ADVANCING EARTH AND SPACE SCIENCES

Earth's Future

RESEARCH ARTICLE

10.1029/2022EF003472

Special Section:
The Future of Critical Zone Science: Towards Shared Goals, Tools, Approaches and Philosophy

Key Points:

- A blueprint for future critical zone observatories and planetary health research is presented that combines science, social science and local knowledge
- We show how social science can usefully inform knowledge exchange (KE) for collaborative science, to build capacity while avoiding knowledge mismatches
- Spatial variations in how farmers learn through bonding, bridging and linking networks exist, showing the need for a local approach to KE

Correspondence to:
L. A. Naylor,
Larissa.Naylor@glasgow.ac.uk

Citation:
Naylor, L. A., Zheng, Y., Munro, N., Stanton, A., Wang, W., Chng, N. R., et al. (2023). Bringing social science into Critical Zone Science: Exploring smallholder farmers' learning preferences in Chinese human-modified critical zones. *Earth's Future*, *11*, e2022EF003472. https://doi.org/10.1029/2022EF003472

Received 9 JAN 2023
Accepted 17 JUL 2023

Author Contributions:
Conceptualization: Larissa A. Naylor, David M. Oliver, Jennifer A. J. Dungait
Data curation: Neil Munro, Alasdair Stanton
Formal analysis: Larissa A. Naylor, Ying Zheng, Alasdair Stanton, Weikai Wang, Nai R. Chng, David M. Oliver

Bringing Social Science Into Critical Zone Science: Exploring Smallholder Farmers' Learning Preferences in Chinese Human-Modified Critical Zones

Larissa A. Naylor[1], Ying Zheng[1], Neil Munro[2], Alasdair Stanton[2], Weikai Wang[3], Nai R. Chng[4], David M. Oliver[5], Jennifer A. J. Dungait[6,7], and Susan Waldron[1]

[1]School of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK, [2]School of Social and Political Sciences, University of Glasgow, Glasgow, UK, [3]The Bartlett School of Planning, University College London, London, UK, [4]Institute of Health and Wellbeing, University of Glasgow, Glasgow, UK, [5]Biological and Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Stirling, UK, [6]Geography, College of Life and Environmental Science, University of Exeter, Exeter, UK, [7]Carbon Management Centre, SRUC-Scotland's Rural College, Edinburgh, UK

Abstract There is a growing global emphasis on sustainable agriculture to reduce human impacts and improve delivery of Sustainable Development Goals (SDGs). With increasing investment in critical zone observatories (CZOs), it becomes important to understand how sustainable agricultural knowledge is produced, shared and used between different groups including farmers, scientists and government. To explore these issues, scientists leading the knowledge exchange (KE) component of a China-UK CZO program studied three farming regions with contrasting geologies and varying economic levels, using a practice-based research method. We demonstrate how additional funding for social science research allowed us to understand how farmers access and share farming knowledge through bonding, bridging and linking networks, and how this varies spatially, using interviews and survey questionnaires. Knowledge flows, barriers and opportunities for designing locally suited two-way KE activities were identified. First, we highlight the need for a more locally, socially embedded and reflexive approach to build trust and better address pressing local environmental challenges. Second, we show how social science can usefully inform KE for collaborative, international development science, to draw on local knowledge, promote research impacts and capacity building while avoiding knowledge mismatches. Lastly, a blueprint for the design and funding of future CZOs, social-ecological and planetary health research agendas that combine science, social science, local knowledge and KE is presented, including the need for substantive social science research to take place in addition to science research in human-modified landscapes—enabling the CZ science to be better grounded in, informed by and useful to local communities.

Plain Language Summary There is a growing global need for sustainable agriculture to reduce human impacts on the environment. To do this, we need to have a better understanding of how sustainable agricultural knowledge is produced, shared and used between different groups including farmers, scientists and government. In this paper, we explored these issues in three farming regions in China, using a practice-based research method where we interviewed and surveyed several 100 farmers. We found that in two of the three regions, farmers access and share farming knowledge through family networks, whilst in the third region farmers learned from a broader range of groups including scientists and government. We recommend that future science studies in stressed agricultural landscapes use a more local approach to build trust and carry out science that better addresses pressing local environmental challenges. This requires us to study people, the residents in these landscapes, using social science, alongside understanding how the landscape is functioning ecologically. Lastly, we propose a new "blueprint" for funding of future science, social-ecological and planetary health research agendas that combine science, social science, local knowledge and knowledge exchange. This will enable environmental science to be better grounded in, informed by and useful to local communities.

