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Journal of Cleaner Production

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https://doi.org/10.1016/j.jclepro.2023.140150

Journal of Cleaner Production 434 (2024) 140150

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

How maize-legume intercropping and rotation contribute to food security and environmental sustainability

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ARTICLE INFO

Handling Editor: Zhifu Mi

Keywords:
Cropping system
Intercropping
Crop rotation
Food security
Environmental sustainability

ABSTRACT

A revolution of cropping systems offers a promising opportunity to address complex and interconnected challenges to food security and environmental protection. Intercropping and crop rotation especially of legumes and maize are prominent candidates due to their wide applicability and advantages, given their differences in crop photosynthetic pathways. Scientific research on transition towards sustainable cropping systems continues to grow rapidly and there is an urgent need to systematize its knowledge map. Based on 6574 articles published from 1990 to 2022, we use bibliometric indicators such as publication trends, authorship patterns, and citation analyses to explore the research hotspots, frontiers and trends of maize-legume intercropping and crop rotation. The unbalanced research and practice patterns worldwide, different emphases between economic and environmental objectives of two cropping systems are analyzed. Finally, the potential and perspectives of the combination of intercropping and crop rotation to address challenges to food security and environmental sustainability are discussed.

1. Introduction

Hunger continues to be a pervasive problem throughout the world, with 193 million individuals across 53 countries/territories experiencing profound food insecurity (UN, 2022), and the situation is expected to be intensified by the increasing global population. In order to meet the urgent demand for calories and nutrients, agricultural production will need to increase by 70% or more (FAO, 2018). The Asian green revolution as an innovation of intensive agriculture has trebled grain yields, but brought soil degradation, increased risk of pest and disease outbreaks, and environmental pollution since it increased the application of fertilizer, pesticide, irrigation and agricultural machinery (Snapp et al., 2010). Future agriculture is expected to address simultaneously several intertwined challenges through increased productivity, reduced environmental impact and enhancement in climate change adaptation and mitigation (Raseduzzaman and Jensen, 2017; Wei et al., 2023). Crop rotation (temporal diversification) and intercropping (spatial diversification) strategies have been proven to improve agricultural sustainability (Li et al., 2021a,b), providing a tradeoff between crop productivity and other ecosystem services (Rockström et al., 2017; Martin-Guay et al., 2018; Mingotte et al., 2021).

Globally, maize is grown in a large area (197.23 Mha), accounting for 30% of the food supply in the Americas, 38% in Africa and 6.5% in Asia, and is a major contributor to local food security (Prasanna et al., 2020; Tripathi et al., 2021). Besides being a major source of food and feed for humans and animals, it is also a potential source of bioenergy (Erickson and Berger, 2013). Additionally, legumes are rich source of protein and has a high market value (Ainsworth et al., 2012; Chimonyo

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https://doi.org/10.1016/j.jclepro.2023.140150
Received 23 July 2023; Received in revised form 1 December 2023; Accepted 10 December 2023
Available online 15 December 2023

et al., 2019). Global demand for legumes, especially soybeans, has exploded in recent decades due to their use as a feedstock for soy–animal feed, biofuels and vegetable oil (Ritchie et al., 2023). In order to meet production needs, land expansion for soybean production has increased by 160% in Brazil and 57% in Argentina, and much of this expansion has come at the cost of deforestation. By 2016, 9% of the continent's forests were converted to soybeans (Song et al., 2021; Chen et al., 2022). Among the UN sustainable development goals (SDGs), mitigating climate change and biodiversity loss to achieve zero deforestation is prominent in the global supply chains of commodities such as palm oil and soybeans (Song et al., 2021).

The combination of intercropping and crop rotation of maize and legume has emerged as a promising agricultural practice that can improve yields and soil health while reducing the environmental impact of conventional farming practices. For example, the maize-soybean intercropping-rotation model in China can achieve maize yields comparable to those of monoculture maize system while additionally harvesting a season of soybeans, with an experimental land-equivalent ratio of 1.4 (Du et al., 2018). As a result, intercropping and rotation of crops have received a lot of attention in scientific and technological circles and are also promoted by the Central No.1 document of China in 2022 (State Council of CPC, 2022).

The objective of this study is to improve our understanding of how different historical breakthroughs in agriculture such as the Green Revolution etc. have influenced the research efforts on maize-legume intercropping and crop rotation, and whether the most traditional cropping systems align with the world's need for future sustainable agriculture. For this purpose, we use bibliometric analysis to identify research hotspots, trends, and gaps in maize-legume intercropping and rotation over the past 30 years. We also provide a systematical comparison of the development history and patterns of intercropping and crop rotation systems. As a transition towards sustainable agriculture, our systematic mapping of promising cropping systems might be valuable for inspiring and informing countries and regions facing food and environmental insecurity, and consequently offers a possible direction for global sustainable development.

2. Methods and data

Bibliometrics is an interdisciplinary that uses mathematical and statistical methods to quantitatively analyze all carriers of knowledge in a field of interest (Donthu et al., 2021), to help understand the prospects and characteristics of the field.

2.1. Data sources and research process

The data used in this study are from the Web of Science Core Collection. We concentrated on studies performed from 1990 to 2022. Studies for this analysis are restricted to original articles published in English and the document types were research articles and review articles. The retrieved documents were saved in "plain text file" and "full record and cited references" formats. Documents related to crop rotation and intercropping were downloaded separately and then analyzed for their content. We further refined the search strategies for four key subfields (agronomic practice, crop physiology & ecology, economic benefits and environmental benefits) based on the main search strategies for the general theme of intercropping and rotation. Additionally, we conducted a secondary search to compare publication quantities within each subcategory to derive the variations in research intensity. The detailed search strategies are presented in *Appendix* Table S1.

2.2. Analytical tools

We use the VOSviewer (1.6.18) and CiteSpace (6.1.R6) to identify the top countries, institutions, authors, journals, cited literature, keywords, and trends. The VOSviewer is a visualization software, oriented to literature data and adapted to the analysis of one-mode undirected networks, ultimately forming the visualization of scientific knowledge and generating keyword clustering maps. The VOSviewer provides a new way to organize and analyze the literature to reveal the core structure and intrinsic connections of scientific knowledge. It is used to display web maps of keyword clustering. The CiteSpace (6.1.R6) is a Java-based application that is a multidimensional, time-phased, and dynamic visual analytics tool. We use it to display web maps of countries and institutions as well as timeline maps of keywords and keyword bursts. We also use the "Bibliometrix" package (R Core Team, 2022) to obtain the thematic map. The above techniques are used to show the current research hotspots and future research trends.

3. Results

Based on the bibliometric analysis of the maize-legume intercropping and rotation research, the prominent countries/regions, research areas, and keywords in this field are highlighted. The data is analyzed and discussed in detail to provide a comprehensive and systemic understanding of the research progress and trends.

3.1. Evolution and patterns of scientific output

From 1990 to 2022, the number of publications on maize-legume intercropping and rotation shows a continuous upward trend, with a sharp increase starting in 2014 (Fig. 1). Taking the entire period into account, the Compound Annual Growth Rate (CAGR) of publications for maize-legume intercropping and rotation is 17.4% and 19.0%, respectively.

