

Toward serving land consolidation on the table of sustainability: An overview of the research landscape and future directions

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ABSTRACT

Land consolidation, as a sustainability-oriented policy design, has been implemented worldwide for promoting agricultural production and rural development. Although there has been a large number of publications on land consolidation, few attempts have been made to systematically assess the existing research. To fill this gap, here we present a comprehensive literature review of land consolidation based on materials collected from Web of Science. Through applying quantitative and qualitative analysis to the collected literature, including statistical analysis, cluster analysis and main path analysis, we found: (1) Land consolidation has formed an interdisciplinary research field with more than one century's history, with scientists from developing countries more active than those from developed countries. (2) The hot topics of rural sustainability, impacts evaluation, land fragmentation and land reallocation are closely related to the theme of land consolidation. (3) Research of land consolidation mainly covers three knowledge domains: origins of land consolidation, operation process of land consolidation, and impacts of land consolidation. To advance land consolidation to better serve the pursuit of sustainability, we suggest to take a diagnostic approach to assessing the suitability and feasibility of land consolidation before launching a project, and to adopt a transdisciplinary approach to linking science with knowledge through involving both scientists and stakeholders into the knowledge production and application process.

1. Introduction

Land, as the interface of human-environmental interactions, has long been a research frontier of sustainability studies (Kates et al., 2001; Fang et al., 2018), with growing research fields such as landscape sustainability (Wu, 2013; Zhou et al., 2019) and land system science (Turner et al., 2007; Verburg et al., 2015). A converging research priority of the sustainability-oriented land studies is to invent and apply land-based policy instruments to facilitate sustainability transitions (Liu, 2018; Wu, 2019). Such studies are exemplified by the emerging research direction of land system architecture (Turner, 2010). Somewhat parallelly, land consolidation—though with a long research history—has been relatively understudied in terms of its potential for serving the pursuit of sustainability (but see Pasakarnis and Maliene, 2010; Huang et al., 2011; Li et al., 2018; Liu, 2018).

In fact, land consolidation has a long tradition of practice in Western European countries. The “Enclosure Movement” of the UK in the 19th

century was seen as a rudiment of land consolidation. In as early as the 1920s, many countries dominated by small-scale agriculture (e.g., France and Netherlands) began to make legislations to facilitate land consolidation projects (van Dijk and Kopeva, 2006). Until the 1980s, land consolidation had developed a mature model and started to become a popular agriculture policy in Asia as well as Eastern Europe (Niroula and Thapa, 2005; Pasakarnis and Maliene, 2010; Bryan et al., 2018). Since the turn of the twenty-first century, the FAO has published a series of manuals to promote international cooperation and to instruct the worldwide land consolidation projects (FAO, 2003, 2004, 2008, 2012, 2015).

Usually, land consolidation is deemed as a policy instrument to promote agricultural production in rural areas (Vitikainen, 2004; van Den Brink and Molema, 2008). Sometimes though, land consolidation was also applied in the urban context with a purpose of reorganizing land parcels to facilitate urban expansion and infrastructure construction (Agrawal, 1999), to which was also referred as “land readjustment”

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(Larsson, 1997; Sorensen, 2000). Both practices of land consolidation and land readjustment play an important role in sustaining rural as well as urban development (Bullard, 2007). However, these overlapping and confusing terminologies make it difficult for scientist groups to communicate with each other and cumulate knowledge to support sustainable practices.

To develop comprehensive understanding of a terminology, we need to grasp its main research theme and knowledge domain. The present study is a timely attempt to fill that gap by presenting a systematic review of land consolidation (here we treat land consolidation and land readjustment as two individual terminologies, since they may have different research themes and knowledge domains). Specifically, our research will address the following four questions to understand land consolidation: First, what is land consolidation? Second, how to implement land consolidation? Third, what will land consolidation bring about? Fourth, how to respond to the potential challenges for advancing land consolidation?

The remainder is organized as follows: Section 2 introduces the data source and analysis methods in our research; Section 3 reports the evolutionary trajectory and scientific landscape of land consolidation research; Section 4 identifies the potential challenges and proposes suggestions to advance land consolidation; Section 5 draws the conclusions.

2. Methodology

2.1. Data source and collection

To conduct a systematic literature review in terms of land consolidation, we chose Web of Science, one of the most widely-used citation databases in the world, to collect related publications. We did an exhaustive search with topical query of “land consolidation” or “land consolidations” in the title, abstract, and keywords. Our search was limited to the core collection of Web of Science, including Science Citation Index Expanded (SCIE), Social Sciences Citation Index (SSCI), Conference Proceedings Index-Science (CPI-S), Conference Proceedings Index-Social Science and Humanities (CPI-SSH) and Emerging Sources Citation Index (ESCI) to avoid irrelevant voices.

We obtained a data collection of 879 records through implementing the topical search on December 09, 2020. Then, we manually checked the title and abstract of each record to check whether it covered the topic of land consolidation. Finally, we got a database of 507 records after removing irrelevant research. Our database is composed of document types of article, proceedings paper, and book review etc., mainly written by English and German (Table 1). (Details of the records can be found in Supplement 1).

2.2. Analysis methods

To get an objective review of land consolidation research, we

Table 1
Document type and language of collected records.

