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

Wen-Feng CONG, Chaochun ZHANG, Chunjie LI, Guangzhou WANG, Fusuo ZHANG

College of Resources and Environmental Sciences; National Academy of Agriculture Green Development; Key Laboratory of Plant-Soil Interactions (Ministry of Education), China Agricultural University, Beijing 100193, China.

Front. Agr. Sci. Eng., Just Accepted Manuscript • https://doi.org/10.15302/J-FASE-2021392
http://journal.hep.com.cn on March 19, 2021
© The Author(s) 2021. Published by Higher Education Press. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0)

Just Accepted
This is a “Just Accepted” manuscript, which has been examined by the peer-review process and has been accepted for publication. A “Just Accepted” manuscript is published online shortly after its acceptance, which is prior to technical editing and formatting and author proofing. Higher Education Press (HEP) provides “Just Accepted” as an optional and free service which allows authors to make their results available to the research community as soon as possible after acceptance. After a manuscript has been technically edited and formatted, it will be removed from the “Just Accepted” Web site and published as an Online First article.

Please note that technical editing may introduce minor changes to the manuscript text and/or graphics which may affect the content, and all legal disclaimers that apply to the journal pertain. In no event shall HEP be held responsible for errors or consequences arising from the use of any information contained in these “Just Accepted” manuscripts. To cite this manuscript please use its Digital Object Identifier (DOI(r)), which is identical for all formats of publication.
DESIGNING DIVERSIFIED CROPPING SYSTEMS IN CHINA: THEORY, APPROACHES AND IMPLEMENTATION

Wen-Feng CONG, Chaochun ZHANG, Chunjie LI, Guangzhou WANG, Fusuo ZHANG (✉)

College of Resources and Environmental Sciences; National Academy of Agriculture Green Development; Key Laboratory of Plant-Soil Interactions (Ministry of Education), China Agricultural University, Beijing 100193, China.

Received December 30, 2020; Accepted February 26, 2021.
Correspondence: zhangfs@cau.edu.cn
© The Author(s) 2021. Published by Higher Education Press. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0)

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.

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.

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

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 though 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\(^{[3,19,20]}\). Crop rotation, another important diversification strategy, has increased grain yield by 20% in China compared to continuous cropping systems\(^{[21]}\). 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%\(^{[22]}\). 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\(^{[23]}\). Crop diversification has always been regarded as an environmentally-friendly
model. For example, cover crops can reduce nitrate leaching by 35%\cite{24} 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\cite{25–27}. 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\cite{28,29}.

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\cite{30–32}; (2) application of intercropping and rotation can reduce agrochemical inputs and increase income\cite{20,21}; and (3) adaptation in extreme climates and avoidance of variable market conditions\cite{33}. 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\cite{34–40} and soil fertility increase, reducing the inputs of pesticides and fertilizers in farm production and mitigating negative environmental impacts\cite{41}; (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\cite{42}; and (3) mixed farms can achieve efficient nutrient cycling, increase soil organic matter content and reduce nutrient loss\cite{43}. 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\cite{44}. 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\cite{45}. 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\cite{46}. 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\cite{47,48}. 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\cite{49}, which is conducive to the improvement of biological control and pollination services\cite{50}. For example, planting flower belts within or adjacent to wheat fields can effectively reduce 61% of yield loss caused by the cereal leaf beetle\cite{51}. Hedgerows can promote various soil-related ecosystem services such as soil C sequestration\cite{52}. Agroforestry can provide services such as reducing soil erosion, increasing biodiversity and increasing soil fertility\cite{53}. 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\cite{54}. Intercropping with flowering plants will also increase pollination services and increase yield and quality, for example, intercropping capsicum (\textit{Capsicum annuum}) with flowering basil (\textit{Ocimum basilicum})\cite{55}. 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 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 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.

Fig. 1 Framework of crop diversification schemes.