In the early years, agronomic research occupied a significant portion of both intercropping and rotation studies, representing 40% of all intercropping publications in 1990 and 50% of all rotation publications. However, since 2000, the contribution of agronomic research has been on a declining trend. By 2022, these proportions dropped to 22.8% and 22.5%, respectively (Fig. 1, Table S2), possibly attributed to researchers' longstanding interest in enhancing production efficiency through crop management. The subfield of crop physiology and ecology has always maintained rapid progress ($CAGR_{IC}$ = 16.23%, $CAGR_{RO}$ = 16.37%), while the number of publications has consistently accounted for a significant proportion ($mean_{IC}$ = 43.6%, $mean_{RO}$ = 34.1% of rotation). The absolute number of studies on the economic and environmental benefits of maize-legume intercropping have been relatively scarce. However, the number of publications in these areas has been steadily increasing over time. In particular, the environmental benefits have experienced a CAGR of 31.1% over the past 15 years, (Table S2a), indicating a growing interest in the potential benefits of intercropping as a sustainable agricultural practice. Similarly, CAGR of the environmental benefits of crop rotation in the past 15 years has been as high as 37.52% (Table S2b). This could be attributed to the growing interest in sustainable agriculture practices and the importance of understanding how crop rotation can help mitigate the negative environmental impacts of conventional farming methods. Agronomic practice, which has the second-highest number of publications in the early years, also plays a crucial role in rotation research, as it involves the application of rotation methods in crop production.

At the regional scale, the pattern of publication numbers for intercropping and that for crop rotation is in contrast (Fig. 2, S1). The results suggest that more studies on maize-legume intercropping are conducted in Asia (n = 1326, accounting 48%) and Africa (n = 794, accounting 19%). However, more research on crop rotation is done in North America (n = 2832, accounting 55%), where agriculture is highly developed, and a significant portion of research focuses on improving crop productivity and sustainability at the same time. The different levels of research among continents reflect the varying priorities and challenges faced by farmers and researchers. Asia and Africa are densely populated regions characterized by limited arable land, and smallholder

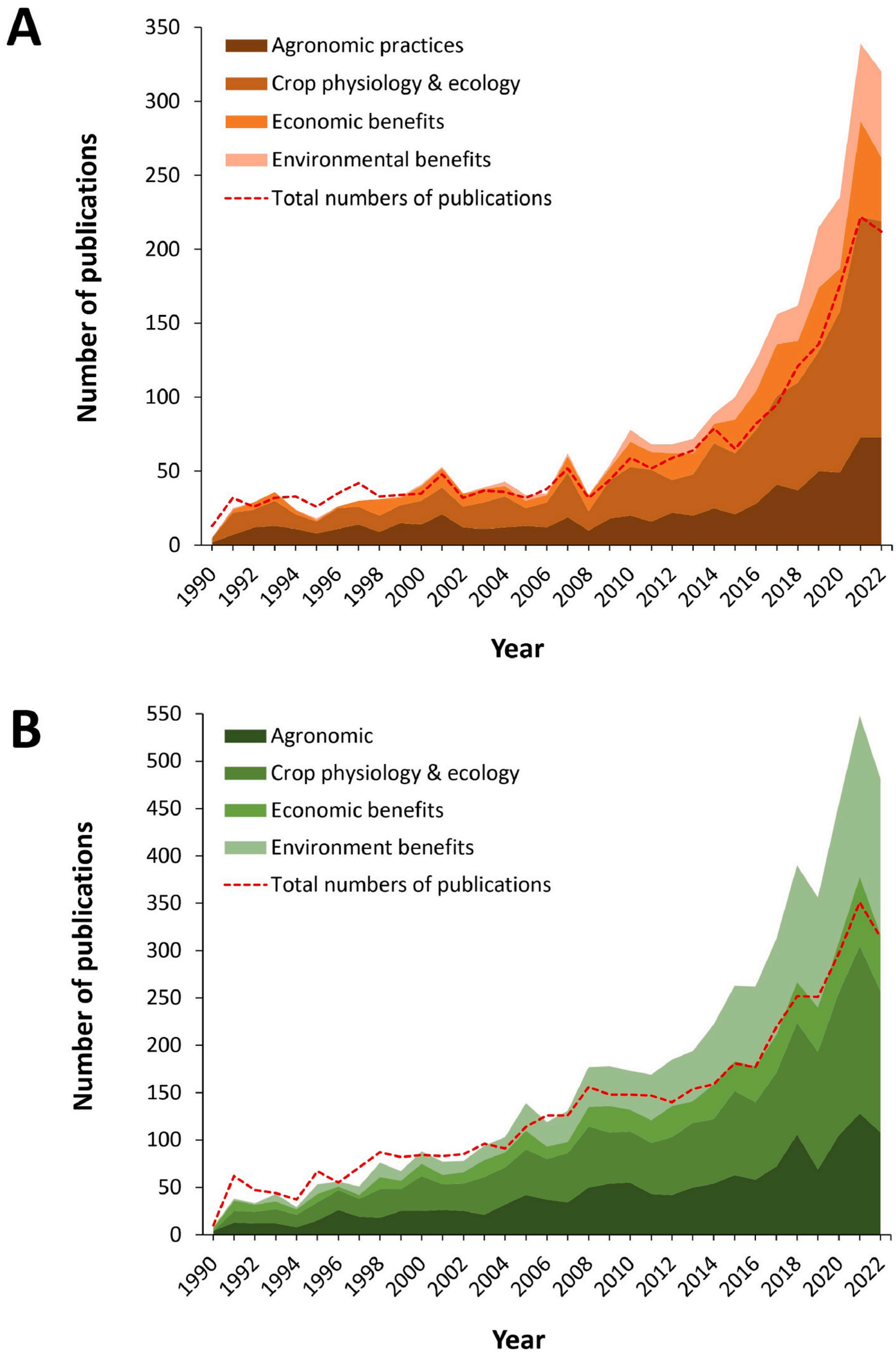

Fig. 1. Development trend of (A) maize-legume intercropping and (B) rotation research in four subfields (agronomic practice, crop physiology & ecology, economic benefits, and environmental benefits) from 1990 to 2022: the number of publications.

farmers are prevalent (Bagheramiri and Keshvarz Shaal, 2020; McConville, 2016), where intercropping can be an effective way to maximize the use of limited resources and increase crop productivity (Chai et al., 2021). In North America, where large-scale farming dominates, crop rotation is critical to sustain soil health and prevent the build-up of pests and diseases.

3.2. Research hotspots

The high frequency of the keyword "yield" is the focus of intercropping research. Words such as "availability", "competition", "diversity", "fertilizer", "grain-yield", "intercropping", "productivity", and "yield advantage" highlight the foci on various factors that may affect the productivity of maize-legume intercropping, as well as the potential of intercropping to increase yield compared with monoculture (Fig. 3A). According to the clustering result, intercropping research has focused on the following: yield and economic benefits, conservation tillage and sustainable development, resources utilization and efficiency, interspecific competition and facilitation between crops, intercropping for forage production.

