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REVIEW

DESIGNING DIVERSIFIED CROPPING SYSTEMS IN CHINA: THEORY, APPROACHES AND IMPLEMENTATION

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KEYWORDS

Agriculture Green Development, crop diversification, cropping system modeling, ecosystem services, sustainable agriculture

HIGHLIGHTS

- Agricultural green transformation of China requires restructuring of cropping systems.
- Ecosystem services enhanced by crop diversification is key to sustainable agriculture.
- Crop diversification improve ecosystem services at field, farm and landscape scales.
- Cropping system design should meet regional characteristics and socio-economic demand.

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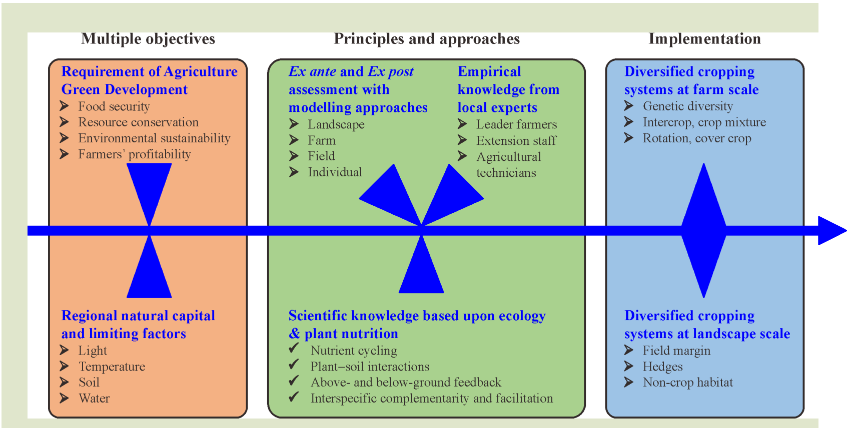
GRAPHICAL ABSTRACT



ABSTRACT

Intensive agriculture in China over recent decades has successfully realized food security but at the expense of negative environmental impacts. Achieving green transformation of agriculture in China requires fundamental restructuring of cropping systems. This paper presents a theoretical framework of theory, approaches and implementation of crop diversification schemes in China. Initially, crop diversification schemes require identifying multiple objectives by simultaneously considering natural resources, limiting factors/constraints, and social and economic demands of different stakeholders. Then, it is necessary to optimize existing and/or design novel cropping systems based upon farming practices and ecological principles, and to strengthen targeted ecosystem services to achieve the identified objectives. Next, the resulting diversified cropping systems need to be evaluated and examined by employing experimental and modeling approaches. Finally, a strategic plan, as presented in this paper, is needed for implementing an optimized crop diversification in China based upon regional characteristics with the concurrent objectives of safe, nutritious food production and environmental protection. The North China Plain is used as an example to illustrate the strategic plan to optimize and design diversified cropping systems. The implementation of crop diversification in China will set an example for other countries undergoing agricultural transition, and contribute to global sustainable development.

1 CHALLENGES FOR SUSTAINABLE CROP PRODUCTION

Intensive agriculture, characterized by high inputs and high outputs, has made a tremendous contribution to meeting the food demand of an increasing population across the globe. However, it has also led to huge environmental consequences and weakened ecosystem services[1–3] through processes such as soil acidification, soil quality deterioration and loss of wildlife species diversity[4,5]. Therefore, development of an innovative and highly sustainable and resilient agricultural regime is urgently required to reduce excessive consumption of non-renewable resources (e.g., rock phosphate) and the negative environmental consequences of intensive agriculture while ensuring sufficient safe and nutritious food for the increasing population of the world[6,7].

Agricultural science has provided many technical innovations including integrated soil-crop system management to produce more crop yield with less agrochemicals[8], and to enhance resource use efficiency through exploiting the biological potential of crops[9]. With best management practices[10] it is possible for millions of Chinese smallholder farmers to reduce nitrogen application by nearly 16%, reactive N losses by nearly 16% and greenhouse gas emissions by nearly 8%[10], and for groundwater nitrate concentrations due to excessive agricultural N input to be lowered to meet drinking water safety levels[11]. In contrast to intensive agriculture based on monocropping, crop diversification (e.g., intercropping) has been widely demonstrated to enhance grain yield and nutrient use efficiency through exploiting niche differentiation and positive interactions between organisms while concurrently reducing environmental impacts[12–15]. Therefore, it is imperative to harness ecosystem services enhanced by crop diversification to achieve sustainable agriculture.