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. Different crops have their distinct strategies for resource acquisition and use. 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, and species combinations with shallow and deep roots can make full use of nutrients and water at different soil depths. Combining species with specific adaption for different forms of P can increase P use efficiency. 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\textsubscript{2} fixation of intercropped faba bean by depleting root-zone soil nitrate concentrations available to faba bean and by promoting nodulation and N fixation in response to specific maize root exudates\cite{61,62}. The principle of plant–soil feedback provides guidance for designing beneficial crop rotations that maximize nutrient cycling and minimize pest and disease stress\cite{63,64}. 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\cite{65,66}.

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\cite{47}. 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\cite{51}.

### 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\cite{67}. 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\cite{68}, 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\cite{69} 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.

---

**Fig. 2** A portfolio of modeling approaches for crop diversification. This figure is modified based upon course materials from Jeroen Groot.
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 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 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. 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 efficiency.[25,71,72]. 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[40], and wheat/faba bean intercropping is also commonly grown by local farmers.[9]. In addition, maize/soybean is now becoming a popular cropping system in this area due to its high N use efficiency.[74]. In north-east China where 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[75]. 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[76,77]. 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.

![Fig. 4](image) Three steps to implement crop diversification on the North China Plain.
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.

Acknowledgements

This work was funded by the National Natural Science Foundation of China (32072676), the National Key R & D Program (2017YFD0200207), and the Program of Advanced Discipline Construction in Beijing (Agriculture Green Development).

Compliance with ethics guidelines

Wen-Feng Cong, Chaocun 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.

REFERENCES

1. Matson P A, Parton W J, Power A G, Swift M J. Agricultural intensification and ecosystem properties. Science, 1997, 277(5325): 504–509 doi:10.1126/science.277.5325.504 PMID:20662149
2. Tilman D, Reich P B, Knops J, Wedin D, Mielke T, Lehman C. Diversity and productivity in a long-term grassland experiment. Science, 2001, 294(5543): 843–845 doi:10.1126/science.1060391 PMID:11679667
3. Gaba S, Lescourret F, Boudsocq S, Enjalbert J, Hinsinger P, Journet E P, Navas M L, Wery J, Louarn G, Malezieux E, Pelzer E, Prudent M, Ozier-Lafontaine H. Multiple cropping systems as drivers for providing multiple ecosystem services: from concepts to design. Agronomy for Sustainable Development, 2015, 35(2): 607–623 doi:10.1007/s13593-014-0272-z
4. Renard D, Tilman D. National food production stabilized by crop diversity. Nature, 2019, 571(7764): 257–260 doi:10.1038/s41586-019-1316-y PMID:31217589
5. Guo J H, Liu X J, Zhang Y, Shen J L, Han W X, Zhang W F, Christie P, Goulding K W T, Vitousek P M, Zhang F S. Significant acidification in major Chinese croplands. Science, 2010, 327(5968): 1008–1010 doi:10.1126/science.1182570 PMID:20150447
6. Grebmer K V, Bernstein J, Nabarro D, Prasai N, Amin S, Yohannes Y, Sonntag A, Patterson F, Towey O, Thompson J. 2016 Global Hunger Index: getting to zero hunger. Washington: International Food Policy Research Institute, 2016
7. Beillouin D, Ben-Ari T, Makowski D. Evidence map of crop diversification strategies at the global scale. Environmental Research Letters, 2019, 14(12): 123001
8. Chen X, Cui Z, Fan M, Vitousek P, Zhao M, Ma W, Wang Z, Zhang W, Yan X, Yang J, Deng X, Gao Q, Zhang Q, Guo S, Ren J, Li S, Ye Y, Wang Z, Huang J, Tang Q, Sun Y, Peng X, Zhang J, He M, Zhu Y, Xue J, Wang G, Wu L, An N, Wu L, Ma L, Zhang W, Zhang F. Producing more grain with lower environmental costs. Nature, 2014, 514(7523): 486–489 doi:10.1038/nature13609 PMID:25186728
9. Zhang F S, Shen J B, Zhang J L, Zuo Y M, Li L, Chen X P. Chapter One-Rhizosphere Processes and Management for Improving Nutrient Use Efficiency and Crop Productivity: Implications for China. Advances in Agronomy, 2010, 107: 1–32 doi:10.1016/S0065-2113(10)07001-X
10. Cui Z, Zhang H, Chen X, Zhang C, Ma W, Huang C, Zhang W, Mi G, Miao Y, Li X, Gao Q, Yang J, Wang Z, Ye Y, Guo S, Lu J, Huang J, Lv S, Sun Y, Liu Y, Peng X, Ren J, Li S, Deng X, Shi X, Zhang Q, Yang Z, Tang L, Wei C, Jia L, Zhang J, He M, Tong Y, Tang Q, Zhong X, Liu Z, Cao N, Kou C, Yang H, Yin Y, Jiao X, Zhang Q, Fan M, Jiang R, Zhang F, Dou Z. Pursuing sustainable productivity with millions of smallholder farmers. Nature, 2018, 558(7706): 363–366 doi:10.1038/nature25785 PMID:29513654
11. Ying H, Xue Y, Yan K, Wang Y, Yin Y, Liu Z, Zhang Q, Tian X, Li Z, Liu Y, Cui Z. Safeguarding food supply and groundwater safety for maize production in China. Environmental Science & Technology, 2020, 54(16): 9939–9948 doi:10.1021/acs.est.0c05642 PMID:32706248
12. Martin-Guay M O, Paquette A, Dupras J, Rivest D. The new Green Revolution: sustainable intensification of agriculture by intercropping. Science of the Total Environment, 2018, 615: 767–772 doi:10.1016/j.scitotenv.2017.10.024 PMID:28992501
13. Li C, Hoffland E, Kuyper T W, Yu Y, Zhang C, Li H, Zhang F, van der Werf W. Syndromes of production in intercropping impact yield gains. *Nature Plants*, 2020, 6(6): 653–660 doi:10.1038/s41477-020-0680-9 PMID:32483328