1. Introduction

Governments increasingly recognize the need to involve stakeholders and local knowledge to improve policy-making for pressing environmental issues such as climate change adaptation, environmental protection and land management (Diver, 2017; Edelenbos et al., 2011). Through active bilateral knowledge sharing (Zheng et al., 2019a) new insights can be co-created to aid decision-making, and shared to meet the needs of policy-makers and resource managers (Baker et al., 2020; Edelenbos et al., 2011). However, despite the advances in environmental knowledge

Funding acquisition: Larissa A. Naylor, David M. Oliver, Susan Waldron
Methodology: Larissa A. Naylor, Ying Zheng, Neil Munro, Alasdair Stanton, Weikai Wang, Nai R. Chng, David M. Oliver
Project Administration: Larissa A. Naylor, Susan Waldron
Supervision: Larissa A. Naylor, David M. Oliver, Susan Waldron
Visualization: Larissa A. Naylor
Writing – original draft: Larissa A. Naylor, Ying Zheng, Neil Munro, Alasdair Stanton, Weikai Wang, Nai R. Chng, David M. Oliver, Jennifer A. J. Dungait, Susan Waldron
Writing – review & editing: Larissa A. Naylor, Neil Munro, Alasdair Stanton, Weikai Wang, Nai R. Chng, David M. Oliver, Jennifer A. J. Dungait

and the increased recognition of the importance of stakeholder engagement in environmental contexts (Fazey et al., 2014), science communication between environmental researchers and local practitioners is often weak (Baker et al., 2020; Weichselgartner & Kasperson, 2010). Sustainable agri-environmental research follows a similar trend where local knowledge is increasingly valued as a crucial source of expert data to inform sustainable management practice (Diver, 2017; Oliver et al., 2012) and as one of many forms of knowledge in sustainability practice (Norström et al., 2020). Critical zone scientists are increasingly working in human-modified systems, with researchers studying 2nd generation, agricultural CZOs (Critical Zone Observatories) including a component of knowledge exchange (KE) in their research programmes (Kumar et al., 2018; White et al., 2015). Newly emerging transdisciplinary CZOs for sustainable earth futures (3rd generation CZOs), which combine traditional CZ science with social science (see Naylor et al., 2023), illustrate how Critical Zone science (CZS) can usefully draw on local knowledge and social science research principles to develop CZO programmes to meet scientific as well as wider socio-ecological system benefits, such as improving achievement against sustainable development goals (SDGs).

The field of agri-environmental management is becoming more conscious of KE between different groups and individuals to improve knowledge-based practices (Keen et al., 2005; Rist et al., 2007), and to facilitate evidence-based decision making (Lucey et al., 2017). New insights and practices can be incorporated into behavior changes through social learning (Storr et al., 2017; Vogl et al., 2015) and social interactions (Morgan, 2011). To achieve effective two-way agri-environmental knowledge communication, a key step is gaining a better understanding of farmers' and local government knowledge sharing and learning processes to improve farming sustainability (Thomas et al., 2020). As knowledge practices are "thoroughly social" (Tsouvalis et al., 2000), it is critical to understand that different sources of knowledge obtain salience, credibility, and legitimacy in different social contexts (Thomas et al., 2020). Scientists need to position themselves reflexively within the social context of the landscapes and ecosystem processes they study (Montana et al., 2020), and this is where social science comes in. Good social science in this context would involve studying rural social processes across scales, that is, from the relevant level of policymakers down through the community to the level of individuals. This approach needs to embrace the diversity and complexity of human-human interactions in critical zone landscapes, by situating and grounding the social science research in relevant theories, so that key issues such as social power dynamics and trust can be captured (Fielke et al., 2022). Without a nuanced and critical understanding of these multi-scale and key social interactions which, few, if any effective KE and/or management interventions are likely to be possible.

Understanding how people learn, who they learn from, and the social dynamics within which learning takes place (Fielke et al., 2022) is an example of reflexivity in relation to knowledge co-production, such as shared CZ research design between scientists and local communities in which transdisciplinary CZ science is situated (Naylor et al., 2023).

We carried out a Scopus review of papers between 2018–2023 (extending the study of Zheng et al., 2019a) to include social science and farmer learning in the keywords. This identified 25 papers mainly from Europe and African regions that discussed knowledge exchange, social science and farmer learning. These papers showed that the relationship between social science and KE in agricultural and environmental sciences remains a very narrow but emerging research field. The extant research mainly focused on the following aspects: (a) social learning process via knowledge co-production that emphasizes the importance of building trusted partnerships between scientists and agricultural stakeholders (e.g., agricultural trade associations, farmers, marketing agencies, social scientists) as a mechanism for KE where social factors influenced outcomes of KE (e.g., Bayne et al., 2016; Krzywoszynska, 2019; Sewell et al., 2014; Nocco et al., 2020; Stroud and Goulding (2022). For example, Bayne et al., 2016 demonstrates that key success factors in enhancing science knowledge uptake requires relationship building, particularly trust building between parties in developing informal and formal relationships where informal interactions can better foster good knowledge exchange-co-ordination, co-operation and communication. (b) new digital technologies and methods to facilitate uptake and diffusion of divergent agricultural including social media (Stroud & Goulding, 2022), social learning videos (Fry & Theime, 2019; Karubanga et al., 2017), participatory Geographical Information System (GIS, Gonzalez, 2002) and their potential contribution to social learning via farmer field schools and/or discussion groups (Wyckhuys et al., 2018). (c) the fundamental role that farmers' social interpersonal networks influence their learning and implementation of innovative farming practices where different networks and diverse social practices contributing to learning processes (e.g., Chiffoleau, 2005; Fry & Theime, 2019). In these studies, social scientists and agricultural scientists are often brought together to improve

Figure 1. The geographic setting of three agricultural regions in China studied in this research. Map source from Google Maps (2021).