2 BENEFITS OF CROP DIVERSIFICATION

Crop diversification is the agricultural practice of concurrently growing a range of crop species in a farm system through intercropping, crop rotations and cover crops, as well as increasing plant diversity in non-crop habitats such as tree lines, grasslands[16,17] and flower strips[18]. Crop diversification is considered to be one of the important components of ecological intensification of agriculture, relying on ecological principles such as positive interactions between species to increase crop yields and reduce dependence on mineral fertilizers and synthetic pesticides. Compared with intensive monocropping, crop diversification can improve multiple ecosystem services of agroecosystems at field, farm and landscape scales.

2.1 Field scale

Intercropping, one of the key strategies for crop diversification, has shown both relative and absolute yield advantages compared to monoculture and the size of the benefits depends on crop species combination, temporal and spatial arrangement of crops and management practices[12,13]. Intercropping makes use of morphological or physiologic differences of different crops to increase the complementarity and efficiency of resource use, such as the complementary utilization of N resources and light and heat resources[3,14,19]. Crop rotation, another important diversification strategy, has increased grain yield by 20% in China compared to continuous cropping systems[20]. Furthermore, crop rotation has increased total soil carbon content by 3.6% by adding one or more crops, and the further addition of cover crops in the rotation system has increased the total soil C by 8.5%[21]. These benefits of crop rotation are largely attributed to the reduction of pests in various ways such as inhibiting the growth and preventing the reproduction and spread of pests. The basic principle is to remove the conditions that favor the growth and reproduction of pests[3]. Crop rotation can also break the life cycle of weeds, pests and pathogens with limited mobility and narrow host ranges[22]. Crop diversification has always been regarded as an environmentally-friendly model. For example, cover crops can reduce nitrate leaching by 35%[23] and lower the ineffective evaporation of water by reducing the area of bare ground. Intercropping can produce more crop yield per unit water than sole cropping[24–26]. Last but not least, a large number of studies have shown that diversified cropping systems are spatially and temporally more stable than the monocropping systems and may better cope with the adverse effects of climate change[27,28].

2.2 Farm scale

Compared to farms growing only a few crops, diversified/mixed farming has certain advantages in terms of economic, ecological and social benefits. In terms of economic benefits, diversified/mixed farming achieves economic growth in three main ways: (1) reasonable introduction of high-value crops and animal production benefits brought about by growing diversified feed crops[29–31]; (2) application of intercropping and rotation can reduce agrochemical inputs and increase income[14,20]; and (3) adaptation in extreme climates and avoidance of variable market conditions[32]. With respect to the ecological benefits, the mechanisms for diversified crop farms to achieve efficient resource use and eco-environmental friendliness mainly include: (1) diversified cropping systems that include, for example, crop rotations, intercropping and cover crops can contribute to pathogen, pest and weed control[33–39] and soil fertility increase, reducing the inputs of pesticides and fertilizers in farm production and mitigating negative environmental impacts[40]; (2) the optimization and adjustment of the spatial and temporal layout of crops can overcome the resource constraints at a whole farm scale to achieve efficient use of agricultural resources[41]; and (3) mixed farms can achieve efficient nutrient cycling, increase soil organic matter content and reduce nutrient loss[42]. In terms of social benefits, diversified cropping systems can produce a range of plant-derived foods and provide multiple dietary options on the farm, thereby ensuring the food and nutrition security of farmers[43]. However, current research on the comprehensive benefits of diversified cropping systems at farm scale is relatively limited.