Although both intercropping and crop rotation are sustainable agricultural practices, according to the clustering results, we found that intercropping-related research is more yield-oriented, and several directions of crop rotation may focus more on agronomic and

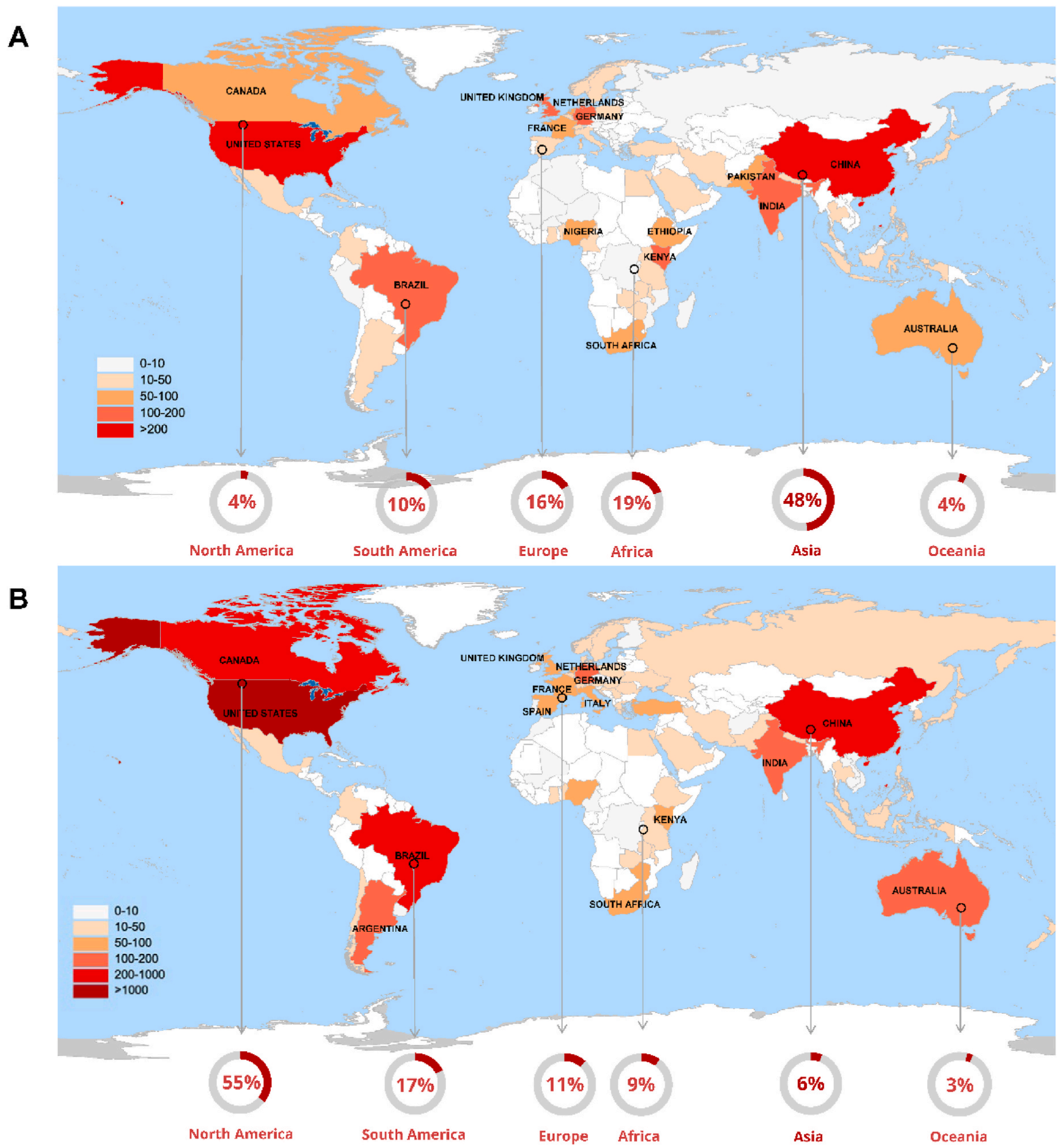

Fig. 2. Mapping the global characteristics of publications in the field of (A) maize -legume intercropping and (B) maize-legume rotation. Percentage contribution per continent and the top 15 countries/region in terms of the number of publications are indicated on the map.

environmental benefits than economic benefits. Studies on crop rotation focus on three main directions (Fig. 4A). Studies on "diversity and productivity" highlight the importance of biodiversity and the impact of crop rotation on growth, productivity, and yields of maize and legume crops. Studies have shown that rotation can enhance soil fertility by increasing the availability of nutrients and improving the rhizosphere, which can result in higher crop yields and better plant performance. Studies on "soil science" focus on the role of maize-legume rotation in carbon sequestration and management of soil organic matter, demonstrating that it contributes to reducing greenhouse gas emissions and mitigating the impacts of climate change. Additionally, conservation tillage practices, such as no-till, have been shown to be effective in improving soil carbon sequestration and soil quality. Studies on "environmental benefits" focus on the environmental impact, such as greenhouse gas emissions, soil health, and water quality, as well as fertilizer management and manure application.

3.3. Research trends

Evolution analysis can accurately characterize temporal properties of co-citation clusters, aiding in uncovering the changing trends and development direction of disciplinary research (Chen et al., 2010).The evolution of keyword timeline is shown in Figs. 3B and 4B, S2. Both intercropping and crop rotation research can be distinctly divided into two phases in the development process of more than 30 years.

3.3.1. Evolution of intercropping research

Since the 1980s, high-yield crop research has received increasing attention in many countries. As shown in Fig. 3B and Fig. S2, until the early 2000s, key hit words such as "density", "weed control", "soil fertility", "management", "yield", emerged continued to emerge, a concentration of research on the role of intercropping as an agronomic measure in improving soil fertility and enhancing crop yields.

