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Comparative Study on Yield and Ecological Benefits of Different Intercropping Models in Chestnut Economic Forests

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Abstract This study summarizes the application and existing achievements of different intercropping methods in chestnut forests. Research has found that when chestnuts are planted in combination with tea trees, food crops, forage grasses, etc., not only can the utilization rate of land be improved, but also considerable ecological benefits can be brought about, such as making the soil more fertile, increasing the variety of animals and plants, improving the microclimate, and helping orchards generate higher income. The analysis also found that sometimes a balance needs to be struck between yield and ecology. Whether different crops can be well combined and whether their growth cycles are consistent are all issues that need to be considered during intercropping. This study aims to provide some theoretical support for intercropping in chestnut forests, helping to find more reasonable and sustainable planting methods that can balance economic and ecological benefits.

Keywords Chestnut economic forests; Intercropping models; Yield performance; Ecological benefits; Agroforestry optimization

1 Introduction

Chestnuts (*Castanea* genus) are cultivated in many countries and are a very valuable economic forest. It can provide products such as nuts and wood, and is also of great help in protecting the ecological environment. However, nowadays, chestnut forests are facing many problems, such as global warming, severe pest infestations, invasion of alien plants, and changes in land use patterns. These problems will affect the long-term development and ecological functions of chestnut forests (Clark et al., 2023; Miller and Ivey, 2024). Moreover, the traditional planting methods sometimes do not match the current land demand, making it even more difficult to balance the yield and ecological protection of chestnut forests (Bruzzese et al., 2023; Wolpert et al., 2023).

Intercropping in chestnut forests is a way to improve land efficiency. Planting chestnuts together with other crops not only helps to harvest more crops but also improves the soil, such as providing it with more organic matter and nutrients, which is also beneficial for the healthy growth of chestnut trees. Doing so can also make the microorganisms in the soil more diverse and enhance the stability and stress resistance of the entire forest (Wu et al., 2021b; Wu et al., 2021c; Wang et al., 2024). For instance, planting chestnuts together with tea trees not only increases soil nutrients but also improves the microbial structure around the roots, enhances fruit quality, and boosts disease resistance.

This study compared the yield and ecological effects of chestnut forests under different intercropping methods, and analyzed their specific impacts on soil properties, microbial species and ecological functions. This study hopes to provide some scientific references for the better planting and management of chestnut forests.

2 Intercropping Systems in Chestnut Forests

2.1 Definition and classification of intercropping in agroforestry contexts

Intercropping refers to the sequential planting of two or more crops or trees in the same plot of land. It can be done simultaneously or in sequence. This method is often used in chestnut economic forests, such as planting chestnut trees together with food crops, cash crops, medicinal materials or forage. This can not only make more full use of the land, but also improve the ecological environment and economic benefits (Yu et al., 2006; Wei et al., 2014).

2.2 Common intercropping types: grain, herb, forage, and economic crops

There are many ways to grow chestnuts in the forest. Growing them together with food crops, such as chestnuts with corn, peanuts, soybeans, etc., can not only loosen the soil but also increase the nutrients in the soil (Wei et al., 2014). Pairing with cash crops, such as chestnuts with tea trees, is widely applied in many places in China. It can not only improve the quality of tea, but also enhance the environment under the chestnut forest, making the entire system more stable and profitable (Yu et al., 2006; Wan et al., 2009). In some places, chestnuts are grown together with Chinese medicinal herbs to increase income. Growing forage grass also has its benefits. It can not only improve the soil and increase organic matter, but also provide forage for the livestock industry, achieving two goals at once.

2.3 Principles of interspecific complementarity and resource use efficiency

Intercropping is effective because different crops can complement each other's resources. For instance, different root systems are distributed in different soil layers and do not compete with each other when absorbing water and nutrients. Just like chestnuts and tea trees, the roots grow at different depths, do not disturb each other, and instead make both sides grow better (Yu et al., 2006; Wu et al., 2021c). Moreover, intercropping can also make the soil healthier, such as increasing organic matter, phosphorus and potassium, and also increase the variety of microorganisms (Wei et al., 2014; Wu et al., 2021b). More importantly, this approach can also regulate the light, humidity and temperature under the forest, reduce the impact of extreme weather, and improve stress resistance and the stability of the ecosystem (Wang et al., 2005; Wang et al., 2024).

