

Achieving food security and high production of bioenergy crops through intercropping with efficient resource use in China

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Abstract With high rates of food and nonrenewable fossil fuel consumption worldwide, we are facing great challenges in ensuring food and energy security to satisfy the world population. Intercropping, as an important and sustainable cropping practice in agroecosystems, has been widely practiced around the world. Many studies have shown that some plants can deliver high yields when intercropped with other plants. Here, we review the biological mechanisms in improving resource utilization efficiency and illustrate the practical application of intercropping in ensuring food and energy security through improving production. Identifying suitable energy plants for marginal land, land not suitable for food crops growth, is an effective strategy to acquire high production of bioenergy, thus removing competition between the use of land for food and energy. The effective application of intercropping provides a potential pathway for production of food crops and energy plants by improving resource use efficiency and resistance to environmental stress.

Keywords intercropping, food security, energy security, high production, marginal land

1 Introduction

Food insecurity and energy risks have seriously increased from the 21st century and are likely to worsen with climate change and population growth^[1]. Food and energy security are closely related to the survival and development of the world's population. Food and Agriculture Organization (FAO) statistics reveal that food supply satisfies overall demand, but regional shortages and food insecurity are

significant^[2]. The rate of crop yield increase has slowed since the 1980s, and even stagnated in many areas^[3]. In some countries, the rate of undernutrition is extremely high, which means there is chronic inadequacy of dietary energy supply. Meanwhile, environmental costs are imposed by agricultural production, including degradation of land, emission of green gases and pollution of fresh water. With the increasing global population, the future demand for grain production is huge, thus food security is facing huge challenges^[4]. Food security is always the foundation of economic development, social stability and prosperity for a country, and it has become an urgent public concern, arguably inextricably entangled with social, political and environmental problems at many levels. Improving resource utilization efficiency and ecological protection should be urgently addressed for agricultural sustainable development in China with over 1.3 billion people and for such a large agricultural country to realize food security^[5].

Increased energy consumption follows a rapid surge in population growth. Global primary energy consumption will probably rise by 41% by 2035^[6]. Among available energy, nonrenewable fossil energy, such as oil, fuel and gas consumption, accounts for about 90% of the world's total energy consumption. BP Statistical Review of World Energy statistics reveal that oil and gas reserves can only last 53.3 and 54.8 more years, respectively^[7]. Fossil energy reserves will be exhausted one day, and many environment pollutants such as SO₂, CO₂, and suspended particulates derived from fossil energy combustion have serious effects on human health and threaten human survival and the environment^[8]. Research on and adoption of renewable and environmentally sustainable energy needs to be given immediate priority. Bioenergy as renewable and clean energy has received great attention around the world and in recent years, many countries have developed policies and objectives for bioenergy.

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Biological resources, such as energy plants, which are the most direct and low-cost bioenergy raw materials, can now be used to produce heat, electricity, and fuel^[9]. With limited cultivated land in China, the development of bioenergy must follow the principles of not using the grain intended for human consumption and not occupying the land intended for grain production^[10]. Improving bioenergy production and ensuring food security should be synchronized. According to the statistics, there is approximately 260 million hm² of wasteland in China^[11]. Cultivation of energy plants on this land would effectively improve energy production, and also prevent water and soil erosion, and protect the environment, which is likely to be an important driver for other industries. The exploitation of marginal land to cultivate energy plants needs to be well reasoned, and other effective strategies should be tried to ensure sustainable development of bioenergy system in order to prevent bioenergy industry using food as raw materials; food which is needed for food security.

Intercropping, the mixed growth of two or more crop species simultaneously, is practiced on more than 28 million hm² annually in China^[12], and has been widely practiced worldwide, such as Africa, India, Latin America and South-east Asia^[13]. The advantages of numerous intercropping systems to enhance high productivity have been demonstrated^[14]. Researchers have shown that intercropping yields can benefit from niche partitioning in which crop species utilize different soil (nutrient) and aboveground resources (light, water) spatially and temporally leading to higher resource utilization than when grown in monoculture^[13,15]. The right combinations of crops can also reduce pests and disease attack, and help in controlling weeds^[16]. So, this pattern applied in bioenergy production can probably improve the efficiency of marginal land use and enhance biomass production. A number of studies have shown that intercropping has great potential to contribute to food and energy security, as an efficient cropping system for sustainable agriculture economically and environmentally.