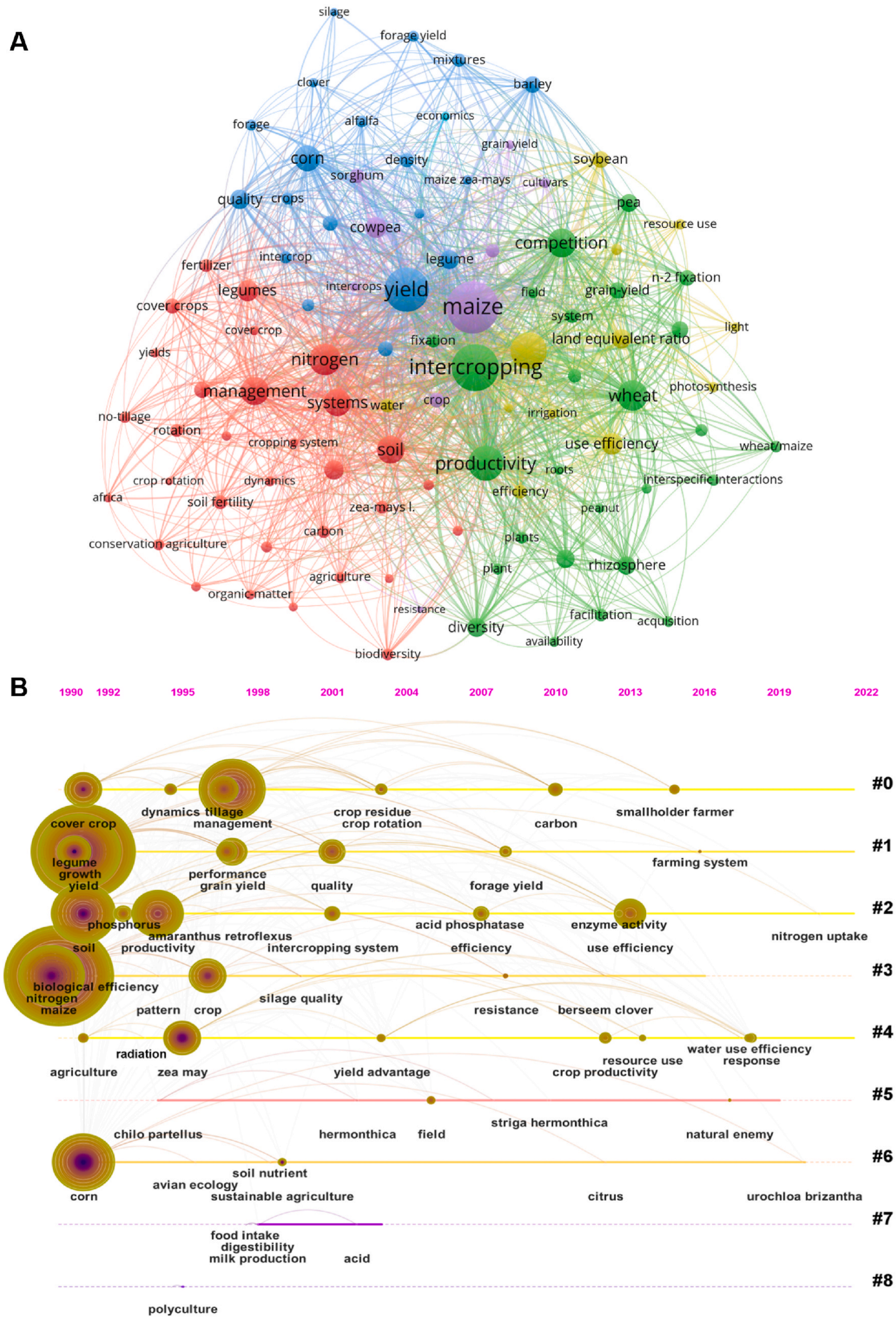

Fig. 3. Evolution of hotspots and the research trends of maize-legume intercropping strongest citation bursts. (A) Clusters of keywords (B) The timeline of keywords evolution: #0, conservation agriculture; #1, yield; 2#, nutrient cycling; 3#, biological efficiency; 4#, resource use efficiency; #5, biotic stress; #6, sustainable agriculture; 7#, silage; #8, varietal mixtures.

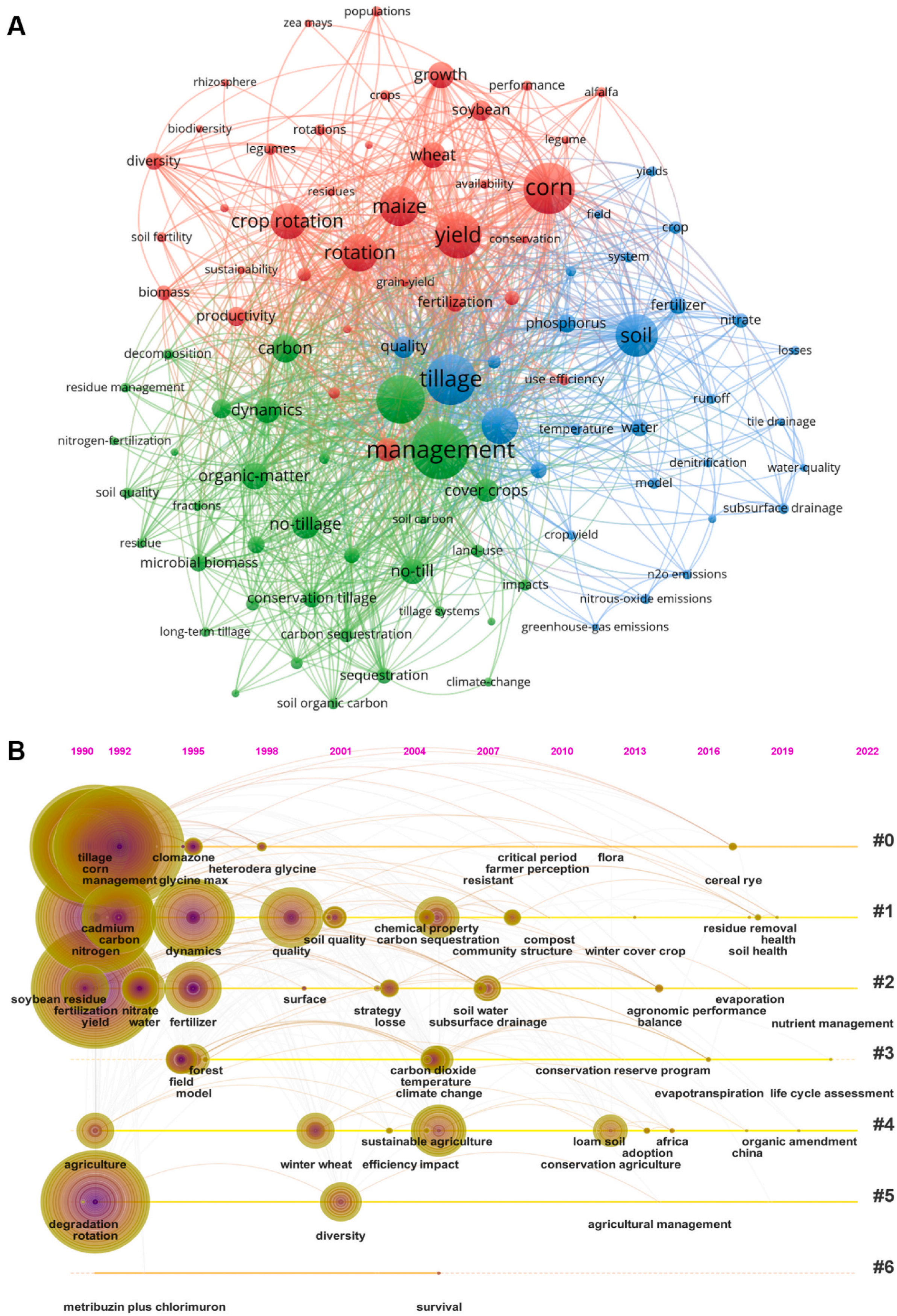

Fig. 4. Evolution of hotspots and the research trends of maize-legume rotation: (A) Clusters of keywords (B) The timeline of keywords evolution: #0, conservation agriculture; #1, soil; 2#, water quality; 3#, environment benefits; 4#, sustainable agriculture; #5, rotation; #6, crop rotation.