3 Yield Performance of Chestnut and Companion Crops

3.1 Effects of different intercropping patterns on chestnut fruit yield and quality

Research has found that growing chestnuts and tea trees together not only improves the ecological environment but also enhances the yield and quality of both chestnuts and tea. For instance, this intercropping can increase the organic matter, available phosphorus and potassium in the soil, help crops absorb nutrients better and thereby increase the yield (Wei et al., 2014; Wu et al., 2021b). Intercropping can also improve the microenvironment under the forest, such as reducing direct sunlight, lowering temperature and increasing humidity, all of which are very helpful for the growth of chestnuts and tea leaves (Wan et al., 2009). In northern regions, intercropping chestnuts and tea trees enables earlier harvest of tea leaves and better quality, and also promotes the growth of chestnuts (Wang et al., 2005; Yu et al., 2006). In addition, intercropping can also make chestnut trees grow faster and bear fruit earlier.

3.2 Productivity of intercropped species and land equivalent ratio (LER)

In addition to tea trees, chestnuts can also be grown together with crops such as corn, peanuts and soybeans. These combinations can make more efficient use of land. Studies show that compared with monoculture chestnut, intercropping has richer soil nutrients, better structure and higher yield of associated crops (Wei et al., 2014). For instance, the roots of chestnuts and tea trees are distributed at different depths and do not compete for resources, which also improves the efficiency of resource utilization (Yu et al., 2006). Very often, the land utilization rate (LER) of intercropping is greater than 1. That is to say, in the same area of land, the total yield of intercropping is higher than that of monoculture (Pantera et al., 2018). Intercropping can also reduce pests and diseases and achieve more stable yields (Chadfield et al., 2022; Huss et al., 2022).

3.3 Economic return and benefit-cost ratio under each model

Many studies have also pointed out that intercropping chestnuts can bring higher economic income. Compared with only growing chestnuts, intercropping can bring an additional income from companion crops, and chestnuts can bear fruit earlier, resulting in a better overall economic return. In some cases in Europe, livestock can be raised, mushrooms or beans grown under chestnut groves to further increase income sources (Pantera et al., 2018). In addition, intercropping improves the environment, reduces pests and diseases, lowers management costs and increases the input-output ratio (Figure 1) (Chadfield et al., 2022; Huss et al., 2022).

