds suffer from frost injury during winter. In the following spring, usually the fourth or the fifth axillary buds that are unaffected by frost develop into new branches. The second to third pairs of buds on newly formed branches are damaged again during the following winter and the fourth to sixth pairs of axillary buds sprout and form new lateral branches in the spring. The growth of the crown progresses in this pattern year after year. Therefore, in field surveys tree ages can be calculated from studying the number of branches formed and the crown morphology (Figs. 21–24) (Table 5).

Table 5. Crown growth in *P. elongata*.

Age of the tree	No. of trees measured	Crown size			Increment in size index	% of increment
		East-West length (m)	South-North width (m)	Size Index (L x W)		
1	–	–	–	–	–	–
2	6	1.1	1.1	1.21	–	–
3	10	3.2	2.8	8.96	7.75	640
4	15	4.6	4.3	19.78	10.82	120
5	15	6.0	5.4	32.40	12.62	64
6	15	6.3	6.5	40.95	8.55	26
7	15	7.2	6.8	48.96	8.01	20
8	10	7.9	7.5	59.25	10.29	21
9	7	8.7	7.9	68.73	9.48	16
10	15	8.9	9.3	82.77	14.04	20
11	14	9.9	9.7	96.03	13.26	16
12	5	10.7	9.8	104.86	8.83	9
13	7	10.5	11.1	116.55	11.69	11
Total	134					

The crown of *P. elongata* usually grows around one metre in the year of planting and rapidly expands in the second and third year with around 1.5–2.0 m of height increment. When the trees are 3–4 years old one or more renewal axes shoot up from the lower part of the larger branches extending the trunk, growth and forming a two-storeyed crown which expands slowly in the next two years. The general patterns of branching and the crown growth are shown in Figs. 21–24. The growth is generally sympodial but the quick and fast growth of the lateral give the appearance of monopodial growth (Fig. 24). The branching pattern is distinct even in some of the old trees.

5. Growth of the tree trunk

The pattern of growth varies in different species and the details of *P. elongata* and *P. fortunei,* the two main cultivated species, are described here.

Figs. 21–24. 21. Crown development in *P. elongata,* 4-year old tree. 1, 2, 3, and 4 indicate the development of branches at the end of each year. 22–24. General pattern of branching and crown growth, trunk form in young trees of *Paulownia.* 22. *P. tomentosa;* 23. *P. elongata;* 24. *P. fortueni.*

A. *P. elongata:*

Extension of the sapling trunk takes place by the production of a renewal axis from the larger lateral branches between the second and third year after planting. Further growth of the trunk takes place in every two to four years, producing intermittent height growth. Thus, a 10-year old tree will usually have passed through three to four periods of successive or rhythmic growth involving height increase. Usually the first extension is the longest, reaching 3–4 m, and later extensions are shorter (Table 6). Breast diameter in *P. elongata* propagated from root cuttings reaches maximum increase between four to eight years. After this period, the growth increment declines year by year. This data is based on trees growing in eastern Henan Province (Fig. 21).

Table 6. Elongation of *P. elongata* in the two Honan counties at Lat. N 34°50' and Long. E 115°50'.

Tree No.	Location County	Tree age	d.b.h. (cm)	Tree height (m)	Main stem length (m)	Height Increment (m)						
						1	2	3	4	5	6	7
#1	Sui County	10	42	12.9	2.8	3.8	2.0	0.6	2.0	–	–	–
#2	Sui County	13	57.2	14.2	4.6	3.4	2.6	1.6	–	–	–	–
#9	Minchuan County	16	50	16.6	4.0	3.1	2.4	1.1	2.0	0.8	0.8	0.9
#10	Minchuan County	8	36.2	11.1	2.6	0.5	4.4	0.4	0.6	–	–	–
#11	Minchuan County	19	49.9	16.1	5.8	1.1	3.1	2.1	1.2	0.4	0.6	–
#12	Minchuan County	14	53.9	16.5	2.7	4.2	2.0	1.2	1.2	1.0	0.9	–

Under normal conditions, the maximum rate of increase of timber volume is attained between 8 and 13 years, during which period the annual timber volume increment equals the total increment in the first six years. After 14–15 years, the curves for annual increment in timber volume and average increment decrease. Thereafter the volume increment drops year by year. Therefore, the felling age of vegetatively propagated *P. elongata* trees in Henan Province should ideally be around 15 years. However, under good soil conditions, the period for timber volume increment can last for more than 20 years (Table 7).

The data of 171 trees of *P. elongata* (Shangchou Prefecture, Henan Province) were analysed. The results are expressed in the following regression equations (D = diameter at breast height in cm, V = volume in m^3).

Total trunk timber volume	$\text{Log } V = -3.822 + 2.281 \text{ Log } D$
	$\text{Log } V = -3.943 + 2.257 \text{ Log } D$
First trunk extension	$\text{Log } V = -4.424 + 2.260 \text{ Log } D$
Second trunk extension	$\text{Log } V = -5.050 + 2.164 \text{ Log } D$

By using the above equation the timber volume of trees of various diameter was calculated (Tables 2, 3, 7 and 8). The following generalisations can be made.

a. The timber volume in the trunk is equivalent to 70% of the total wood produced.

b. The timber volume of the first trunk extension is about 23% of the total timber volume.

c. The timber volume of the second trunk extension is only 4% of the total timber volume.

It can be seen from the above that more than 90% of the timber volume of *P. elongata* develops from the basal part of the trunk and the first extension. Therefore, special attention should be paid to the tree during its early part of growth.

Table 7. Growth of individual stand of *P. elongata* in Henan Province.

Age	d.b.h. (cm)	Tree (height (m)	Timber volume of individual tree trunk	Timber volume of tree trunk	Timber volume of the first elongated trunk	Average increment of timber volume	Timber volume increament in successive years	Growth rate of timber volume	Elongated form rate	Form numbers
2	6.0	5.2	0.0209	0.0209	–	0.0105	–	–	–	1.4202
3	10.5	6.5	0.0462	0.0416	0.0033	0.0154	0.0253	121.05	0.390	0.8207
4	17.1	7.5	0.0809	0.0689	0.0073	0.0202	0.0347	75.10	0.444	0.4696
5	20.5	8.4	0.1250	0.1019	0.0135	0.0250	0.0441	54.51	0.486	0.4508
6	23.8	9.2	0.1783	0.1403	0.0223	0.0297	0.0533	42.64	0.520	0.4356
7	26.9	10.0	0.2409	0.1838	0.0340	0.0344	0.0626	35.10	0.459	0.4239
8	30.0	10.7	0.3125	0.2324	0.0490	0.0391	0.0716	29.72	0.574	0.4132
9	33.0	11.4	0.3932	0.2857	0.0677	0.0437	0.0807	25.82	0.609	0.4033
10	35.9	12.0	0.4829	0.3437	0.0904	0.0483	0.0897	22.81	0.616	0.3976
11	38.8	12.6	0.5815	0.4062	0.1174	0.0529	0.0986	20.41	0.633	0.3903
12	41.6	13.2	0.6890	0.4732	0.1490	0.0574	0.1075	18.48	0.650	0.3840
13	44.3	13.7	0.8054	0.5445	0.1855	0.0620	0.1164	16.89	0.665	0.3814
14	47.1	14.2	0.9307	0.6201	0.2273	0.0665	0.1253	15.55	0.679	0.3462
15	49.8	14.8	1.0647	0.6999	0.2746	0.0710	0.1340	14.39	0.692	0.3693
16	52.4	15.3	1.2075	0.7838	0.3278	0.0755	0.1428	13.41	0.702	0.3660
17	55.1	15.7	1.3590	0.8717	0.3870	0.0799	0.1515	12.54	0.715	0.3631
18	57.6	16.2	1.5192	0.9500	0.4527	0.0844	0.1602	11.78	0.726	0.3599
19	60.2	16.7	1.6882	1.0300	0.5149	0.0889	0.1690	11.12	0.736	0.3552
20	62.8	17.1	1.8658	1.1110	0.5842	0.0933	–	10.52	0.745	0.3523

B. ***P. fortunei:***

In *P. fortunei*, one of the two pseudodichotomous branches formed is often stronger than the other. The stronger branch is responsible for the extended growth of the trunk. Thus *P. fortunei* usually has a straight main stem and the height increase is rapid in the first few years, although it declines later, sometimes with minor fluctuations. For instance, with *P. fortunei* (root sprouts) in Kwangsi the height increase of the main stem in the first year is 2.3 m. After the second and subsequent years, the growth is 3.0, 4.0 and 2.0 m, respectively. In the following years the growth declines slowly. The growth rate stabilizes to 0.5–0.6 m in the 15th to 16th years and in trees 30 years old it is further reduced to only 0.1–0.2 m per year.

The increase in timber volume in *P. fortunei* is attained much later than in *P. elongata,* usually during or around the 15th year, when the annual increment of timber volume is equivalent to the total increment of timber volume during the first five years. Both the timber volume and vertical growth increase take place year by year. The 20–25 years old trees were still growing and 43 trees were studied in Peilin Prefecture, Szechuan Province. Even in trees 40–45 years old, the average annual increment was still 0.4–0.3 m^3/year.

From the data obtained from 102 trees of *P. fortunei* from all over China, the regression formula for breast diameter and the timber volume for each tree is determined:

Log V = –3.81606 + 2.355 Log D (r = 0.99). The timber volume of individual tree trunks of various diameters calculated according to this regression formula are shown in Tables 7 and 8.

Table 8. Correlative values of breast diameter (D) and trunk timber volume (V) of *P. fortunei*.

D cm	4	6	8	10	12	14	16	18	20	22
V m^3	0.004	0.010	0.020	0.035	0.053	0.076	0.103	0.138	0.177	0.222
D cm	24	26	28	30	32	34	36	38	40	42
V m^3	0.272	0.322	0.391	0.460	0.537	0.617	0.706	0.802	0.908	1.015
D cm	44	46	48	50	52	54	56	58	60	62
V m^3	1.133	1.258	1.391	1.531	1.679	1.835	2.000	2.172	2.352	2.541
D cm	64	66	68	70	72	74	76	78	80	–
V m^3	2.739	2.944	3.159	3.382	3.622	3.855	4.104	4.363	4.642	–

Comparison of *P. fortunei* and *P. elongata* show that the trunk timber volume of *P. fortunei* is usually 18–36% larger than that of *P. elongata* of the same diameter (Tables 7, 8). From investigations made in various places, the highest increase in timber volume in cultivated *Paulownia* trees is attained much earlier than in wild trees.

Trees raised from seeds grow at a fast rate in the late period than the vegetatively propagated trees, which also show a growth peak of a longer duration.

IV. ECOLOGICAL REQUIREMENTS

1. Temperature

Paulownia can adapt to a wide range of temperatures. The northern limit of species distribution approximately coincides with the mean January isotherm of –5°C (Fig. 25). The absolute lowest temperature is around –20°C. With regard to altitude, most of *P. farbesii* trees are seen around 1,000 m where the lowest temperature is around –10°C. Different *Paulownia* species have different reactions to low temperatures. Several species of *Paulownia* were introduced into Beijing in the spring of 1976. Through the winter of 1976 (lowest temperature –16°C), majority of the *P. tomentosa* saplings were free from frost injury; those of *P. elongata* and *P. catalpifolia* which were on sunny side suffered slight frost injury. The above ground parts of *P. taiwaniana* and *P. kawakamii* suffered serious frost injury and all the trees of *P. fargesii* died. The trees of *P. fortunei* introduced from Guangzhou and Hongzhou (22–30°N) provinces to Beijing died but those from Nanjing (32°N) suffered less serious frost injury. All the seedlings of *P. fargesii* in Beijing probably died because this species is adapted to the cold and moist climate of the high mountains but could not adapt to the very dry and cold winter in north central China (Table 9).

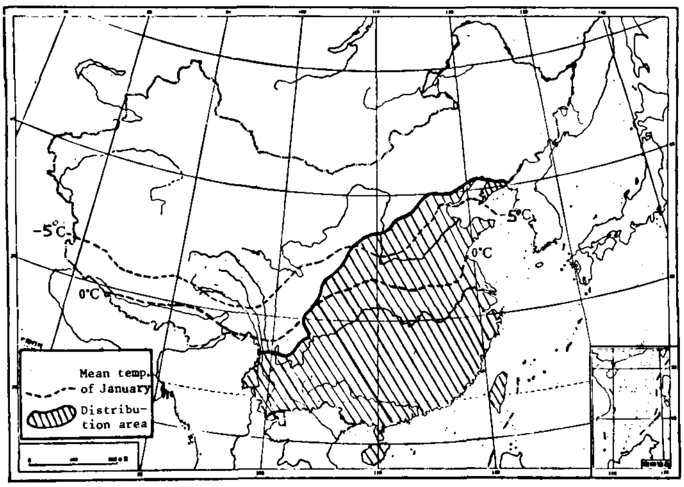


Fig. 25. Distribution area of *Paulownia* and mean temperature in January.

Table 9. Ecology and distribution of *Paulownia* in China.

Species	Distribution			Temperature			Rainfall		Soil	
	LAT	LONG	ALT	Max	Min	Mean	AN mm	Dry months	pH	Texture
P. tomentosa	N28–40	E105–128	1500	40°C	–20°C	17–11°C	1500–500	3–9	5–8.5	light clay-sandy
P. elongata	N28–36	E112–120	1200	40°C	–15°C	17–12°C	1500–600	3–9	5–8.5	heavy loam-sandy
P. catalpifolia	N32–36	E113–120	800	38°C	–15°C	15–12°C	1300–700	4–8	6–8.0	light clay-sandy
P. fortunei	N18–30	E105–122	1100	40°C	–10°C	23–15°C	2500–1200	2–3	4.5–7.5	light clay-sandy
P. taiwaniana	N22–25	E120–122	1000	39°C	2°C	20–23°C	2300–1800	2–3	4.5–7.0	light clay-sandy
P. albiphloea	N28–30	E100–110	600	41°C	– 3°C	18–20°C	900–1400	3–4	4.5–7.5	medium clay-sandy
P. australis	N22–30	E110–122	700	38°C	– 6°C	14–20°C	900–2100	2–3	4.5–7.0	light clay-sandy
P. kawakamii	N22–30	E110–122	800	38°C	– 8°C	14–20°C	1100–2200	2–4	4.5–7.5	medium clay-sandy
P. fargesii	N23–31	E100–110	2000	34°C	–11°C	13–18°C	1200–1900	1–2	4.5–6.5	medium clay-sandy

Different species vary in their cold resistance. *P. tomentosa* is the hardiest species which can withstand temperatures of around –20°C. *P. elongata* and *P. catalpifolia* can withstand –15°C to –18°C. *P. fortunei, P. australis, P. kawakamii* and *P. fargesii* can withstand –5°C to –10°C. *P. albiphloea* can withstand around –5°C. The growth of *Paulownia* commences around a temperature level of +8°C. Thus the good growth of *Paulownia* is closely related to temperature. Experiments conducted in various places showed that the optimum temperatures for diameter and height growth is similar and usually around 24–29°C of mean daily temperature. The longer the optimum temperature lasts, the better the growth. Thus the growth of *Paulownia* tends favourably to respond better under higher temperature regime.

The temperature range at which the various species stop growth varies greatly. In eastern Honan (34°N) new shoots of *P. tomentosa* developed from buried roots. The height increase stopped in the first part of September at an average temperature of around 20°C. *P. elongata* normally stops growing at the beginning of October, at around 18°C and *P. fortunei* during mid October or early November. *P. kawakamii* stops height growth in mid October at around 15°C. Some species introduced into the northern part of China from south do not form good wood and the water content in the stem is high and they are susceptible to frost injury in winter. Sprouts are usually more cold resistant than saplings in their first year of growth, mainly because they stop height growth earlier and wood lignification increases. The time of cessation of diameter growth is very similar in all species and coincides with the time of leaf fall.

Unlike in the other *Paulownia* species, most of the terminal buds of *P. fortunei* are not covered throughout the winter and the younger buds are suceptible to cold. Consequently they die of frost injury and the older buds give rise to pseudo-dichotomous branches. But in the warm south, the terminal buds of *P. fortunei* usually survive and continue to grow. However, in many species of *Paulownia* there are certain adaptations for heat retention. Essential structures in the flower buds are wrapped by thick and succulent calyx lobes. The calyx tissues have a very high starch and sugar content, which also seem to provide good insulation. Besides the calyces of most species are covered by hairs or scales at the bud stage. The young *Paulownia* leaves are also covered by hairs on both sides. The epidermal surface covered by hairs and scales entrap many air spaces which serve as good insulators too limiting the sudden rise and fall in surface temperature of leaves during early spring.

Insufficiently lignified *Paulownia* seedlings and weaker juvenile trees are susceptible to frost injury during winter, especially on the sunny side, even in the low altitude areas in the warmer south. After being injured by cold, skin-rot appears on the injured portions. Woodrotting fungi invade, with deleterious effects on tree growth and wood quality. This injury is not simply the result of the extremely low temperature but is also caused by the great difference between day and night temperatures. In some areas, application of soaked lime on the tree trunk or wrapping the trees with grass bandage have effectively prevented frost injury.

2. Rainfall

Paulownia has a very large leaf area with a high transpiration rate, and has a well developed root system. Therefore, sufficient moisture is very important for *Paulownia* growth. However, the annual precipitation in the extensive areas where *Paulownia* is growing either naturally or cultivated varies greatly, from as low as 500 mm to a maximum of 2,000–3,000 mm as it is in Taiwan. Even in the hilly loess north of the Wei River, where the annual precipitation is below 500 mm, *P. elongata* and *P. tomentosa* grow quite well without artificial irrigation. This is mainly because most of the rainfall is during the warm season of the year which is also the fast growing period when *Paulownia* requires a lot of water. In eastern Honan, *Paulownia* grows fast from June to September, and 65% of the annual rainfall coincides with the growth period of the species. The rainfall distribution is thus helpful to the growth of *Paulownia.* The decreasing order of the species with respect to drought resistance is *P. elongata, P. fortunei, P. Kawakamii, P. catalpifolia, P. australis* and *P. fargesii* (Table 9).

Paulownia is not very sensitive to atmospheric humidity. For instance, in recent years, some species of *Paulownia* have been introduced into Sha Che County, (38°N, 77.3°E), Sinkiang Uighur Autonomous Region, where the annual precipitation is only 41.8 mm, the annual evaporation is 22.3 mm, the average relative humidity is 52%. There are 129 days with dry wind/year. Even in this region both *P. elongata* and

P. tomentosa grow well with some artificial irrigation (Table 9).

3. Light conditions

Paulownia produces distinct branches and leaves sparsely arranged which allow light penetration. Natural pruning is very intensive. A slight shade on one side can distort the shape of the tree or damage it completely. Experiments with saplings show that around 70% shade can be fatal. This shows that *Paulownia* responds well to bright light or light-loving and it is therefore usually unsuitable for mixing with other light-demanding fast growing tree species. It is not advisable to have taller trees of other species around. In Wu Gueng area, Shensi Province, a mixed forest of *P. tomentosa* and *Populus nigra* was raised with a spacing of 3 x 2 m. In six years it was found that the *Paulownia* trees had inferior growth and mortality of 20%.