the effectiveness of farmer learning (Skaalsveen et al., 2020). For example, a study on no-till farmers in England reveals that intermediary farmers were the biggest influencers in increasing the information flow and KE between the different clusters of the farmer network (Skaalsveen et al., 2020). (d) boundaries spanning between science and society. This type of research recognizes various sources of knowledge and highlighted the key roles for farmer's local knowledge in agricultural innovation systems where these papers argue that more knowledge management efforts at the boundary between science and society are needed (e.g., Baars, 2011; Girard, 2015; Leitgeb et al., 2011). For example, a literature analysis of 273 scientific articles (Girard, 2015) shows that by 2015 no review had yet been done of the use of farmers' knowledge in the development of agricultural systems regardless of its wide application in agricultural innovation systems. The study also stresses the need to go beyond the dichotomy between scientific and empirical knowledge and to recognize the hybrid nature of knowledge. There is very limited research investigating KE in farmer learning processes in China; this paper seeks to address this gap by exploring how social science approaches can be used to develop locally situated, transdisciplinary CZ research and KE programmes for sustainable Earth futures.

In China, the transformation of agriculture practices and land use, from smallholder to larger farming companies (Huang et al., 2012; Ye, 2015), is highly dependent on effective KE involving both public and private sectors and designated approaches based on different agricultural entities (Shen et al., 2013). The changing structure of farming communities has complicated the interactions between different subjects and broadened the knowledge sources of smallholder farmers where smallholder farmers still play a significant role in land management and food production (Wu et al., 2018). Moreover, the challenges in agricultural productivity (e.g., Green et al., 2019), along with the pressures of climate change (e.g., Grainger et al., 2021), provide further impetus for strengthening resilient development pathways of smallholder Chinese farmers, including providing education and technology (Stringer et al., 2020) to improve knowledge acquisition and its application. There is so far limited analysis of farmers' knowledge flows and learning practices related to sustainable farming and environmental protection; little is known about their willingness to learn, how they learn, who they learn from and why. This limited understanding about farmers' learning processes is essential for effective KE as part of CZS programmes and government training for agri-environmental concerns.

This social context is also necessary to help better align CZ research agendas with pressing local societal needs (Naylor et al., 2023), and thus to ensure that science and policy actions to address global climate change mitigation, climate resilience, ecosystem degradation and delivery of sustainable development goals, also directly support the livelihoods of local people. This study, therefore, used a practice-based research process to fill this gap by investigating the learning preferences dynamics within smallholder farming communities in three of China's diversified rural areas using a mixed methods approach. It forms part of a wider KE research process that sought to understand smallholder farmers' key pressures on farming (Naylor et al., 2023; Oliver et al., 2020) and their awareness of human impacts on the landscape (Naylor et al., 2023) and sustainable farming techniques (Buckerfield et al., 2019a, 2019b; Oliver et al., 2020).

2. Study Areas

This research was conducted as part of the China-UK Critical Zone program (2016–2019) program that examined soil-water-human interactions in three different stressed agricultural landscapes in China, including karst (in Puding County, Guizhou Province), red soil (in Yujiang County, Jiangxi Province) and Loess Plateau (in Changwu County, Shaanxi Province) (Figure 1, Table 1). The socio-demographic characteristics of the three studied counties area described below and summarized in Table 1, providing useful social context alongside the physical geography settings described in Naylor et al. (2023). In all three regions, Grain for Green has been a key National Environmental policy designed to reverse soil and ecosystem degradation in these regions.

Table 1
Socio-Demographics Characteristics of the Three Studied Counties

	Puding[a]	Yujiang[b]	Changwu[c]
Total population (Persons)	376,285 (2020) (20% minority 80% Han)	326,162 (2020)	148,200 (2021)
Urban population (Persons)		293,600 (2018)	61,200 (2021)
GDP (Yuan, Billions)	13.272 Bn (2019)	15.1864 Bn (2019) (16.445 B 2020[d])	11.8323 Bn (2021)
Primary industry GDP	2.279 Bn (2019)		2.0171 Bn (2021)
GDP per capita	33,754 (2019)	50,420	79,785 (2021)
Rural disposable income per capita	8,337 (2017)	16,600 (2018)	12,795 (2021)

[a]https://baike.baidu.com/item/普定县/10371579 with references from government website.
[b]https://baike.baidu.com/item/余江区/22558267 with references from government website.
[c]https://baike.baidu.com/item/长武县/1653505 with references from government website.
[d]https://view.inews.qq.com/a/20210803A098LD0 online news.

Karst aquifers are crucial irrigation and drinking water sources; the karst landscape in Guizhou Province is part of the largest continuous karst region in the world (Zhao & Seip, 1991). Karst systems are highly vulnerable to contamination (Qin et al., 2020), affecting delivery of SDG6 access to clean water. Increased deforestation and reclaimed land for farming (1970s–present) has resulted in substantive ecosystem deterioration where rocky desertification in Puding County contributed >35% of the total desertification in Guizhou Province. Farmer income was also low in this county (Table 1), and until 2019 was on the poverty-stricken list (the People's Government of Puding County, http://www.aspd.gov.cn). In 2021 it had a gross domestic product (GDP) of 15.5 billion RMB with a year-on-year increase of 10.4%, and an 8.2% increase in primary industry. In 2022, 35% of the land was agricultural (the People's Government of Puding County, http://www.aspd.gov.cn). The region is still facing increasing environmental challenges particularly resulting from drought, water pollution from fertilizer leaching, and soil erosion from intensive cultivation (Qin et al., 2020; Yue et al., 2020).