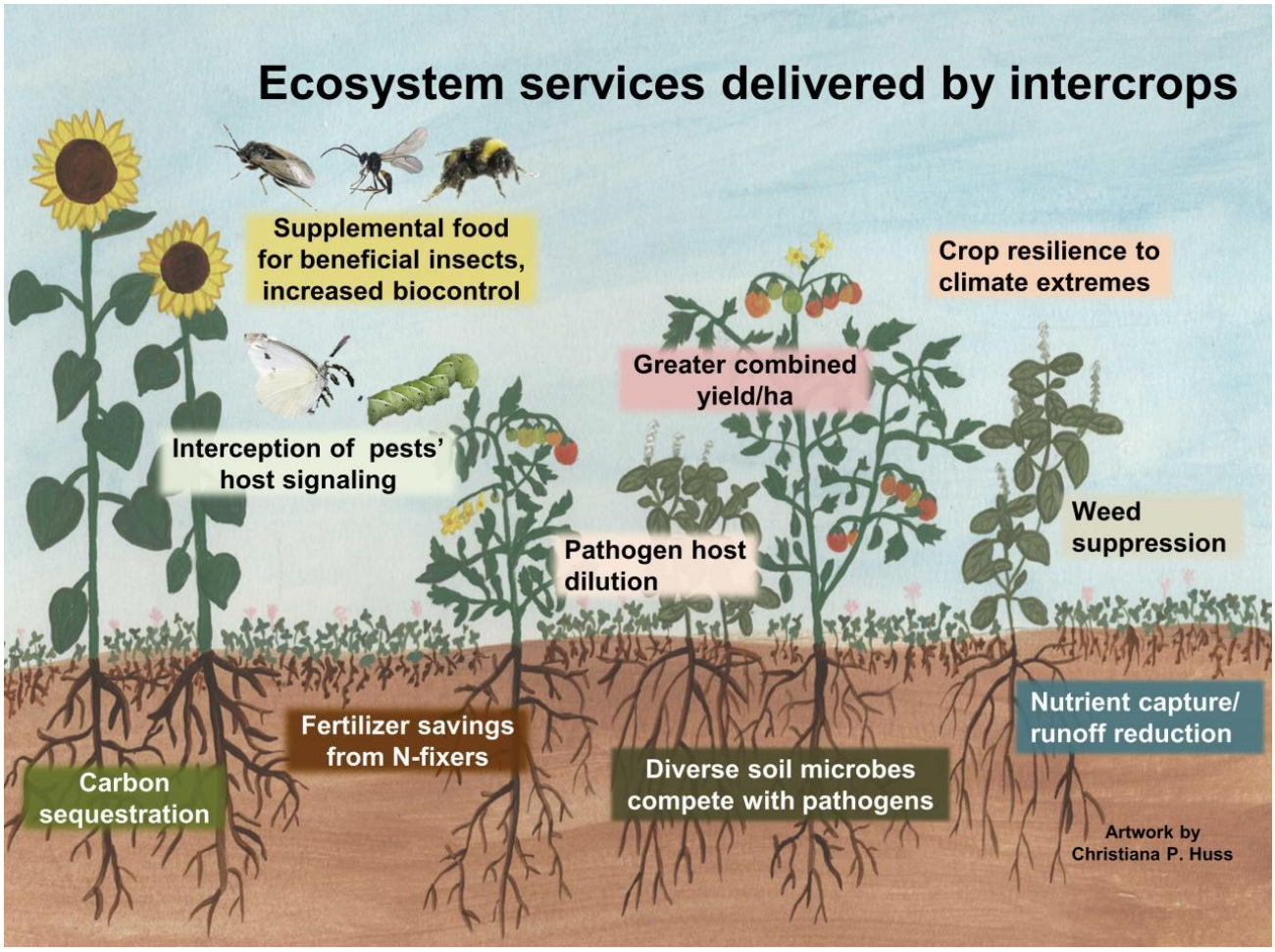

Figure 1 Illustration of benefits of intercropping for crop resilience and crop yields, management of soils, weeds, pests, and pathogens, along with environmental benefits of carbon sequestration and reduction of fossil fuel inputs (Adopted from Huss et al., 2022)

4 Ecological and Environmental Benefits

4.1 Soil improvement: organic matter, nutrients, and microbial activity

After intercropping in chestnut forests, the contents of organic matter, available phosphorus and soluble nitrogen in the soil increased significantly. Compared with only growing chestnuts or using herbicides, intercropping can make the soil more fertile and help chestnut trees grow better and bear fruit earlier. For instance, in a garden where chestnuts and tea trees are grown together, the content of organic matter, phosphorus and potassium in the soil is all higher than that in a garden where only chestnuts are grown. Such soil also has more beneficial bacteria, such as Chloroflexi and Bacteroidota, which can help decompose organic matter and release nutrients, making the soil healthier (Wu et al., 2021b). In addition, some bacteria such as Geobacter and Halomonas also occur in the intercropping system and are considered beneficial to the soil as well.

4.2 Microclimate regulation and water retention capacity

Intercropping can also stabilize the temperature and humidity in the forest by increasing plants of different layers, thereby alleviating the damage caused by extreme weather to crops. It can also enhance the soil's capacity to store and utilize water and counteract the impacts of climate change such as drought (Huss et al., 2022). However, some studies have also pointed out that in some areas, the soil infiltration rate of chestnut monoculture or chestnut-tea intercropping is not as good as that of mixed forests of multiple trees. This indicates that different intercropping methods have different effects on water retention, and the choice should be based on the actual ecological conditions (Sun et al., 2024).