Meanwhile, researchers sought to understand the benefits of maize intercropping with different legumes, the corresponding patterns and management practices, and their mechanisms behind.

Since 2010, the emergence of the keywords “climate change”, “sustainable intensification”, and “facilitation” indicate that research has gradually shifted its attention from crude agricultural systems with high resource consumption to efficient and sustainable use of limited land, fertility, water and other resources. These keywords experienced a burst from 2019 to 2022 (Fig. S2). Research on intercropping in recent years has also focused on, e.g., resource use efficiency (Fig. 3B #4), interspecific relationships (Fig. S2), above- and below-ground extension and the soil microcosm (#2), theoretical foundations and mechanisms.

3.3.2. *Evolution of crop rotation research*

In the early 1990s, terms “soil”, “soybean residue”, “fertilization”, " (weed) population dynamic”, and “nitrate” emerged as prominent terms (Fig. 4B. S2), suggesting that legume residues in rotation establish a cycle where high-quality residue generates effective fertilizer, subsequently enhancing soil fertility and mitigating soil fertility degradation. In the mid-1990s, researchers began to focus on the ability of maize-legume rotation to manage biotic stresses (e.g., the *Heterodera glycines* and *Diabrotica virgifera virgifera*). Research has also turned to the agrichemical negative impacts and control measures of herbicides (clomazone, atrazine etc.).

Research on maize-legume rotation remained silent after 1999 (see Fig. S2B), but experienced a resurgence after 2011. At that time, the focus of researchers changed radically - the role and benefits of crop rotation as one of the means of conservation agriculture practice in and against risks such as extreme weather and global warming (see the thriving of #3, #4 in Fig. 4B and Fig. S2B). For example, there has been an increased interest in the ability of maize-legume rotation to sequester carbon and reduce greenhouse gas emissions (cluster#2, color green in Fig. 4A). These studies highlight the potential for maize-legume rotation to contribute to a more sustainable agriculture system. Another area of attention has been on the impact of maize-legume rotation on nutrient cycling and soil health (cluster#3, color blue in Fig. 4A).

3.3.3. *Future trends analysis*

We also summarized the top 10 publications by the usage count in the last three months, to observe the interest and intention of researchers, and the potential hot areas can be distinguished by combining with the citation frequency of a paper (Table S3). We find that the main keywords of the articles that received the most attention include water, fertilizer use efficiency (nutrient uptake), root system, soil, etc., indicating that researchers are still interested in the potential benefits of intercropping. Researchers have also been exploring the mechanisms underlying these benefits, including root plasticity, complementarity of crop traits, and the influence of soil microbial communities. In terms of crop rotation research (Table S3 b), the focus is quite concentrated, and the focal point is soil carbon sequestration. Among the top 10 publications, seven are about soil carbon. In addition, soil labile carbon and nitrogen fractions, soil bacterial and fungal communities and soil aggregate stability are also hot spots. In general, the protection mechanism of crop rotation and other conservation tillage may be a research hotspot and trend (Table S3, Fig. S3).

Four of the top 10 publications on intercropping and rotation utilize meta-analyses or reviews. These approaches are favored by researchers for their ability to identify knowledge gaps, quantify effects, and inform future research directions, policies, and interventions.

4. Discussion

4.1. *Benefits of Intercropping and crop rotation*

Intercropping and crop rotation have the potential for a beneficial balance, providing ecosystem services while increasing yields, which makes them promising practices that can contribute to ecological (or eco-functional) and sustainable intensification on crop production. A decade-long monitoring study revealed that maize-legume intercropping systems, on average, outperformed monoculture by 22% in grain yield (Li et al., 2021a). Similarly, rotation has shown the potential to boost yields by 20% (Zhao et al., 2020). Nevertheless, the enhanced yield benefits of the practices exhibit inconsistency across world (Nurgi et al., 2023; Sarobol and Anderson, 1992; Xu et al., 2020; Zhao et al., 2022), and may attribute to different climate conditions, variety selections, management strategies etc. Moreover, maize-legume intercropping and rotation enhance the efficient utilization of agricultural resources (such as land, nutrients, water, and radiation) in both temporal and spatial dimensions, resulting in higher yields or farmer income and a range of ecological benefits.

We review and summarize the key evidence and mechanisms for the benefits of diversified cropping systems mediated by intercropping and crop rotation in recent years (Fig. 5, Table S4). One of the most notable advantages of intercropping is the conservation of land resources. A global-scale meta-study examining the efficiency of land and fertilizer nitrogen use in maize-soybean intercropping revealed that, under similar yield conditions, maize-soybean intercropping can save an average of 32% (Q1 = 11%, Q3 = 44%) of land resources and 44% (Q1 = 20%, Q3 = 67%) of fertilizer nitrogen (Xu et al., 2020). While the practice improves land use efficiency worldwide, the extent of improvement varies significantly, ranging from 4% in South America to 48% in Europe (Xu et al., 2020). In addition, both intercropping and rotation have been proven to enhance soil fertility by increasing soil organic matter, nitrogen, and macroaggregates, leading to long-term improvements in yield benefits and overall sustainability (Li et al., 2021a). A study compiling data from 167 studies worldwide, indicated that rotation generally increases soil organic carbon (SOC) content by 6.6% (Liu et al., 2022). Stable organic carbon is less prone to release as greenhouse gases, thereby reducing carbon emissions (Singh and Kumar, 2021; Raza et al., 2021; Hassan et al., 2022). Plant-to-plant interactions, including complementarity, resource partitioning, and facilitation, enable greater nutrient acquisition and improve fertilizer and water use efficiency (Drinkwater et al., 2021). Due to their water use efficiency and higher recovery capacity for NH_4+ and NO_3- (Shen et al., 2018), maize-soybean intercropping and rotation systems are also more likely to reduce cumulative N_2O emissions (Sun et al., 2021). Moreover, interactions in the rhizosphere, such as allelopathy, can suppress weed growth (Khan et al., 2002), control pathogens (Nemadodzi et al., 2023), and reduce arthropod pests (Hailu et al., 2018), among other benefits.

Efficient utilization of agricultural resources is a key approach towards sustainable agricultural development (Li et al., 2021b). Relevant with this goal, several projects have been developed, such as DIVERFARMING, DiverIMPACTS, LEGVALUE, TRUE, DIVERSify, and ReMIX (Amrom et al., 2021; Parras Galán et al., 2019; Smadja and Muel, 2021). These projects aim to promote excellent cropping systems based on intercropping and crop rotation, harnessing the benefits of intercropping and crop rotation in terms of enhanced resource use efficiency, improved soil health, reduced pest and disease pressure, and increased biodiversity. These initiatives support the transition towards more sustainable and resilient agricultural systems.