2 Biological mechanisms of improved resource utilization in intercropping system

2.1 Intercropping improves acquisition of light, heat and water

The right combination of crops could increase the efficiency of solar radiation use by extending light time and improving light capture for high yields^[13,17]. C4 plants with high light saturation and C3 plants cultivated concurrently in the same field enhance the quality of light. Also, the C3 plants have high low energy light utilization, so as to improve light use efficiency. Intercropping with crops of different height, leaf type, plant type,

can increase plant density and leaf area index, thus improving the amount of light interception^[17]. The mean efficiency of radiation use of intercropped peanut was 79% higher than that of peanut in monoculture. The combined radiation-use efficiency was more than twice that of peanut alone, but slightly lower than that of corresponding maize alone. The harvest index of intercropped peanut was about 13% lower than that of peanut alone, but monocultured peanut only produced 46% of the pods of peanut in intercropping system. These results indicated that maize/peanut intercropping could help to increase yields through the efficient utilization of available light^[18]. At the molecular level, photosynthesis-related proteins were both in higher abundance in the young leaves of intercropped peanut and maize compared to the plant in monocultures. Therefore, intercropping of maize and peanut can increase photosynthetic efficiency^[19].

Water is a critical factor in metabolism of plants and essential for achieving high yields. Water use efficiency is higher in intercropping compared to monoculture due to the spatial and temporal difference in the water requirements of the component crops^[20]. Due to the different distribution of roots, component crops can take up water from different depths in soil^[15]. Variation in plant density often affects water-utilization efficiency. This suggests that only the right combination of plants can achieve improved water utilization. Intercropped plants have increased ability to conserve water, largely because of high leaf area index and higher leaf area. Growth of maize and pea together lead to increased water uptake by pea^[21]. Wheat/soybean intercropping increased water and radiation productivity in the south-east Pampas of Argentina^[22]. The combined water use efficiency was 52% higher than for single crops in a maize/sunhemp intercropping system^[23].

2.2 Intercropping improves acquisition of nutrients

Intercropping is a cropping system delivering resource use efficiencies^[3]. The mechanisms of achieving high-yield in intercropping systems are generally attributed to niche complementarity and positive interspecific interactions in resource use^[24]. Research on rhizosphere processes and nutrient utilization in intercropping systems has provided a wealth of physiological evidence for interspecific facilitation between species^[25].

2.2.1 Nitrogen

The combined N uptake is higher in legume and non-legume mixtures, which will improve nutrient status of crops. The mechanisms underlying N facilitation are probably as follows: (1) crops in an intercropping system acquire different N sources in order to grow well, (2) non-legume crops take up N₂ fixed by legume companion crop in different ways, such as direct root contact, root

exudation and mycorrhizal association, and (3) the N fixing performance of the legume is improved, due to the non-legume competing for N from the soil and fertilizer. Farmers all over the world have known that legume/cereal intercropping increases the N nutrition of cereals leading to high yield of cereals, especially in unfertilized fields^[26]. Wheat/soybean or maize/faba bean intercropping enhanced N acquisition significantly compared with monoculture^[27,28]. Similar results with N uptake have also been found in barley/pea and sorghum/soybean intercropping^[29,30]. N derived from the atmosphere by faba bean when intercropped with maize increased by 8%–33% at the start of flowering, 54%–61% at peak flowering, 18%–50% at the grain-filling stage, and up to 72% at maturity compared with faba bean alone. Based on experimental results, about 100 kg·hm⁻² of N fertilizer can be saved in faba bean/maize intercropping^[31].