Red soil in Jiangxi Province is part of the highly weathered, widely-distributed red soil landscape (covering 21% of China's land area, Liu et al., 2017), to the south of the Yangtze River in subtropical and tropical China (Zhang et al., 2020). Nitrogen is a major issue here. The Jiangxi red soil region has experienced increasing impacts of chemical fertilisers over the past six decades (Zhang et al., 2013), while human atmospheric N inputs have further increased N inputs to the soils (Cui et al., 2014; Liu et al., 2013). By 2020, forests cover 40.13% of the total land area (the People's Government of Yujiang http://www.yujiang.gov.cn). In 2019, Yujiang had a GDP of 15.2 billion RMB with a year-on-year increase of 26%. An 3.8% increase in primary industry was observed in 2018, with about 75% (0.29 millions) of Yujiang's population depended on the agricultural sector, which decreased from 80% in 2013.

The Chinese Loess Plateau covering about 640,000 km^2 in the upper and middle reaches of China's Yellow River, is the largest and deepest loess deposit area in the world (Ren et al., 2020) which sustains about 8.5% of the Chinese population with only 6.6% of the national land area with a population density of 168 people per km^2 (Lv et al., 2019). Socio-economically, it is a critical part of China's great western development strategy and stands as a bridge linking western and eastern regional economies. However, the soils in the region have been characterized as the most highly erodible globally (Laflen et al., 2000), resulting from poor agricultural practice, overgrazing and deforestation leading to degraded ecosystems, desertification and unproductive agriculture over the past several decades (Fu et al., 2017; Zhao et al., 2013). Changwu County is located in Shaanxi Province. By 2021, 60% of Changwu's population live in rural areas, GDP is 11.8 billion RMB with a year-on-year increase of 1.5%, with an increase of 6.2% (2.02 billion RMB) in primary industry output.

3. Research Process

A practice-based, reflective research approach, focusing on not only the learning practices within communities of practice, but also the research practice per se (Keen, et al., 2005; Morgan, 2011) was used for the team of CZ scientists involved (Naylor, Oliver, Waldron, Zheng). There is growing recognition of the need for and value of critical reflexivity by scientists working on environmental sustainability topics including conservation (Montana et al., 2020) and flood risk management (Whatmore, 2009), and how practice-based research drawn from the arts and design fields, can enrich interdisciplinary research processes (Koskinen et al., 2012). Our research process evolved from initial framing as data gathering to inform CZ science (Zheng et al., 2018), to understand scientist's experience of KE (Zheng et al., 2019a) and qualitative and quantitative surveys of farmer pressures and experiences (Oliver et al., 2020) to KE research (Naylor et al., 2023). This led to the realization that understanding farmers' challenges could only be achieved through a more thorough engagement with theory and methods from social science.

This social science informed KE research was conducted in two phases and in two levels of detail, using questionnaires and semi-structured interviews with smallholder farmers and officials at different governance levels—village, town and county. This first phase aimed to support the CZ scientists with their research and inform the KE activities for the project. It was designed and executed by scientists. Phase 1 was carried out in 2016 in the Puding county in the Karst CZO, one of the poorest regions of China (Figure 2, Buckerfield et al., 2019a) and aimed to understand

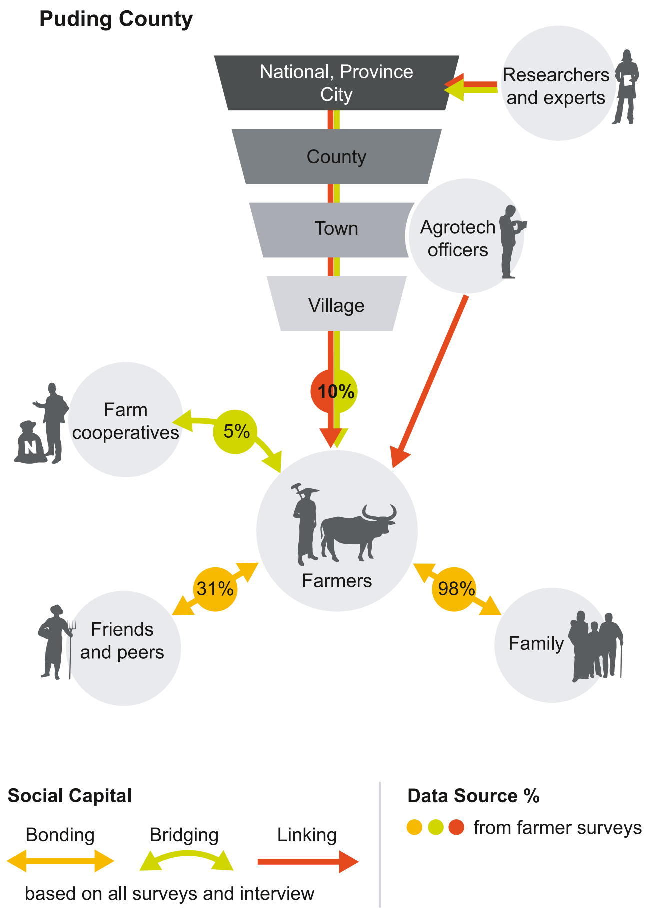

Figure 2. Conceptual framework illustrating smallholder farmers' knowledge flow and social capital influencing farmers' learning processes in Puding County. Arrows represent the direction of connections and knowledge flow in the networks. The percentages in the circles are derived from farmer questionnaires.