Paulownia seeds are light, small and winged, and should make natural regeneration easy. However, both germination and seedling growth require intensive light. Therefore, *Paulownia* cannot regenerate naturally within the forest but only on exposed areas like abandoned land, felled and burnt sites where it can be considered as a pioneer species. Under natural conditions both *P. fortunei* and *P. fargesii* grow as scattered trees on the mountains in the south and south-west part of China. Very few dense stands of any large size have been seen. Mostly they grow in a successional pattern rather than as climax vegetation. In natural mixed forest, *Paulownia* is generally equal to or taller than the other tree species. This shows that *Paulownia* satisfies its high light-demanding requirement by fast growth but quickly dies if shaded by other trees.

The light saturation point of *P. elongata* and *P. taiwaniana* is 60,000 lux which is higher than that of ordinary tree species (20,000–30,000 lux), and its light compensation point is 2,000 lux. Different species of *Paulownia* have different light requirements. From field observations, *P. fortunei* and *P. fargesii* have a limited degree of shade tolerance and regenerate naturally in open or scrub forest. At present we lack experimental data on this aspect and more studies are needed.

4. Wind

The winged seeds of *Paulownia* are easily distributed. The wind plays a major role in seed dispersal. It was recorded earlier that the seeds can travel half to 1 km away from the mother tree. The saplings, young trees and even well established isolated trees can be damaged or broken by strong winds. Therefore, it is best to avoid highly exposed areas with strong wind when choosing sites for afforestation.

5. Soil

Paulownia has a very wide natural distribution in China and has been successfully introduced over large areas. It grows well on the rich humus soil in the temperate zone, on the dry poor soil on the north central China Plain, on the rich forest soil in Szechuan Basin in the northern subtropics, on the claye soil in the subtropics, on the laterite in the tropics of southern China, and on the carbonate drab soil of loess parent material on the dry steppe of western China. *P. elongata*, for example, grows well on several types of soil (Table 9).

Paulownia is found mostly on sandy and clayey soil – heavy earth. The clay content of the soil on which the different species are found varies. *P. fortunei* grows on soils with 16.25–23.49% clay while the other species are found on soils with less than 10% clay. Most *Paulownia* species are deep rooted with well developed lateral roots. The extension of the root system requires not only suitable water and temperature conditions, but also deep, loose, moist and well-aerated soil. *Paulownia* requires a total soil porosity above 50%, a non-pore porosity above 10%, soil ventilation above 30% and a mean bulk density of 1.03–1.3 g/cm^{-3}. On excessively clayey soils, *P. fortunei*, *P. tomentosa*, *P. albiphloea* and *P. albiphloea* var. *chengtuensis* do best while growth of *P. elongata* is relatively inferior.

Paulownia is sensitive to the depth of the underground water table and to soil salinity. The water table should generally be below 1.5 m depth and stagnant water for three to four days can prove fatal. Growth is seriously impaired if the total salt content of the soil reaches 1%.

The range and degree of tolerance to soil pH is different in the various species: *P. elongata* and *P. tomentosa* ph 5.0–8.9, *P. fortunei* 5.0–8.0, *P. fargesii, P. albiphloea* and *P. albiphloea* var. *chengtuensis* 5.0–6.0. *P. fortunei* can attain an annual average diameter increment of 3.6–4.2 cm on acid soil yet also grows well on soil with pH 8.0. *P. elongata* and *P. tomentosa* grow well over an even wider range. Comparisons of soil and foliage analyses for trees growing on a variety of soils show that *Paulownia* has the ability to selectively absorb calcium and magnesium from the soil.

Paulownia is tolerant of poor soil and can still attain appreciable diameter increments. However, it grows much better on fertile soils. Fertilizer experiments show that it is best to apply a complete fertilizer of nitrogen, phosphate and potassium when the trees are 8–10 years old. Nitrogen is more effective if it is supplied as a single element.

6. Species selection to suit local conditions

The selection of the correct species suitable for local site and soil conditions is a pre-requisite for fast growth and high yields.

Northern China (warm temperate zone). On the plains and in the loess hilly areas, *P. elongata* should be used as the main species. This species should be planted at places with deep (around 50 cm) loose sandy soil. The total porosity of the soil should exceed 50% with more than 30% air and the water table in the rainy season below 2 m. *P. catalpifolia* is suitable for hilly and near mountainous regions. *P. tomentosa* is suitable for remote mountainous regions at altitudes above 800–1,000 m. In most areas on the northern plains, *P. tomentosa* cannot grow well, therefore, their planting should be restricted. However, in eastern Kansu, the north of the Wei River, Beijing and southern Liaoning, *P. tomentosa* grows well, so it should be planted in these areas.

Southern China (subtropics). *P. fortunei,* which grows fast with a good trunk form and good adaptability, should be planted as the main species. However, as it is a very variable species, the best provenance and type for each area should be selected. It should be planted in loose soil, usually on heavy loam-light clay with more than 50% total porosity and at least 20% ventilation. The site location should be such where the water table should be below 1 m depth in the rainy season and the soil must be deeper than 50 cm. Attention should also be paid to the soil depth and water conditions when afforestation with *P. fortunei* is carried out on mountains. On the middle and upper part of mountains, it should not be planted because of the thin soil layer and poorer water conditions. In the remote mountainous regions at an altitude of 1,000 – 1,800 m, *P. fargesii* should be the main species. *P. kawakamii* should not be grown in great quantity because it has inferior trunk form and grows slowly. However, it can be used as a breeding parent because it has many glandular hairs and is resistant to insect attacks. For this reason, it can be planted in southern China where attacks by insects are serious causing considerable damage.

V. BREEDING

1. GENETIC CHARACTERISTICS

(i) Flower biology

There is a distinct difference in the flowering age among various species of *Paulownia. P. tomentosa* and *P. kawakamii* usually flower in the second year after planting, while *P. fortunei* and *P. catalpifolia* flower in the fifth or sixth year. The flower buds are formed in the summer previous to the year of flowering. Meiosis normally takes place between July and September, and the pollen grains overwinter in uninucleate state. The flowers are entomophilous and bright purple. Flowering lasts about one month in all species, and appears earlier in the south and later in the north, from March and to May. Different species have different flowering periods with considerable overlap. When different species are grown in the same area, the order of flowering is as follows: *P. fortunei, P. taiwaniana, P. australis, P. albiphloea, P. catalpifolia, P. elongata, P. kawakamii* and *P. tomentosa.* The period of flowering in *P. fortunei* comes to an end as *P. kawakamii* and *P. tomentosa* begin to flower.

The stored pollen in viable even after six months at room temperature (15–20°C). It can be kept viable for over one year under low temperature (0°C).

(ii) Crossability

Presently there is no information on the hybridization of different species or between individuals of the same species irrespective of the location and other growth conditions. In general, it has been observed that percentage fruit set is low in the north, but much higher in the south.

(iii) Intraspecific variations and selection

There is clear intraspecific variation in morphological, physiological and ecological characteristics and wood properties. This variation is mainly due to *Paulownia's* wide range of distribution under many ecological conditions, gene exchange, sympatric distribution of different species and overlapping flowering periods. The variation is even more complex in the distribution centre of this genus i.e. in the middle and lower reaches of the Yangtze River. As *Paulownia* is a strongly light-demanding ·ee, it cannot usually regenerate naturally in closed forest. As part of natural vegetation the *Paulownia* trees grew mainly along rivers and open valleys. The isolation of populations in different valleys has contributed to the genetic variability of the genus. Consequently, clear differences exist between different varieties of the same species isolated geographically. In such populations certain trees produce a higher quantity of timber and superior trees can be selected from among them. In an experimental study on *P. fortunei* some of the trees in a community of cultivated plants produced 40% more timber and they can be selected as superior trees and propagated further.

2. BREEDING PROGRAMME

Paulownia is very variable, heterosis can be obtained from the interspecific crosses, and it is very easy to carry out sexual and vegetative propagation. Certain interspecific crosses show obvious heterosis, especially the cross made between *P. tomentosa* and *P. fortunei,* where the progeny often surpasses both parents in height growth and is tolerant to many adverse conditions. Selected clones of some fine hybrids are being grown at present. Therefore, mass selection, individual selection, controlled pollination and other methods should be combined in the selection of fine clones. The breeding programme is outlined in Fig. 26.

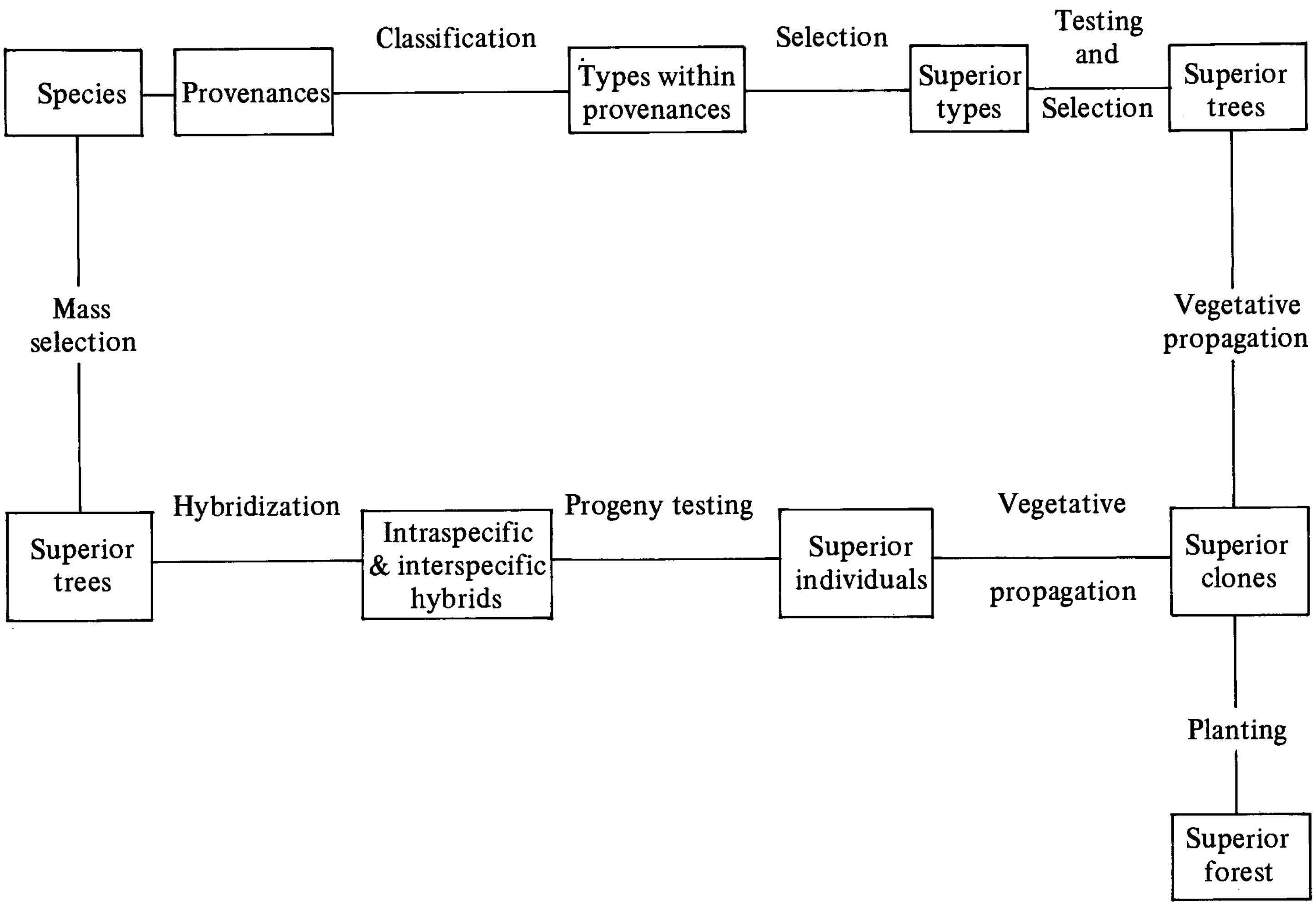


Fig. 26. Schematic diagram showing breeding programme for *Paulownia.*

VI. PROPAGATION

Good selected young trees are suitable for afforestation programmes. The production of high quality *Paulownia* saplings is important in improving the yield and quality of wood. *Paulownia* can be propagated from seeds, roots or stem cuttings. The number of seeds per fruit varies from hundred to several thousands. In quantity and weight one kilogram may contain 4–6 million seeds. A 4 m high, 1-year old *Paulownia* sapling can not only be used directly for afforestation but also as a resource material for vegetative propagation. Each sapling can also produce 25–30 root cuttings. Plants grown on one hectare of nursery land can produce 150,000–200,000 root cuttings. Easy propagation is a major advantage which has helped rapid development of *Paulownia* as a tree crop.

Paulownia seedlings grow fast and can be ready for transplanting within the same year if properly managed. For instance, in Feng Lin Forestry Farm, Gui Lin City, Kwangsi Autonomous Region, plants of *P. fortunei* grown from seeds grew into high quality saplings, 5.6 m in height and around 7 cm in ground diameter, in the first year. The Research Institute of Minchuan County, Honan Province, grew one hectare of saplings of *P. elongata* from root cuttings in 1983, at a density of 12,000 seedlings per hectare. These reached an average height of 5.23 m in the same year; the best of them reached 6.30 m. The peasants in Ciyang County, Szechuan Province, grew some saplings in 1975 from root cuttings which attained 6.03 m in the same year; the best individual seedlings reached 7.56 m. The tallest saplings grown from root cuttings in Suei Ning County, Szechuan Province, reached a height of 8 m and 12 cm in ground diameter in the first year. The best sprouts (2-year old roots, 1-year trunk) in San Shu Forestry Farm in Cichung County, Szechuan Province in 1977 reached 10.38 m in height and 14.0 cm in root collar diameter which created an exceptional record in the history of forest sapling production.

As *Paulownia* has false dichotomous branching, special stress should be laid on the production of saplings with a tall stem. Otherwise, the plants may develop to a short trunk which reduces timber yield and the growth of agricultural crops in intercropping due to close shading. For intercropping with *Paulownia* and for roadsides, the sapling height should be at least 4 m and 6 cm in diameter, except for *P. fortunei* which shows better subsequent natural elongation.

What are the good quality saplings? From experience of *Paulownia* cultivation in various places, the following criteria are considered important for choosing superior saplings.

(1) The height and the ground diameter of the saplings should reach certain measurements and ratio. The height of the saplings in their first year should exceed 4 m. The ratio of the height to diameter of root collar should be 60–70. The above specific values of height and diameter refer to *P. elongata* and can be used as a rough guide for other species. The height to ground diameter ratio for *P. fortunei* is smaller than that for *P. elongata*, around 60 for saplings grown from root cuttings.

(2) The stem should be straight, firm and well lignified.

(3) The root system should be complete and abundant and the diameter of root spread should not be less than 50 cm.

(4) There should be no serious injuries caused by witch's broom, other diseases, insect pests or subject to mechanical damage.

The above-mentioned criteria apply to ordinary conditions. In mountainous regions, where roads are few and transportation is difficult, afforestation programme should be carried out with small plants which should be cut at ground level after one year, to encourage production of a tall, straight sprout.

There are many ways of producing *Paulownia* saplings. These are discussed separately below.

1. Propagation by root cuttings

Paulownia trees are propagated from the root cuttings of 1–2 years old seedlings or from the roots of mature trees. This is a simple method which brings about rapid, uniform growth, a high survival rate, easy to manage and there are other advantages. It is, therefore, widely used as a principal method of propagation.

(i) Nursery and site preparation

The nursery should be on flat terrain (in the south, on unirrigated land, a slight slope is helpful for good drainage), with convenient drainage and suitable irrigation, protected from the wind and exposed to the sun, and with deep, fertile, loose soil with moderate pH, loam or sandy loam with a water table below 1.5 m. In order to reduce the incidence of diseases and insect pests, the nursery should be away from large trees and should not be on the same site of a previous *Paulownia* nursery.

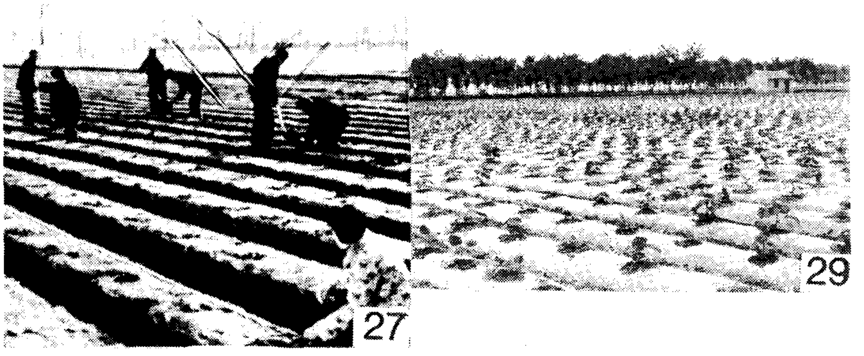
Deep tillage and deep ploughing should be carried out in the nursery by the end of autumn or at the beginning of winter. Deep tillage is very effective in the production of *Paulownia* saplings because the root system requires good aeration. The depth of tillage and ploughing should preferably exceed 40 cm. The soil should be raked and levelled in the spring after it thaws. Organic fertilizer should be applied as a base fertilizer and 6% soluble BHC (benzene hexachloride) should be spread on the soil at a rate of 30 kg per hectare to control underground insect pests. Then, shallow tillage and careful raking to level the ground should be carried out.

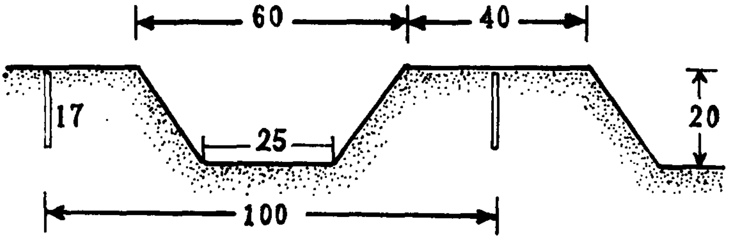
Two types of beds for planting are generally used. One is the flat bed, a comparatively popular bed style, around 20 m long, with low ridges 25–30 cm wide and 10–15 cm high. The second is the high ridged bed, on which flat-topped ridges are normally constructed 1 m apart, 20 cm high, 40 cm across the top and around 75 cm across the bottom. The root cuttings are buried in the middle of the top surface of the bed (Figs. 27–29). The advantages of this kind of bed are the thickened soil layers and concentrated fertilizer. It can raise the ground temperature in early spring and promote early rooting and early emergence of the shoot. Under the same conditions, the plantlets on the high ridged bed can be 7.3% taller than those on the flat bed and their ground diameter can be 21.5% larger. However, the disadvantages of the high ridged bed are the risk of high alkalinity in the early stage and the inconvenience of hilling up in middle stage, as well as the occurrence of serious wind erosion and water stress. Therefore, it is not advisable to follow this method in places where there is no proper irrigation facilities or the soil is alkaline.