2.2.2 Phosphorus

Plants often perform poorly on soils with low concentrations of available P. Some of these soils contain a considerable amount of P that is unavailable to most species. P occurs in both organic and inorganic forms in soil, where organic P may account for 30%–70% of total P^[32]. Plants cannot take up organic P directly, however, and organic P needs to be hydrolyzed by microbial or root-released phosphatases. Plants growing together often comprise species with and without P-mobilizing ability. P-mobilizing plants can facilitate non-P-mobilizing plants by mobilization of either organic or insoluble inorganic P, through release of carboxylates, protons and enzymes from the roots. P-mobilizing plants release protons (in alkaline soil) and/or carboxylates (in any soil) into the rhizosphere to solubilize phosphates that are taken up by both the P-mobilizing plants and non-P-mobilizing plants in intercropping systems^[33]. In P-impooverished soil, some species form dauciform roots or cluster roots^[34]. Dauciform roots or cluster roots exude carboxylates and mobilize soluble P in soil. These plants enhance P acquisition for themselves and benefit their neighbors where P is limiting^[35]. Numerous studies have shown facilitation of P utilization in the rhizosphere of intercropping systems. Lupin, pigeon pea and peanut are P-mobilizing crops and when intercropped with wheat, sorghum or maize, respectively, the P acquisition improved significantly^[24,36]. Chickpea, a species that releases acid phosphatases from roots into the rhizosphere to hydrolyze organic P into inorganic P, facilitating P acquisition by associated non-mobilizing wheat and maize^[37]. Faba bean can release protons, malate and citrate into the rhizosphere, thus mobilizing insoluble soil P to enhance P acquisition by the associated maize. Some intercropping systems can reduce fertilizer P requirements by efficient use soluble P in soil. Fertilizer P can be reduced by at least two thirds in faba bean/maize

intercropping compared to that in wheat/maize intercropping^[24].

2.2.3 Micronutrients

The World Health Organization reports that the lack of micronutrients such as iron and zinc represents a major threat to the health and development of populations around the world^[38]. Enriching the nutrient content of crops as they grow provides a sustainable solution to malnutrition. In addition to mineral fertilization, standard breeding and transgenic approaches, intercropping has received increasing attention as a way to improve nutrient status of crops^[39]. However, relatively little research has been undertaken on the effects of intercropping on micronutrient status of crops. Some studies indicate intercropping between dicots and graminaceous species, which are strategy I and strategy II plants, respectively, would be the key to Fe and Zn biofortification^[40]. In strategy I, an acidification/reduction mechanism, based on the secretion of protons into the rhizosphere, and the reduction of Fe(III) to Fe(II) by root ferric chelate reductase is used to enhance Fe solubility prior to uptake. The response of strategy II species include the biosynthesis and secretion of phytosiderophores which are chelators with a high affinity for Fe(III). Because of the secretion of these compounds, Strategy II species are more effective at mobilizing precipitated Fe and less affected by high pH and bicarbonate levels. Therefore, their tolerance to Fe stress in calcareous soils is higher than that of Strategy I plants^[41]. Recently, several researchers have reported that graminaceous species improve Fe nutrition in Strategy I or low-phytosiderophore-secreting plants when they are cultured together, as well as enhancing Zn uptake^[42]. Peanut/maize intercropping is a successful crop management strategy that results in more effective and sustainable practice for farmers due to improvement in Fe content of the peanut plants. When peanut and maize are grown together, the secretion of phytosiderophores from maize, as Strategy II plant, resulted in the efficient uptake of Fe(III)-phytosiderophore complexes from the rhizosphere by peanut^[43]. Peanut/maize intercropping not only improved the Fe status of peanuts, but also improved the shoot concentrations of other nutrients, including K, P and Zn. Moreover, the concentration of Fe and Zn in peanut seeds increased greatly in intercropping systems^[44]. Also, improvement of Fe and Zn uptake in chickpea/wheat intercropping through interspecific root interactions has been reported^[45].

2.3 Intercropping reduces the impact of pests, disease and weeds

Intercropping has also been used as an efficient technology to reduce the impact of pests, disease and weeds.

Compared with monoculture, intercropping improves the ability of crops to suppress pests, disease and weeds effectively, allowing significant reduction in pesticide use. Intercropping is seen as a more economically and environmentally sustainable strategy for the development of agriculture^[44].

Some researches have shown the biodiversity of ecosystem effects on phytophagous insect behavior, including host location, mating, movement, oviposition and feeding. There are probably two strategies in intercropping systems to control insect pests. Some plants can release volatile compounds that affect the ability of insects to locate hosts thereby reducing insect damage. The germination rate of sugarcane intercropped with garlic was higher and termite infestation rates significantly lower than in sugarcane monoculture because of volatiles from garlic repelled the termites^[46]. Tobacco plants near clipped sagebrush had greatly reduced leaf damage from grasshoppers and cutworms during three field seasons compared to unclipped controls^[47]. Some other plants can trap pests in order to protect the host crops. When sesame is intercropped with cotton, sesame with a higher rate of parasitic natural enemies can attract bollworm away from the cotton^[48]. The damage to the kales caused by *Lygus rugulipennis* decreased when they were intercropped with alfalfa because it attracts *L. rugulipennis*^[49].