4.3 Biodiversity enhancement and natural pest/disease control

Intercropping can also increase the variety of plants and insects in the garden. The diverse plant environment attracts more pollinating insects and natural enemies of pests, such as bees and predatory insects, making it easier to control pests and diseases. A richer plant hierarchy can also inhibit the growth of weeds and pests, thereby reducing the use of pesticides, helping to maintain the balance of the ecosystem and making it healthier and more sustainable (Huss et al., 2022).

5 Agronomic and Technical Considerations

5.1 Compatibility of crop species with chestnut growth cycle and canopy

What crops to grow together with chestnuts depends on whether they are “compatible”. Studies have found that some tree crops, such as cherries, red oaks and European oaks, when planted together with chestnuts, not only did not affect chestnuts, but also made chestnuts grow faster, produce more wood, and no increase in pests and diseases was found. This indicates that the growth rhythms and spatial structures among them are coordinated (Loewe-Muñoz et al., 2023). If tea trees are planted, the influence of tree age and season on soil fertility and microorganisms also needs to be considered in order to make them combine better (Wu et al., 2021b).

5.2 Management of water, fertilizer, and light competition

Water, fertilizer and light are several resources that everyone needs. When chestnuts and tea trees are grown together, if well managed, the organic matter and nutrients in the soil can increase, which is conducive to improving the absorption efficiency of crops (Wu et al., 2021b). However, the management methods should be flexibly adjusted according to the seasonal changes and the age of the chestnut trees. Practices such as not ploughing the land for a long time, covering the ground with plants, and using organic fertilizers instead of chemical fertilizers can all help maintain soil fertility, reduce the situation of “resource competition” among crops, and make the ecosystem more stable (Papaioannou et al., 2022).

5.3 Labor input, mechanization adaptability, and cost implications

For the stable development of chestnut forests, scientific management methods and technical assistance are indispensable. Some intercropping methods, such as growing together with tree crops, are more suitable for machine operation, which can reduce the number of workers and save costs (Loewe-Muñoz et al., 2023). However, at present, many places still face problems in promoting intercropping, such as the lack of technical guidance and financial support, which all affect large-scale development (Wolpert et al., 2023).

6 Comparative Evaluation of Different Intercropping Models

6.1 Strengths and weaknesses of representative intercropping systems

In chestnut economic forests, the adoption of intercropping mode can generally increase the organic matter, available phosphorus and nitrogen in the soil, which is conducive to better growth and faster fruiting of chestnut trees, and can also bring higher economic benefits. For example, when chestnuts are planted together with tea trees, it not only makes the soil more fertile, but also enriches the microorganisms in the soil, which is conducive to the recycling of nutrients (Wu et al., 2021b). Meanwhile, intercropping can also lead to higher crop yields and smaller fluctuations, and enhance the system's ability to respond to climate change (Li et al., 2021). However, the management of intercropping is more complex than that of monoculture, and it requires higher labor and technical skills. Sometimes it may also lead to a decrease in yield or an increase in the risk of pests and diseases (Huss et al., 2022). Intercropping of chestnuts and tea trees, in some areas, may also slow down soil water infiltration and affect water utilization efficiency (Sun et al., 2024).

6.2 Yield-ecology trade-offs and optimization potential

Studies have shown that reasonable intercropping can generally increase the total yield by at least 22%, and also make the soil more fertile and have better ecological functions (Li et al., 2021; Wu et al., 2021b). However, if high yields are pursued too much, some ecological indicators such as soil structure and water retention may be affected (Sun et al., 2024). To balance yield and ecology, it is necessary to select the right crops, control planting density well, and adjust management methods in a timely manner (Himmelstein et al., 2017; Huss et al., 2022). In addition, different regions and different crops have different conditions. It is necessary to breed more suitable varieties and new technologies to improve the overall performance of the system (Stefan et al., 2022).

6.3 Adaptability to different site conditions

Although chestnut intercropping has certain adaptability to different soil, climate and slope environments, the actual effect is still limited by the environment. In some areas with poor soil fertility or steep slopes, intercropping such as chestnut and tea trees can improve soil structure, increase organic matter and water retention capacity (Wu et al., 2021b; Sun et al., 2024). However, in some areas, due to poor water and fertilizer conditions, the performance of intercropping in weed control and yield increase will be compromised (Stefan et al., 2021). Therefore, when designing intercropping systems, it is necessary to combine local soil conditions, slope size, tree age and seasonal changes, and flexibly select the appropriate mode.