14. Xu Z, Li C J, Zhang C C, Yu Y, van der Werf W, Zhang F S. Intercropping maize and soybean increases efficiency of land and fertilizer nitrogen use: a meta-analysis. *Field Crops Research*, 2020, 246: 107661 doi:10.1016/j.fcr.2019.107661

15. Tang X Y, Zhang C C, Yu Y, Shen J B, van der Werf W, Zhang F S. Intercropping legumes and cereals increases phosphorus use efficiency; a meta-analysis. *Plant and Soil*, 2020 doi:10.1007/s11104-020-04768-x

16. Yang L, Xu L, Liu B, Zhang Q, Pan Y F, Li Q, Li H Q, Lu Y H. Non-crop habitats promote the abundance of predatory ladybeetles in maize fields in the agricultural landscape of northern China. *Agriculture, Ecosystems & Environment*, 2019, 277: 44–52 doi:10.1016/j.agee.2019.03.008

17. Lee M B, Goodale E. Crop heterogeneity and non-crop vegetation can enhance avian diversity in a tropical agricultural landscape. *Agriculture, Ecosystems & Environment*, 2018, 265: 254–263 doi:10.1016/j.agee.2018.06.016

18. Garr G M, Liu Z, Zheng X, Xu H, Zhub P, Chen G, Yao X, Cheng I, Zhu Z, Catindig J L, Villareal S, Van Chien H, Cuong Q, Channoo C, Chengwattana N, Lan L P, Hai H, Chaiwong J, Nicol H I, Perovic D J, Wratten S D, Heong K L. Multi-country evidence that crop diversification promotes ecological intensification of agriculture. *Nature Plants*, 2016, 2(3): 16014 doi:10.1038/nplants.2016.14 PMID:27249349