a key aspect of KE—the learning practices of local farming communities and government (village to country level). Specifically, we sought to understand who smallholder farmers learn from, what they learn about and how they prefer to learn. Findings from interviews and questionnaires during this phase allowed us to develop an initial conceptual understanding of learning processes and pathways, along with data on human impacts, pressures on livelihoods and current sustainable farm management experiences (Buckerfield et al., 2019a; Naylor et al., 2023; Oliver et al., 2020) that could guide KE activities of the Karst CZO project. However, the richness of the data on social dynamics in the studied villages (see analysis below), and our realization of how these social processes strongly influenced to whom and how CZ science could be shared, led us to investigate these social processes in more detail.

3.1. Phase 2 Including Social Science

Fortunately, additional funding was secured (see Naylor et al., 2023) enabling us to increase the depth and spatial breadth of our work, to undertake a more extensive comparative analysis between three regions (Figure 1). Phase 2 surveys took place in 2018 and 2019 and included a detailed follow-up series of interviews in the primary case study location, in Puding County (Figure 1), to further explore farmers' learning networks, to improve understanding of local social dynamics within and between groups and to identify any new actors involved in smallholder agricultural practice. At this point in the KE research process, we realized, that as a team of scientists (Oliver, Waldron, Zheng) and a KE specialist (Naylor) coming from a science-policy-practice background, that we needed to bring in human geography and social science perspectives to help us frame, interpret and analyze these data. A voluntary team of social scientists joined our team as research collaborators (Munro, Rui Chng, Stanton) along with a human geographer hired to assist with a further follow-on project (NERC MIDST, Wang), to help us theoretically ground and analyze our data. This led us to borrow concepts from a social capital frame, allowing us to interrogate our data more rigorously, to identify where and how scientists are involved in these social processes. For example, our questionnaire data showed (link to results, Section 4) that the types of social ties that were important to learning about sustainable farming varied between groups and locations.

The second goal of Phase 2 was to test and refine this conceptual model in two other regions to explore the spatial variations in knowledge sharing and information flows; knowledge that can usefully guide KE activities between CZ scientists and the inhabitants of human-modified CZOs (Naylor et al., 2023). These refined interview questions along with the original questionnaire surveys were replicated in two of the other CZOs in the China-UK program, Red soil (Yujiang, Jiangxi) and Loess Plateau (Changwu, Shaanxi), to examine spatial variations in learning dynamics (Figure 1). We chose to utilize social capital as the major theoretical framework because it had a good fit with the results from our Phase 1 survey findings, where strong bonding networks and limited bridging and linking networks were found. Adopting the principles of this approach allowed the data gathered here to be qualitatively classified using a well-developed framework, and described using a common vocabulary (bonding, bridging, linking), helping to discuss which relationships are important and to better understand the social context within which CZ science and KE activities are being carried out.

Social capital has been understood in a number of different ways (e.g., Cofré-Bravo et al., 2019; Hurley, 2017; Levebvre et al., 2016; Narayan, 2002; Woolcock, 1998) where bonding, bridging and linking capital are commonly used concepts. Bonding social capital are bonds within communities that facilitate cooperation and connection between members of families and their local farming communities (Fisher, 2013; Narayan, 2002; Tregear & Cooper, 2016). Kinship ties are important social relations in rural Chinese society (Tang et al., 2019) where bonding social capital among villagers is typically strong and easily established (Pretty & Ward, 2001). Bridging social capital, between groups, increases the access to sources of new information from different groups where degree of support, trust and the norms of other networks is used to assess the strength of this capital. In China, village officials form an important bridge between smallholder farmers and government; they are not only accountable to local governments, but also embedded in agricultural production and rural life (Liu & Zheng, 2021). Linking social capital allows individuals access to sources of power, finance, training and scientific-based information from more distal groups of actors, including academics (Saint Ville et al., 2016). Knowledge sharing with bonding and bridging social capital is typically more tacit and context dependent (e.g., experiential knowledge from family and peers), than the explicit and standardized types, such as new knowledge from researchers, passed on through linking social capital networks (Putnam et al., 1994). While social capital has been increasingly utilized as a useful tool to facilitate knowledge sharing and establish social learning partnerships within farming communities (Leta et al., 2018; Pretty & Ward, 2001; Skaalsveen et al., 2020), studies have insufficiently addressed how the local social structure, learning dynamics, relationships of trust and social norms influence KE and co-production between farmers, policy-makers and scientists. Here, we used bonding, bridging and linking social capital (after Klerkx & Proctor, 2013) to analyze farmers' knowledge and learning process through their interpersonal networks (Table 2).