2.3 Landscape scale

Agricultural landscapes are the visible outcome of the interaction between agriculture, natural resources and environment, and encompasses culture, livability and other social values[44]. Agricultural intensification and landscape simplification will lead to the loss of biodiversity, which will weaken the regulation and supporting services of agricultural ecosystems and reduce sustainability[45]. Increasing the complexity of agricultural landscape through land sparing and land sharing strategies can improve regulation, supporting and cultural services, making an overall balance between various services[46,47]. The land sparing strategy, defined as some land being used intensively to produce agricultural commodities while other land is set aside for conservation, can be achieved by increasing semi-natural habitats in agricultural landscapes. Semi-natural habitats can provide habitats for beneficial insects and food resources[48], which is conducive to the improvement of biological control and pollination services[49]. For example, planting flower belts within or adjacent to wheat fields can effectively reduce 61% of yield loss caused by the cereal leaf beetle[50]. Hedgerows can promote various soil-related ecosystem services such as soil C sequestration[51]. Agroforestry can provide services such as reducing soil erosion, increasing biodiversity and increasing soil fertility[52]. The land sharing strategy, meaning that less intensive production techniques are used to maintain some biodiversity on agricultural land, mainly increases the diversity of ecosystem services by increasing species diversity on the same piece of land, such as intercropping and mixed planting. Intercropping can increase soil C and N status and improve soil supporting services[53]. Intercropping with flowering plants will also increase pollination services and increase yield and quality, for example, intercropping capsicum (*Capsicum annuum*) with flowering basil (*Ocimum basilicum*)[54]. Current research mostly focuses on single or several ecosystem services but future research needs to focus also on comprehensive assessment, management, and trade-offs of ecosystem services.

3 FRAMEWORK, PRINCIPLES AND METHODOLOGY OF CROP DIVERSIFICATION SCHEMES

3.1 Design framework

Despite widely demonstrated benefits delivered by diversified cropping systems, an innovative design of crop diversification is urgently required to meet agricultural green transformation in China. Crop diversification schemes need to simultaneously consider local natural endowments and limiting factors (including light, temperature, soil and water), and also the requirements of agricultural green development (e.g., food security, resource conservation, environmental sustainability and farm profitability), and finally prototyping multi-objective cropping systems (Fig. 1). Then a combination of top-down and bottom-up approaches are employed to develop those cropping systems. The top-down approach mainly uses modeling tools (see below) across the landscape, farms, fields and individual scales in combination with local experimental data as well as experts and farmer knowledge to perform *ex ante* and *ex post* assessment and prototype cropping systems that meet the above objectives. The bottom-up approach is mainly based on knowledge from ecology and plant nutrition[55] such as nutrient cycling, plant–soil interactions, above- and below-ground feedback, interspecific complementarity and facilitation. These principles will maximize biological potential to reduce the input of agricultural chemicals. The promising cropping systems