Crop disease is also a major limiting factor in agroecosystems. The total yield loss caused by crop disease is estimated at 10% for the whole world^[50]. Crop heterogeneity is a possible solution to the vulnerability of monocultured crops to disease. Intercropping pattern can reduce disease severity in experimental plots and in the field. The fungus that causes blast disease in rice, which spreads through multiple cycles of asexual conidiospore

production during the cropping seasons, cause necrotic spots on leaves and necrosis of panicles^[51]. Disease susceptible and resistant rice cultivars planted together had 89% greater yield and 94% less blast compared to single cultivar monoculture^[52]. Garlic/rape intercropping reduced white rot in garlic^[53]. A container-grown watermelon/rice combination relieved the occurrence of watermelon fusarium wilt which is the major obstacle to continuous cropping of watermelon^[54].

The loss of yield resulting from weeds accounts for 10% of the yield potential, and if not regulated the yield loss can reach 46%–96%^[55]. Physical and chemical methods have been used by farmers around the world to control weeds competing with crops for light, water and nutrients. Physical methods are labor intensive and chemical methods can pollute the environment, harming human and animal health and limiting sustainable development of agriculture. Secondary metabolites produced by one kind of plant can inhibit the growth of another kind of plant. Taking advantage of this phenomenon can effectively suppress weeds in intercropping systems. Wheat intercropped with chickpea, not only increased land use efficiency, also significantly reduced the density and biomass of weeds in the field^[56]. Banana intercropped with soybean or maize increased the yield of soybean and maize and controlled weeds, thus reducing the use of herbicides^[57].

Intercropping promotes stability and productivity. These positive biodiversity effects on stability and productivity arise from complementarity between species in above and below ground interactions in both natural and agricultural systems (Fig. 1). The above and below ground interactions can be exploited to improve plant growth and nutrition, with benefits from mutualists and defense against

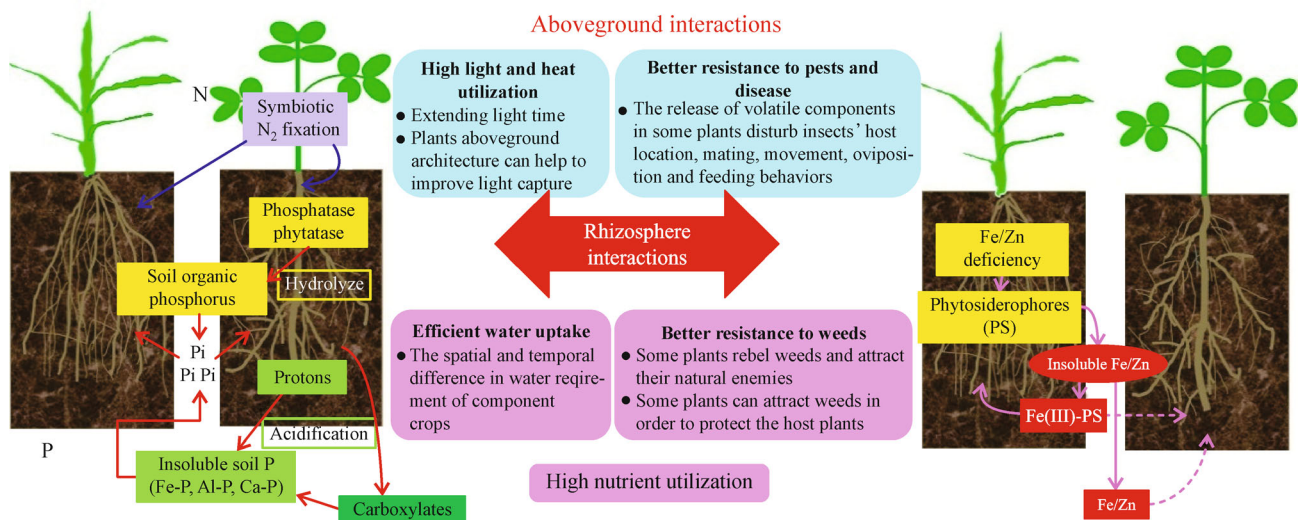


Fig. 1 Biological mechanisms of improving resource use efficiency in intercropping system

antagonists. The ways in which these can influence food security and bioenergy plant production strategies are described below.