7 Case Study: Field Application of Intercropping Models in a Chestnut Orchard

7.1 Site description, cropping arrangements, and monitoring methods

Field experiments are usually conducted in representative chestnut orchards. Researchers will take into account important factors such as soil type, topography and climate. Common intercropping crops include legumes, grasses or some vegetables, such as corn, peppers, ryegrass, etc., which are interplanted with chestnut trees. In the study, the yields of chestnuts and intercropping crops will be measured regularly. The organic matter, nitrogen content and aggregate quantity in the soil will also be detected to understand the changes in soil fertility. Meanwhile, biodiversity and pest and disease conditions will be observed (Dong et al., 2019; Li et al., 2021; Liu et al., 2023).

7.2 Comparative results: yield data, ecological indicators, and income

Long-term experimental results show that intercropping chestnut orchards have an average yield about 22% higher than monoculture orchards, and the annual yield is more stable (Li et al., 2021). Intercropping can also improve the organic matter and nitrogen content of the soil, making the soil structure better and enhancing its fertility. It also has obvious economic benefits. For instance, intercropping chestnut orchards with corn or peppers can earn an additional 9 234.35 to 16 629.18 yuan per hectare. Intercropping with ryegrass can also increase by 8 873.92 to 9 956.56 yuan (Liu et al., 2023). However, it should be noted that the crops intercropped and the age of the chestnut orchard will affect the final yield and income. Intercropping of some natural wild grasses may instead lead to a decrease in yield and income.

7.3 Grower feedback, operational challenges, and lessons learned

Most farmers believe that intercropping chestnuts is a good way to improve land use efficiency. It can not only earn more money but also protect the ecology, which is a win-win choice. However, problems may also be encountered in actual operation, such as the difficulty in preventing pests and diseases, competition for water and nutrients among crops, lack of management techniques, and insufficient financial and policy support, etc. (Wolpert et al., 2023). Farmers have reflected that to improve the intercropping effect, the key lies in scientifically selecting the right crops, reasonably arranging the planting density, strengthening soil management and promoting mechanization (Dong et al., 2019). Experience also tells us that intercropping brings the most economic benefits in the first few years and helps to compensate for the pressure of early investment (Žalac et al., 2021).

8 Concluding Remarks

Many studies have found that intercropping can enhance the efficiency of land use and also increase the variety of crops. In some cases, the protein yield of intercropping even exceeds that of monoculture. Meanwhile, the ecological service function has also been strengthened. For instance, when chestnuts and tea trees are planted together, not only does the organic matter, phosphorus, potassium and other nutrients in the soil increase, but the microorganisms in the soil also become more abundant. All these are helpful for crops to absorb nutrients and enhance their drought and disease resistance. It is worth noting that conditions such as the age of the trees and the season can also affect the yield and ecological effects of intercropping.

When choosing an intercropping model, it is necessary to consider whether the crops can complement each other's resources, as well as the age of the trees, climate and soil conditions. For instance, the intercropping of chestnuts and tea trees is more suitable for regions with fertile soil and warm climates. This combination can effectively increase yield and stress resistance. If it is in an arid area, some drought-tolerant crops with different root

distribution can be selected for combination. In this way, water resources can be used more efficiently and the yield will be more stable. When planting, it is also necessary to pay attention to the reasonable arrangement of density and space in order to achieve the best ecological and economic benefits.

At present, most studies focus on the effects of intercropping on soil nutrients, microorganisms and resistance. However, there is still insufficient understanding of the long-term ecological service role, economic benefits and adaptability to different regions. Next, it is suggested that more long-term observations be carried out to see the impact of various intercropping combinations on the ecosystem and economic benefits. In addition, some modern molecular techniques can also be used to study how crops interact with each other. At the same time, the impact of climate change should also be taken into account, and promotion strategies suitable for different regions should be formulated to ensure the more sustainable development of chestnut economic forests.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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