(ii) Preparation of root cuttings

The propagation by roots is an important method in the production of high-quality saplings and therefore it should receive sufficient attention. Species suitable for local conditions should be selected and the roots of 1– or 2-year old plants should be collected after they are dug out of the nursery between leaf fall and the start of new growth. After collection, roots of 1–4 cm in diameter are selected and cut into pieces 15–18 cm long. Roots less than 1 cm in diameter or those shorter in length can also be used for propagation when there is a shortage of planting materials. In order to prevent roots from being buried upside-down, their tops should be cut flat and their bottoms slanting. In order to obtain uniform growth and high viability, the properly cut root cuttings should be strictly classified in accordance with their thickness and then air dried for two to three days. It is best to spread them out to dry and not to pile them up before they are transported. In order to avoid freezing, they should not be transported when the air temperature is lower than $-2^{\circ}C$. Roots collected in autumn and winter should be stored if they are not used immediately. The temperature and humidity in the place of storage should be carefully adjusted to keep it humid and to keep the temperature between $0–10^{\circ}C$ so that the roots do not dry up. One week before they are used for planting the temperature should be raised to $12–18^{\circ}C$ in order to accelerate the growth, and the formation of root and bud primordia. They can be taken out when the bark cracks and a few root tips emerge (Table 10).

The propagating roots can be 'healed' when the ground temperature is above $5^{\circ}C$ and the accumulated temperature (the sum of mean daily temperatures minus five degrees) has reached $60–80^{\circ}C$. In order to get a high survival rate and early root growth, accelerated treatment should be carried out in a hot bed before the roots are planted. *Paulownia* roots can be quickly healed in four to five days when the





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Figs. 27–29. 27. Ridged bed preparation to be covered with plastic sheet and planting the seedlings. 28. Cross section of high ridged seedling bed showing depth and width measurements. 29. Beds with *Paulownia* seedlings, covered with plastic sheets.

Table 10. Growth of *P. elongata* plantlets from root cuttings (cm).

Month, date	5.20	5.25	5.30	6.5	6.10	6.15	6.20	6.25	6.30	7.5	7.10
Height	15.32	19.80	25.12	30.68	36.56	40.23	48.60	60.01	75.40	100.28	123.33
Height increase	–	4.48	5.32	5.56	5.88	3.67	8.37	11.41	15.39	24.88	23.05
Diameter at ground level	0.47	–	0.71	–	0.95	–	1.33	–	1.87	–	2.32
Diameter increase	–	–	0.24	–	0.24	–	0.38	–	0.54	–	0.45

Month, date	7.15	7.20	7.25	7.30	8.5	8.10	8.15	8.20	8.25	8.30
Height	151.701	169.65	201.19	243.01	282.40	301.36	334.55	369.80	390.96	393.90
Height increase	28.37	17.95	31.54	41.82	39.39	18.96	33.19	35.25	21.16	2.94
Diameter at ground level	–	3.29	–	4.03	–	4.61	–	4.88	–	5.41
Diameter increase	–	0.97	–	0.74	–	0.58	–	0.27	–	0.53

temperature is around 20°C.

(iii) Sapling production

The root cuttings should generally be planted out in spring when the mean ground temperature is above 4–8°C. The saplings grow fast and require larger growing space. Production of saplings at too high a density can result in a low survival rate when they are used for afforestation and some of them may be broken or damaged by wind. Too low a density results in a small quantity of saplings per unit area. Therefore, close planting must be carried out if we want to obtain high quality and high yield. For this reason it is advisable to grow 10,000 (1 x 1 m) or 12,600 (1 x 8 m) saplings per hectare. No more than 9,000 saplings should be planted if seedlings of 5–6 m in height are to be obtained.

It is best to bury the roots upright so that they can touch deeper soil, which helps absorption of water and nutrients. The big ends of the roots should be upward, to avoid planting them upside-down. The tops of the roots should be 1 cm below the soil surface. After burying, each root should be covered with a small heap of earth, 5–7 cm in diameter, to preserve heat and soil moisture. Later, all the plantings should be covered with plastic sheet to raise the ground temperature and to preserve soil moisture.

(iv) Tending and management of saplings

A proper understanding of the sapling growth is essential for good management. Data on the growth of *P. elongata* (in Suei County, Honan Province) (Table10; Fig. 30) shows that the annual growth process of the plantlets can be approximately divided into three phases: primary, fast growing and mature.

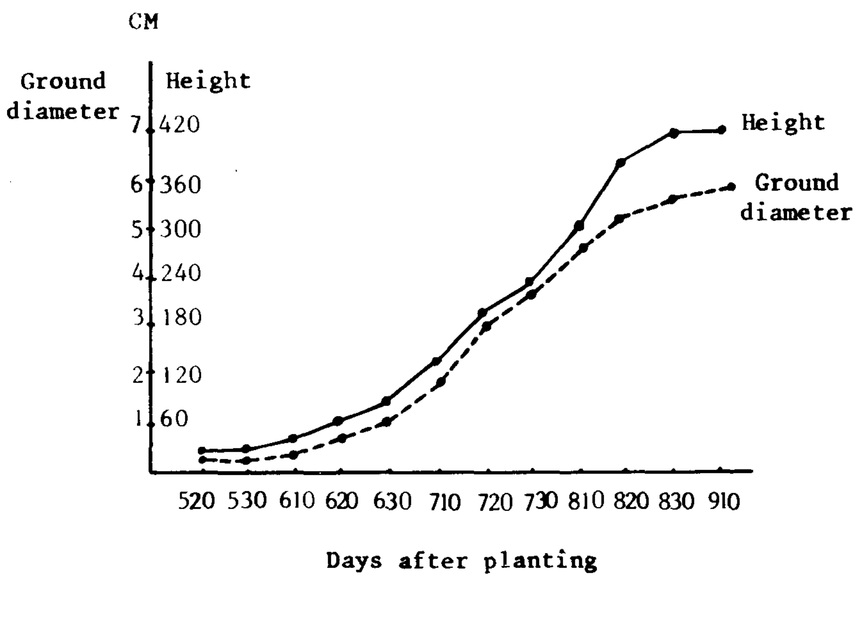


Fig. 30. The growth process of seedling of *P. elongata* from root cuttings; increase in height and diameter. For details, see text. 520 – 5 = month of May, 20 = date in the month.

During the primary phase, i.e. during the first two months from the first appearance of the plantlets the shoot portion grows slowly, while the root system develops relatively fast. At this time, the major management should be loosening of the soil to preserve soil moisture and raise the ground temperature in order to accelerate the development of the root system. In the beginning several buds come up simultaneously from each *Paulownia* root, and some of the weak buds should be cut off and the strong ones retained when the plantlets are around 5 cm high. Additional manuring and watering should commence when the plantlets are 10 cm high. In May–June, when rainfall is less in north-central China, a thin layer of human excreta should be applied once every 10–15 days, with more manure applied to the weak seedlings to get uniform growth and to lay a good foundation for the fast growing period.

The second phase is the fast growing period, i.e. from second to fourth month after planting, which extends from the end of June or the beginning of July until mid or up to August. In this period, the mean temperature is 24°C to 29°C, which is the optimum temperature for the growth of *Paulownia* saplings. The leaf area increases rapidly and the root system is well developed. Both the diameter and height growth reach the maximum values. Around 75–80% of the total height increment for the whole year occurs during these four months which is a key period for the production of high quality plants (Fig. 30).

After the fast growing period, the base of the seedlings should be slightly earthed up to accelerate the growth of new roots on the collar so as to prevent the plants from falling over and becoming crooking. In this period, careful management of water and fertilizer is necessary to achieve the full growth potential. Additional fast-acting fertilizer should be applied three to four times in conjunction with watering. The axillary buds on the trunks of some *Paulownia* species, such as *P. fortunei* and *P. catalpifolia*, sprout in the same year and produce lateral branches and these should be removed.

The third phase starts from the last part of August, i.e. from three and a half to four months after planting. The height increase of the plants rapidly slows as the mean temperature drops below 20°C. Height growth ceases around mid September in the study area. The increase in diameter growth also declines slowly and ceases in mid October. In this period, watering and manuring should be stopped to accelerate lignification and prevent shoot wilting or sunscald after field planting because of vigorous growth of the seedlings in the late period.

In order to promote good growth the following precautions should be taken throughout the period of plantlet growth. (1) Leaves are the major organs of photosynthesis in *Paulownia* plantlets and therefore should not be picked but should be protected until they are shed naturally. (2) Active prevention and control measures should be taken against diseases and pests throughout the period of growth. Anthracnose disease is the most common one besides the damages caused by cutworm and some leaf-eating insects. When witches' broom infection is seen the affected seedlings must be removed immediately. (3) Accumulated water should be drained immediately in the rainy season because stagnant water for more than three or four days could cause high mortality. Saturated soil is also harmful to seedling growth even if the land is not waterlogged, so deep drainage ditches should be dug around the nursery and between the several planting rows in the nursery.

2. Cuttings from saplings

On the stem of the young plants and on branches of large trees root buds develop which sprout and produce adventitious roots. These are important for propagation. The survival rate of branches on these young trees is very low and stems cuttings are often obtained from them. This method is called stem cutting in some areas when compared with root cuttings it is relatively difficult to root *Paulownia* sapling stem cuttings but if successful this method can produce high-quality and strong plantlets. As it is easier to produce plantlets from root cuttings, stem cuttings are seldom used at present but it is to be noted that nodal segments provide good supplementary materials for expanding vegetative propagation. Therefore, shoots are valuable in introduction, selection and propagation of fine clones, especially when there is a shortage of root cuttings.

3. 'Regeneration' of saplings

This method can be applied to 1-year old saplings which are insufficiently developed and they need to be dug out of the nursery beds and replanted. Regenerated saplings can normally reach more than 6 m in height and in Cichung County, Szechuan Province reached up to 10.38 m. The saplings should be cut off with a knife at the base of the stem or the root-collar. The wound should be smooth without splits. This work should be carried out in winter or in early spring when *Paulownia* is dormant; the whole operation should be completed before the growth starts.

As regenerated saplings already have a complete root system with stored nutrients and an efficient absorption system, they sprout and grow fast about one month earlier than the plants from root cuttings. The lignification in them is comparatively high because their vertical growth stops 10–15 days earlier. Their growth rate is similar to that of the saplings from root cuttings, so their management is similar. Since they start growth about a month earlier, the quantity of additional manuring and water should be increased.

4. Propagation by seed

Paulownia seeds are small (1,000 of them weigh only 0.17–0.25 g) and produce shoot and root rapidly. Seedling production from seeds is an important method of *Paulownia* propagation. It has many advantages. The roots are better developed in seedlings than in those propagated by root or stem cuttings. The plants grow stronger, faster and are hardly affected by heartwood-rot.

Experiments show that seeds are normally free of the pathogen and propagation by seed is an effective control measure against the disease. *Paulownia* plants grown from seed can normally reach around 2–3 m high in the same year and can even exceed 4 m if they are well managed. The specific methods of *Paulownia* seedling production are described with some details.

(i) Collection and storage of seeds

The aim should be to select seeds of superior phenotypes, which are adapted to local conditions. Good individual trees which are strong in growth, straight trunked, free of disease and more than 8-year old should be selected as mother trees for seed collection. Seed maturity is very important. The germination rate is low if the seeds are collected too early in the season. The fruits crack and the seeds could disperse if they are collected late. It is usually best to collect them in autumn when the pericarp changes from green to yellowish brown and the tops of individual fruits are slightly opened. The maturation time of the fruits depends on the species and the local climate. *P. elongata* matures in late September to mid October in Honan Province, which is situated in the warm temperate zone. *P. fortunei* matures in late October to the first part of November in the Hongzhou area, Chekiang Province which is situated in the northern subtropics, but in mid November in the Gui Lin area, Kwangsi Autonomous Region, which is situated in the central sub-tropics. After the fruits are picked they should be air dried under the sun for five to seven days. Then they should be put into sacks and stored in a shady, cool, dry and ventilated place. The fruits dehisce and the seeds are released. The seed germination rate normally reaches 70–90% even after one year if the fruits are fully mature and properly preserved. The germination percent of *P. glabra, P. fortunei, P. elongata* and *P. australis* can reach 95%, 94%, 52% and 36% respectively when they have been stored for two and a half to three years indoors under normal conditions at room temperature. Therefore, they can be used for propagation over a long period of time.

(ii) Seed soaking and accelerating germination

Seeds should be soaked before sowing to ensure a rapid and complete start to seedling growth. The method is to wet the seeds first and then soak them in warm water (40°C) for 10 minutes. They are then soaked for 24 hours in water at normal room temperature before surface drying them for one to two hours. When put in a warm place (25–35°C), the seeds coat opens at the micropylar end and reveals the radicle in four days. They can be sown in five to six days.

(iii) Sowing in the field

The time of sowing varies in different places and climates but should normally be as early as possible to avoid frost injury. Early sowing can prolong the time for growth and improve the quality of the seedlings on the one hand and can reduce sunscald on the young shoots and raise the survival rate on the other. The young shoots should be covered by plastic sheet in order to prevent them from being affected by disease, to raise the temperature and improve seedling growth. For convenience of management, sowing in a small area and transplanting the seedlings into larger areas is usually adopted. Around 0.6 g of seeds are used per square metre of land area.

(iv) Growing seedlings in containers

Growing seedlings in containers in a warm bed covered with plastic sheet or in a greenhouse is common because young seedlings are thin and weak, liable to be attacked by pathogens and pests and inconvenient for management. Growing seedlings in containers has the advantage of easy handling, improved growth and freedom to eliminate pests and diseases. Seedlings can be produced 40–60 days earlier in this way than by sowing in the field directly. There is an obvious improvement in both seedling growth and stability.

Transplanting can be carried out when most of the seedlings have got four to five pairs of leaves, and are about 2–4 cm high, and atmospheric temperature and ground temperature are suitable.

The seedlings should not be separated but transplanted in the containers preferably in the afternoons (usually 3–4 pm). The planting holes should be filled with earth up to the tops of the containers and watered. They should be transplanted 50–60 cm apart in rows 1 m apart. Seedlings produced in a bed of around 150 square metres are sufficient in number to transplant into a field of one hectare. Special attention should also be paid to the proper month for transplanting. Early transplanting will restrain the growth of seedlings because of the low ground temperature in the field. It is proper to transplant them when the daily mean air temperature is around 16–18°C and the soil temperature reaches 18°C at a depth of 5–10 cm. The stages of good growth of some of the saplings or plantlets transplanted into the field are shown in Figs. 31–36.

Field management practices for seedlings are basically the same as those for plants grown from root cuttings but special attention should be paid to damping-off and anthracnose diseases which are particularly liable to infect young plants. A large number of shoots die especially after rain when the weather is warm and wet. The prevention of injuries is important to the success of seedling growth. In order to prevent damping-off and anthracnose disease, strong Bordeaux mixture or 0.1% pentachloronitrobenzene should be sprayed once every 10–15 days when the seedlings are at the two leaf stage.

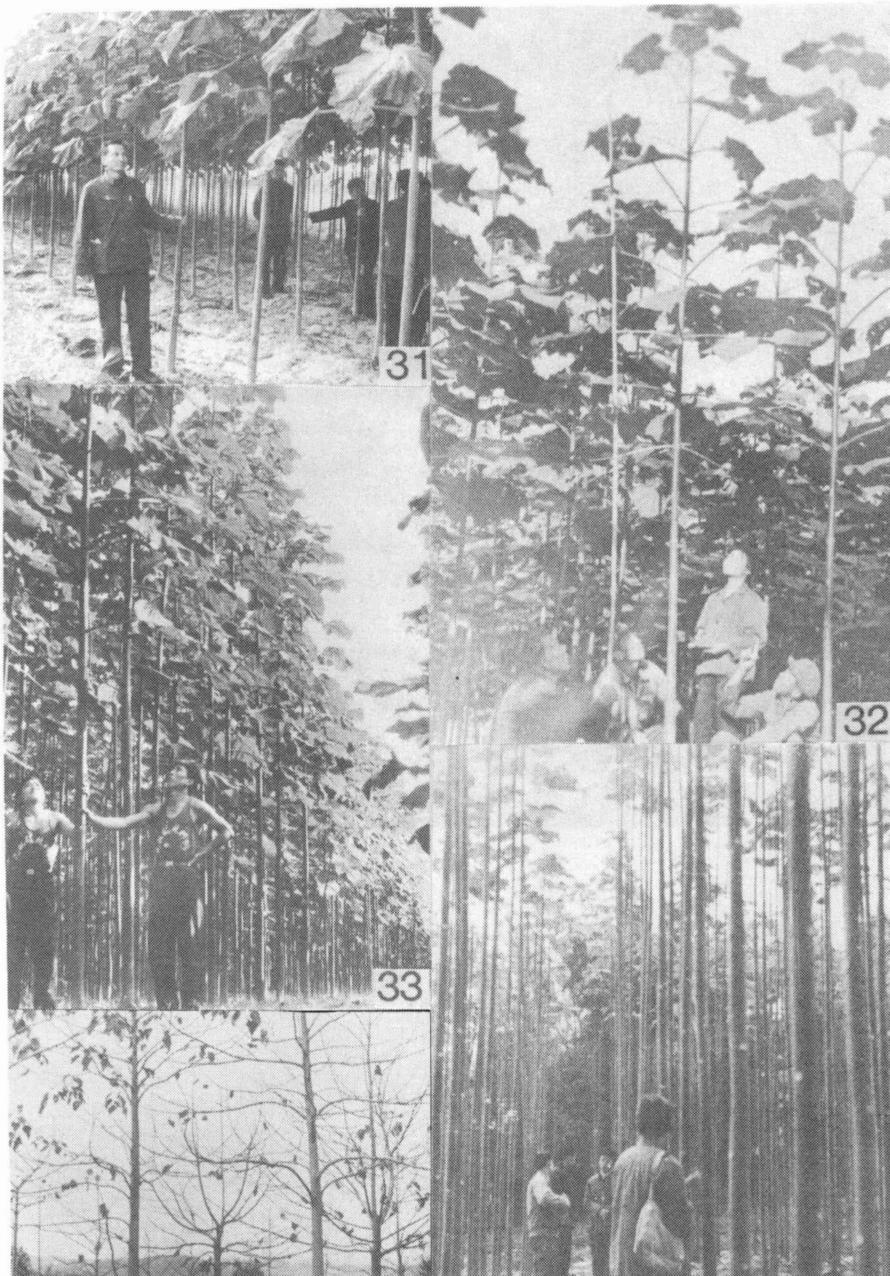
5. Left over roots from seedlings

This method produces saplings for afforestation by using the sprouts from part of the root left in the ground when the seedlings are dug out of the nursery. This method is a simple operation and saves labour costs.