Document Type	Records	Language	Records
Article	326	English	443
Proceedings Paper	155	German	43
Book Review	7	Chinese	6
Review	7	Czech	4
Article; Proceedings Paper	5	Slovene	3
Editorial Material	2	Slovak	2
Article; Early Access	1	Croatian	1
Discussion	1	Dutch	1
Journal Article	1	French	1
Meeting Abstract	1	Japanese	1
Review; Early Access	1	Slovenian	1
		Turkish	1

Generated by HistCite™ software (Garfield et al., 2006).

combined qualitative analysis with quantitative methods to detect the main knowledge domains of land consolidation research, and mapped its evolving research landscape. The general development trend of land consolidation research was demonstrated through basic statistics generated by HistCite™ software (Garfield et al., 2006). The yearly output, journal output and country output were analyzed with statistical indicators. Co-author relations at the country level were visualized via an online bibliometric analysis platform (available at <https://bibliometric.com/>).

To identify the main knowledge domains of land consolidation research, we applied cluster analysis to the keywords and publications based on co-occurrence and co-citation relations. Extraction of key words and the subsequent cluster analysis were implemented via VOS-viewer software (available at www.vosviewer.com) (Waltman et al., 2010; Van Eck and Waltman, 2010, 2011). Publication grouping was conducted via the software of CitNetExplorer (available at www.citnetexplorer.nl) (Waltman and Van Eck, 2012, 2013; Van Eck and Waltman, 2014). CitNetExplorer visualizes different thematic clusters with different colors.

With cluster analysis, the 507 publications would be classified into different groups based on their co-citation relations. Each group would represent a sub-network of land consolidation research. Yet, it is still not easy to capture the major topics of each cluster by artificial reading. Accordingly, we applied main path analysis to each cluster to identify the seminal papers that connect the whole network (Carley et al., 1993). Main path analysis was conducted via the software of Pajek (available at <http://mrvar.fdv.uni-lj.si/pajek/>) (Batagelj and Mrvar, 2004). The backbone literatures are not necessarily the most-cited publications, but they are important nodes that are built on former literatures and have significant influence on later works (Lucio-Arias and Leydesdorff, 2008). By full-text reading of the identified seminal papers, we can then summarize the major research topics of each cluster.

3. Results

3.1. Statistics of land consolidation publications

3.1.1. Temporal pattern of land consolidation publication

Publication is essential for scientists to communicate with each other and diffuse knowledge. By analyzing publication activities of the academia, we can get a general glimpse of the development momentum of a certain research field. Based on the literature collected from Web of Science, the publication activities of land consolidation research spanned from 1914 to date (Fig. 1). In the earliest stage, from 1914 to 1976, the scientific community was nearly dormant with few outputs. After 1977, the science community seemed to grow up, featured by increasing

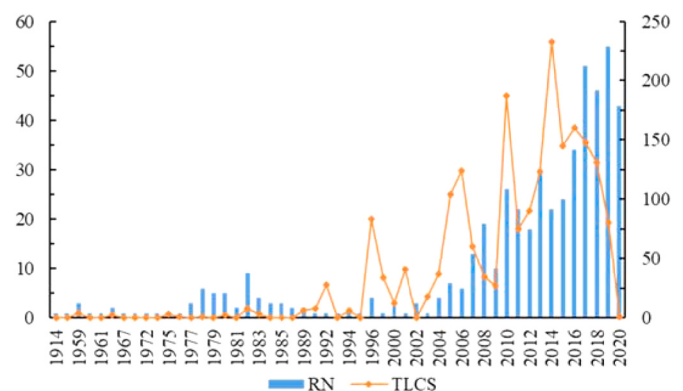


Fig. 1. Yearly output and local citation score of land consolidation publications (RN, records number; TLCS, total local citation score). The left axis indicates records number and the right axis indicates total local citation score. Both the RN and TLCS were generated by Histcite™ software (Garfield et al., 2006).).

publications. Yet, the growing momentum was not stable, it began to slow down since 1982. The following second dormant stage lasted until 2004, when the scientific community started booming with annual publication increasing stably. The most active phase of land consolidation research was from 2017 to date, with a yearly output of over 45 publications. Growing scientist group of land consolidation research contributed to the increasing publications since 2004. In 2002, the FAO Regional Office for Europe and Central Asia conducted the first land consolidation workshops to provide guidelines for land consolidation projects, which evolved into an academic network of LANDNET in 2010. Furthermore, in 2004, the FIG (International Federation of Surveyors) held the first symposium on modern land consolidation to introduce mature land consolidation models. Both the conferences and workshops acted as communication channels for the scientists and inspired their publication activities.

The cited times of a publication can reflect its influence on later research. More cited times mean that a publication plays more important roles in diffusing knowledge in a certain research field. In our research, we used the local citation score to compare the cited times of publications on land consolidation. Differing from publication activities, the citation strength of publications fluctuated over time. There were several peaks of the local citation score. The first peak value emerged in 1996, followed by the second peak in 2006. Although there were low outputs in 1996–2006, these publications contributed much more intelligence to later research works than some highly output years. In the recent decade, there were two peaks distributed in 2010 and 2014, which means research works in these two years provide important foundation and inspiration for later research.

3.1.2. Spatial pattern of land consolidation publication

Although land consolidation is a worldwide practice, it attracts much more academic interests in the developing countries than developed countries (Table 2). As shown by our database collected from Web of Science, more than half of land consolidation publications were from developing countries, among which China accounts for 36.74% of the total volume. Scientists from Poland and Turkey are also active in land consolidation research, contributing 11.2% and 7.07% publications, respectively. Among the developed countries, the UK, FRG and USA take the leading position with regard to land consolidation publications. However, larger publications are not necessarily bringing about higher citation score. Academia in the FRG published 33 papers, but their total local citation score is only 7, far below those of the UK and USA. China, as the country with the most publications, also has the highest local citation score, which means China's scientists are the most active in land consolidation research.