3.2. Data Collection and Analysis

Data were gathered using a mixed methods approach combining primary semi-structured interviews and questionnaire surveys of smallholder farmers, and village, town and county leaders (Oliver et al., 2020; Zheng et al., 2019a; all data is held in freely accessible depositories via Zheng et al., 2019b, 2022). Researchers had support from Chinese collaborators where Chinese college students from farming families pilot tested the surveys and were trained to gather farmer questionnaire data in the local dialects (Oliver et al., 2020). Officials completed their own questionnaires in Mandarin. Interviews for both farmers and officials were carried out, transcribed and coded in Mandarin. For the learning aspect of the KE research reported in this paper, the farmers' questionnaire consisted of: (a) farmer sociodemographic information; (b) farming practices and environmental awareness of soil and water management; (c) experience and attitudes toward learning new farming techniques. The officials' questionnaire consisted of: (a) perceptions of local agri-environmental issues, (b) the best way to support farmers; (c) the advice and training they provided farmers for agri-environmental management. In total across both phases, 351, 114 and 167 smallholder farmers in Puding, Yujiang and Changwu completed questionnaires, respectively. In total, 47, 15 and 15 officials completed questionnaires in Puding, Yujiang and Changwu, respectively. These data were analyzed quantitively, based on our earlier work (Oliver et al., 2020). Chi-square tests were used to test for associations ($p < 0.05$) between location (Puding, Yujiang, Changwu) and perceived views on farming challenges, environmental awareness, and experience of and interest in learning. Cramer's V was used as a post-hoc test to determine strengths of association, with a threshold of >0.25 indicating a very strong association and >0.15 strong. The officials' questionnaire data were used qualitatively (due to small sample size) to enhance the analysis and conceptual framework development.

Semi-structured interviews were conducted with 30 farmers and two-agri technicians in Puding county and 37, 14 and 13 interviews with government officials in all three regions (Puding, Yujiang and Changwu respectively). These interviews allowed us to further understand respondents' perspectives and experience of sustainable farm management approaches and farmer training. Knowledge sharing and information flows in the studied communities were thus qualitatively evaluated by inductively coding the data (Thomas, 2006) using a social capital theoretical frame (Table 2). These data were used to explain the interaction between different social groups and to further refine the framework, as they allowed us to understand some of the interactions between scientific researchers and government, the flows of this information between actors and their contributions to farmers' learning.

4. Results and Analysis

4.1. Phase 1 and 2 Questionnaire Data Results

The qualitative and quantitative analysis of questionnaire data allowed us to test the strength of social network preferences. It allowed us to gain information about- who they learn from, identifying the key actors involved in sustainable agriculture learning and training and if they varied spatially between regions.

4.1.1. Willingness to Learn

An overwhelming interest in learning new farming methods was observed between farmers (76% in Puding, 73% in Yujiang and 75% in Changwu), and farmer training was strongly supported by the town leaders (88% in Puding, 75% in Yujiang and 100% in Changwu), which was encouraging for future KE. *The key question/challenge here*

Table 2
Different Types of Social Capital Within a Social Knowledge Network (Modified From Cofré-Bravo et al. (2019) and Klerkx & Proctor (2013))

Social capital	Definition	Identity	Feature of network	Type of knowledge sharing	Knowledge source	Dimensions
Bonding	Trusting and cooperative relationships between members of a community	Similar	Thick trust, dense networks, strong ties, informal, long-term reciprocity	Tacit; local	Family members; friends and peers	• Personal support; • Bonding structures; • Trust in person; • Obtaining/providing resources from/to individuals
Bridging	Links between separated dense networks for collaboration and coordination	Shared	Thinner trust, larger but looser networks, weaker ties, more formal	Tacit/explicit; specialized	Farm workers; commercial farming advisors	• Supporting networks; • Trust in organizations; • Obtaining/providing resources from/to clients; • Service provision; • Bridging structures
Linking	Norms of respect and networks of trusting relationships between people who are interac ting across formal or institutionalized power or authority gradients in society	Few similarities	Formal, explicit, or institutionalized interactions	Explicit, strategic	Researchers; government agencies	• Financial support; • Training and education; • Political involvement; • Trust in government; • Community building; • Interactions with researchers; • Linking structures

Note. The dimensions of each type of social capital are summarized from Cofré-Bravo et al. (2019), Hurley, (2017), Luckasiewicz et al. (2019), Woolcock and Naryan (2000).

becomes how to improve knowledge accessibility and KE efficiency for smallholder farmers who typically have limited educational resources (Huang et al., 2012)? This requires an analysis of how farmers learn within their social context, which survey data alone cannot provide. It is the addition of social science concepts like social capital that helps to create the necessary context.