3 Benefits of intercropping for food security

3.1 Beneficial effects of intercropping on food security through improving nutrient resource use efficiency

Global agriculture faces considerable challenges and risks to ensure food security by increasing yields while reducing environment impacts^[2,4]. Developing countries, including China, Ethiopia, India, Indonesia, Mali and Niger have paid considerable attention to enhancing productivity through intercropping^[58]. There are very close relationships between yield advantage and nutrient uptake in intercropping systems. Exploiting beneficial above and below ground interactions could improve nutrient uptake, and form a part of a sustainable and long-term strategy to aid in improvement of crop yields (Table 1). There are a number of intercropping systems in north-west China including maize/faba bean, maize/potato, maize/vegetable, wheat/maize, wheat/soybean, wheat/sunflower, wheat/vegetable systems^[27,28,59,63]. N acquisition of faba bean significantly increased when intercropped with maize and the increase in grain yields of faba bean and maize were 21%–23% and 6.5%–11.8% of that in monoculture, respectively^[60]. In a wheat/maize intercropping system, the yield of wheat was about 48%–56% higher compared to wheat alone. The growth of maize was suppressed during the growth stage of the wheat. However, after wheat was harvested, the maize recovered from the earlier suppression from the wheat and yield was higher than or similar to maize alone^[28]. The yield of maize intercropped with bean increased by 26%^[59]. The concentration of iron in wheat grain and the concentration of iron and zinc in chickpea seeds both increased when they were grown together in the same field experiment. Intercropping could relieve potential Fe and Zn nutrient deficiency, particularly

in harvested seeds^[61]. Adopting such cropping systems with a more efficient use of soil nutrients and less reliance on chemical fertilizers is one promising way to develop sustainable crop production while maintaining high yields^[63,64]. It is suggested that intercropping is a vital strategy for sustainable agriculture with high yields, high efficiency of nutrient use and environmental benefits^[65].

3.2 Benefits of food security through mutualism in intercropping systems

Beneficial interactions between crop species and mutualists allow improved yield and reduction of both biotic and abiotic above and below ground stresses and hold the potential to ensure productive and stable agroecosystems. Africa faces serious risks in feeding its population, and has reverted from being a net exporter of agricultural commodities to being a net importer over the last three decades. The amount imported is increasing at an almost exponential level^[66]. With the increase of human population, average growth in food production in the continent has at best stagnated, and even declined over the last few decades in several places within the continent^[67]. More than 500 million people will face food security risks by 2020^[1]. One of the main reasons of the chronic food insecurity in Africa is poor crop yields, largely caused by insect pests, weeds and degraded soils. Smallholder cereal yield is severely constrained by insect pests and parasitic weeds in the genus *Striga* (Orobanchaceae)^[68]. The yield loss damage caused by the larval stages of stem borers can be up to 88%^[69]. Push-pull technology, based on locally available companion plants, effectively addresses these constraints so as to increase grain yield. It involves intercropping cereal crops with a forage legume, *Desmodium*, and planting Napier grass as a border crop. *Desmodium* repels stemborer moths (push) and attracts their natural enemies, while Napier grass attracts them (pull). *Desmodium* is very effective in suppressing *Striga* while improving soil fertility through nitrogen fixation and improved organic matter content. Studies have shown that

Table 1 Evidence of high yield acquisition through improving nutrient uptake and reduce pests and weeds

Resource utilization	Type of evidence	Reference
High nutrient acquisition	The yield of wheat was about 48%–56% higher compared to the sole wheat in wheat/maize intercropping system	[28]
	The yield of maize intercropped with bean increased by 26%	[59]
	The increase of grain yields of faba bean and maize were 21%–23% and 6.5%–11.8% of that in monoculture respectively	[60]
	The concentration of iron in wheat seeds and the concentration of iron and zinc in chickpea seeds both increased when they grew in the same field experiment simultaneously	[61]
Resistance to disease	Disease-susceptible rice varieties and resistant varieties planted together had 89% greater yield and blast was 94% less severe than when they were grown in monoculture	[52]
Reduce weeds and pests	Banana intercropping with soybean or maize can increase yield of soybean and maize and control weeds	[57]
	Control of striga and cereal stemborers resulting in significant increases in grain yields such as maize, sorghum and finger millet	[62]

using push-pull technology provides effective control of stemborers and *Striga*, resulting in significant grain yield increases^[62]. Both companion plants provide high-value animal fodder, facilitating milk production and diversifying farm income^[70].