Table 2

Total volume of land consolidation publications at country level.

Country	Recs	Proportion	TLCS
PRC	187	36.74%	625
Poland	57	11.20%	143
Turkey	36	7.07%	178
UK	29	5.70%	312
FRG	33	6.48%	7
USA	25	4.91%	128
Czech Republic	23	4.52%	108
Germany	18	3.54%	47
Slovakia	17	3.34%	29
Netherlands	15	2.95%	56
Spain	15	2.95%	128
Australia	12	2.36%	87
Austria	8	1.57%	88
Croatia	7	1.38%	2
Japan	7	1.38%	15

Recs: total number of records; TLCS: total local citation score. Both Recs and TLCS were generated by Histcite™ software. Only countries with more than 5 publications were shown in the table.

Although Chinese scientist are active in land consolidation research, they tend to be less engaged in international cooperation (Fig. 2). Most of the publications in China have domestic co-authors, only a tiny proportion of scientists have foreign co-authors. Scientists from the USA are the most popular group for Chinese scholars to cooperate with. Academia in other developing countries, like Poland and Turkey, are also not so active in international cooperation (Fig. 2). Conversely, scholars in the developed countries are much more active in international cooperation. In the UK and the USA, more than half of the publications have co-authors from other countries.

3.1.3. Disciplinary pattern of land consolidation publication

In our collected records, there are 11 journals and conference proceedings each with over 5 land consolidation publications. These journals and conference proceedings cover diverse disciplinary fields such as Social Science (e.g. *Land Use Policy*), Computer Science (e.g. *Computational Science*), Geography (e.g. *Journal of Geographical Sciences*) and Sustainability Science (e.g. *Sustainability*) (Table 3). The multidisciplinary publications mean that land consolidation is an interdisciplinary research field.

Among these journals, *Land Use Policy* has the most publications and highest total local citation score (Table 3), which indicates the prominent position of *Land Use Policy* in land consolidation research. Another top 2 journals with large publications are *Zeitschrift für Kulturtechnik und flurbereinigung* (*Journal of Rural Engineering and Development*) and *Computers and Electronics in Agriculture*. The agglomeration of land consolidation publications indicates that land consolidation is a popular topic in both rural and agricultural policy design. Another noteworthy journal is *Journal of Geographical Sciences*, which has only 10 publications but have a high local citation score of 106. The asymmetric feature of low publication but high citation implies this journal has a significant influence in land consolidation research.

3.2. Cluster analysis of land consolidation publications

3.2.1. Keywords cluster based on words relations

Keywords reflect the kernel topics that a publication reports. Through applying cluster analysis to keywords, we can capture the prominent topics of land consolidation research. Both Author Keywords (provided by contributors) and Keywords Plus (provided by WoS) (Liu et al., 2015) were used as terms source in our research. To reduce information redundancy, we set the threshold of co-occurrence times as 10 to filter keywords that co-occurred less than 10 times. By implementing cluster analysis on VOSviewer, we got a co-occurrence network with 36 nodes and 468 links. The whole network was classified into four clusters based on the co-occurrence relationships. Each cluster is identified with a specific color: Cluster Red, Cluster Green, Cluster Blue and Cluster Yellow (Fig. 3).

Cluster Green is one of the largest sub-networks composed of 10 nodes, where “land consolidation” is in a notable position surrounded by keywords of “GIS”, “areas”, “land reallocation”, “criteria” and “model” etc. Cluster Red also consists of 10 items, which is a keywords union of “management”, “policy”, “productivity”, “efficiency” and “land consolidation project” etc. Cluster Blue connects keywords of “fragmentation” and “land fragmentation” with keywords of “consolidation”, “ownership”, and “size” etc., forming a 9-nodes network. Cluster Blue is closely intertwined with Cluster Red and Cluster Green, indicating the highly overlapping topics of these three clusters. Cluster Yellow is the smallest group with 7 items, among which keywords of “China”, “reform” and “land use” occurred more frequently than other items. The total link strength of nodes in Cluster Yellow was only 552, far below that of Cluster Green, Cluster Blue and Cluster Red, which are 1149, 1002 and 637, respectively. Total link strength measures the frequency of co-occurrences of a given item with other items. The higher total link strength of Cluster Green and Cluster Blue indicates that these two clusters contain the most popular topics in the domain of land