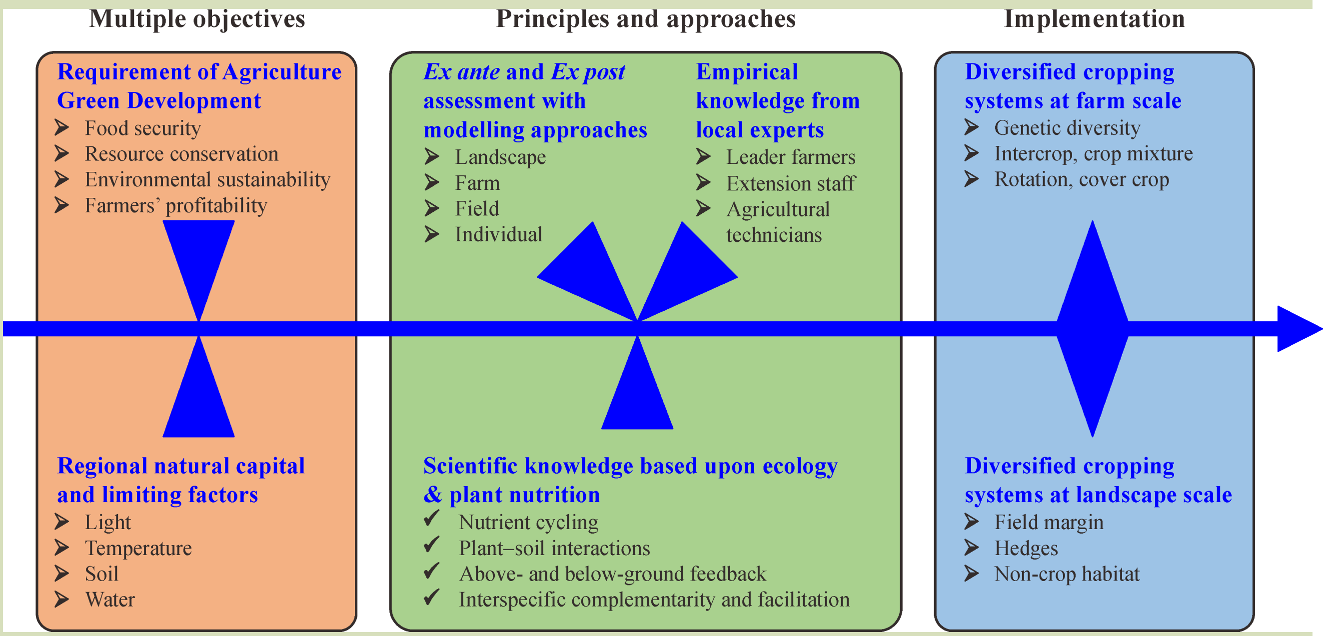


Fig. 1 Framework of crop diversification schemes.

screened through modeling and ecological principles will be monitored and evaluated in experimental fields. Superior cropping systems will be examined and optimized in the field in close interaction with local farmers. Finally, these diversified cropping systems developed across multiple scales will be implemented in a specific region to push agricultural green transformation in China.

3.2 Ecological principles

The ecological principles of crop diversification schemes such as interspecific complementarity and facilitation and plant–soil feedback are applied by increasing the temporal and spatial diversity of cropping systems by beneficial crop allocation and cropping sequences (e.g., intercropping, rotation and cover crops). Interspecific complementarity and facilitation are the key principles to synergistically increase resource use efficiency both above- and below-ground at a field scale[52,55]. Different crops have their distinct strategies for resource acquisition and use[56]. A beneficial crop combination can take advantage of complementary effects of different crops with distinct strategies to improve resources of the whole diversified system. For example, intercrops with different plant height can increase light interception and reduce light competition between species[57], and species combinations with shallow and deep roots can make full use of nutrients and water at different soil depths[58]. Combining species with specific adaption for different forms of P can increase P use efficiency[58,59]. In addition, intercropping legumes with cereals provides complementarity in utilization of N derived from soil and atmosphere. Recent studies have shown that intercrops with maize can increase biological N_2 fixation of intercropped faba bean by depleting root-zone soil nitrate concentrations available to faba vean and by promoting nodulation and N fixation in response to specific maize root exudates[60,61]. The principle of plant–soil feedback provides guidance for designing beneficial crop rotations that maximize nutrient cycling and minimize pest and disease stress[62,63]. For example, the legacy effect of previous crop via root residues and exudates on soil microbial communities can increase nutrient use efficiency of the subsequent crop and reduce the severity of host specific pathogens and generate positive feedback for crop growth[64,65].

The landscape regulation-insurance hypothesis and the resource-continuity theory are used to design diversified landscapes by configuring the composition and heterogeneity of agricultural landscapes to effectively increase the storage, flow and stability of ecosystem services[46]. Furthermore, inclusion of flower belts, hedges and other non-crop habitats near cropped fields can increase sustainability of food production through promoting biological pest control and insect pollination[50].

3.3 Methodology

Identifying promising cropping systems needs to simultaneously consider knowledge of biophysical processes in agricultural production, the goals of stakeholders and the influence of external factors, and this is a complex process[66]. Cropping system modeling can help generate a variety of feasible and diversified cropping systems and management plans (such as crop rotations and intercropping), and predict optimized land use and management combinations through combining multi-objective optimization algorithms. The optimization model of cropping systems can evaluate the trade-offs and synergies of multiple objectives and the design results will be suitable for further communication and negotiation with stakeholders, and finally the stakeholders will determine the feasibility of the design.

A range of modeling approaches for designing diversified cropping systems across temporal and spatial scales are given in Fig. 2. For long-term diversified cropping design and evaluation, the *NDICEA*[67], a target-oriented model of the rotation system at the field scale, can integrally assess N availability and budget for each crop, as well as expected N availability from mineral fertilizers and manures, crop residues, green manures and soil. At the same scale, the *ROTAT*[68] model can generate all possible crop rotation sequences under certain agronomic rules and restrictions, and quantitative evaluation of sustainability of the cropping system based on the Pareto principle.