(i) Root isolates – The method of isolating part of the roots and the quality of the roots left in the ground are very important in the propagation by using these leftover roots. One lateral root more than 1.5 cm in diameter is cut from each sapling and left in the soil when the saplings are dug out of the nursery. The thickness of the root and depth of planting the roots below the soil level should be approximately similar between different plantings. They should be planted in lines with uniform spacing and row distance. The rows should be marked for convenience of management and to prevent any possible damage.

(ii) Site preparation and fertilizer application – Site preparation and application of fertilizers should be carried out immediately after the saplings are lifted and part of their roots left in the soil. Surplus *Paulownia* roots should be removed and the tops of the replanted roots should be covered with around 10 cm of soil. If the seedlings are lifted out during winter the soil layer should be thicker to prevent frost injury. Finally, following proper levelling of the land, one ridge should be built up between every two to three rows for watering (Fig. 31).

(iii) Nursery management – Many sprouts appear in the nursery because of some of the roots left there in addition to the reserved roots. Saplings from root segments grow more vigorously and ealier than those from root cuttings. The shoot length can reach more than 5 m average height in the same year if they are well managed.



Figs. 31–36. 31. *Paulownia* saplings – 3-month old. These were planted before wheat harvest from root cuttings. 32. The *Paulownia* saplings from root cuttings. These were planted after wheat harvest in the same year. 33. In Min Chuan County, Honan Province, the sapling developed in the same year. Mean height 5.3 m, the tallest 6.2 m. 34. In Cichueng County, Szechuan Province, the sprouts from the roots of the removed seedlings (2-year old roots, 1-year old stems), mean height 8.26 m, the tallest 10.38 m. 35. A clone of a *P. fortunei* plus tree, 26 cm at dbh and average height of 9.6 m. 36. The plantations of clone PH-1 which was selected from interspecific cross of *P. tomentosa* x *P. fortunei.* 32 cm diameter of BHD in 5-year old trees.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VII. AFFORESTATION AND MANAGEMENT

1. Suitable sites for large scale planting

The selection of large sites suitable for planting different *Paulownia* species according to their ecological characteristics is a key factor which determines the success or failure of afforestation and to achieve fast growth and high yield.

Paulownia is very adaptable except for places with too clayey, dry or poor soil, too strong wind, highly saline or alkaline soil, bad drainage, excessively high water table (less than 1.5 m deep) and extremely low minimum temperature (below –20°C). It can be planted on plains and mountains up to around 2,000 m elevation. However, it is best to plant them in places with fertile, deep, loose sandy loam or loam soil with good drainage and a water table deeper than 1.5 m. As described earlier the different species vary in their silvical growth and ecological characteristics. Therefore, it is essential to choose species best suited to the local site conditions.

2. Sites for small scale planting

(i) Planting 'on four sides'

Planting in different locations is described namely 'four sides' – house side, village side, roadside and water side are the main suitable sites for small scale planting of *Paulownia* (Figs. 37–40). Planting on these sites makes full use of scattered waste-land. In addition, these sites usually have deep and fertile soil and are convenient for management. From experience gained in various places, self-sufficiency in timber can be largely achieved in a very short period (seven to eight years) if each person plants three to four *Paulownia* trees on 'four sides'.

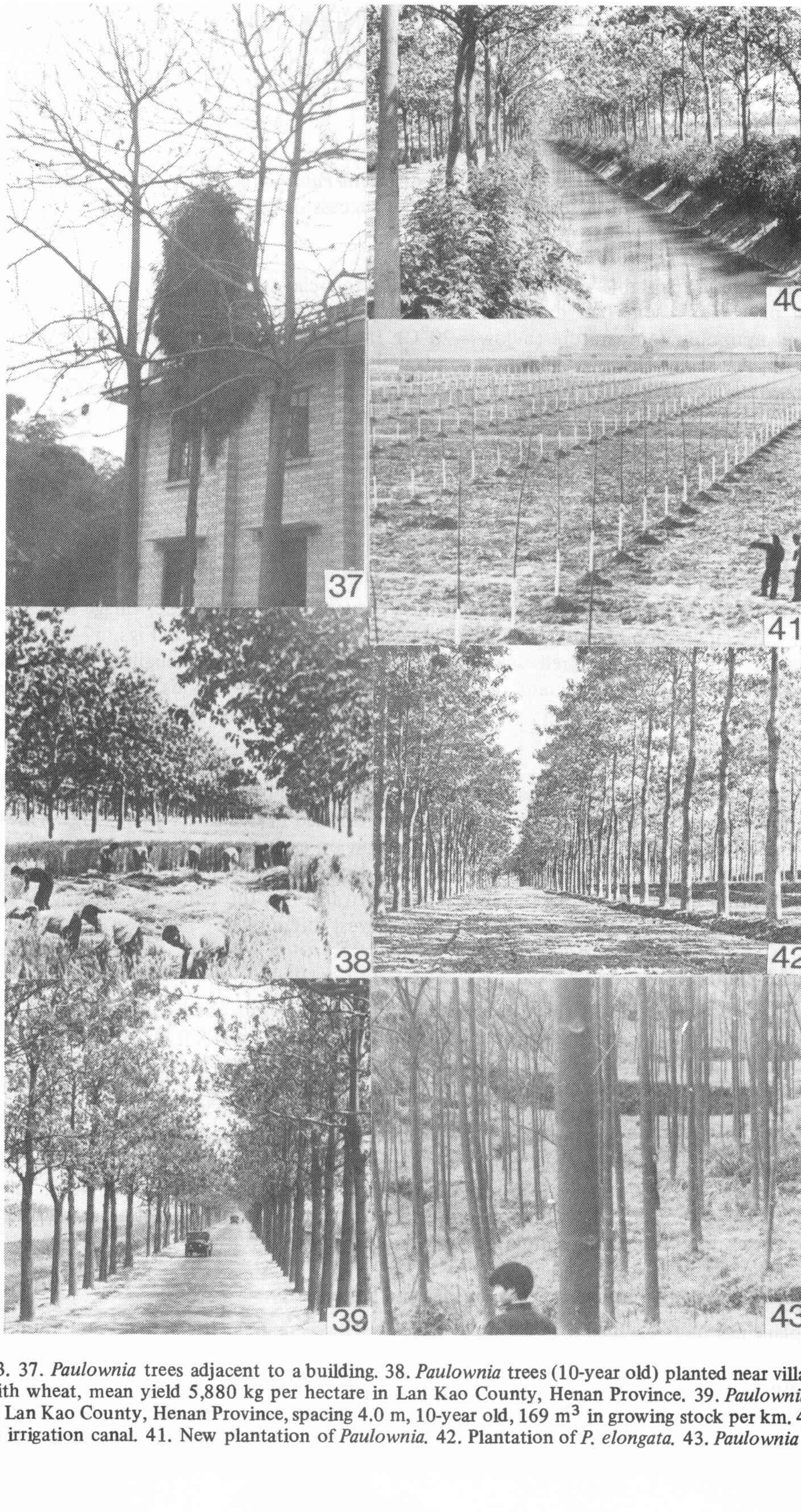
The trees should be planted in strips and plots as appropriate beside villages and houses, with a spacing 5 x 5 m or 5 x 6 m for strip planting, and should be thinned in five to six years (Figs. 41–43). Along roads and waterways, they can be planted in rows, one row on each side, 4–5 m apart. If only planted on one side, they should be on the southern side if the road runs east-west and the east side if the road runs north-south. Planting in this way does not interfere with traffic. In the fields the shading of agricultural crops can also be minimised by planting them in the east-west directions.

(ii) Spacing for planting

Based on experimental results the following spacings are recommended for establishing plantations. Under normal conditions the spacing for the initial planting should be 6 x 6 m, 5 x 5 m or 5 x 4 m, with 278, 400 or 500 trees per hectare respectively. Thinning can be carried out when the trees are 5–6 years old (Figs. 42, 43). Alternate rows are removed to give a final spacing of 6 x 12 m, 5 x 10 m or 5 x 8 m. Overall thinning should be carried out later when they grow larger. The density limit should remain flexible and suited to local situations in mountainous regions. For instance, in southern China, there are large areas of seriously eroded limestone below which there are some remnant patches of alluvial soil from the slopes. No fixed spacing can be recommended for planting in these areas (Fig. 43a). In the plains, where *Paulownia* is intercropped with food crops the density of primary planting should be 5 x 10 m (200 trees per hectare) and thinning should be carried out in six to seven years.

(iii) Mixed forest and combinations of trees, bushes and grasses

Mixed plantings of trees, bushes and grasses can be used to create artificial plant communities according to the ecological characteristics of the various plants used (Fig. 44). This is an effective way of improving afforestation programmes making full use of the available land, raising economic yield per unit area and improving the site conditions. It is also an effective measure of preventing serious outbreaks of diseases and attack by insect pests. As mentioned previously, *Paulownia* is light-demanding which is not suitable for mixing with fast-growing trees such as *Populus tomentosa, Salix, Ulmus, Robinia, Ailanthus*



Figs. 37–43. 37. *Paulownia* trees adjacent to a building. 38. *Paulownia* trees (10-year old) planted near villages for inter-cropping with wheat, mean yield 5,880 kg per hectare in Lan Kao County, Henan Province. 39. *Paulownia* trees beside highway, in Lan Kao County, Henan Province, spacing 4.0 m, 10-year old, 169 m^3 in growing stock per km. 40. *Paulownia* trees beside irrigation canal. 41. New plantation of *Paulownia.* 42. Plantation of *P. elongata.* 43. *Paulownia* plantation in hilly area.

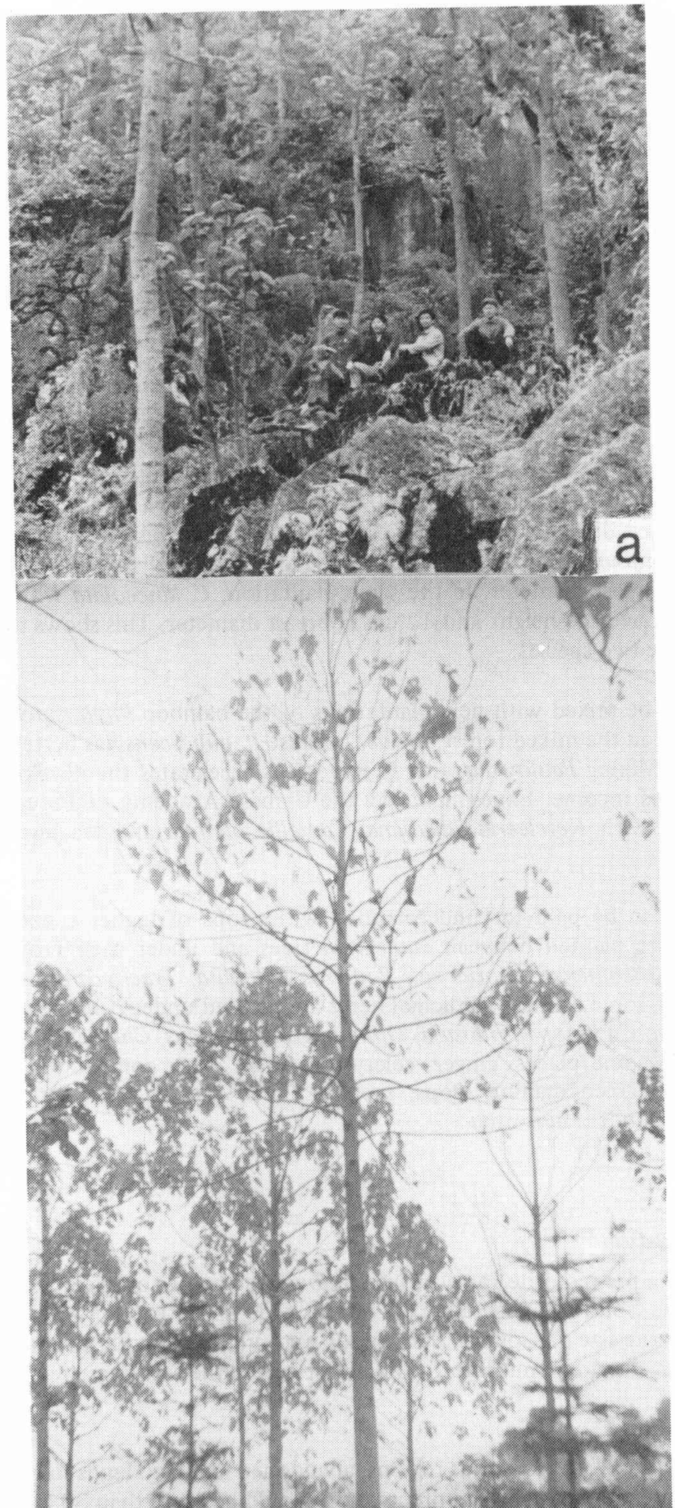


Fig. 43a, b. a. *Paulownia* plantation on uncovered limestone mountain area. b. Juvenile forest of *Cunninghamia lanceolata* under *Paulownia* trees in Chang Xing County, Chekiang Province.

altissima, Melia azaderach, Camptotheca acuminata and *Pterocarya stenoptera.* However, as *Paulownia* is shade intolerant with a sparse crown, good light penetration and a deep root system, the tree is suitable for raising mixed forest and for intercropping with food or other types of crops.

As large areas of pure *Paulownia* forests are liable to be attacked by diseases and insect pests, the density of primary planting should not be too high. Very close planting is not desirable. On the other hand, the sparse planting allows light penetration and encourages the vigorous growth of weeds and bushes and brings difficulties in tending and management. Yet these are the beneficial methods that would create appropriate conditions for the regeneration of other tree species in the forest or for encouraging the growth of mixed forests or intercropping. Therefore, special consideration should be given for the growth of mixed forests or intercropping in *Paulownia* afforestation.

Very little research has been done so far on raising mixed forests. Experiments should be carried out according to the particular soil and climatic conditions at various places. For instance, in southern China, the planting of mixed forests of *Paulownia* with *Cunninghamia lanceolata* can be tried with the latter as the dominant, in plots or strips. In Muchuan County, Szechuan Province mixed forest of *P. fargesii.* with *C. lanceolata* is successful at an elevation of 1,140 m. The 10-year old *C. lanceolata* was 7.46 m in average height, 12.05 cm in breast diameter, and 7–8 years old *Paulownia* was 9.4 m in average height, 18 cm in breast diameter. In this mixed forest, the *C. lanceolata* under the *Paulownia* crowns was 7.33 m in average height and 12.1 cm in breast diameter. In the same plantation, *C. lanceolata* which was not covered by *Paulownia* was 7.6 m in average height and 12 cm in breast diameter. This shows that there is no obvious competition between the two species.

Paulownia can also be mixed with new plantations of the bamboo *Phyllostachys pubescens.* Both of them can grow very well in the mixed forest, mainly because *P. pubescens* has better shade tolerance and a shallower root system. Mixing *Paulownia* with *P. pubescens* accelerates the development of the bamboo forest and thus increases income. Experiments by the Chinese Academy of Forestry showed that intercropping of *Paulownia* with *Keteleeria davidiana, Camellia oleifera* and tea bushes among others was successful (Fig. 43b).

Attention should also be paid for underplanting with crops of higher economic value. At present trees and bushes that are planted between *Paulownia* trees and under their crowns in various parts of China include: *Fraxinus chinensis, Morus* sp., *Poncirus trifoliata, Trachycarpus fortunei* and *Lonicera japonica.* In some places, some Chinese medicinal herbs are planted under *Paulownia,* such as *Paeonia* spp., *Arisaema heterophyllum, Codonopsis pilosula, Ophiopogon japonicus, Chrysanthemum, Mentha piperata, Ligusticum wallichii.* In some places, ginger, celery and some other comparatively shade tolerant vegetables are grown. Some green manure crops, such as *Coriaria sinica, Crotalaria juncea* and *Melilotus suaveola* are also planted under *Paulownia.*

3. Site preparation

(i) Planting hole preparation

Hole preparation is a pre-requisite for planting *Paulownia,* whether on plains, in mountainous regions, or in intercropping. The holes are generally 70–80 cm wide and 50–60 cm deep. Sometimes the hole sizes are determined by the size of saplings. Surface soil and sub-soil should be separated when digging the holes and the surface soil should be put into the hole first before the seedlings are planted.

(ii) Overall site preparation

Flat, uncultivated land in mountainous regions, abandoned land and lands in gullies and on slopes are suitable for overall site preparation. The soil preparation should be more than 30 cm deep and it should be carried out in summer, autumn or winter of the year before planting. In mountainous regions, especially on steeper slopes, attention should be paid to water and soil conservation when overall site preparation is carried out. Therefore, large continuous areas or whole slopes should not be prepared in this way but only small patches or strips parallel with the contours should be worked out first and subsequently extended in stages.

(iii) Preparation of strips and reverse-slope terraced land

Strip preparation is suited to mountain sides with gentle slopes and for places with deep soil. Site Preparation is carried out in strips along contours, the strips being 1–1.3 m wide and more than 50 cm deep. This method is suitable to use the available top soil and to build ridges with the sub-soil. After the ridges are made the crushed top soil should be spread on the positions where the trees are to be planted. On mountains with steeper slopes, reverse-slope terraces, which are high outside and low inside, should be built to improve water and soil conservation. Water run off with soil should be prevented. The original vegetation between terraces should be retained as far as possible.

4. Planting and regeneration from sprouts

(i) Planting

Afforestation programmes can be carried out with saplings grown in a nursery or by direct planting of root cuttings.

a) **Planting of saplings** – This method is extensively used at present, mainly in winter. But in recent years the usual planting period in autumn (around the period when the growth in height ceases and just before leaf fall), is being extended in various places and better results have been obtained. At this time, the air temperature drops rapidly and the growth of the above ground portion is stopped but the ground temperature is still high, so the trees can form callus and grow some new roots before winter. These new roots will be able to absorb water and nutrients from the soil to support growth and greatly shorten the period of adjustment in spring when sap flows. However, this method should not be used in colder areas. Saplings with inferior lignification should not be planted in autumn. Regenerated saplings usually perform better.