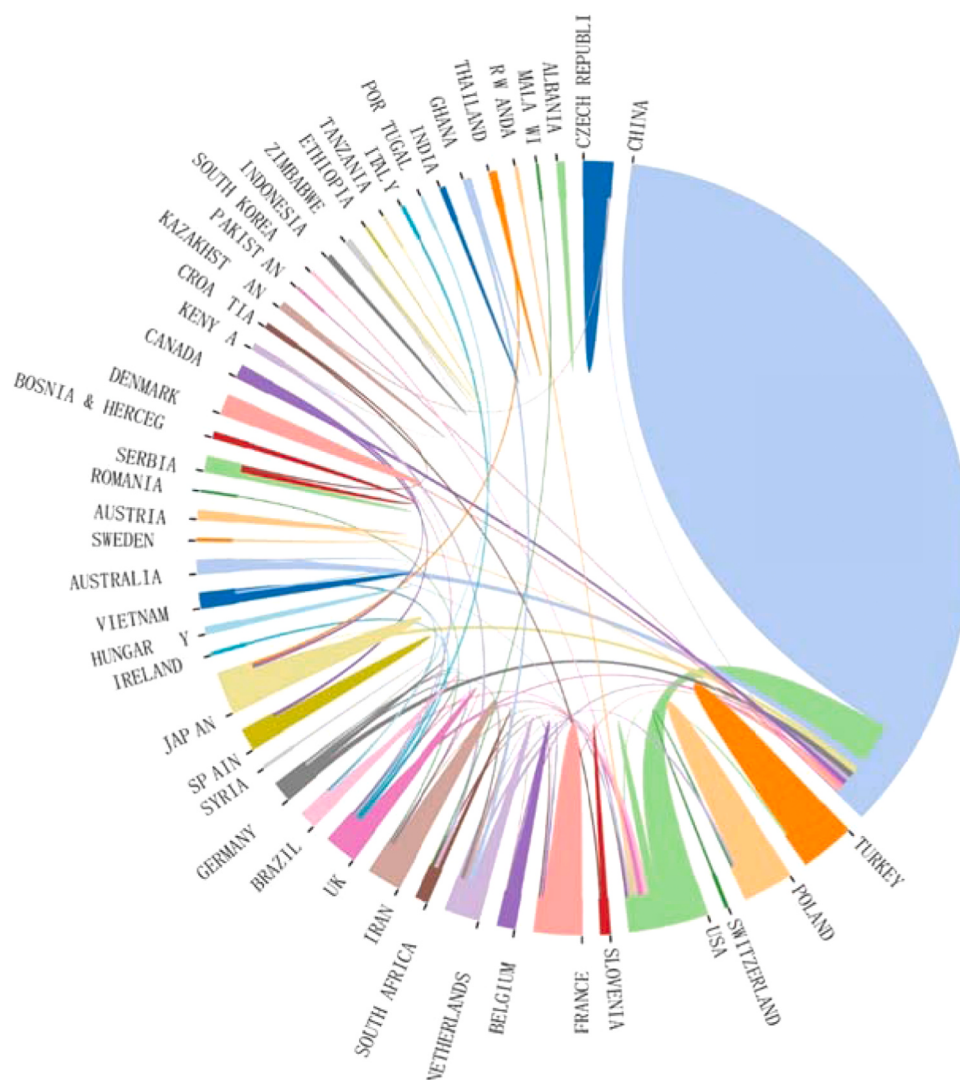


Fig. 2. Co-author relations of land consolidation publications at the country level.

Table 3

Land consolidation publications in different disciplinary field.

Journal	Recs	Proportion	TLCS
Land Use Policy	73	14.40%	949
Zeitschrift Fur Kulturtechnik Und Flurbereinigung	31	6.11%	3
Computers and Electronics in Agriculture	16	3.16%	84
Sustainability	12	2.37%	1
Journal of Geographical Sciences	10	1.97%	106
10th International Conference Environmental Engineering (10TH ICEE)	7	1.38%	0
Fresenius Environmental Bulletin	7	1.38%	1
Geodetski Vestnik	7	1.38%	9
Land	7	1.38%	0
WSEAS: Advances on Applied Computer and Applied Computational Science	7	1.38%	3
Journal of Rural Studies	6	1.18%	56

Recs: total number of records; TLCS: total local citation score. Both Recs and TLCS were generated by Histcite™ software. Only journals or conference proceedings have more than 5 records are shown in the table.

consolidation research. With respect to the specific keywords, terms of “land consolidation”, “land fragmentation/fragmentation” and “China” were the top three frequent topics appeared in our collected literature.

3.2.2. Literature clustering based on citation relations

Cluster analysis of keywords presented the most popular topics of land consolidation research. In this section, we used another literature mining strategy of citation-based analysis to complement the words-based analysis (Chen, 2009). Based on citation relations, we applied cluster analysis to our collected literatures via CitNetExplorer software. In the environment of CitNetExplorer, literatures are mapped according to their publication year and relevance to each other. Two publications were removed from our database before applying cluster analysis due to the lack of specific publication time. With a resolution value of 2.00 and a minimum cluster size of 1, all the publications in our database were classified into 174 clusters (Table 4 and Fig. 4).

There are only 4 clusters with a cluster size of more than 10% of the total publications (Table 4), we thus focused on the top 4 large clusters to dive deeper. Clusters are marked with different color. Cluster 1 is marked with blue color. Cluster 2 is marked with green color. Cluster 3 is marked with purple color. Cluster 4 is marked with orange color. Links between nodes indicates citation relations between literatures, a shorter distance means a closer relevance between nodes (Fig. 4). As shown by the visualized map, literatures in clusters 1 and 4 have more citation links than those in clusters 2 and 3, implying more overlapping research topics in clusters 1 and 4. Clusters 1, 2, and 4 are adjacent to each other, suggesting there are closely intertwined research fields in these three clusters. Conversely, the relatively isolated position of cluster 3 indicates