19. Malézieux E, Crozat Y, Dupraz C, Laurans M, Makowski D, Ozier-Lafontaine H, Rapidel B, Tournédon S, Valantin-Morris M. Mixing plant species in cropping systems: concepts, tools and models. A review. *Agronomy for Sustainable Development*, 2009, 29(1): 43–62 doi:10.1051/agro:2007057

20. Xu Z, Li C J, Zhang C C, Yu Y, van der Werf W, Zhang F S. Intercropping maize and soybean increases efficiency of land and fertilizer nitrogen use: a meta-analysis. *Field Crops Research*, 2020, 246: 107661 doi:10.1016/j.fcr.2019.107661

21. Zhao J, Yang Y D, Zhang K, Jeong J, Zeng Z H, Zhang H D. Does crop rotation yield more in China? A meta-analysis. *Field Crops Research*, 2020, 246: 107659 doi:10.1016/j.fcr.2019.107659

22. McDaniel M D, Tiemann L K, Grandy A S. Does agricultural crop diversity enhance soil microbial biomass and organic matter dynamics? A meta-analysis. *Ecological Applications*, 2014, 24(3): 560–570 doi:10.1890/13-0616.1 PMID:24834741

23. Bellon M R, Kotu B H, Azzarri C, Caracciolo F. To diversify or not to diversify, that is the question. Pursuing agricultural development for smallholder farmers in marginal areas of Ghana. *World Development*, 2020, 125: 104682 doi:10.1016/j.worlddev.2019.104682 PMID:31909272

24. Quemada M, Baranski M, Nobel-De Lange M N J, Vallejo A, Cooper J M. Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. *Agriculture, Ecosystems & Environment*, 2013, 174: 1–10 doi:10.1016/j.agee.2013.04.018

25. Mao L L, Zhang L Z, Li W Q, van der Werf W, Sun J H, Spiertz H, Li L. Yield advantage and water saving in maize/pea intercrop. *Field Crops Research*, 2012, 138: 11–20 doi:10.1016/j.fcr.2012.09.019

26. Ren J H, Zhang L Z, Duan Y, Zhang J, Evers J B, Zhang Y, Su Z C, van der Werf W. Intercropping potato (*Solanum tuberosum* L.) with hairy vetch (*Vicia villosa*) increases water use efficiency in dry conditions. *Field Crops Research*, 2019, 246: 168–176 doi:10.1016/j.fcr.2018.12.002

27. Bai W, Sun Z X, Zheng J M, Du G J, Feng L S, Cai Q, Yang N, Feng C, Zhang Z, Evers J B, van der Werf W, Zhang L Z. Mixing trees and crops increases land and water use efficiencies in a semi-arid area. *Agricultural Water Management*, 2016, 178: 281–290 doi:10.1016/j.agwat.2016.10.007

28. Raseduzzaman M, Jensen E S. Does intercropping enhance yield stability in arable crop production? A meta-analysis. *European Journal of Agronomy*, 2017, 91: 25–33 doi:10.1016/j.eja.2017.09.009

29. Knapp S, van der Heijden M G A. A global meta-analysis of yield stability in organic and conservation agriculture. *Nature Communications*, 2018, 9(1): 3632 doi:10.1038/s41467-018-05956-1 PMID:30194344

30. Groot J C J, Oomen G J M, Rossing W A H. Multi-objective optimization and design of farming systems. *Agricultural Systems*, 2012, 110: 63–77 doi:10.1016/j.agsy.2012.03.012

31. Bonnardo T, Bendahan A B, Sabatier R, Ryschawy J, Bellon S, Leger F, Magda D, Tichit M. Agroecological principles for the redesign of integrated crop-livestock systems. *European Journal of Agronomy*, 2014, 57: 43–51 doi:10.1016/j.eja.2013.09.010