4.2. *Development pattern of maize-legume intercropping and crop rotation research*

4.2.1. *Temporal pattern*

Throughout human history, intercropping and crop rotation have been traditional practices for food crop production (Feng et al., 2022). These practices remain essential for crop production, as indicated by the evolving research topics and hotspots. Maize-legume intercropping and rotation exhibit similar patterns of development and evolution (Fig. 6), summarized as follows:

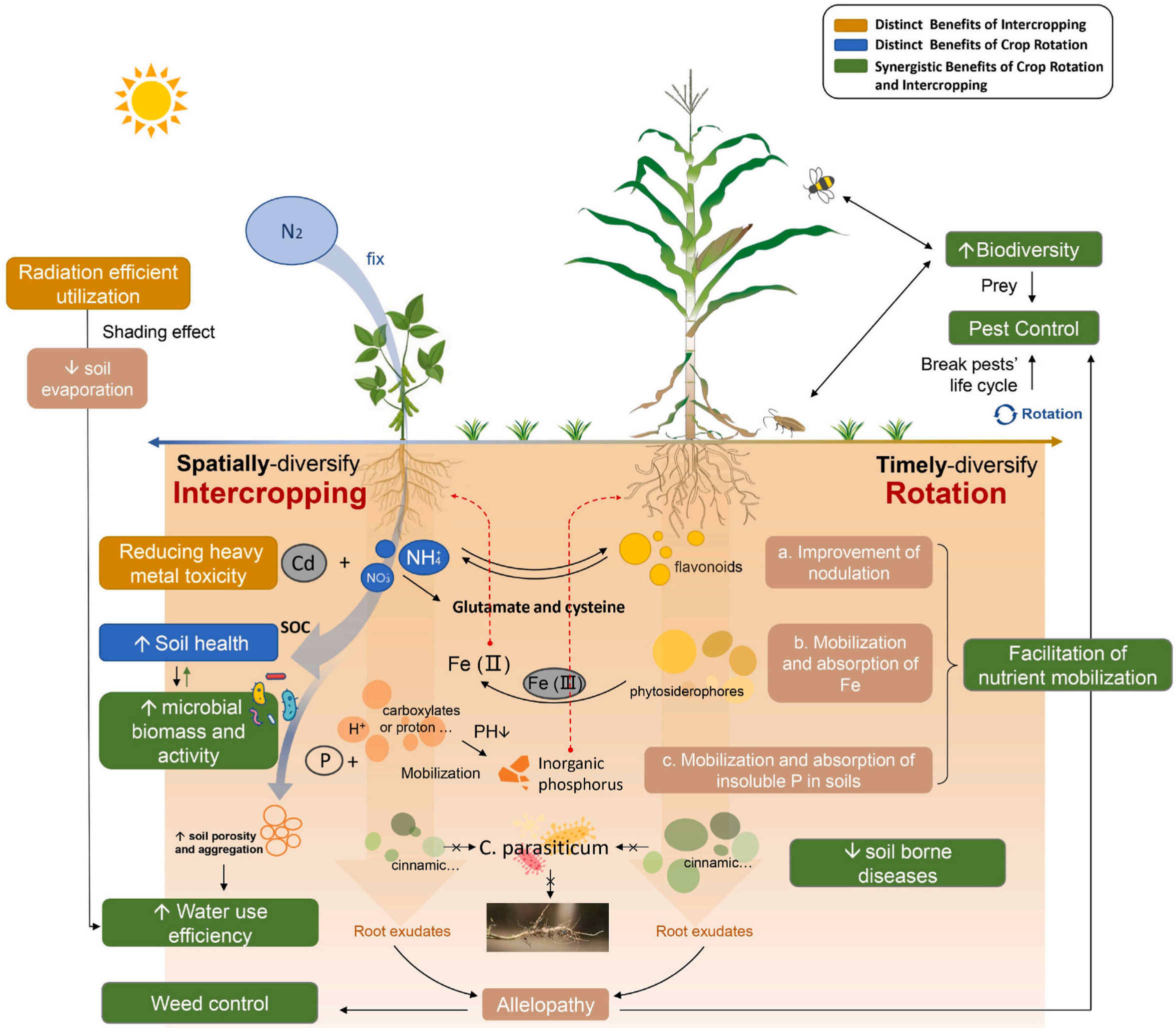

Fig. 5. Mechanisms of benefits of maize-legume Intercropping and crop rotation. See the Appendix Table S4 for relevant supporting materials.

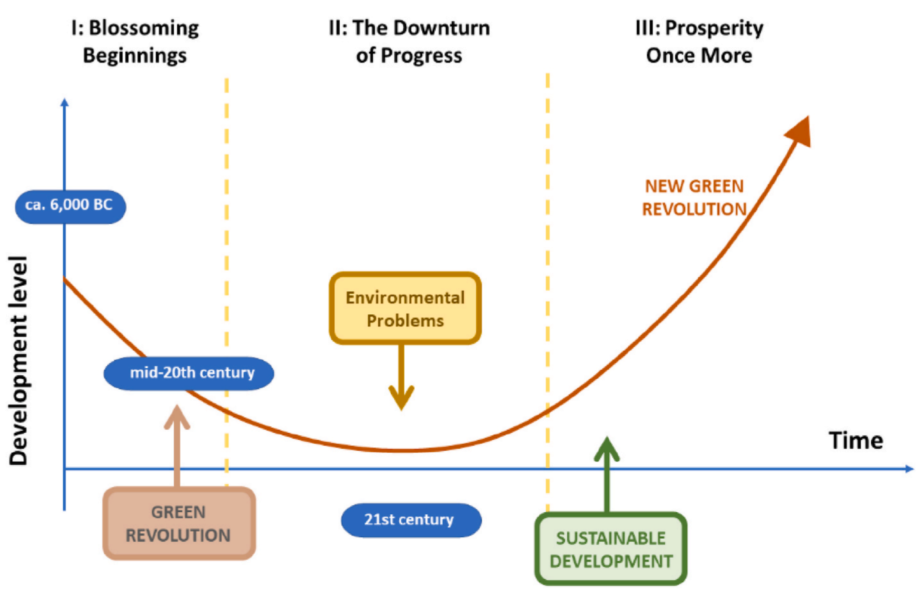

Fig. 6. Development curve of maize-legume intercropping and rotation practice.

Stage I: Blossoming Beginnings (ca. 6000 BC-1950s)

Crop rotation has been practiced by Middle Eastern farmers since 6000 BC, alternately planting cereals and legumes (Henkel, 2015). Since the Indus Valley Civilization (ca. 2600 BC to 1900 BC), the prototype of intercropping has emerged in the South Asian subcontinent (Petrie and Bates, 2017). Early intercropping and crop rotations were designed for the highest immediate return without much regard for the continued use of the underlying resources.