4.1.2. How They Would Like to Learn

When designing KE activities as part of CZ science projects, a key question becomes how would farmers prefer to learn and how do government agencies delivering training prefer to train farmers? Our questionnaire data found farmers' preferences in learning methods varied spatially ($p < 0.001$, $V = 0.22$), where farm visits by professionals were strongly favored by all counties (60%, 96%, 56% in Puding ($n = 286$), Yujiang ($n = 92$) and Changwu ($n = 154$) whilst training courses were only valued by 30%, 43% and 55% of respondents in in Puding ($n = 286$), Yujiang ($n = 92$) and Changwu ($n = 154$), respectively. In contrast to the farmers' preferences, training courses were most frequently used by local government, while farm visits were lacking. Only about 60% of village leaders in Puding and Yujiang had experience of farm visits, and none had experience in Changwu. However, interview data showed more receptivity for farm visits by officials. For example, when asked for suggestions on effective KE methods, farm visits and demonstration farms were actually often recommended by the officials in interviews:

> "…It would be better to teach farming techniques on the farms. If we provide guidance in a training class, it is just about theories. Firstly, they (the farmers) can't remember all the theories. Secondly, they still lack practical guidance." (Puding Village leader 4)
> "…We prefer new and effective training methods, such as a demonstration farm. We can bring farmers to visit the farm and give training there. Then they can disseminate to wider groups." (Changwu County leader 1)

These data highlight the potential use of farm visits but also raises important questions: Why is there a mismatch between groups, and how can these issues be better understood? What social dynamics, power relations and economic constraints might be influencing these different responses and thus the practical suitability of different ways of learning in CZOs?

4.1.3. Who They Learned From

In Puding county, strong local farming knowledge flow was observed between smallholder farmers with family, friends and peers being the key groups. Family was the dominant knowledge source for 98% of farmers, and exclusively so for 71% (Figure 2). This knowledge was highly valued and considered as mostly helpful by 73% of farmers. Quantitative analysis of questionnaire data revealed that knowledge sources for farmers showed strong associations between counties ($p < 0.001$, $V > 0.25$). Bonding networks, including family, were less dominant as a major knowledge source in Yujiang (74%) compared to Puding (98%), and even less so in Changwu (39%). Instead, friends and peers played a more important role in learning for more than 60% farmers in these two counties (Figure 3).

The role of government as linking capital was incredibly weak in all regions; this was a common major barrier for farmers to acquire professional knowledge. Across the counties, only 13% of the farmers reported receiving government training, while 88% of town leaders and 92% village leaders reported providing farming advice to their farmers. However, farmers in Changwu seemed to have stronger linking connections for acquiring formal knowledge than Yujiang and Puding. In Changwu 10% of farmers reported they learned from the local research stations (Changwu Agro-Ecological Experimental Station), through, for example, training courses and on-site guidance, while this connection was only reported by 1% farmers in Yujiang, and none in Puding. Furthermore, while both Yujiang (23%) and Puding (10%) farmers had weak connections with government (similar to findings in Fisher, 2013), in Changwu government was a major knowledge source for 58% of their farmers. The key finding from the questionnaire data was thus that there are clear regional variations in who farmers learn from.

4.2. Phase 2 Analysis Applying Social Capital Theoretical Frame

4.2.1. Social Networks Underpinning Smallholder Farmers Learning in Puding

Analysis of farmers' social learning networks in Puding confirms that not all social networks are created equal. Figure 2 below summarizes these bonding, bridging and linking networks for Puding, illustrating the dominance of bonding networks, limited bridging and linking networks.

4.2.2. Learning Through Bonding Networks

Interview analysis aligned with questionnaire data results, where almost every participant interviewed in Puding confirmed strong bonding networks, where they gained experienced-based farming skills intergenerationally within families, from their parents or grandparents:

> "…The elders teach the younger generation. This is our tradition." (Farmer 20)
> "…The elders would teach their children when they start to learn farming from a young age." (Farmers 13, 14)

High recognition of this bonding network confirms farmers' strong trust in this experiential knowledge source, which has been practised and tested over generations in traditional farming (Riley, 2008). However, limits on the types of knowledge flow through the bonding networks were also observed due to their tight structure and exclusive nature. Dependence on family knowledge can limit farmers' willingness to incorporate other forms of knowledge in their farming practices and hinder the community's transition to sustainable farming (Oliver et al., 2020). Strong trust between family members was often exclusive to the immediate family (Farmer 27) which constrains wider knowledge sharing.

Friends and peer also formed a bonding network which, some interviewees found to be useful sources of learning:

> "…Surely (we learn from friends). We often discuss when to spray insecticide, or why your rice grows better than mine. We can share experience with each other." (Farmer 10)

This network appeared to be maintained by moral incentives from "shared local identity" and "common goals to improve welfare" (Farmers 10, 11). However, the majority of questionnaire respondents viewed this as a weaker (used by 31% of farmers) bond compared with family, and only 54% believed it was mostly helpful. It thus had