   High-quality saplings should be selected for planting and sorted out by height before using. The height requirement of the seedlings should vary according to the site. Tall saplings should not be planted in places with poorer soil and strong wind. The root system should be retained as far as possible when digging up the saplings. Saplings 4–5 m high normally require root length ranging around 40–50 cm. *Paulownia* should be shallowly planted. The depth of planting should be 6–10 cm deeper than the saplings in nursery. After planting, earth should be heaped up around the saplings to a height of 15–20 cm.

b) **Planting of root cuttings** – As discussed earlier, using root cuttings is a suitable good method for afforestation where there are insufficient seedlings. The advantages of root cuttings are 1) that it is unnecessary to grow and transplant saplings; 2) the recovery period can be shortened; and 3) the plants are quick growing and can produce useful timber early. However, they are not easy to manage and the trees may be uneven in size. If the plants from root cuttings are less than 3–4 m in height during the first year, they should be cut off so that they regenerate again. Replanting excess saplings very close by is very effective. The barren hills may be brought under cultivation and some of them may be developed as nurseries. When the saplings are tall enough for planting some are retained in the nursery at the correct spacing and all the rest are transplanted outside (Figs. 31, 32).

(ii) Regeneration from sprouts

Paulownia has very strong coppicing ability. The new shoots from the basal portion of the stumps or from accessory buds on the underground roots retained after felling can be used to regenerate the forest. The regenerated sprouts grow fast in the early period and normally reach 5–6 m in the first year and sometimes can exceed 10 m. This method of regeneration is simple and is widely used by the growers. However, the trees from sprout regeneration decline very early and are susceptible to diseases. Therefore, this method can be used in mountainous regions where seedlings are insufficient and management is extensive but the method should not be practised for many generations.

5. Tending and management

To encourage fast growth and high yield, protection, tending and management of the young forest is important, especially during the first three to four years.

(i) Protection

The bark of the saplings and young trees is very thin. Injuries heal with difficulty and damage timber quality. Therefore, bark injuries caused by various agencies, physical impact and damage by animals should be avoided after planting. Freeze injury and sunscald should be prevented in trees 1–2 years old. Soaked lime should be applied on their trunks in late autumn, early winter or early spring or the trunks should be wrapped with grass in winter. As *Paulownia* trees are tall and have few roots in the first one to two years after planting, strong wind and rainstorms often cause inclined stems which should be straightened out, propped up and mounded up immediately.

(ii) Watering and drainage

Timely and regular watering should be carried out especially in the dry season. Saplings should not be watered twice on the day of planting but should be watered again seven to eight days after planting. Flooding causes most damage. The growth of *Paulownia* is affected and its leaves wilt or drop and the plant dies when it is submerged. Therefore, a well-constructed drainage and water run off system is essential.

(iii) Pruning

After *Paulownia* is planted in the field, according to the size of the saplings, five to six pairs of lateral buds should be retained in the first year. They would develop into new branches with leaves which will rapidly form the crown and promote vigorous growth. Pruning begins in the third or fourth year after planting, according to the growth condition. By this time, trees of *P. elongata,* the most widely grown species, will have produced their first stem extension. In order to create sufficient light and space for the growth of the main trunk, nearby branches and unnecessary lateral branches of the same tree should be removed. If there are several lateral branches which need removing, the large ones should be retained and the small ones removed to prevent heartwood-rot, caused by fungi entering the large wounds. Through pruning and tending, growth conditions for the main axis can be improved and the trunk can extend rapidly. The previously retained branches on the crown should be completely removed in winter or spring within less than two years. Tall and straight trunks take good shape as a result.

(iv) Thinning

The time for thinning *Paulownia* plantations is very closely related to the initial planting density. In a plantation with 5 x 5 m or 6 x 6 m initial spacing as well as in avenue and intercropping forests with 3–5 m spacing, which are already closed, the first thinning should be done five to six years after planting. At this stage the branches grow close to each other, the crowns are crowded and their further growth is inhibited. In an intercropped plantation with 5 x 10 m or 6 x 12 m spacing the first thinning with one row removed and one row retained, should be carried out five to six years after planting.

6. Methods of improving trunk growth

Short saplings tend to give rise to low and crooked trunks. This not only adversely affects the light conditions for agricultural crops but also reduces timber yield and quality. Therefore, artificial methods should be used to convert the low trunks into tall trunks. This is a major problem in the cultivation of *Paulownia.*

As *Paulownia* has pseudo-dichotomous branching, there are terminal buds, axillary buds and accessory buds respectively on the main stem and branches. The terminal buds and the axillary buds on the first to third nodes generally die during winter. During next spring, the axillary buds on the third to fourth nodes develop into a pair of lateral branches growing over the main stem. These branches look like dichotomies so they are called pseudo-dichotomous branches. The growth habit of the stems varies with different *Paulownia* species and the growth forms can be approximately divided into three types.

The first type is the continuous extension type which is found in *P. fortunei, P. albiphloea, P. taiwaniana* and *P. catalpifolia.* Of the pair of lateral branches that develop at the top of the main stem, one is strong and the other weak in its development. The strong one gradually grows upwards in the direction of the main stem while the weak one grows horizontally or obliquely. In species with this type of growth form, a straight main trunk develops. In southern China, the terminal buds of *P. fortunei* sometimes do not die and grow straight upwards. A tall trunk and good-quality timber can be produced if this fine growth performance is utilized and some necessary measures for pruning and tending are taken (Figs. 34, 36).

The second type is the intermittent natural extension type found in *P. elongata, P. fargesii* and *P. australis.* Several vertical renewal axes shoot up from near the base of the lateral branches three to four years after planting. A single, strong renewal axis near the apex of the saplings stem should be selected to extend the growth of the trunk and the others removed. However, natural extension often gives rise to a very thin, pointed end to the upright branch or to the main stem which does not grow in a desirable position. Therefore, some measures for artificial trunk extension should be taken (Fig. 21).

In the third type, natural extension is difficult. This type is found in *P. tomentosa, P. kawakamii* and *P. tomentosa* var. *tsinlingensis.* If renewable axes are produced, they are often in undesirable positions and inferior in growth. Artificial means of trunk extension are usually adapted. There is a need to adjust the pruning and tree management strategy according to the growth characteristics of the various *Paulownia* species in order to produce trees with a good tall trunk. At present, the following four major methods are used.

(i) Shoot regeneration method

On the newly afforested land, the short-trunked saplings grow freely in the first year with the corresponding development of the root systems. During the second year the saplings are cut off at ground level during autumn or early spring (Fig. 44). The new shoot will develop as a tall structure and later into a strong trunk. This method is also applicable for removing inferior seedlings (Fig. 44).

(ii) Removal of top and promotion of a lateral branch

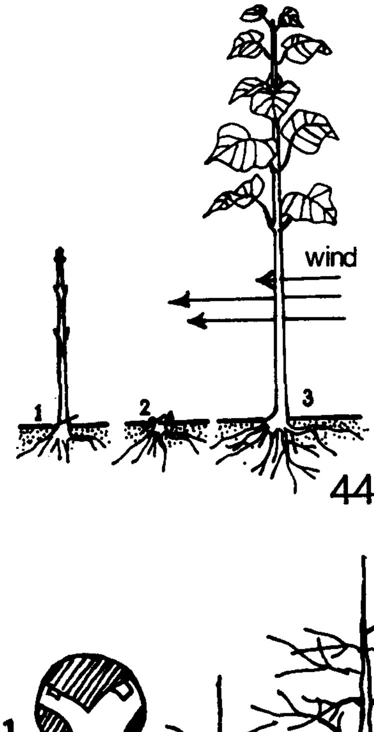
This method is suitable for young trees which are less than 3 m tall in their second or third year after being planted in the field, or have crooked trunks. In spring before sap flow, the whole crown should be cut off directly under the branches (Fig. 45). Alternately, the first pair of branches are removed allowing the main trunk to develop (Fig. 46). The crooked part of the trunk should be cut off at the same time, if necessary. The saw-cut should be within 1 cm above the dormant bud. It should be pared flat with a sharp knife to prevent splitting and the wound should be covered with mud to prevent water evaporation. If several buds sprout simultaneously, only one healthy and strong bud sprouted from the first pair is retained and others removed (Fig. 47). The new stem produced by this method can grow 3–5 m in the same year (Figs. 46, 47), and the wounds are completely covered in two to three years.

Stem extension through bud removal is one of the major methods for producing long stems in *Paulownia.* It is simple to practise and does not affect timber quality. This method is practised during the second year after the seedlings are planted in the field. In some places, this method is used again in the third year after cutting off the original stem in the second year. When the axillary buds develop into lateral branches 3–5 cm long, one of the lateral branches (out of the first three pairs) which is healthy and strong and growing parallel to the main trunk should be selected to form the new trunk extension. The lateral branches that are not wanted should be removed. Any withered terminal part should be cut off and three to four pairs of lateral branches under it should be retained as supporting branches and their tops also cut off when they are 20–30 cm long. The rest of the lateral branches should also be removed (Figs. 45–50). Under good site conditions, this method can heighten the trunk by 1–2 m, sometimes even 4 m, in the same year.

(iii) Crown pruning

Manipulation with the crown starts with 3–4 year old trees having low stems and not suitable branches for trunk extension. In spring, around two weeks before active growth, a dormant bud near the trunk should be selected. A wound perpendicular to the branch is made with a knife at a position 2–3 cm above the bud, about 1 cm wide, and two-thirds of the way through the branch. The crown should be thinned to provide better nutrition for the remaining branches, increase light penetration and accelerate bud development just under the wound (Figs. 49, 50). All these would help the vigorous growth of the branch normally 4–5 m tall. After the trunk extension comes up, most of the branches on the original crown should be removed before or during the winter of the same year or in the following spring. A small number of the branches can be retained until the following winter (Fig. 50). It should not be assumed that taller the trunk better is the extension. Under some poor site conditions or in strong winds, excessively tall trunks are not good. Therefore, the crown extension method should be chosen according to local site conditions, the status of the trees and the level of management.

Occasionally double trunks may sprout from a single stock as shown in Fig. 50a, b. Basal part of the trunk is enlarged in Fig. 50b.



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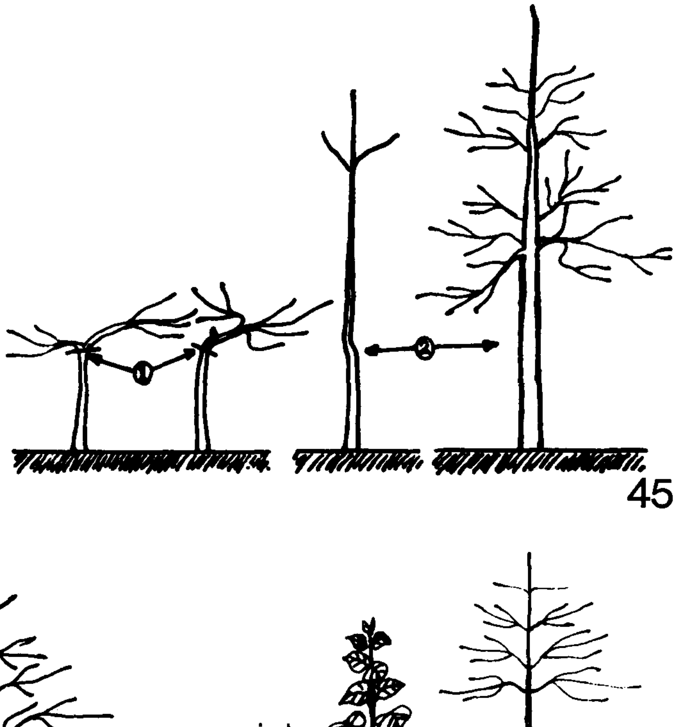

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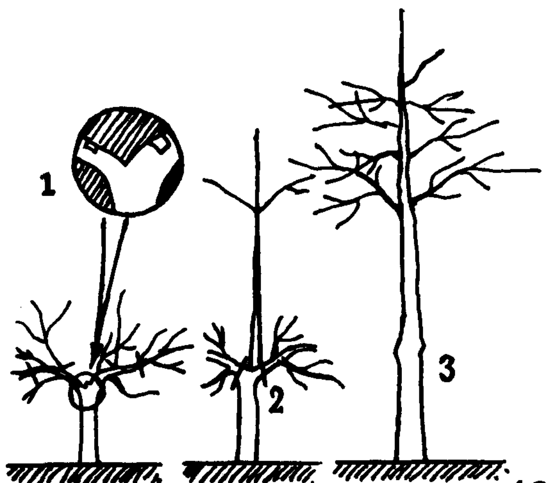

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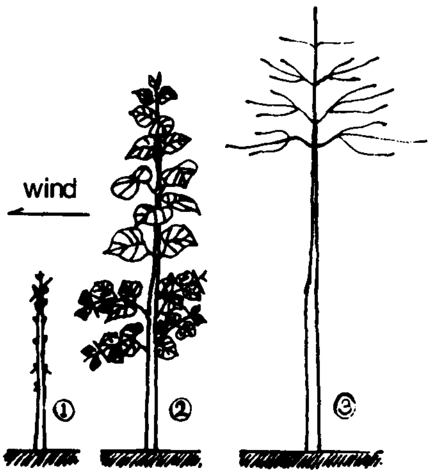

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Figs. 44–50a, b. 44. Method of removing inferior seedlings. (1) Position of cut; (2) New bud development; (3) Elongation. 45. Elongation by cutting off the tops. (1) Position of cutting off the tops; (2) Effect of elongation by cutting off the tops. 46. Method for making cuts. (1) Position of cut; (2) The branches should be pruned year after year after the new trunk grows up; (3) Effect of elongation and branching. 47. Position of cutting buds; (1) Object and position of cutting buds; (2) The growth in the same year after cutting buds; (3) When the upper storeyed crown developed into completion (in three years), the lateral branches in the lower storey should be cut off. 48. Pointing the point of the cut on the tree. 49, 50. Regenerated growth after cutting. a. Double sprout regeneration from a single stock. b. Basal part enlarged.

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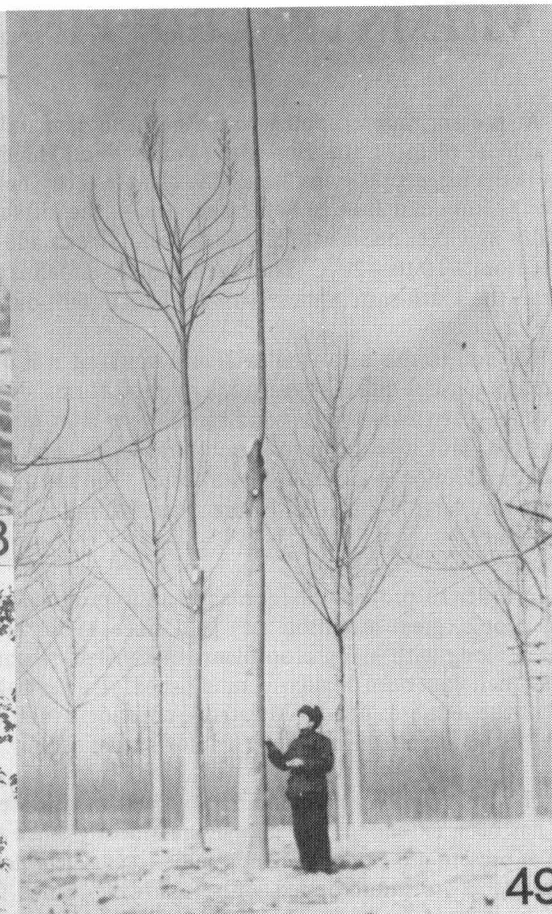

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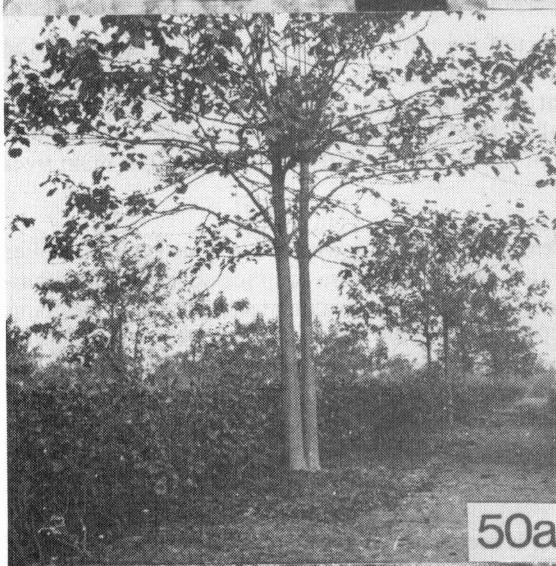

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VIII. INTERCROPPING WITH *PAULOWNIA*

At present, intercropping with *Paulownia* is mainly concentrated in the north-central plain area, i.e. the alluvial plain of the Huanghe (Yellow) and Huaihe River valleys (30°–40°N and 109°30'–122°E). This is the biggest plain in China. The climate is dry between October and the first part of June. The rainy season is from mid June to September due to the influence of the monsoon wind from East Asia. It is cold and dry in winter because of the wind from Siberia and the Mongolian Plateau. The minimum temperature varies from –10 to –20°C. The mean annual rainfall is 500–900 mm, increasing gradually from the north-west to the south-east. Almost 80% of the rain falls during the wet season.

The soil in this area is alluvial and much of it is quite poor. It is sandy, salty and alkaline. Also there are many natural disasters, particularly sandstorms, droughts, floods and freezing. From May to June, hot dry wind often blows with wind speeds over 3 m/sec, temperature over 30°C and relative humidity less than 30%. This is harmful to agricultural crops, especially wheat, the main crop of the area and 20–40% of the production is often lost as a result. The north central area is the main agriculture region of China with a very large population (more than 300 million people). Both timber and firewood for farmers are quite scarce.

In order to protect the farmland and to produce part of the timber and firewood requirements of the local people, great attention was paid since 1950s to the construction of shelter belts. Paulownias are planted along with many crop plants like maize, wheat and others (Figs. 51–55). Since 1960s, farmland shelter belt has been regularly established. This is called the farmland shelter belt net and has a 'mesh size' or the unit area of 6–17 hectares, covering a total of 8.7 million hectares of farmland. The main trees used for this purpose are Poplars, Paulownias and Elms.