Following a similar principle, the *Farm STEPS* model is more focused on designing both temporal and spatial diversity and evaluating sustainability at a farm scale, including both biophysical and economic properties. For short-term farming system design and evaluation, the *Farm DESIGN*[29] model aims to provide the spatial diversity design plan by Pareto based multi-objective optimization at farm and household scales, including both biophysical and economic properties. The *Landscape IMAGES*[69] model integrates biophysical, economic and properties, aiming to provide landscape composition and configuration diversity design by differential evolutionary algorithm at landscape and regional scales.

4 STRATEGIC PLANNING FOR IMPLEMENTING CROP DIVERSIFICATION IN CHINA

The key to implementing crop diversification is to enhance targeted ecosystem services consisting of provision, regulation and cultural services according to regional characteristics (natural resources and limiting factors/constraints), and social and economic demands (Fig. 3).

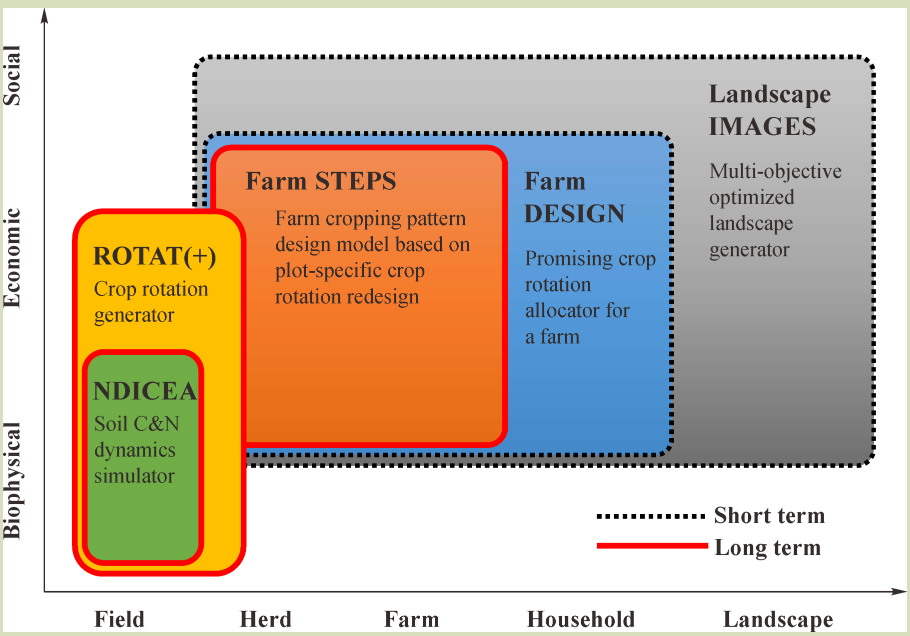


Fig. 2 A portfolio of modeling approaches for crop diversification. This figure is modified based upon course materials from Jeroen Groot (Wageningen University).