Stage II: the downturn of progress (1950s–2000s)

As population grew and the challenge of meeting the demand for food became apparent, the need to increase food production through traditional intercropping and crop rotation could no longer be met. At this time, the dawn of the Green Revolution began (mid-20th century) (Conway, 1997). With the adoption of industrial agriculture, traditional intercropping began to disappear in different countries (Bracken, 2019). Monoculture became popular. This shift was motivated by the use of high-resource inputs, improved agricultural machinery and specialization, which were considered the main strategies to increase crop yields (Wei et al., 2022b). Similarly, traditional crop rotation practices were giving way to restoring soil pH through the application of fertilizers, i.e., the addition of ammonium nitrate, urea, or lime (Mulvaney and Robbins, 2023). Global fertilizer use rose from 14 MT in 1950 to 197 MT in 2007–2008 (Morari et al., 2011; Kugbe et al., 2018). It seemed no longer necessary to intercrop legumes with main grains to increase yields, or to rotate crops to provide the nutrients needed by the main crop. Taking China as an example, the proportion of cultivated land using intercropping in China has decreased from around 30% in the 1990s to 18% in 2007 (Hong et al., 2017). Since the beginning of the 21st century, the traditional planting model formed by the practical experience of ancestors has gradually withdrawn from the stage of history.

Stage III: prosperity once more (2000s -present)

While the green revolution led to an increase in agricultural production, the energy input to produce crops increased even faster (Church, 2005). The excessive use of fertilizers and chemicals caused several environmental problems such as groundwater and surface contamination, soil acidification, and ammonia volatilization (Horrigan et al., 2002; Wang et al., 2018; Shah et al., 2021). Monoculture worsened weed and pest pressures and reduces diversity (Crews et al., 2018). These environmental costs are widely recognized as a threat to the long-term sustainability and replication of the success of the Green Revolution (Pingali, 2012; Wei et al., 2022a).

As the problems of monoculture systems become increasingly prominent, traditional planting modes such as intercropping and crop rotation are back on the researchers' agenda. Combining them with modern agricultural technologies such as precision agriculture is gradually considered an important solution to achieve agricultural sustainability (Wan et al., 2021). This is evidenced by the rapid and sustained upward trend since 1990 (Fig. 1) and new multi-point bursts after 2010 in the intercropping and crop rotation research (Fig. 4 and Fig. S2).

4.2.2. Spatial pattern

Globally, maize-legume intercropping research is led by China in research development (Fig. S1A). Low-income countries such as Kenya in Africa have also made outstanding contributions in this area. In contrast, crop rotation research is dominated by developed countries, with the U.S. as the absolute authority. The intercropping model and its structural advantages are consistent with the national conditions of developing countries and may be related to four reasons: low input and high output; limited land; smallholder farming; and resistance to extreme weather.

In economically disadvantaged developing countries, it is more important to achieve high crop yields with minimal resources (Himmelstein et al., 2017; Xu et al., 2020). Cereal-legume intercropping is particularly advantageous in low-input systems (Mahmoud et al., 2022). Legumes can fix approximately 39–182 kg N ha^{-1} (Peoples et al., 2009). When legumes are intercropped with cereals, they fix more N (per plant) than when grown as a mono-crop because of the intense competition for N from cereals (Xu et al., 2020).

Relative to intercropping, developing countries do not seem to have fully appreciated the important value of crop rotation (Fig. S1B). Crop rotation is essentially a conservation farming practice and is considered to lead to lower maize yields because maize is not grown in the legume stage of the rotation. Smallholder farmers in developing countries are most concerned with economic benefits rather than environmental ones and therefore are less likely to implement crop rotation systems. Although studies have demonstrated the significant effectiveness of soybean rotation in enhancing yields, as well as its ability to reduce annual phosphorus application requirements for maize, the resulting input reduction can bring substantial economic returns (Droppelmann et al., 2017). However, limited financial resources, low-risk tolerance and low levels of education make it difficult for many smallholder farmers to take this initial step. In comparison, the most obvious ecological advantage of intercropping is land saving (Martin-Guay et al., 2018), which is important for developing countries where land resources are scarce. Furthermore, crop cultivation is one of the most sensitive and vulnerable sectors in the context of climate change (Kurukulasuriya and Rosenthal, 2013). Extreme weather events globally, such as heat waves, heavy rainfalls, floods etc., have led to crop yield reduction, which is particularly fatal for smallholder agriculture in developing countries, especially in tropical regions with rain-fed production systems. Smallholder farms using traditional or informal tenure, are less resilient to risk (Morton, 2007). Intercropping systems can avoid compromising long-term stability (Raseduzzaman and Jensen, 2017; Renwick et al., 2020).

The majority of cropland in developed countries, represented by the U.S., is farmed on a rotational basis (Wallander, 2013). According to the USDA Agricultural Resource Management Survey (ARMS), only about 18% of cropland was continuously planted solely maize. The 2-year rotation of maize and soybeans is one of the most widely adopted crop rotation systems. An important reason is that soybeans help maize escape damage from the corn rootworm beetle (*Diabrotica* spp.) and western corn rootworm (*D. virgifera virgifera*) by providing a year in which the field was not infested with rootworm eggs and subsequent root-chewing larvae. Farmers could avoid the use of chemical pesticides to control corn rootworms (Levin, 2001). In addition to considerations of insecticide resistance and the cost of insecticides, US farmers are willing to adopt crop rotation systems may also be related to the national policy, where crop rotation is a necessary condition for farms to obtain organic certification (NOP, 2000).

4.3. Hotspots and future outlook

A primary challenge in agriculture today is to concurrently boost grain production and mitigate environmental pollution (Xu et al., 2020). Maize is one of the world's most important grain crops (Nuss and Tanumihardjo, 2010), while legumes serve as a crucial source of plant-based protein (Semba et al., 2021). Particularly, soybeans are a significant oilseed crop (Pratap et al., 2012), and their cultivation is regarded as one of the direct contributors to tropical deforestation (Song et al., 2021). Addressing the exceedingly high global demand for these two crucial crops while minimizing resource consumption and environmental damage, maize-legume intercropping and crop rotation emerge as potential key solutions.

4.3.1. Unveiling mechanisms behind

Maize-legume intercropping and rotation not only aim to balance productivity but also contribute to ecosystem services through enhanced biodiversity spatially and temporally (Shah et al., 2021), i.e., pest and disease control (Himmelstein et al., 2017), carbon sequestration (Thierfelder et al., 2013), and production stability in extreme weather (Yu et al., 2022), representing a key strategy for sustainable agriculture (Selim, 2019; Zhao et al., 2022).

Although intercropping and crop rotation are ancient cropping systems with well-recognized advantages, the mechanisms behind are still not fully understood. According to the analysis results based on keyword hotspot evolution, keyword outbreak, cluster analysis and thematic maps, exploring the efficiency of resource (water, nutrient and radiation) use in cropping systems and testing the resilience of yields to weather variability under intercropping and crop rotation systems has been a hot topic of research in recent years and is likely to continue to receive attentions in the future. Researchers have reported the below-ground interactions between crop species under intercropping and crop rotation systems (Homulle et al., 2022), root-root interactions (Li et al., 2016) and rhizosphere interactions (Zheng et al., 2022). Processes occurring in rhizosphere are controlled by phenotypic traits, such as water or nutrient use efficiency, systemic and local immune responses, as well as root architecture and resource acquisition efficiency. These plant traits, in turn, can be significantly influenced by associated below-ground interactions involving plants, microbes, and soil (Oburger et al., 2022). Roots bridge the above- and below-ground world and have become one of the common topics of study among researchers in recent years. By combining insights into above- and below-ground plant traits, researchers hope to make more informed decisions about adopting sustainable agricultural practices and plant breeding strategies, and develop cropping systems that can maintain supplies and regulate ecosystem services in the face of unusual weather conditions.