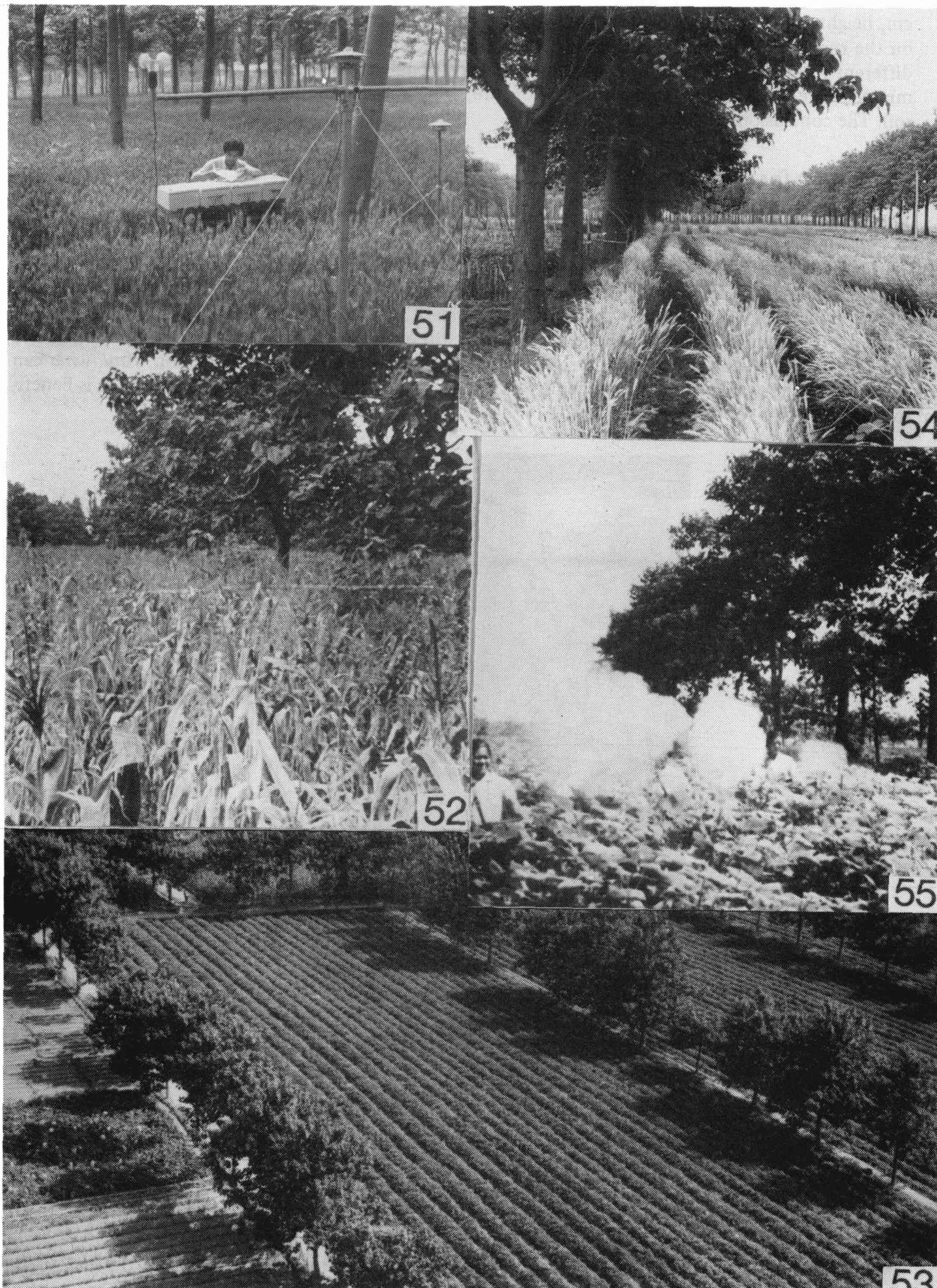
The third type of farmland shelter belt in this area is intercropping with trees. This type of shelter belt has been extended over a large area mostly since the 1970s. The most common species for this purpose at present are *Paulownia* and jujube trees (*Ziziphus jujuba* Mill.). Approximately, 1.5 million hectares of farmland are intercropped with *Paulownia.* Since farmland shelter belt nets and intercropping with trees have been widely established, the microclimate of the farmland has been greatly improved and natural catastrophes have been reduced. At the same time, a lot of timber and forest products have been produced.

Three kinds of intercropping are common.

a) **Primary objectives is silviculture and intercropping is secondary**: In this case the spacing should be 5 x 5–10 m, with 200–400 trees per hectare. In the first three years after planting the trees, it is normally possible to obtain yields similar to those in the control plot. After four to six years, the yield of summer crops (wheat, rape seeds and vegetables) is still normal but the yield of autumn crops, except some shade-tolerant crops, is significantly reduced. After six to ten years, 80% of the normal yield of summer crops can still be obtained. Under the usual conditions in the north central area, if the rotation is ten years, the total yield of crops can be about 37.5 tons and timber volume 80–140 m^3 per hectare during this rotation.

b) **Intercropping and silviculture are equally important**: In this case the spacing is usually 5 x 5–15 m, with 80–133 trees per hectare. In the first five years after intercropping, the yield of the agricultural crops is rather higher than in the control plot. In the next five years, the yield of summer crops usually increases but the yield of autumn crops decreases. Over ten years, the total yield of the agricultural crops is approximately the same as that in the control plot and the *Paulownia* timber volume reaches 36–53 m^3 per hectare.

c) **Primary objective is intercropping, silviculture is secondary**: The spacing should be 5 x 30–50 m, with 40–67 trees per hectare. This method is most widely used at present and has been the main object of our research since 1976. In intercropped areas with trees 5–11 years old, (diameter 16–34

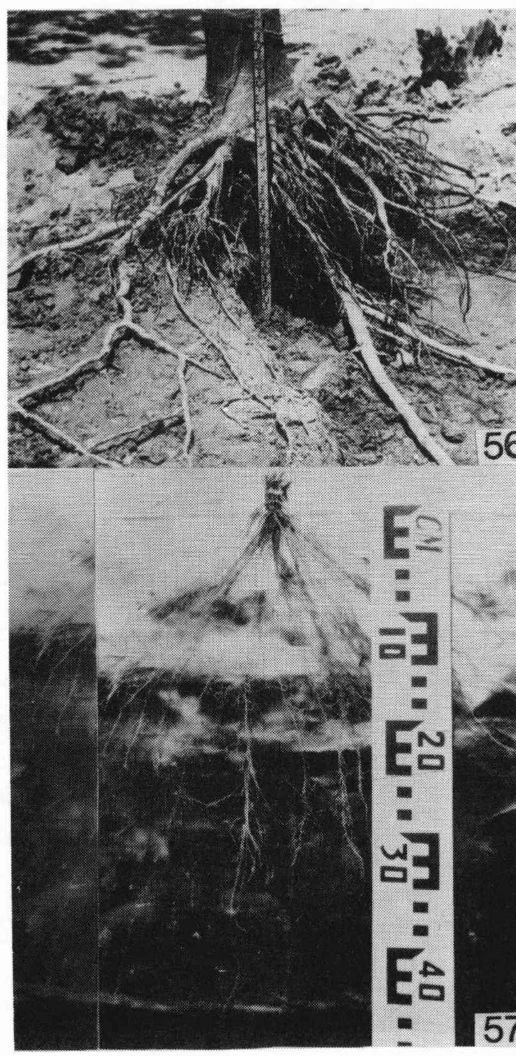


Figs. 51–55. 51. *Paulownia* intercropping measurement of microclimatic factors. 52. *Paulownia* intercropping with corn. 53. Bird's eye view over the intercropping with *Paulownia* in Min Chuan County, Henan Province. 54, 55. *Paulownia* intercropping with wheat, yield is 4.500 kg/ha. *Paulownia* intercropping with cotton, yield is 975 kg/ha.

cm, height 6–12 m, crown diameter 6.2–8.4 m, spacing 4–6 m x 30–50 m), observations were made on the root distribution, the light penetration through the canopy and the variation in the output of different food crops. In addition, systematic observations were also made on different factors of the microclimate as radiation, temperature, moisture, wind speed, evaporation and moisture content of soil. The conclusions reached are as follows.

1. *Paulownia* for intercropping

Paulownia trees, especially *P. elongata,* are deep rooting. In sandy and other soils, an average of 76% of the absorbing root system is at a depth of 40–100 cm, and only 12% in the cultivated land at a depth of 0–40 cm (Fig. 56). In contrast, the root systems of the main crop plants are distributed mainly near the surface layer (Fig. 57). Nearly 80% of the roots of wheat, 95% of maize and 97% of millet are found within a soil depth of 40 cm (Fig. 57). Therefore, competition for water and fertilizer between the trees and food crops is almost negligible. On the contrary, the water in the deeper layer and the fertilizers leached into it may be absorbed by the roots of the *Paulownia* trees. In the dry season, *Paulownia* can absorb underground water from the deeper layers and humidify the air by transpiration, which is beneficial for the growth of food crops.



Figs. 56–57. 56. Distribution of *Paulownia* root system. 57. Distribution of wheat root system underground.

The crowns of *Paulownia,* especially of *P. elongata,* are thin and a large amount of light can pass through. The light penetration through the crown at the beginning of summer (in June) at the age of seven or eight years is 40–50%, and remains stable around 20–40% in the middle and later periods of crown growth. Since the branching angle of *Paulownia* is large, the leaves are spread systematically and seldom overlap, so the food crops may obtain much light at any time (Figs. 51, 54). The light penetration through *P. elongata* crowns is 20% higher than that of poplars (*Populus tomentosa*) and 38% higher than black locust (*Robinia pseudoacacia*). The leaf renewal and leaf fall periods of *Paulownia* are later than most of the other tree species. Late leaf renewal favours the growth of summer crops and late leaf fall protects autumn crops from frost damage.

2. Intercropping and the changes in microclimate

Comparisons made between an intercropped field and a control plot show that intercropping can reduce the wind speed by 21–52% on an average (Fig. 58), and reduce the evaporation rate by 9.7% in the day time, 4.3% in the night time. The moisture content of the soil at 0–50 cm is 19.4% higher than that of the control land. Intercropping also favourably influences temperature. At the end of autumn, in winter and in early spring when the trees are leafless, the wind speed is reduced by the wind resistance of the branches. As a result, the temperature is 0.2–1°C higher than the control land. In summer, in the intercropped land, the temperature is reduced by 0.2–1.2°C during day time (Figs. 59, 60). All this helps to protect against natural disasters such as drought, wind, sandstorm, dry and hot wind, and early and late frost.

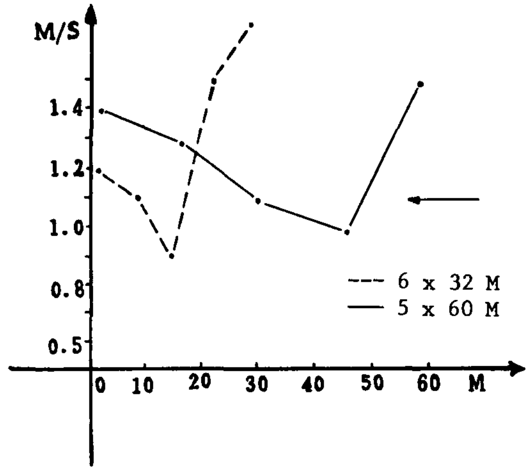
Random samples were collected to compare yield of intercropped and control land, basically under the same management conditions. In the intercropped land, the yield of wheat increased by 6–23%, millet by 20%, maize by 7.5–17%. The yield of cotton and soya beans was basically the same as in regular fields but sometimes the yield increased or decreased depending on climatic conditions. Normally, it increased when it was dry but decreased when it was wet either due to rain or irrigation. The yield of sesame decreased by 5–10%, and sweet potato by 32–38%. These crops are not suitable for intercropping with *Paulownia,* especially with large trees more than 5-year old.

3. Economics of intercropping

During intercropping, the intensive management of the agricultural crops creates better growing conditions for *Paulownia* than in a pure *Paulownia* plantation. Under intercropped conditions, 10-year old *Paulownia* trees reach a mean diameter of 35–40 cm giving a timber volume of 0.4–0.5 m^3/tree, with the better ones up to 1.5 m^3/tree. If 50 trees are planted per hectare, 20–25 m^3/tree of timber will be produced in ten years. This timber volume will be worth 6,000–7,500 Yuan (RMB$319.35 equivalent to US$100 in 1985) or a substantial income of 600 Yuan per hectare per year. This is of great significance for increasing the income and improving the living standard of the rural people.

The whole *Paulownia* tree is a valuable asset to the farmer. Besides the timber, the branches, leaves and flowers are used. One *Paulownia* tree, about 10-year old can produce 350–400 kg of branches for fuel. The leaves and flowers are rich in nutrients and are suitable for feeding the pigs, sheep and rabbits. The leaves are rich in nitrogen (3.09% dry weight). A single *Paulownia* tree 8–10 years old, normally produces 100 kg of fresh leaves per year (equal to 28 kg of dry leaves). Therefore, the development of intercropping can supply a natural source of nutrients.

In conclusion, intercropping over large areas in the plains promotes timber production. Thus, the vast area of farmland will be used for producing agricultural products, but also for producing timber and firewood. This constitutes a new type of shelter belt forest for farmland which creates a proper environment for growth of both food crops and *Paulownia* trees.



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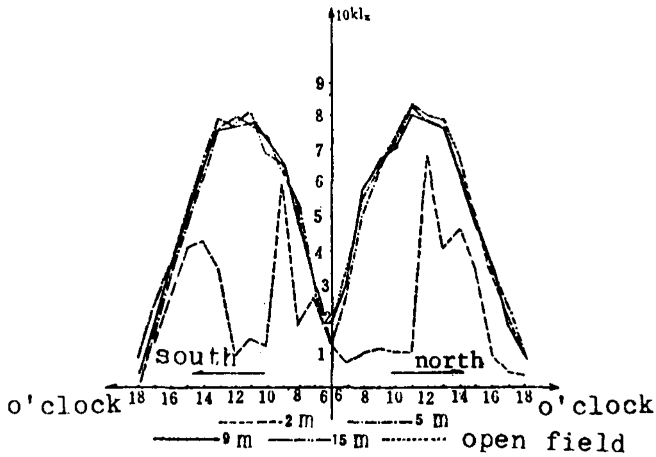

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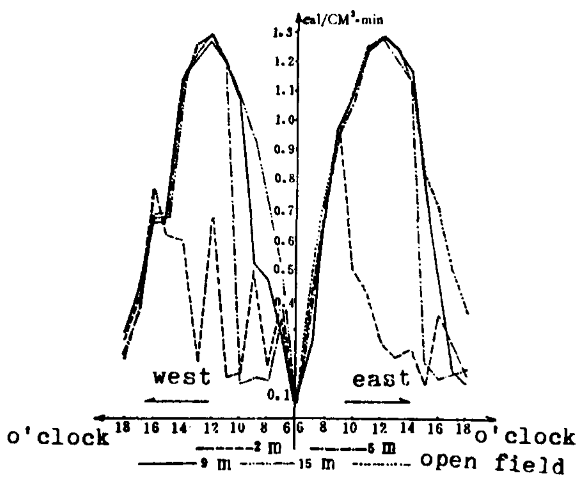

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Figs. 58–60. 58. The effect of different spacing of *Paulownia* on wind speed. 59. Curves showing the changes of the whole day radiation intensity of different distances from the trees from the south to the north. 60. Curves showing the changes of the whole day sunlight intensity of different distances from the trees from the east to the west.

IX. MAJOR DISEASES AND INSECT PESTS

Paulownia is attacked by many diseases and insect pests. In the north, it is mainly infected by witches' broom although attack by leaf-eating insects is also a serious problem. In the south, it is mainly attacked by leaf-eating insects and borers such as longhorn beetles. In addition, scale-insects and woodpeckers are also common.

1. Witches' broom disease

Witches' broom of *Paulownia* is a serious disease at present (Figs. 61–63). It occurs most seriously in northern provinces such as Honan, Shensi, Anhwei, Shantung, Shansi and others. In recent years, it has been observed that the witches' broom is spreading to the south. It impairs the growth of trees and kills young seedlings and juvenile trees. The witches' broom is spreading along with the increase in the area planted with *Paulownia* and also the great amount of material used for vegetative propagation.

(i) Symptoms

Witches' broom is an infectious disease. Symptoms appear on branches, trunks, flowers and roots. The main symptoms are as follows but they vary with the species. In infected branches the axillary and accessory buds sprout in great quantity and form bunches of twigs. The internodes are condensed and phyllotaxy is in disorder. Leaf blades are yellow, small and thin with clear veins and wrinkles. These twigs do not drop in winter and look like brooms, hence the name of the disease. Eventually they dry up and die within one or two years after being affected (Figs. 62, 63). Petals become leaf-like and pedicels grow into twigs on which axillary buds develop and new bunches of twigs are formed. The calyx becomes thin, pale yellow, transparent and hairless. The receptacle is completely deformed.

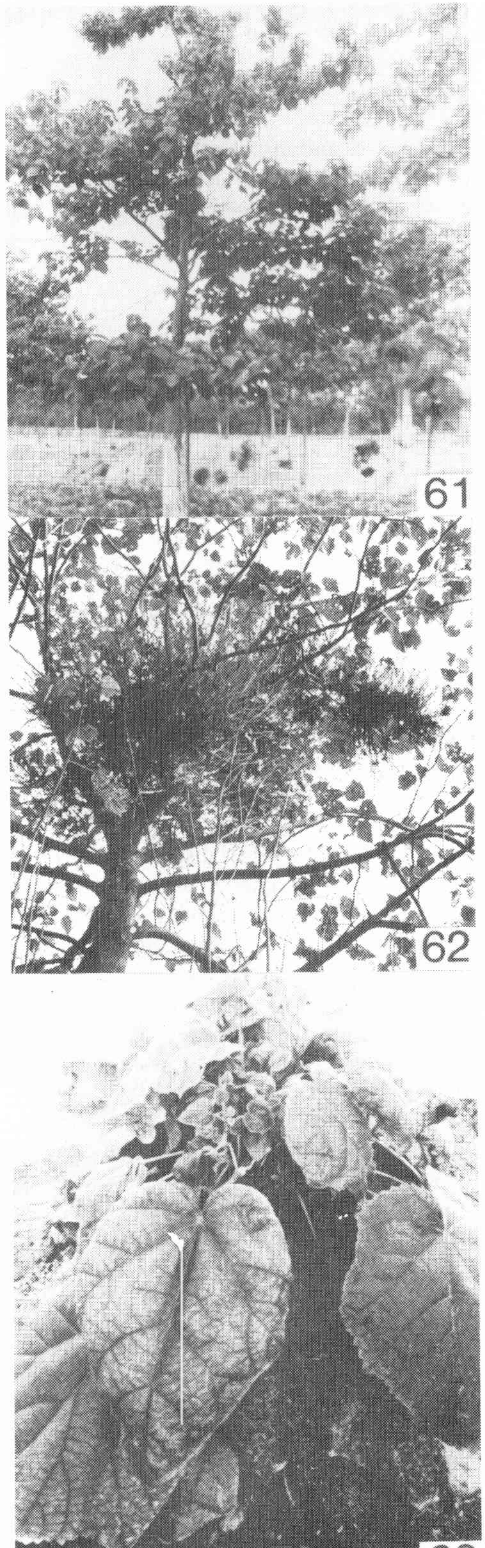
Paulownia trees of all ages can be affected by this disease. In areas where witches' broom is a serious disease, the incidence in saplings is around 5%; higher in saplings from reserved roots in old nurseries. In juvenile trees it is 5–30%. Regenerated saplings are seriously affected. The accumulated incidence of disease is 50–80% in *Paulownia* trees more than 4–5 years old. Witches' broom of *Paulownia* seriously affects the growth of juvenile trees and reduces the tree growth by 20–25%. It also seriously affects the growth of the root system. In 1975, investigations were made on the plants in the nursery, mostly on the root systems of wholly affected saplings, sprouts with affected roots and healthy saplings less than 1 m tall. The results showed that the total length of the root system of the healthy saplings was 1,230 cm compared with only 465 cm in infected saplings.