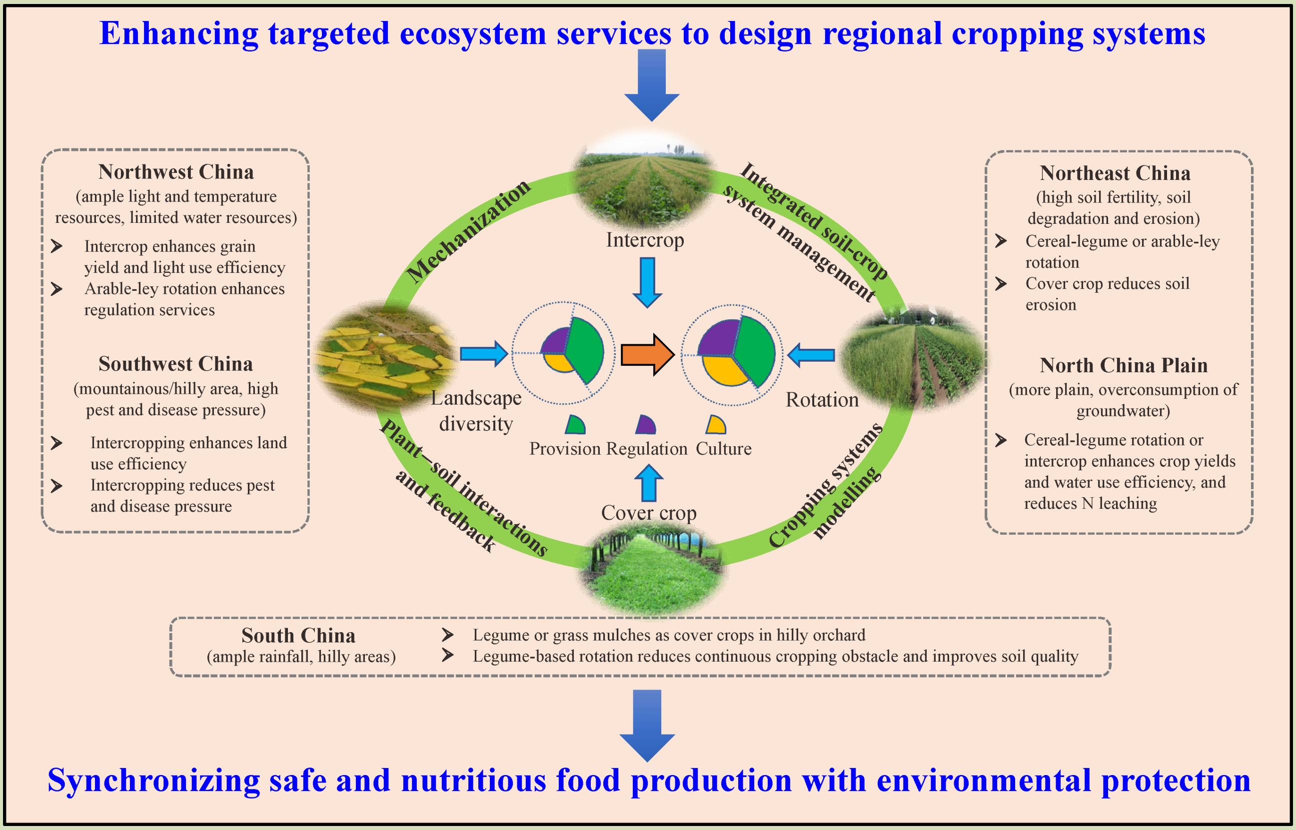


Fig. 3 The strategic planning for implementing crop diversification in China.

To develop a roadmap for a specific region requires the comprehensive integration of ecological principles, integrated soil-crop system management, cropping system modeling and mechanization. In north-west China where the light and temperature conditions allow only one not two crops per year, we advocate implementing maize/legume intercropping characterized by high yields and resource use efficiency to enhance provisioning services, and crop-pasture rotation to enhance soil C sequestration and soil fertility, thereby enhancing supporting and regulation services. The local farmers commonly use maize/wheat, maize/faba bean, and maize/pea intercropping due to the advantages in grain yield and water use[24,70,71]. In south-west China characterized by mountainous/hilly areas and with high pest and disease incidence, we recommend implementing intercropping to enhance food production within limited arable land areas and promote regulation services through reducing pest and disease incidence. Mixtures of rice varieties differing in disease resistance largely reduce rice blast incidence[39], and wheat/faba bean intercropping is also commonly grown by local farmers[72]. In addition, maize/soybean is now becoming a popular cropping system in this area due to its high N use efficiency[73]. In north-east China where water/wind erosion of fertile soils is a pressing issue, crop-pasture rotation and cover crops are recommended to increase soil C sequestration while reducing and controlling water losses. On the North China Plain where the degree of intensification is relatively high and nonrenewable resources (e.g., groundwater) are relatively limited, cereal-legume rotations or intercrops are recommended to enhance crop yields and water use efficiency and to reduce N leaching. Maize/peanut and maize/soybean intercropping systems have become increasingly interesting to the local farmers due to government promotion of growing legume crops on the North China Plain[74]. In southern China, with abundant water and heat resources but typically hilly areas, legume or grass mulches as cover crops in hilly orchard and legume-based rotations are recommended to reduce continuous cropping and improve soil quality. For example, applying green manure (e.g., Chinese milk vetch) in rice field of subtropical China can enhance the quantity and quality of soil organic matter[75,76]. Overall, the region-specific design of crop diversification will aim to concurrently achieve safe, nutritious food production and environmental protection.