32. Huang C, Liu Q, Heerink N, Stomph T, Li B, Liu R, Zhang H, Wang C, Li X, Zhang C, van der Werf W, Zhang F. Economic performance and sustainability of a novel intercropping system on the North China Plain. *PLoS One*, 2015, 10(8): e0135518 doi:10.1371/journal.pone.0135518 PMID:26273297

33. Rosa-Schleich J, Loos J, Mulhoff O, Tscharktte T. Ecological-economic trade-offs of Diversified Farming Systems — A review. *Ecological Economics*, 2019, 160: 251–263 doi:10.1016/j.ecolecon.2019.03.002

34. Wang G Z, Li H G, Christie P, Zhang F S, Zhang J L, Bever J D. Plant-soil feedback contributes to intercropping overyielding by reducing the negative effect of take-all on wheat and compensating the growth of faba bean. *Plant and Soil*, 2017, 415(1–2): 1–12 doi:10.1007/s11104-016-3139-z

35. Boudreau M A. Diseases in intercropping systems. *Annual Review of Phytopathology*, 2013, 51: 499–519

36. Liebman M, Dyck E. Crop rotation and intercropping strategies for weed management. *Ecological Applications: a Publication of the Ecological Society of America*, 1993, 3(1): 92–122
Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist*, 2015, **206**(1): 107–117 doi:10.1111/nph.13132

57. Li C J, Kuyper T W, van der Werf W, Zhang J L, Li H G, Zhang F S, Hoffland E. Testing for complementarity in phosphorus resource use by mixtures of crop species. *Plant and Soil*, 2019, **439**(1–2): 163–177 doi:10.1007/s11104-018-3732-4

58. Bedoussac L, Justes E. Dynamic analysis of competition and complementarity for light and N use to understand the yield and the protein content of a durum wheat-pea intercrop. *Plant and Soil*, 2010, **330**(1–2): 37–54 doi:10.1007/s11104-010-0303-8

59. Li L, Sun J, Zhang F, Guo T, Bao X, Smith F A, Smith S E. Root distribution and interactions between intercropped species. *Oecologia*, 2006, **147**(2): 280–290 doi:10.1007/s00442-005-0256-4 PMID:16211394

60. Morris R A, Garrity D P. Resource capture and utilization in intercropping: non-nitrogen nutrients. *Field Crops Research*, 1993, **34**(3–4): 319–334 doi:10.1016/0378-4290(93)90120-C

61. Li L, Tilman D, Lambers H, Zhang F S. Plant diversity and overyielding: insights from belowground facilitation of intercropping in agriculture. *New Phytologist*, 2014, **203**(1): 63–69 doi:10.1111/nph.12778 PMID:25013876

62. Li B, Li Y Y, Wu H M, Zhang F F, Li C J, Li X X, Lambers H, Li L. Root exudates drive interspecific facilitation by enhancing nodulation and N: fixation. *Proceedings of the National Academy of Sciences of the United States of America*, 2016, **113**(23): 6496–6501 doi:10.1073/pnas.1523580113 PMID:27217575

63. Wang G, Schultz P, Tipton A, Zhang J, Zhang F, Bever J D. Soil microbiome mediates positive plant diversity-productivity relationships in late successional grassland species. *Ecology Letters*, 2019, **22**(8): 1221–1232 doi:10.1111/ele.13273 PMID:31131969

64. Wang G Z, Bei S K, Bao X G, Zhang J D, Schultz P A, Li H G, Li L, Zhang F S, Bever J D, Zhang J L. Soil microbial legacy drives crop diversity advantage: linking ecological plant-soil feedback with agricultural intercropping. *Journal of Applied Ecology*, 2021, **58**(3): 496–506 doi:10.1111/1365-2664.13802

65. Dias T, Dukes A, Antunes P M. Accounting for soil biotic effects on soil health and crop productivity in the design of crop rotations. *Journal of the Science of Food and Agriculture*, 2015, **95**(3): 447–454 doi:10.1002/jsfa.6565 PMID:24408021