The introduction of the witches' broom pathogen into the trees sets in a series of physiological changes that cause metabolic disorders, imbalance in the supply and demand of energy, undernourishment and gradual death. Tests conducted show that the chlorophyll and protein contents of infected leaves were reduced by 30–40%, as compared with healthy leaves.

(ii) The pathogen and infection

The infected materials were examined under light and electron microscope. Ultra thin sections were prepared of the leaf stalks and lamina tissues and mycoplasma were detected and studied under the electron microscope. Numerous mycoplasmas exist in the sieve tubes of the affected trees, with large and small particles mixed in the same sieve tube. The mycoplasma varies in shape (circular or ellipsoidal etc.) and size is (200–820 m in diameter).

The disease is usually spread by using the infected planting materials for grafting and by some insects such as *Empoasca flavescens*. Seeds from affected trees are free from the disease and on germination and growth normal seedlings and juvenile trees are formed. Inoculation of the pathogen by mechanical means is also possible.



Figs. 61–63. 61. Symptoms of witches' broom on the whole tree of *P. elongata*. 62. Symptoms of witches' broom on the branches of *P. elongata* tree. 63. A close up view of some of the affected branches.

(iii) Control methods

The following control methods are followed.

1) The affected trees should be removed from the nursery as well as the newly planted areas as soon as they are discovered and burnt.

2) Affected branches should be cut off from the trees, preferably three years and older, and an ointment of terramycin and vaseline (1:9) should be applied to the wounds, which should be wrapped and tied with plastic cloth. After three years the pruned trees with and without application of the ointment, both showed improvement. However, it is better to apply the ointment as it helps to heal the wounds and reduce further infections, as well as contains the pathogen within the trees. From comparative data on the effects of pruning in different seasons, it was found that pruning twice, in summer (usually in mid June) and early autumn (the first part of September), had better results, because summer and early autumn are the vigorous periods of tree growth in which the pathogen moves with the main nutrient stream and shows the symptoms of infection. Therefore, pruning in summer and early autumn can reduce incidence of the pathogen. The frequency of pruning depends on the state of the disease.

3) **Disinfection of affected roots**: Roots of plants affected by the witches' broom have become one of the main causes of the disease spread in recent years. Growing saplings from treated roots can prevent or reduce infection. There are various possible treatments.

   (1) Soaking roots in warm water at 45–48°C for 20 minutes.

   (2) Soaking roots in an antibiotic solution: 500–1,000 units of antibiotics such as terramycin, tetracycline, neomycin, aureomycin and kanamycin.

   (3) Soaking roots in solutions containing boron (0.01–0.5%), sodium thiosulphate (2%), sodium sulfate (1%) and zinc sulphate (0.1%) for 6–12 hours. Then dry the roots in the sun for one to two days before planting. This is an economic and effective way of preventing and controlling witches' broom disease according to the experiences gained over a period of five to six years.

4) **Integrated control measures are**:

   (1) Root cuttings of healthy, superior trees should be selected for use in vegetative propagation. The use of seeds in propagation should also be promoted. The old nursery where *Paulownia* saplings have been grown for two years should not be used again for a few years.

   (2) Strict quarantine measures should be imposed and the transfer of root cuttings from the affected area to other locations should be controlled. The root cuttings should be pretreated with warm water or chemicals if they have to be transferred to other locations.

   (3) Insect control should be carried out in areas where nursery and juvenile trees are seriously attacked by insect pests, especially *Empoasca flavescens, Cicadalla viridis* and stinkbug. Silvicultural measures such as planting good trees at suitable locations with the correct spacing, pruning in good time and preventing damage caused by machines, should be practised.

2. Anthracnose disease

Anthracnose is one of the major diseases of saplings.

(i) Symptoms

Anthracnose injures the leaves, leaf stalks and shoots of *Paulownia* saplings. The injured leaf blades have pale spots which enlarge into brown, near circular spots, surrounded by yellow-green. The spots are about 1 mm in diameter and later crack in the centre. The infected leaves drop early. When the veins of the new leaves are injured, their blades often shrink and become deformed. When the leaf stalks, leaf veins and shoots are injured, the spots are initially small, light brown and circular, and then extend vertically and become elliptical or irregular with a hollow centre. In serious infections, several spots merge and often give rise to wilting and dead shoots. Heaps of red conidia or black small spots often appear on the spots after rain or in a humid climate.

(ii) Conditions that promote the disease

The optimum temperature for spore germination is 25°C and optimum relative humidity is 90–100%.

During the growing season, rainfall and humidity influence the spread and development of this disease. If the seedlings are too closely planted, poorly ventilated, shaded, wet or thin and weak the infection rate becomes very high.

(iii) Control methods

1) Nurseries should be established away from *Paulownia* plantations and should be moved after outbreaks of the disease. The sowing time should be determined according to the local climate so that the early seedling period does not coincide with the wet season.

2) Management should aim to promote vigorous growth of seedlings to increase their disease resistance.

3) The soil should be treated with 8 g pentachloronitro-benzene per m^2 or ferrous sulfate etc. per m^2, three to five days before sowing. Prior to seeding, seeds should be soaked in 0.2% phenylmercuric acetate solution for 30 minutes. Bordeaux mixture of 0.5–0.7% should be sprayed twice a month in the seedling period and it is an effective control measure.

3. *Sphaceloma paulowniae* Hara

Sphaceloma paulowniae is a common disease which injures *Paulownia* saplings and young trees. When the shoots are infected, brown spots with yellow margin appear on the young leaves and sometimes on stems. Later, small circular holes appear in the spotted areas. The spots on the leaves also join into irregular splits. The injured veins of the young leaves often cause leaf deformation. The spots on leaf stalks and young stems are circular to elliptical in outline. The black brown spots link into strips and raise like scabs, which cause the shoots and young leaves to curl, dry and die when the infection is serious. The time of occurrence of this disease is similar to that of anthracnose. Control methods are the same as for anthracnose.

4. Damping-off disease of seedlings

Damping-off disease mainly affects *Paulownia* seedlings. Its major symptoms are bud rot, damping-off, stem and leaf rot and root rot. The pathogenesis of this disease is very complex but the main causative organisms are *Rhizoctonia solani* and *Fusarium* species. The pathogens survive the winter on fragments of plants in the soil and begin to spread in early spring after the thaw. The seriousness of the infection depends on the soil characteristics, the accumulation of pathogens in the soil, and apparently most important, the method of propagation.

Control methods are as follows:

1) The seedling bed should be disinfected with 3% ferrous sulfate ($FeSO_4$) solution at a rate of 4.5 kg/m^2. Sowing is carried out seven days after disinfection.

2) To control infection Bordeaux mixture should be sprayed once every 10–15 days. In case of infection, 50% methyl radical topsin should be sprayed.

Other fungi which affect *Paulownia* are the following: *Phyllactinia imperialis* Miyabe, *Uncinula clintonii* Peck, *Cercospora paulowniae* Hori, *Mycosphaerella paulowniae* Shirai et Hara, *Valsa paulowniae* Miyabe et Hemmi, *Septobasidium tanakae* (Miyabe) Boed et Steinm. These pathogens are not very common and cause little damage. Improving management to ensure healthy and strong growth of the trees can reduce the incidence and severity of diseases.

Besides there are two species of *Loranthus*, which are the stem parasites that cause considerable damage. They are *Loranthus parasiticus* (Linn.) Merr. and *L. yadoriki* Sieb.

The main insects attacking *Paulownia* are the following:

Agrotis ypsilon (Rott.), *A. toxionis* Butler, *Euxoa segetum* Schiff, *Serica orientalis* Matsch, *Anomala corpulenta* Matsch, *Holotrichia diomphalia, Gryllotalpa unispina* Saussure, *G. africana* palisot de Beauvois, *Empoasca flavescens* (Fabricius), *Cicadalla viridis* L., *Cryptotothlea variegata* Snellen, *Psilogramma menephron* Cramer, *Batocera horsfieldi* Hope, *Megopis sinica* White and *Basiprionota bisignata* Boh. The extent of damage caused by insects varies from region to region and the details are presently compiled.

X. WOOD PROPERTIES AND UTILIZATION OF *PAULOWNIA*

1. Wood structure

(i) Macroscopic structure

The bark is gray brown, rather smooth and without fissures and the wood is pale yellow to pale red. The demarcation between sap and heartwood is not clear. Usually there are only one or two annual rings in the sapwood. The heartwood is wide and its texture is fine to rather coarse, if fast grown with wide growth rings. Pores in rings gradually diminish in size outwards and the place where the ring starts usually does not form a clear early wood strip. Therefore, it is semi-ring porous to ring-porous with very narrow growth rings. The rays are not clearly visible to naked eye but can be apparent with a hand lens or under microscope.

The wood is straight grained, with gloss after being planed, light, soft and odourless.

(ii) Microscopic structure

1) **Vessels:** In cross section pores are round or elliptic. The difference in the vessel size between early and late wood is three to five times; with the maximum variation of about ten times. The vessels are mostly solitary, sometimes whorled or occur in short linear multiples. Perforation is simple. Bubble-shaped tyloses are present in the vessels; more in the vessels of early wood than in late wood. The bordered pits are small, elliptic with a wide opening (Figs. 66, 67).

2) Rays are mostly homogeneous, occasionally heterogeneous (*P. fortunei*), few solitary and more mixed, irregular, spindle-shaped, the lowest less than 0.5 mm high. They are 1–50 cells high, 1–8 cells wide (Figs. 64, 66).

3) Wood parenchyma is well developed, paratracheal, generally annular and wing-like, mostly clear around the vessels of late wood, wide strip-shaped in early wood. Bands are common (Fig. 64).

4) Wood fibre cells are even in size in annual rings more in early wood rather in late wood. Bordered pits are common. Wood fibres are arranged in vertical series, cell wall thin, less than 3 μ thick, medium in length, 550–1,700 μ long (Figs. 66, 67).

2. Wood properties

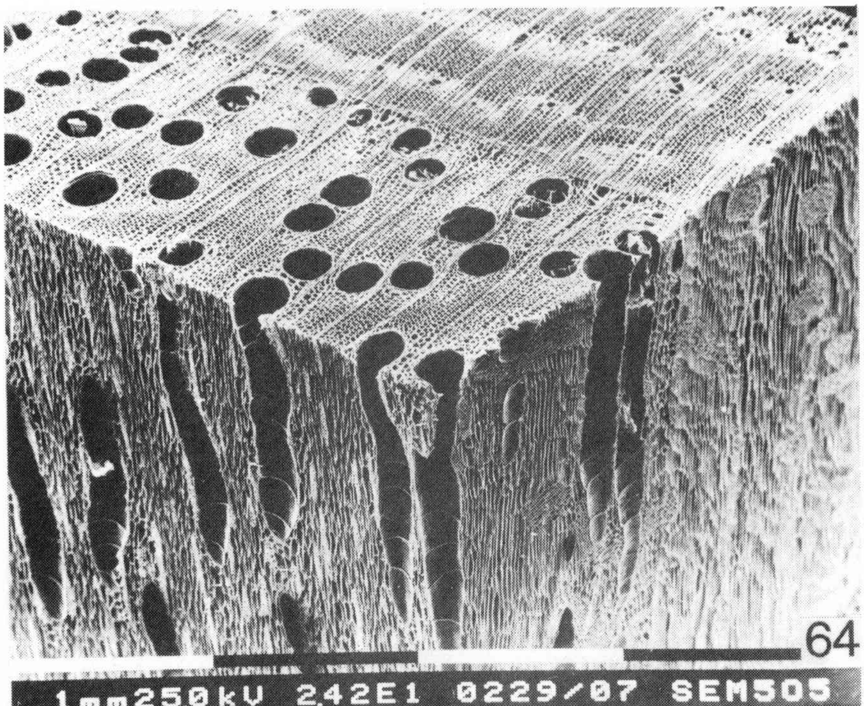
Paulownia wood has the following properties:

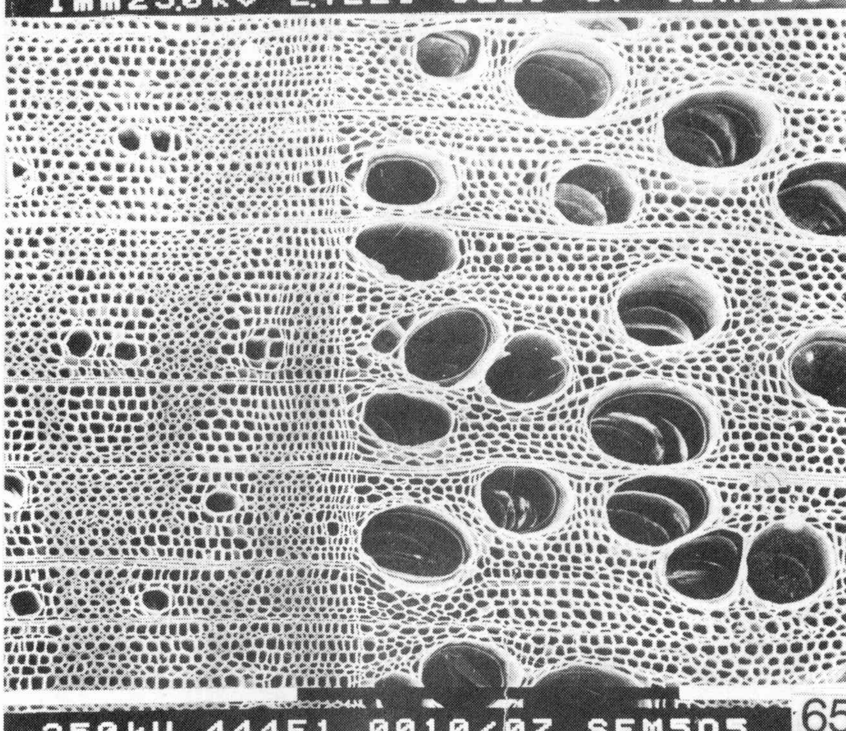
(i) Weight and quality

Lightness is a major advantage of *Paulownia* wood. Its air dried density (moisture content 15%) is 0.26–0.33 g/cm^3. The density varies with different species and site conditions but all of them produce exceptionally light wood. *P. fargesii* and *P. elongata* are the lightest. The pliable wood has low strength (Table 11). Thus, it is not suitable for using as building components that usually require high strength. However, so far as strength-to-weight ratio (quality coefficient) is concerned, the grade of *Paulownia* wood is higher; most species are near or up to medium grade and are suitable for some uses requiring soft but relatively high strength wood.

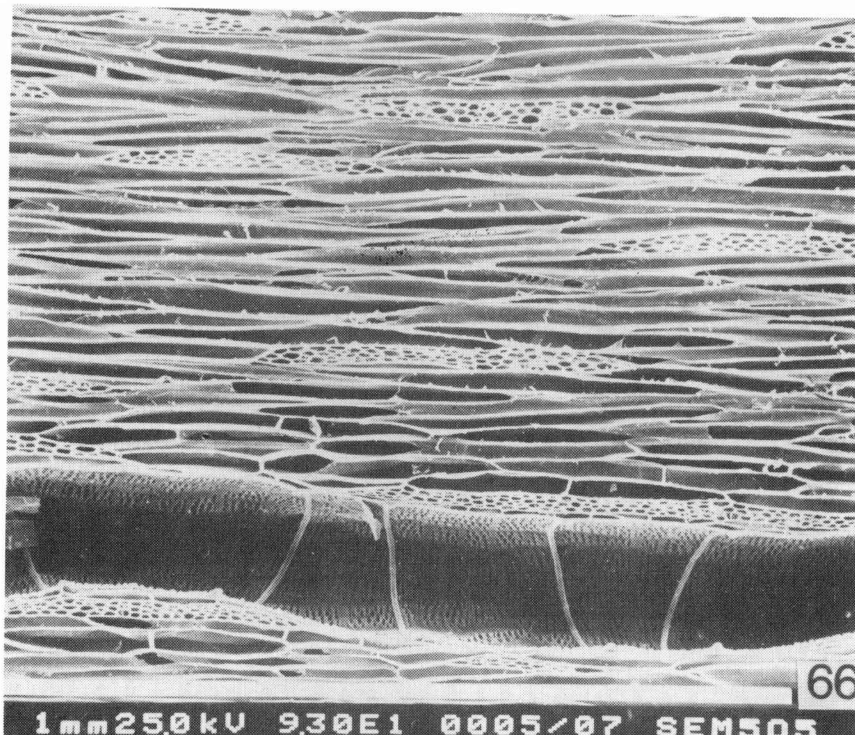
(ii) Deformation and warping

The shrinkage coefficient (0.27–0.37%) of *Paulownia* timber is smaller than the commonly used coniferous and broad-leaved woods (Table 12). Products made of *Paulownia* wood do not easily warp, crack and deform. This is a conspicuous advantage. In an experiment carried out by W.S. Romeka in USA in 1951, *Paulownia*, poplar, oak and other wood boards 1" thick were simultaneously put into a drying





Figs. 64–67. 64. Three dimensional wood section of *P. fortunei* using, scanning electron micrograph. 65. Transection, note the differences between early and late wood, ring porous arrangement. 66. TLS – wood, note the long, multiseriate rays, distribution of pits on the vessels. 67. RLS – wood, mostly procumbent rays and plenty of tyloses in vessels.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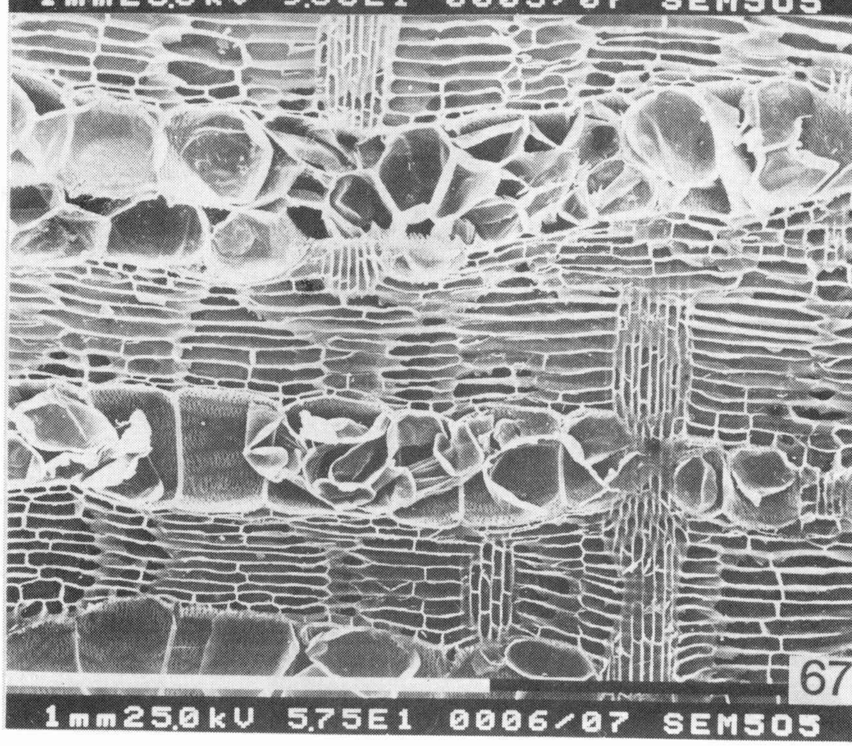
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Table 11. The main physico-mechanical wood properties of six *Paulownia* species.