5 CASE STUDY: THREE STEPS TO IMPLEMENT CROP DIVERSIFICATION ON THE NORTH CHINA PLAIN

The North China Plain is given here as an example to illustrate the pathways to implement crop diversification. Winter wheat-summer maize double cropping is the dominant cropping system, producing about 60% of the wheat and 35% of the maize in China, and is essential for national food security. However, high production is achieved only with substantial inputs of fertilizers, groundwater and pesticides, leading to environmental degradation. Thus, the key objectives are to lower agrochemical inputs and to increase resource use efficiency, thereby increasing environmental sustainability while maintaining high-quality food production. Three steps are proposed to achieve this (Fig. 4). First, the winter wheat-summer maize-spring maize rotation system is optimized by introducing intercropping and cover cropping where possible to significantly reduce water and nutrient inputs and/or to prevent losses. Second, long-term rotation is introduced to further enhance nutrient cycling, increase pest and disease control, and improve soil health. These two steps are mainly executed on a field scale. The final step is to design diversified landscapes to promote ecosystem services such as pollination and biological pest control through introducing biodiversity elements, for example, flower strips. The latter two steps will be designated as safe operating space for food and environmental security purposes. Overall, these three steps will together contribute to high-quality grain production, environmental sustainability and high farming profitability.

6 CONCLUSIONS

Achieving green transformation of agriculture in China to meet food and environmental security requires fundamental restructuring of cropping systems toward diversified cropping systems. We present a framework of theory, approaches and implementation of crop diversification schemes. The key to implementing crop diversification is to enhance targeted ecosystem services consisting of provision, regulation and cultural services according to regional characteristics and social and economic demands. This requires the comprehensive integration of ecological principles, integrated soil-crop system management, cropping system modeling and mechanization. The implementation of crop diversification will set an example to other countries undergoing agricultural transition and contribute to global sustainable development.

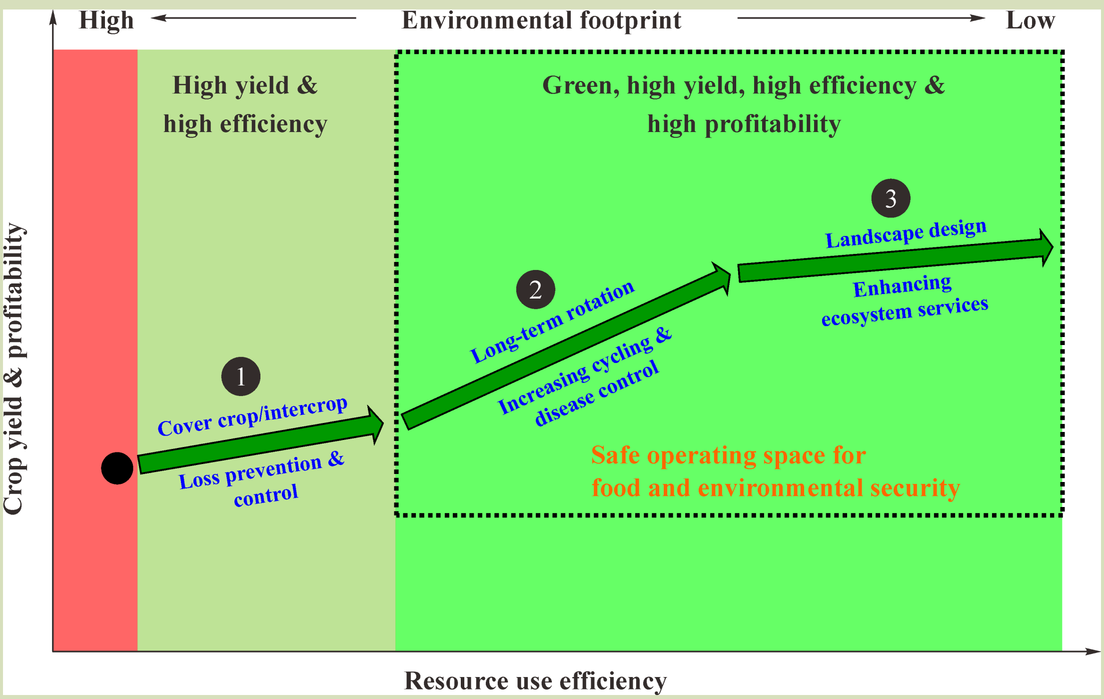


Fig. 4 Three steps to implement crop diversification on the North China Plain.

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Compliance with ethics guidelines

Wen-Feng Cong, Chaochun Zhang, Chunjie Li, Guangzhou Wang, and Fusuo Zhang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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