4.3.2. Towards climate-resilient agriculture

The rise in global surface temperatures and the increasing frequency of extreme weather events are exacerbating the decline in food production, disrupting the stability of crop yields (Holst et al., 2013). Our research indicates that, over the past decade, enhancing crops' adaptability to environmental pressure through agricultural diversification and reducing the interannual yield fluctuations caused by extreme weather have become a focal point for researchers.

Climate change poses increased requirements for the implementation of intercropping and crop rotation techniques. Diverse adaptive planting structures and management strategies can be pivotal in enabling the system to adapt to climate change. For example, adjusting planting date significantly influences yield stability and water use efficiency, especially under drought conditions (Chimonyo et al., 2020). The integration of intercropping and crop rotation with conservation tillage is also an effective strategy for enhancing soil health and addressing climate change. Moreover, employing adapted crops and varieties is also a climate-smart practice for risk reduction, soil and water conservation, and efficient water management (Jacobs et al., 2019). This involves introducing new crops or varieties (Sija et al., 2020), or bringing back heritage crops (Chimonyo et al., 2020), which leads to diversification of agricultural production. Yet, with substantial ecological variations among regions, diverse agricultural zones may demand distinct planting strategies and varieties to suit varied climates and weather events. Consequently, future research should integrate more location-specific experiments to offer farmers targeted climate adaptation strategies.

Intercropping and crop rotation not only enhance the adaptability of agricultural systems to climate change but also contribute to meeting climate change mitigation targets by reducing greenhouse gas emissions. This represents a critical agenda for sustainable development (UN GSP, 2012), and is gaining growing attention from researchers, decision-makers, and other stakeholders. Intercropping and crop rotation have the potential to guide the agricultural production system away from a high dependence on fossil energy and agro-chemicals, positioning them as a new model for sustainable and intensive agricultural development (Martin-Guay et al., 2018). Many studies have reported their nitrogen fixation and carbon sequestration capacity in the soil (Peoples et al., 2009; Li et al., 2016; Liu et al., 2022), but a comprehensive understanding of its environmental and resource benefits throughout its entire lifecycle is still lacking. Therefore, we speculate that an in-depth exploration of relevant content will be further developed.

4.3.3. A pilot compound cropping system lead by China

In addition, we believe that a model integrating maize-legume intercropping and crop rotation may be a promising approach to dealing with challenges of sustainable development and food security (Fig. S3). For example, a new, intercropping and rotation-based maize-soybean compound cropping system is expected to play an important role in increasing maize yields in China (Du et al., 2018). Pilot studies have been conducted on key issues of this cropping system, such as the competitive ratio, planting pattern and resource use efficiency (Liu et al., 2017; Du et al., 2018; Raza et al., 2020, 2021). The system has the potential to be a win-win practice for both food production and environmental protection (Du et al., 2018). It can increase production up to 120% and increase nitrogen fixation by 23.8%, reducing the average annual N_2O and CO_2 intensity by 45. 9% and 15. 8% respectively (Du et al., 2018, 2020; Su, 2016). Hence, the Chinese government has emphasized its support for the promotion of this system in policy documents and development plans since year 2020. By 2025, it is expected that more than 8,000,000 acres of maize-soybean compound cropping fields will be promoted (Outline of the 14th Five-Year Plan (2021–2025) for Plantation development of China).

4.3.4. Socioeconomic insights

In the realm of natural sciences, the yield advantages of intercropping and crop rotation have been extensively studied. The focus is on understanding the characteristics and mechanisms that balance productivity and ecological benefits. Researchers suggest that the continuous practice of diversification can result in ecological redundancy, providing farmer households and their communities with livelihood benefits (Vernooy, 2022). However, for farmers, the selection of crops and planting systems is primarily driven by economic benefits rather than enhanced stability or ecological advantages (Zhang et al., 2016). There is positive evidence of increased crop diversity that can augment household income, improve nutrition and food security, and alleviate poverty (Vernooy, 2022). A study of South Africa also indicates that, under nitrogen-free conditions, maize's marginal income can increase by 108%–225% through various legume rotations (Lengwati et al., 2020). Similarly, research by Li et al. (2021a) suggests that intercropping maize with different legumes could increase farmers' net profits by an average of 47%. More optimistic estimates come from studies indicating that intercropping maize-pigeonpea was more profitable with a rate of return of at least 343% than sole maize cropping (Rusinamhodzi et al., 2012). Although many studies have presented optimistic profit estimates for maize-legume intercropping, most of these are based on field experiments. However, there are still challenges for large-scale implementation in actual farm production. For example, compared to monoculture, intercropping necessitates additional efforts in seed preparation and planting. Moreover, the lack of suitable large-scale equipment in the market for planting and harvesting diverse crop mixtures in strip intercropping leads to increased labor demands (Waddington et al., 2007). Additionally, intercropping systems often lack tolerance to herbicides (Pankou et al., 2022; Stomph et al., 2020). Farmers are generally hesitant to invest their land, labor, and seeds in technologies that do not yield swift economic returns. Therefore, how to enhance farmers' willingness to adopt these practices and convert this substantial potential for enhancing system productivity into tangible actions that alleviate rural poverty, improve livelihoods, and ultimately improve food security is a topic of considerable merit.

5. Conclusion

This study analyzes the developing pattern and trend of maize-legume intercropping and crop rotation based on bibliometric analysis. Based on a long-term review of their application, we observe a new climax driven by global sustainable development. For the spatial distribution, maize-legume intercropping research is dominated by developing countries (smallholder agriculture), represented by China, while crop rotation research is dominated by developed countries (large-scale farms), represented by the U.S. Although both systems have the dual objectives of increasing yields and reducing environmental impacts, the former focuses more on the benefits for humans while the latter pays more attention to the benefits for natural systems. It can be inferred that improved resource use efficiency, soil carbon sequestration, rhizosphere effects and microbial communities will be the hotspots. In addition, we summarize the future direction of integrated maize-legume intercropping and crop rotation with the help of smartification, as an effective way of mitigating food insecurity and increasing environmental benefits through sustainable intensification.

Funding

This work was supported by the National Key Research and Development Program of China (2022YFF1003500; 2021YFF1000302; 2021YFD1200700), Science and Technology Innovation 2030- Major Project, 2022ZD0400607, Beijing Nova Program (20220484114), and Foshan Municipal People's Government Special Fund Project for Scientific and Technological Innovation (BK22BE013).

CRediT authorship contribution statement

Yilin Zhao: Data curation, Methodology, Validation, Writing – original draft. **Songhao Guo:** Formal analysis, Methodology, Software, Visualization. **Xueqin Zhu:** Conceptualization, Writing – review & editing. **Lei Zhang:** Writing – review & editing. **Yan Long:** Funding acquisition, Project administration, Supervision. **Xiangyuan Wan:** Funding acquisition, Project administration, Supervision. **Xun Wei:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.140150.

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