Over 55000 smallholder farmers in East Africa have used this push-pull technology^[16]. Adoption of this technology can suppress pests and control weeds effectively with low-cost, as well as improve soil fertility and prevent soil erosion. Farmers can benefit from this technology, and it is an effective way of exploiting intercropping for sustainable development of agriculture.

4 Production of energy plants by intercropping

Fast economic development has resulted in a significant increase in energy demand in China during the 21st century. Exploiting renewable bioenergy is one of the most effective measures for solving the energy shortage. Energy plants are the main source of biomass energy. As China cannot afford biomass energy production from its croplands, marginal lands will be important for biomass energy production^[71]. In recent years, China has given greater priority to energy plants and to identifying marginal land suitable for energy plant production.

4.1 Benefits of energy plant production in marginal lands in China

The total area of marginal lands suitable for energy plants in China is about 114 million hm², and these lands are mainly found in Inner Mongolia, Sichuan, and Yunnan^[10]. In Inner Mongolia and western regions, water resource deficiency is one of the main limiting factors for high crop yields. Large-scale drip irrigation technology has been adopted since the 1990s, and a set of mature technologies involving efficient utilization of water resources have been established in this region. Irrigation uses 95% of the water resource potential of Xinjiang Province^[72]. The water suitable for crop growth is quite limited, but there is an abundance of poor quality water, with a preliminary estimate of 8.82 billion m³. Plants with high drought and salt tolerance can be irrigated with poor quality water to achieve high biomass, while the common crop plants cannot grow well with this poor quality water. The salt in soil with good permeability can be easily washed off to avoid affecting the growth of plants from excessive salt accumulation^[73]. Thus, the north-west arid regions have evident advantages for high production of resistant bioenergy plants.

There are many plant species in China, more than 4000 of which show high resistance to salt, drought and/or low temperature, and that have been identified as having

potential as energy plants^[74]. Of these, Barbados nut (*Jatropha curcas*), Chinese silvergrass (*Miscanthus sinensis*), Jerusalem artichoke (*Helianthus tuberosus*), and sweet sorghum (*Sorghum bicolor*) are the main energy plants in China^[75]. Jerusalem artichoke has high tolerance to drought, diseases and insect pests, and can survive at between -40°C and -30°C . In the west region of Heilongjiang Province, Jerusalem artichoke can have a tuber yield of 30–45 t·hm⁻², even up to 75–150 t·hm⁻². Sweet sorghum can grow in different regions from the north to the south of China and can produce 4–6 t·hm⁻² of ethanol^[76]. *Caragana korshinskii* and *Xanthoceras sorbifolia* are widely distributed in north-west regions. They have been used successfully used to produce biodiesel and organic acid. Bioenergy can replace fossil energy to reduce greenhouse gas emissions. If more energy plants were grown in marginal land in China, this would contribute to promoting the diversification of energy structure and ensuring energy security. Increasing the amount of clean energy ratio can reduce pollution by the energy industry, improving the environment and increasing biodiversity by high vegetation coverage, as well as reducing soil erosion, which together can deliver coordinated development of energy and environmental protection. The development of the biomass energy industry at a large-scale can also provide employment for the rural workforce and therefore contribute to the improvement of the rural economy^[70].

4.2 Achieving high yield of high tolerance energy plants through intercropping

There has been limited research on how to improve energy plant production. Energy plants are often planted as a single species, which can cause serious ecological imbalance and loss of biodiversity. Different energy plants, or energy plant-crop combinations can be grown together. Using intercropping to improve the output of biomass resources and land output is technically feasible. Firstly, intercropping can improve resource use efficiency and tolerance to environment stress in order to achieve high yields^[13,16]. Secondly, intercropping can help to prevent water and soil loss in marginal lands and protect the environment. Ideally, high biomass and high energy-yielding plants should be planted, and less efficient plants eliminated to increase the productivity of the energy plant system. Use of intercropping is suitable for China, which cannot only avoid using the grain intended for human consumption and occupying the land intended for grain production, but also form an eco-friendly, low-cost new planting system, which can restore the ecological balance in the environment. Achieving these economic and ecological benefits will also increase farm incomes and promote sustainable and stable development of both agricultural and biomass energy production.