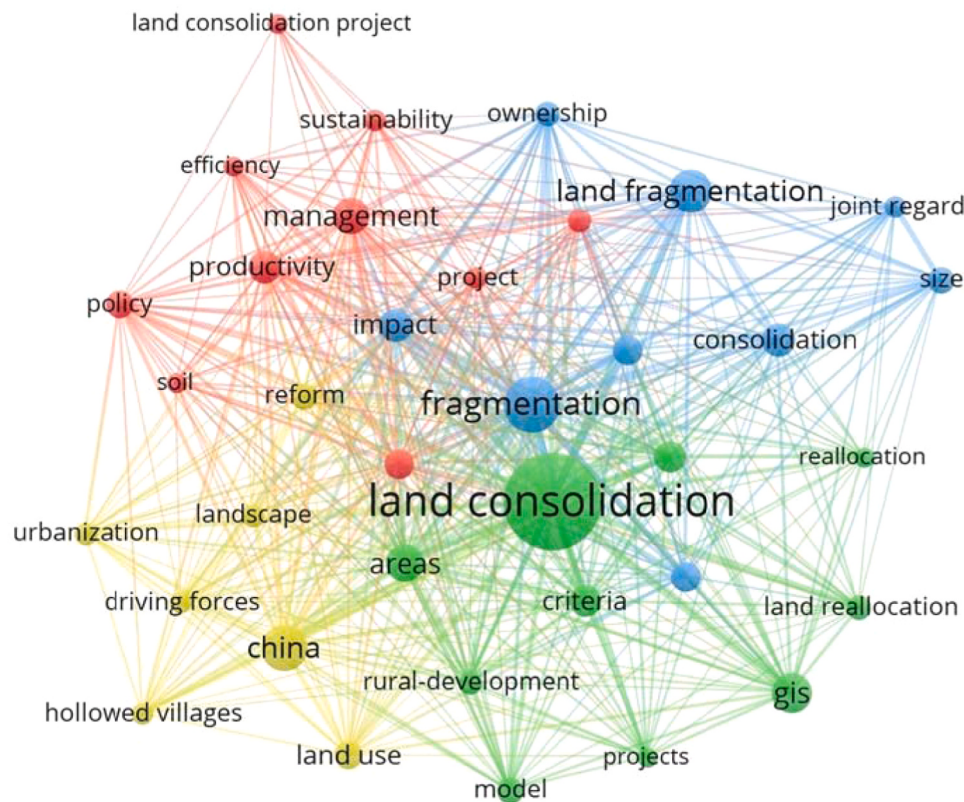


Fig. 3. Clusters of keywords (Node size is proportional to the occurrence number of keywords.).

Table 4
Cluster results of literatures.

Cluster number	Total members	Proportion
Cluster 1	83	16.44%
Cluster 2	69	13.66%
Cluster 3	65	12.87%
Cluster 4	59	11.68%
Cluster 5	13	2.57%
Cluster 6	12	2.38%
Cluster 7	11	2.18%
Clusters with less than 10 members	193	38.22%

its research field is not so related to the other three clusters. (Literature details of the top 4 large clusters can be found in Supplement 2.).

3.2.3. Exploring the major research themes of literature clusters

To explore more expertise embodied in these 4 clusters, we applied main path analysis to the 4 clusters and identified the seminal papers to extract their major research themes (Fig. 5). (Details of the seminal

papers can be found in Supplement 3.).

(1) Major research theme of cluster 1

The main path of cluster 1 starts with van dijk’s report on complications of land consolidation practices in Central Europe (van Dijk, 2007). Contrary to van dijk’s concerns about effects of land consolidation, Pasakarnis and Maliene (2010) as well as Huang et al. (2011) claimed land consolidation was an important approach to sustainable rural development. Long (2014) interpreted the significance of land consolidation to rural restructuring from a geographic perspective. Paralleling with Long, Li et al. (2014) illustrated the positive effects of land consolidation on rural revitalization through a case study in Yucheng, North China.

The following literatures started diverging from former research works except for Zhou et al. (2020), which delineated the mechanisms and paths of land consolidation to promote rural revitalization in China. Yan et al. (2015) and Tang et al. (2019) explained the strategic planning system and structural changes of

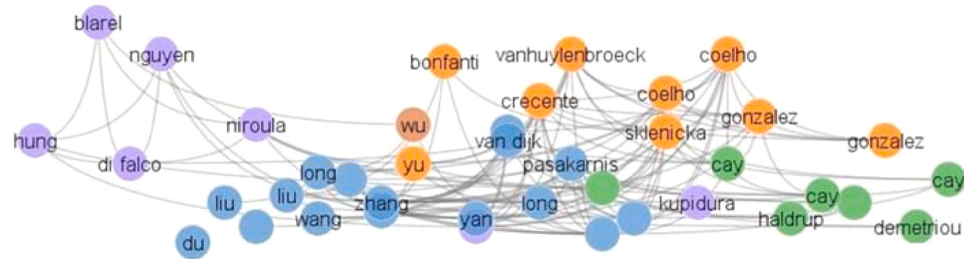


Fig. 4. CitNetExplorer visualization of literature clusters (Only records with higher citation score are shown in the figure. Label is the first author’s last name. Some labels are not shown in the figure to prevent overlapping.). For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