66. Zhou X G, Liu J, Wu F Z. Soil microbial communities in cucumber monoculture and rotation systems and their feedback effects on cucumber seedling growth. *Plant and Soil*, 2017, **415**(1–2): 507–520 doi:10.1007/s11104-017-3181-5

67. van Ittersum M K, Rabbinge R, van Latesteijn H C. Exploratory land use studies and their role in strategic policy making. *Agricultural Systems*, 1998, **58**(3): 309–330 doi:10.1016/S0308-521X(98)00033-X

68. van der Burg J G H M, Oomen G J M, Habets A S J, Rossing W A H. The NDICEA model, a tool to improve nitrogen use efficiency in cropping systems. *Nutrient Cycling in Agroecosystems*, 2006, **74**(3): 275–294 doi:10.1007/s10705-006-9004-3

69. Dogliotti S, Rossing W A H, van Ittersum M K. ROTAT, a tool for systematically generating crop rotations. *European Journal of Agronomy*, 2003, **19**(2): 239–250 doi:10.1016/S1161-0301(02)00047-3

70. Groot J C J, Rossing W A H, Jellemela A, Stobbelaar D J, Rijtening H, Van Ittersum M K. Exploring multi-scale trade-offs between nature conservation, agricultural profits and landscape quality—A methodology to support discussions on land-use perspectives. *Agriculture, Ecosystems & Environment*, 2007, **120**(1): 58–69 doi:10.1016/j.agee.2006.03.037

71. Li L, Sun J H, Zhang F S, Li X L, Yang S C, Rengel Z. Wheat/maize or wheat/soybean strip intercropping I. Yield advantage and inter-specific interactions on nutrients. *Field Crops Research*, 2001, **71**(2): 123–137 doi:10.1016/S0378-4290(01)00156-3

72. Li L, Li S M, Sun J H, Zhou L L, Bao X G, Zhang H G, Zhang F S. Diversity enhances agricultural productivity via rhizosphere phosphorus fertilization on phosphorus-deficient soils. *Proceedings of the National Academy of Sciences of the United States of America*, 2007, **104**(27): 11192–11196 doi:10.1073/pnas.0704591104 PMID:17592130

73. Xiao J X, Yin X H, Ren J B, Zhang M Y, Tang L, Zheng Y. Complementation drives higher growth rate and yield of wheat and saves nitrogen fertilizer in wheat and faba bean intercropping. *Field Crops Research*, 2018, **221**: 119–129 doi:10.1016/j.fcr.2017.12.009

74. Yang F, Liao D P, Wu X L, Gao R C, Fan Y F, Raza M A, Wang X C, Yong T W, Liu W G, Liu J, Du J B, Shi K, Yang W Y. Effect of aboveground and belowground interactions on the intercrop yields in maize-soybean relay intercropping systems. *Field Crops Research*, 2017, **203**: 18–23 doi:10.1016/j.fcr.2016.12.007

75. Gao H X, Meng W W, Zhang C C, van der Werf W, Zhang Z, Wan S B, Zhang F S. Yield and nitrogen uptake of sole and intercropped maize and peanut in response to N fertilizer input. *Food and Energy Security*, 2020, **9**(1): e187 doi:10.1002/fes3.187

76. Gao S J, Gao J S, Cao W D, Zou C Q, Huang J, Bai J S, Dou F G. Effects of long-term green manure application on the content and structure of dissolved organic matter in red paddy soil. *Journal of Integrative Agriculture*, 2018, **17**(8): 1852–1860 doi:10.1016/S2095-3119(17)61901-4

77. Yu Q G, Hu X, Ma J W, Yi J, Sun W C, Wang Q, Liu H. Effects of long-term organic material applications on soil carbon and nitrogen fractions in paddy fields. *Soil & Tillage Research*, 2020, **196**: 104483 doi:10.1016/j.still.2019.104483