Well considered plant combinations are an important

way to insure the productivity of intercropping systems. Cassava is mainly grown in the north of China. Some researchers have shown the yield of cassava could be increased when intercropped with peanut or soybean and this system can improve soil nutrient utilization^[77]. Preliminary studies have reported that some highly efficient energy plants are suitable for production in the western region of China, such as *Haloxylon*, *Salix* and *C. korshinskii*^[75]. It is worth noting that halophytes with high biomass are likely to have potential as energy plants that can grow well on large areas of saline soil in Xinjiang. Legume forages that grow in barren soil, including alfalfa, sweet clover and *Sophora alopecuroides*, with strong biological nitrogen fixation ability, can supply their own demand for nitrogen for growth and also benefit their neighbors. Legume forages and energy plants intercropping could promote the productivity of energy plants, while reducing nitrogen fertilizer inputs. Taking advantage of above and below ground interactions between legume forages and energy plants, and promoting energy plants and economic crop production has important theoretical and practical significance. Apricot/*C. korshinskii* intercropping is also common in Inner Mongolia. The right combinations of local plants, such as intercropping arrow tongue peas with *C. korshinskii* or switchgrass, *S. alopecuroides* intercropping with *Haloxylon* or *Cistanche*, can improve the land output and bring economic benefits. So intercropping also has wide development prospects for semi-arid areas and can contribute to ensuring energy security.

5 Conclusions

This review highlights the biological mechanisms involved

in intercropping that improve natural resource utilization efficiency and control crop disease, pests and weeds to achieve higher crop production, and illustrates the practical application of intercropping in food and energy production. Faced with a serious food and energy crisis, the effective application of intercropping technology provides a potential pathway for cereal crop and energy plant production by improving light, heat, water and nutrient resources use efficiency and tolerance to environmental stress. It is suggested that fine-tuning cropping patterns at different scales from individual to ecosystem level will be an economically and environmentally sustainable way for ensuring food and energy security.

However, intercropping is not always beneficial and does not always increase yields^[78]. So the right combination of plants is critical for successful intercropping. Researchers should further utilize the genetic characteristics and physiological traits of appropriate plants to help farmers to select productive combinations.

Internationally, researchers have begun to pay attention to energy plants inform the 1950s. Although the study of energy plants in China has come later than some other countries, China has, with many energy plant species and large areas of marginal land, good prospects for developing bioenergy production. Cultivation of energy plants in marginal land cannot only provide energy resources, but can also improve the land output and bring economic benefits, while preventing soil erosion, wind erosion and desertification (Fig. 2). However, at present, energy plants production on a large scale face difficulties in the mechanization of planting, harvesting and processing, so appropriate equipment needs to be developed for bioenergy production. In addition, more attention needs to be given to how to efficiently produce clean bioenergy from energy plants and at low cost.

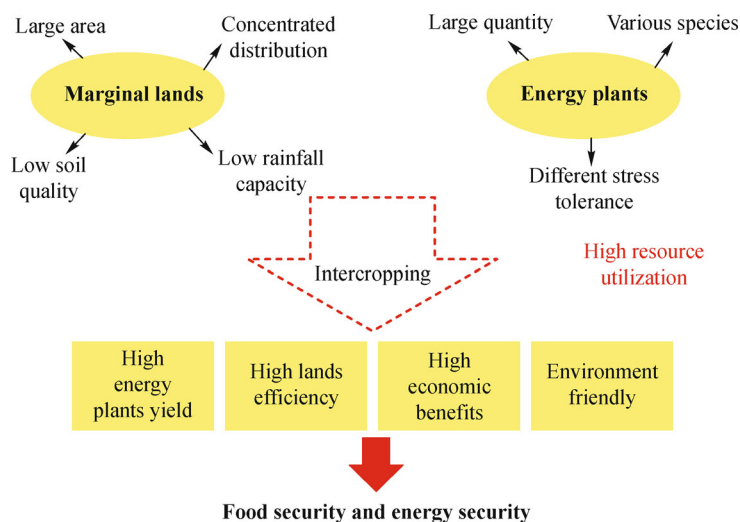


Fig. 2 Model chart of improving energy plant production through intercropping in marginal land to ensure food and energy security

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