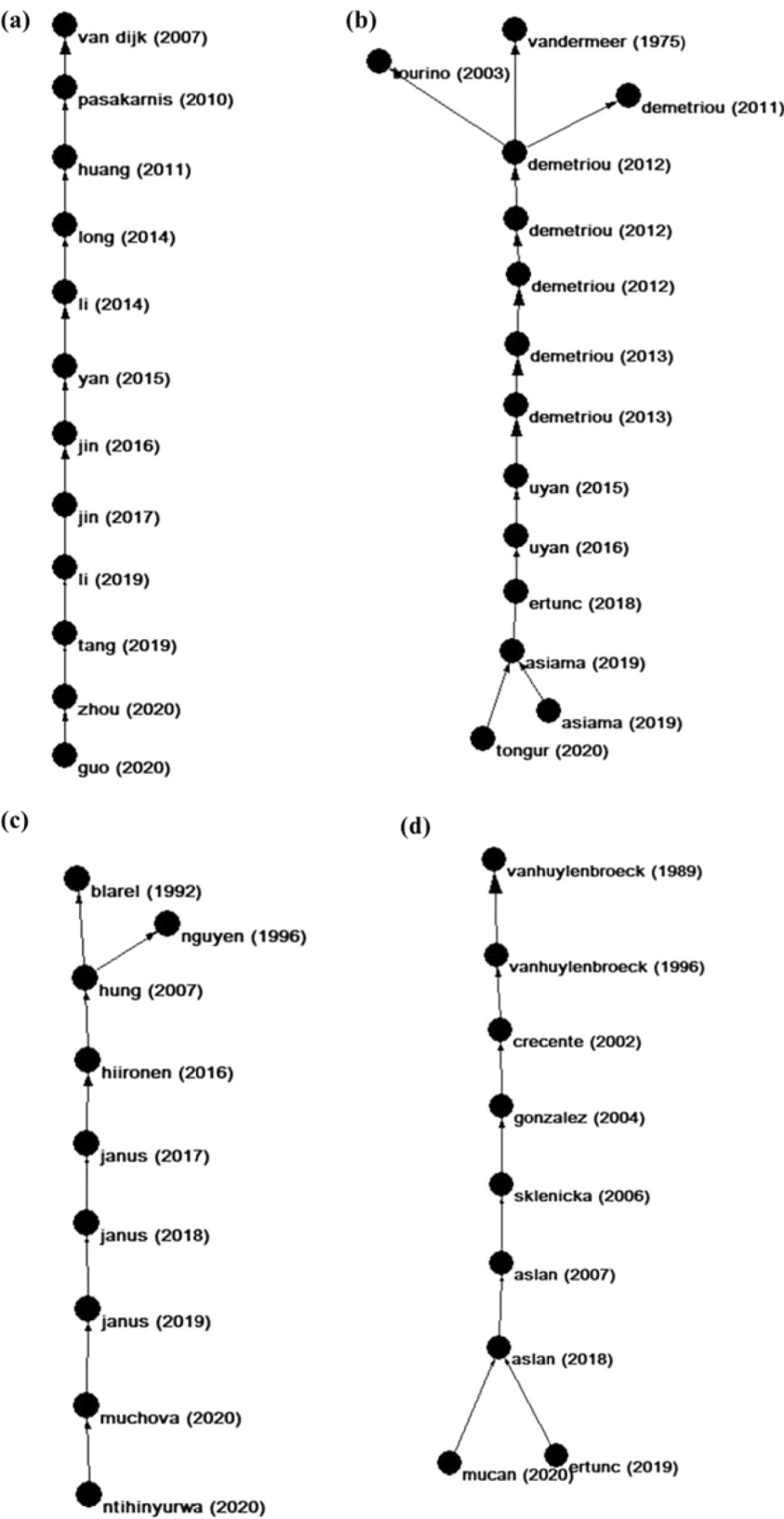


Fig. 5. Main path analysis of top 4 large literature clusters (Labels are the first author's last name and publication year of the backbone literatures. a. cluster 1; b. cluster 2; c. cluster 3; d. cluster 4.).

land consolidation in China, respectively. Jin et al., (2016, 2017), Li et al. (2019) and Guo et al. (2020) focused on analyzing the socio-economic and ecological impacts of land consolidation. Generally, the major research theme of cluster 1 is to examine the feedbacks of land consolidation on rural sustainability and evaluate impacts of land consolidation.

(2) Major research theme of cluster 2

Literatures in cluster 2 mainly report research works that aim to improve efficiency of land consolidation. In view of the long duration and high cost of land consolidation projects, Demetriou et al. (2012a) proposed to develop an integrated planning and decision support system for land consolidation. The envisaged system would cover all stages of land consolidation process, from feasibility analysis, design of alternative solutions, to optimization selection (Demetriou et al., 2012b). Similarly, Tourino et al. (2003) also experimented with a GIS-embedded system to support land consolidation planning in rural areas. The core of the support system was to determine an optimal land reallocation scheme, which is the most complex and time-consuming stage in land consolidation process (Demetriou et al., 2011; Ertunc et al., 2018). Demetriou et al., (2011, 2012c) divided land reallocation into two parts: land redistribution and land partitioning, he also developed two submodules to design land reallocation solutions and evaluate the potential effects of alternative options. Subsequently, diverse index, models and algorithms were developed to advance land reallocation, land distribution and land partitioning process (Demetriou et al., 2013; Uyan et al., 2015; Ertunc et al., 2018; Tongur et al., 2020). Recently, social and cultural characteristics were also considered in land reallocation process. Asiama et al. (2019a) emphasized a responsible land consolidation strategy should be adopted to fit the special customary land tenure system in Sub-Saharan Africa. Furthermore, they developed a process model approach to improve the efficiency of land reallocation on customary lands (Asiama et al., 2019b).

(3) Major research theme of cluster 3

Cluster 3 focuses on the discussion about economic costs of land fragmentation and the need for land consolidation. Most of the papers draw the conclusion that land fragmentation did have negative impacts on agricultural production and that land consolidation was necessary to reduce farming cost and improve agricultural profitability (Nguyen et al., 1996; Hung et al., 2007; Hiironen and Riekkinen, 2016; Janus and Markuszewska, 2017). With case studies in Poland, Janus and Markuszewska (2019) proved land consolidation could have long-lasting positive effects on rural development.