Species	Location (Lat.)	Density (g/cm^3)		Shrinkage coefficient (%)			Compression strength parallel to grain (kgf/cm^2)	Bending strength (kgf/cm^2)	Bending modulus of elasticity (1,000 kgf/cm^2)	Shear strength parallel to grain (kgf/cm^2)		Compression strength perpendicular to grain (kgf/cm^2)				Tensile strength parallel to grain (kgf/cm^2)	Impact toughness (kgf.m/cm^2)	Hardness (kgf/cm^2)			Cleavage resistance (kgf/cm^2)		Quality coefficient
		Oven dried	Air dried	Radial	Tang-gential	Volume				Radial section	Tangential section	Partial compression at proportional limit		Compression at proportional limit				End	Radial section	Tan-gential Section	Radial	Tan-gential section	
												Radial	Tan-gential	Radial	Tan-gential								
P. catalpifolia	Sueng County, Henan Province (34°52')	0.233	0.290	0.093	0.216	0.344	196	329	54	41	47	28	20	17	11	521	0.171	151	87	94	7.7	8.3	1,810
P. elongata	Fugou County, Henan Province	0.209	0.264	0.076	0.187	0.292	159	289	42	44	44	22	16	14	12	394	0.132	125	84	86	7.6	6.3	1,697
	Lankau County, Henan Province (34°20')	0.243	0.283	0.147	0.269	0.453	197	356	44	40	39	24	22	16	12	–	0.180	195	99	122	6.5	6.3	1,954
P. farbesii	Muchuan County, Szechuan Province (29°00')	0.219	0.269	0.107	0.216	0.334	160	363	52	42	35	21	24	14	18	518	0.214	171	114	121	7.6	6.1	1,944
P. fortunei	Gulin County, Szechuan Province (28°10')	0.258	0.309	0.110	0.210	0.320	188	405	63	56	50	29	27	21	19	563	0.325	215	124	124	7.6	7.4	1,919
P. tomentosa	Fugou County, Henan Province	0.236	0.315	0.105	0.203	0.327	223	406	48	51	56	35	28	20	20	605	0.348	183	117	135	10.9	9.6	1,997
	Shu County, Anhei Province (34°20')	0.231	0.278	0.079	0.164	0.261	200	381	50	47	45	23	22	16	13	343	0.240	189	98	106	7.0	6.0	2,090
P. tomentosa var. *tsinlingensis*	Fugou County, Henan Province (34°20')	0.279	0.347	0.107	0.208	0.333	220	415	58	59	54	30	30	17	20	568	0.416	198	142	143	10.2	9.8	1,830

Table 12. **Wood shrinkage coefficient of seven *Paulownia* species.**

Tree species	Shrinkage coefficient (%)		
	Radial	Tangential	Volume
P. australis	0.093	0.179	0.272
P. catalpifolia	0.112	0.259	0.371
P. elongata	0.098	0.213	0.310
P. fargesii	0.074	0.195	0.269
P. fortunei	0.094	0.268	0.362
P. kawakamii	0.134	0.238	0.371
P. tomentosa	0.093	0.207	0.301
P. tomentosa var. *tsinlingensis*	0.107	0.208	0.333

room at 68°C. After 12 hours, the moisture content of the *Paulownia* wood reduced to 24% without any deformation and damage but under the same treatment poplar wood cupped badly and cracked at the ends, oak checked and honey-combed and wood of other kinds was severely damaged.

(iii) Moisture content

It is said that furniture made of dried *Paulownia* wood is very good even under humid conditions. It resists warping, cracking and deformation. Therefore, products made of it are not generally effected by humidity and insects. The moisture content per unit volume is comparable with other timbers that are in common usage (Table 13). The humidity penetration is also said to be lower than the other popular woods well known in trade.

Table 13. Moisture content in the woods of different tree species.

	Paulownia fortunei	Heartwood of *Cryptomeria japonica*	*Fagus*
Moisture content (%)	21.31	18.56	20.60
Water density (g/m^3)	0.056	0.070	0.101

(iv) Good for insulation

1) **Thermal conductivity**: The thermal conductivity of eight *Paulownia* species is 0.063–0.086 Kcal m^{-1} hr^{-1} °C^{-1} which is one of the lowest values for wood. Therefore, *Paulownia* wood has very high heat insulation properties.

2) **Temperature conductivity**: The temperature conductivity of eight *Paulownia* species is 0.000561–0.000631 m^{-2} hr^{-1} the lowest in the 40 species of wood that have been tested.

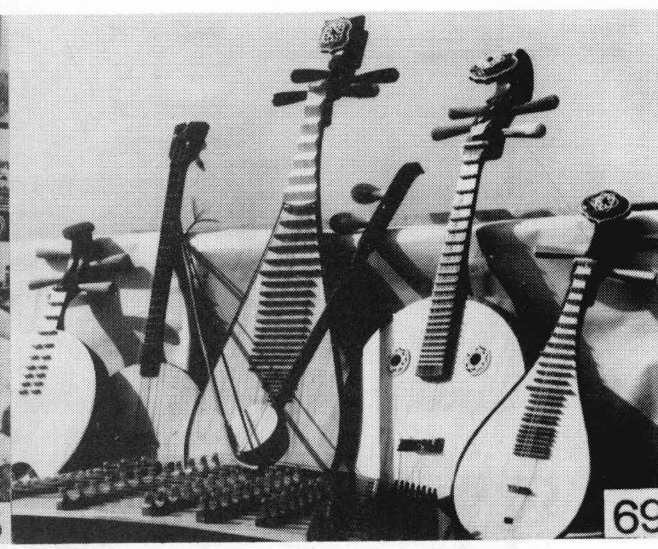
3) **Electric insulation:** The dielectric constant of eight *Paulownia* species is lower than in other species when moisture content is constant and the alternating current specific resistance is usually higher than other tree species. This shows that *Paulownia* wood has better insulating properties than other species.

(v) Rot resistance

Systematic research on rot resistance of *Paulownia* wood has not been done yet. It has, however, been reported that *Paulownia* wood is highly rot-resistant and the rot is only superficial. Clean, white wood appears when the surface is planed. In Luengchou, Kwangsi Autonomous Region, a tropical area where wood rots easily, we saw some *Paulownia* boards which had been soaked in water for ten years and used to make a coffin had lasted more than 30 years without decay. A coffin made of *Paulownia* wood more than 200 years ago was unearthed in Luechan County, Hupeh Province and was found to be in good condition. In addition, from the Szechuan Provincial Research Institute of Forestry, in Hong Ya Forestry Farm, it was reported that *Paulownia* and many other tree species were left in the forest following felling. After 15–16 years, the other trees were completely rotten but *Paulownia* wood only decayed around 1 cm depth on the surface. However, experiments by the Chinese Academy of Forestry produced a conflicting result that *Paulownia* wood is not rot-resistant. More data is required.

(vi) Ease of natural drying

According to a report from USA, *Paulownia* board 1" thick can be dried to 10% moisture content in 25 days at normal room temperature. This property of *Paulownia* wood is convenient for wood processing and can save the expense of artificial drying. The logs are air dried (Fig. 68).



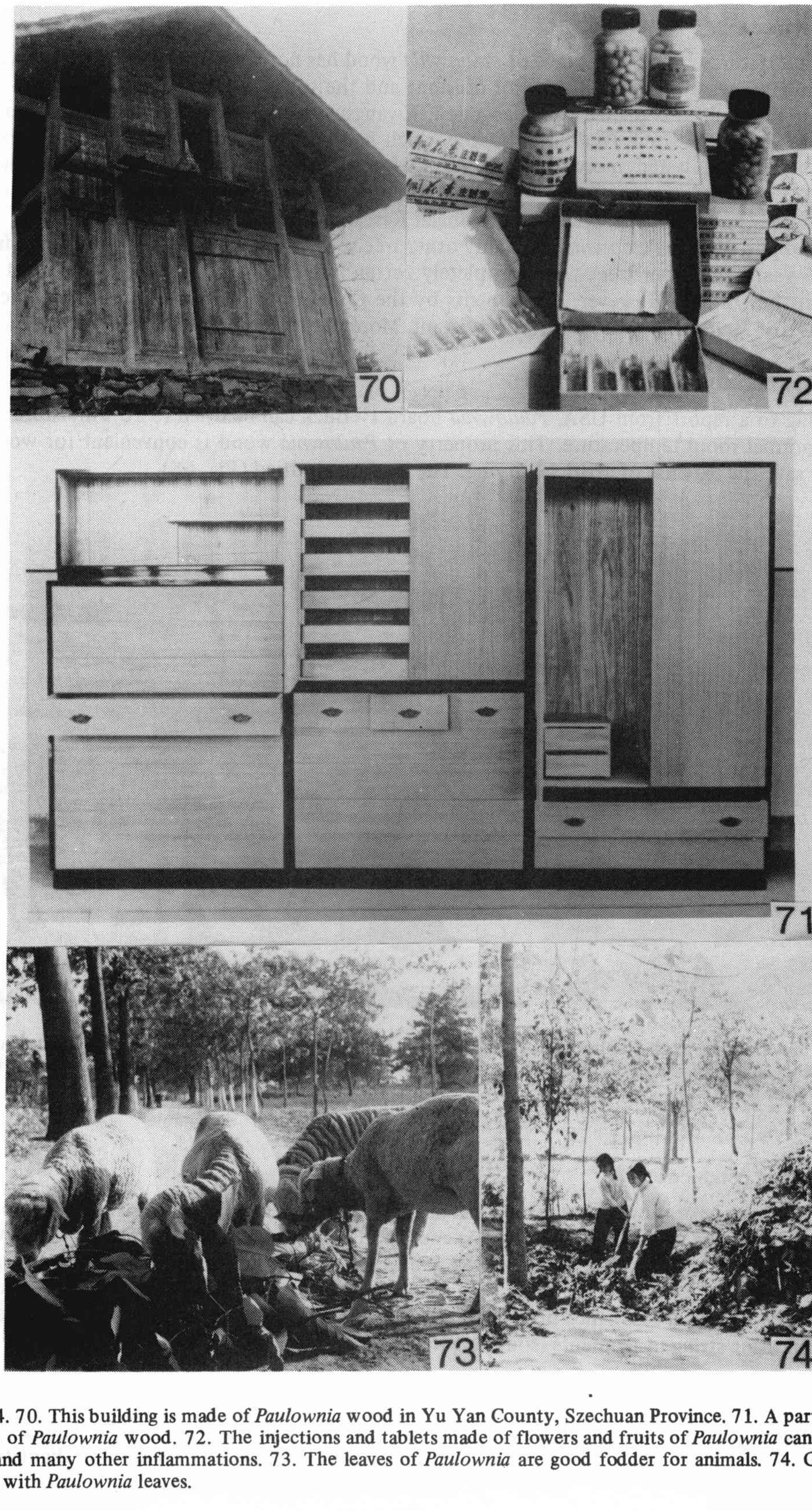
Figs. 68, 69. 68. A corner of the timber yard in Sui County, Henan Province. There was a serious shortage of timber in the past but they are more than self-sufficient in timber today. Logs are air dried. 69. Traditional musical instruments made of *Paulownia* wood.

(vii) Good sound conduction

The sound boards of the Chinese traditional musical instruments are always made of *Paulownia* wood (Fig. 69). In China, the sound boards of violins and pianos are usually made of *Picea jezoensis* var. *microsperma.* However it is reported that the consistency of sound radiation quality of all the *Paulownia* species (14.06–20.84 $m^4\ kg^{-1}\ sec^{-1}$) is better than that of *Picea* (12.41 $m^4\ kg^{-1}\ sec^{-1}$). This shows that *Paulownia* wood has good resonance properties. For centuries, *Paulownia* wood has been extensively used in China for making string instruments (sounding boards).

(viii) Ease of processing

Paulownia wood is easy to plane, saw or carve even in quick processing, without danger of chipping. When veneer is processed, the surface is comparatively rough if it is sliced. Therefore, diametral planing is better.



Figs. 70–74. 70. This building is made of *Paulownia* wood in Yu Yan County, Szechuan Province. 71. A part of furniture constructed of *Paulownia* wood. 72. The injections and tablets made of flowers and fruits of *Paulownia* can cure chronic bronchitis and many other inflammations. 73. The leaves of *Paulownia* are good fodder for animals. 74. Green manure preparation with *Paulownia* leaves.

It is very easy to drive nails into *Paulownia* wood but its nail-holding ability is rather low so it is better to make furniture with tenon and mortise joints when using *Paulownia* wood. *Paulownia* wood is good in absorption of glue, paint and dyes but it consumes more varnish than other woods.

(ix) Beautiful wood colour and grain

Paulownia wood has a beautiful gloss like spun silk, straight grain and no odour. But as it contains polyphenol material stained spots appear on furniture made of *Paulownia* wood within several years or even several months. In order to solve this problem, apart from soaking wood in clear water for decolourisation before processing, particular attention should be paid to the proper felling seasons, which are autumn and winter, avoiding the growing seasons.

3. Wood utilization

Paulownia wood is widely used for various purposes and some of these are briefly described.

(i) For house construction

As the strength of wood is not high, it is not suitable for uses which require mechanical strength but it is quite widely used for houses. Roof beams and purlin made of *Paulownia* wood are light and keep in shape for many years so they do not put the house out of shape. In Cichung County, Szechuan Province, the roof beams of *Paulownia* wood in a temple more than 100 years old are still in good condition. There is no decay in houses more than 100 years old which are completely made of *Paulownia* wood. *Paulownia* wood is very good for making doors, windows, partition boards, ceilings and inner roofs (Fig. 70).

(ii) Wood for paper pulp and other uses

Paulownia wood is an ideal material for model air-planes and gliders and is increasingly used in aircraft, vehicles and ships both in China and in foreign countries because it is light, rot-resistant, free of warping, cracks and knots. As the wood is about 40% lighter than ordinary wood, delivery volume can greatly increase when it is used for packing boxes. *Paulownia* wood wool is an ideal material for use as a cushion filler, an insulation material for cooling systems, "mulching" chips for bedding material in cowsheds or litter in fowl houses and for making toys etc. *Paulownia* is very promising for pulp and paper. The wood is white and produces good, high strength pulp.

Paulownia wood, large in diameter and free of knots, is comparatively good in binding and is good material for plywood. It is easy to slice and plane, with a good colour and beautiful figures. Many factories in China have manufactured plywood (veneer 1.2–1.4 mm thick) for trial and obtained promising results. The planed face veneer can be as thin as 0.25 mm. If the viscosity of the adhesive is correct it does not penetrate to stain the face of the plywood. *Paulownia-faced* composite board and plywood can be used in large amounts for furniture, indoor decorative board, various kinds of boxes, radio set cases etc. It is expected that *Paulownia* will become one of the most important timber trees for face veneer and plywood in China.

(iii) For furniture making

Paulownia is used to manufacture tables and chairs. It is especially suitable for cases and cupboards which are smoke-proof and are little attacked by insects (Fig. 71). There is a traditional custom in China –"*Paulownia* trees are planted when girls are born and *Paulownia* wood is used to make dowries when girls get married".

Slow grown, fine grained *Paulownia* wood is very good for oil drums, wine or beer barrels, tea boxes, fruit boxes, food grain storage etc. *Paulownia* wood can be used to make bee hives which are not only light and convenient for transportation, but are also cooler in summer and warmer in winter than the beehives made of other wood. This reduction in temperature extremes increase honey yield. People in Anhuei Province make vitriol barrels with *Paulownia* because it is acid tolerant.

(iv) For farm implements

Aquaducts made of *Paulownia* wood do not subside and crack, are durable and retain their shape. Threshing tubs of *Paulownia* wood are more durable than those of *Cunninghamia lanceolata.* People in some provinces and the dockers in China are very fond of using the poles made of *Paulownia* wood.

(v) For handicrafts

The people in China, Japan and some other countries in South East Asia have a long tradition of making handicrafts with *Paulownia* wood such as flower vases, statue of Buddha or deities, wooden fish, medal boxes, dressing boxes, TV and radio boxes etc.

Paulownia wood can also be used to make blackboards, life rafts, sleds and surfboards. *Paulownia* charcoal can make charcoal crayons, black powder and fireworks and can also be used in industries as active carbon. *Paulownia* bark can be used to make dyes.

(vii) Medicinal properties

Medicines made of *Paulownia* leaves, fruits and wood have certain effects on bronchitis especially on relieving the cough and reducing phlegm. They are made into tablets and injections. The leaves of *P. tomentosa* contain ursolic acid, $C_{30}H_{48}O_3$ and matteucinol, $C_{18}H_{18}O_5$. Its xylem contains Paulownin, $C_{20}H_{18}O_7 \cdot CH_3OH$ and d-Sesamin. From its bark, syringin, $C_{17}H_{24}O_9 \cdot H_2O$ and Catalpinoside were separated. Its fruits contain acid, fatty oil, flavanone and alkaloid. A solution prepared from the leaves and fruit dissolved in water, when applied daily to the scalp, is said to promote healthy hair growth and turn grey hair black. Another solution, using the leaves and wood, relieves swollen feet. Pharmacological experiment shows that fruit extracts can relieve coughs and asthma and its fruits can reduce blood pressure (Fig. 72).

The large and hairy leaves of *Paulownia* play a very useful role in purifying dust and smoke. *Paulownia* has become the main tree species for afforestation in Chengdou, Szechuan Province, because dust and smoke pollution are comparatively serious there. The sulfur dioxide contents of the clean district where Paulownias are extensively grown (*P. albiphloea* var. *chengtuensis*) and the polluted district were respectively 0.169% and 1.410%. *Paulownia* still grows normally in the polluted districts whereas many other trees drop their leaves or fail to grow at all under the same conditions.

(vii) For fodder and manure

The leaves and flowers of *Paulownia* are good fodder for pigs, sheep and rabbits (Fig. 73). The flower buds, flowers and the leaves of *Paulownia* contain fat, sugar and protein. The nitrogen content in *Paulownia* leaves can be compared favourably with some leguminous plants. People in Kwangsi make green manure with *Paulownia* leaves which is an excellent fertilizer (Fig. 74).

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