On the other hand, Blarel et al. (1992) hold opposite attitudes to the above opinions. They believed land fragmentation was a risk spreading strategy for farmers to ensure food security and solve rural labor surplus issues, land consolidation would make farmers' situation worse off. Ntshinyurwa and de Vries (2020) agreed that land fragmentation was not necessarily detrimental to rural development, they also suggested to develop a critical perspective to assess land fragmentation issues.

(4) Major research theme of cluster 4

The research line of cluster 4 is to some extent overlapped with those of cluster 1 and cluster 2. VanHuylenbroeck et al., (1989, 1996), Crecente et al. (2002), and Sklenicka (2006) developed multiple methods and criteria to evaluate a land consolidation project in terms of its social, ecological, and economic outcomes, which is related to research works in cluster 1. Ertunc and Cay (2019) as well as Mucan and Asian (2020) concentrated on developing optimal land reallocation models for land consolidation projects in Turkey. Gonzalez et al. (2004) presented a new index to measure land distribution for land consolidation planning. All of these research works follow the direction of cluster 2. Only Aslan et al., (2007, 2018), who paid special attention to farmers' perceptions

and requests about land consolidation, made different voices in cluster 4. In summary, studies in cluster 4 fall into three subgroups: evaluation of land consolidation effects, technical support for land consolidation planning, and recognition of stakeholders' opinions.

4. Discussion

4.1. Lessons from the existing research

4.1.1. What do we know about land consolidation?

Combining the hot topics identified by keywords analysis (Fig. 3) and the research themes identified by literatures analysis (Figs. 4, 5), we found land consolidation research mainly covered three fields: the nexus between land consolidation and land fragmentation, the techniques to support land consolidation, and the understanding of land consolidation impacts especially its effects on rural sustainability. Specifically, the existing research has addressed three questions:

First, what is land consolidation? In retrospect, land consolidation was used as a policy instrument to address land fragmentation issues (Vandermeer, 1975). The basic form of land consolidation was to amalgamate land parcels through engineering measurements and integrate fragmented land holdings by readjusting land ownerships (Farmer, 1960). These measures were also reflected in some local terminologies, such as "remembrement" (land regrouping) in France and "jordskifte" (reallocation of holdings by pooling and redistribution) in Norway (Gatty, 1956; Rognes and Sky, 1998). In some countries, the scope of land consolidation also included land reclamation, soil improvement, and optimization of rural settlement pattern (Jacoby, 1959; Li et al., 2014; Liu et al., 2014; Long, 2014). In view of the varied land tenure system worldwide, land consolidation not only refers to reorganization of land rights, but also includes readjustment of land use, such as land use consolidation in Rwandan and Ghana (Asiama et al., 2017). Some scholars concluded that land consolidation was a complicated engineering project that was aimed to address unsustainability syndromes of land system and promote sustainable agricultural development (Liu et al., 2018; Liu and Wang, 2019; Zhou et al., 2019).

Second, how to implement land consolidation? There are two approaches to perform land consolidation: top-down approach and bottom-up approach. Top-down approach was widely used in Central and Eastern Europe as well as in China, which was characterized by compulsory, state-led land consolidation (Hartvigsen, 2015; Tang et al., 2015). Bottom-up approach was popular in some Western European countries (e.g. Netherlands and Denmark) and some developing countries that are still dominated by customary land tenure (e.g. Ethiopia) (Haldrup, 2015; Gedefaw et al., 2019). Differing from top-down approach, bottom-up approach is featured by voluntary, agreement-based land consolidation. Strategic planning and spatial management are emphasized for state-led land consolidations (Jiang et al., 2015; Yan et al., 2015), while legislation and land mobility are underlined for voluntary land consolidations due to the need for private land exchange (Vitikainen, 2004; van Dijk and Kopeva, 2006). The documented operation details of land consolidation are mainly about measurement of land parcels distribution, schemes of land reallocation and procedures of land partitioning (Gonzalez et al., 2004; Cay et al., 2010). In the recent two decades, automation and computerization played an important role in advancing land consolidation process (Demetriou et al., 2012a).

Third, what did land consolidation bring about? Land consolidation seems a double-edged sword for the social-ecological system. On the one hand, land consolidation reduces the economic costs of land fragmentation and provides favorable conditions for large-scale agriculture (Wu et al., 2005; Hiironen and Riekkinen, 2016). In a wider context, land consolidation creates new opportunities for rural development and helps to reverse the socio-economic declining trend in some rural areas (Pasakarnis and Maliene, 2010; Huang et al., 2011; Long, 2014). On the other hand, land consolidation is an artificial disturbance to the natural

environment and may destroy the ecological integrity. Some studies showed that land consolidation led to degradation of ecosystem services and declined landscape diversity (Bonfanti et al., 1997; Zhang et al., 2014; Wang et al., 2015). In some local circumstances, land consolidation even failed to solve the land use problems because it did not change the structural roots of land fragmentation (Niroula and Thapa, 2005).

4.1.2. Potential challenges for advancing land consolidation

With understanding of the above three questions, we can readily draw an outline of land consolidation. Land consolidation is not only an instrument to eliminate fragmentation and improve agricultural production, but also a complex package of measures to promote sustainable rural development under wider context. Both positive and negative effects could be generated by land consolidation. To advance land consolidation to better serve the pursuit of sustainability, we still need to address at least two challenges:

First, if we want to achieve desirable outcomes of land consolidation, we need to determine whether land consolidation is an appropriate solution to the current problems. It should be a precondition for applying land consolidation projects. Unfortunately, based on our findings, few documents recorded the suitability analysis of land consolidation. Some studies reported estimation work of land consolidation effects, but most of them paid attention to the potential economic benefits and neglected the social and cultural factors (Liu et al., 2013; Jiang et al., 2017; Jin et al., 2017). Sometimes, social and cultural characteristics, like the land tenure system, would significantly influence the outcomes of land consolidation (Bentley, 1987; van Dijk, 2007; Abubakari et al., 2016).

Second, much research has been conducted about land consolidation and its effects, but we did not properly serve this knowledge in land consolidation practices. Many studies have uncovered the detrimental impacts of land consolidation on landscape diversity and ecosystem services (Bonfanti et al., 1997; Zhang et al., 2014; Wang et al., 2015), but these factors were still not considered in the design process of land consolidation projects. Some scientists have recognized farmers' attributes would influence the effects of land consolidation on agricultural production (Aslan et al., 2007; Lisee et al., 2014; Luo and Timothy, 2017), but most of the decision support system relied on experts' opinions instead of stakeholders (Tourino et al., 2003; Demetriou et al., 2011). Separation between knowledge and action will impair the function of land consolidation to serve the pursuit of sustainability.

4.2. Future directions for advancing land consolidation

4.2.1. A diagnostic approach to estimating land consolidation outcomes

Land consolidation provides opportunities to facilitate sustainable rural development, but it is not a panacea for rural declining syndromes (Long et al., 2010; Pasakarnis and Maliene, 2010). A diagnostic approach (Ostrom, 2007) is needed to analyze the feasibility and suitability of land consolidation before launching a project. To avoid the panacea traps, the diagnostic approach emphasizes the heterogeneity of perceptions and preferences of stakeholders, even though they are in the same political and institutional context (Ostrom et al., 2007). Underestimation of the reactions and feedbacks from stakeholders may result in undesirable outcomes of land consolidation projects.

Traditional assessment methods for land consolidation are dominated by the pattern-based model, which is not competent to demonstrate interactions at the individual level (Bonabeau, 1997). A process-based model is necessary to incorporate feedbacks of stakeholders into estimation of land consolidation. With a bottom-up modeling strategy, the agent-based model provides an alternative approach to estimating land consolidation effects from the individual level (Macal and North, 2005; Railsback and Grimm, 2019). Agent-based model has been widely used in social science to analyze macro phenomenon through setting behavioral strategies for individuals (Bonabeau, 2002). With application of agent-based modeling, the social and cultural characteristics can be considered in the estimation of land

consolidation, since these factors will influence the action strategies of agents (e.g., farmers' willingness to participate in land consolidation).

4.2.2. Linking knowledge with action to promote land consolidation

Science and technology are playing increasingly important roles in sustainable development (Cash et al., 2003). Aimed at enhancing rural sustainability, land consolidation also needs scientific and technological support. Traditionally, knowledge is created by scientists and scholars, while sustainable practices are designed by policy makers and implemented by communities. To some extent, the boundary between knowledge and action hinders the progress of sustainability practices (Kollmuss and Agyeman, 2002). How to produce actionable knowledge and how to apply knowledge into practices become common challenges for most sustainability projects (Moser and Dilling, 2011; Barth et al., 2012; O'Brien, 2013).

Transdisciplinary research is proposed to be an effective approach to bridging the knowledge-action gaps (Wickson et al., 2006; Brown et al., 2010). By incorporating scientists and stakeholders into the research process, transdisciplinary approach will integrate the most relevant knowledge, reconcile value conflicts, and promote knowledge diffusion to the related communities (Lang et al., 2012). To achieve desirable outcomes of land consolidation, we need to develop an accordant objective among scientists, decision-makers, and stakeholders to ensure that the best available knowledge is applied to land consolidation practices. Through developing transdisciplinary research, scientists, policy makers and farmers will get involved in the knowledge production and application process to advance land consolidation and better serve the pursuit of sustainability.

5. Conclusions

Land consolidation is an interdisciplinary research field, which has a long history of more than one century. Scientists from the developing countries are more active in land consolidation research than those from the developed countries. Based on analysis of the published literatures, we found land consolidation research formed three main knowledge domains: origins of land consolidation (nexus between land fragmentation and land consolidation), operation process of land consolidation (technical support for land consolidation projects) and impacts of land consolidation (effects on the social-ecological systems). To advance land consolidation to better serve the pursuit of sustainability, we suggest to take a diagnostic approach to analyzing the feasibility and suitability of land consolidation before launching a project, to which agent-based modeling can be fruitful. Furthermore, to link science with practices, we propose to adopt a transdisciplinary approach in land consolidation research to involve both scientists and stakeholders into the knowledge production and application process.

Although our findings provide unique insights about land consolidation research, our study includes a few limitations, which are inherent in bibliographic databases and the associated bibliometric methodology. For example, we may have left out some earlier literature, non-English publications, monographs and books as we used Web of Science as data source. For another, the cluster analysis as well as main path analysis may filter some important information. The objective of our research is not to precisely cover every aspect of land consolidation, but to provide a timely overview of the research landscape of land consolidation so as to examine the research challenges and future directions for land consolidation scholars to better contribute to sustainability.

Author statement

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Appendix A. Supporting information

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