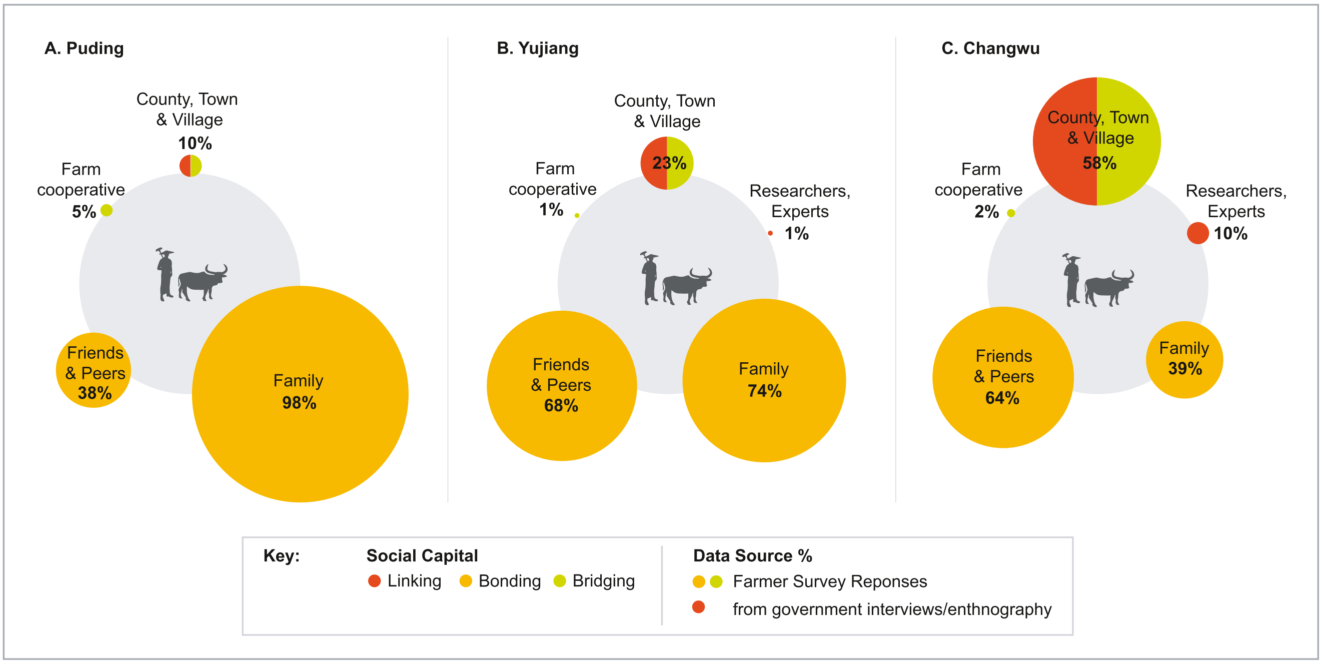

Figure 3. Illustrating the regional variations in knowledge source and social capital bonds used by farmer communities (gray circles) across the three counties studied. The size of the orange (denoting "Bonding"), green (denoting "Bridging") and red (denoting "Linking") circles correspond to the magnitude of the percentages mentioning this tie in farmer surveys.

lower credibility as a source of learning. Less trust in friends and peers was also observed in the interview data due to business competition between farmers, limiting the knowledge sharing and training efficiency between farmers in some cases, showing variable bonding links between peers.

4.2.3. Learning Through Bridging Networks

While bonding networks facilitate connection between groups with similar socio-demographic profiles, bridging social capital allows farmers to share their problems, ideas and innovations to other groups with different interests and backgrounds (e.g. local government). As such it helps farmers to gather external information and better place themselves within the wider community network. However, questionnaire survey results showed that bridging capital was weak in Puding (Figure 2). Interviews showed that smallholder farmers employed by local farming companies (established in the past 20 years) and owned jointly by the village government and private sector (Huang et al., 2012; Ye, 2015) created bridging networks. For example, "*Our firms have technicians who can train us* [for farming]. *Sometimes our managers teach us in person too*" (Farmer 17). By providing such training, the companies aimed to improve farming quality and efficiency via this training, where academic researchers would provide on-farm private training. This provided a bridging tie for some smallholder farmers to access more technical knowledge and information about the farming market. Therefore, although this bridging network was very weak in Puding (only 5% farmers reported learning from farming cooperatives), it could be a new pathway for farmers to learn technical and scientific knowledge, given the potential that more farming companies will emerge with the ongoing national programmes of agricultural modernization.

In addition, commercial suppliers of agricultural products (e.g. seeds, fertilisers, tools) were also mentioned as a form of bridging social capital during farmers' interviews, as also observed in other studies (e.g. Cofré-Bravo et al., 2019). Knowledge sharing occurred when farmers purchased agricultural goods and informally sought product application advice. In many cases, farmers would trust the sellers' advice without any scrutiny: "We don't need to learn. If you need pesticide, just ask the (chemical and fertilizer) shops and they will tell you which one and how to use it." (Farmer 15). The lack of scrutiny limits the value of these bridging networks as different groups have different interests and information within these bridging networks is asymmetric. For example, farmers may be advised by the sellers to use more fertilizer than is necessary to achieve greater profits. In this circumstance, the learning partnership is still at the early stage of informing or consulting, and the lack of shared vision for sustainable farming between groups may compromise farmer's acquisition of evidence-based knowledge.

4.2.4. Learning Through Linking Networks

Linking social capital was shown to be the weakest in farmers' learning system: few resources were available to access formal networks and institutions beyond the village.

Yet, linking networks are known to play an important role in sharing formal and scientific knowledge to farmers. For example, they can provide educational opportunities and connections with professionals including researchers (Cofré-Bravo et al., 2019). In China these measures are often framed under national rural and agricultural development policies, especially the recent Targeted Poverty Alleviation strategy, where local governments at county and township levels design and implement various training activities. Interviews with government officials (Puding Village leaders 3 and 5, Puding Town leader 3) described a linking network where many financially-supported training activities about farming, water protection and fertilisation are developed with experts, to equip poorer farmers with professional farming knowledge). For example, town and village leaders commented:

> "…Training for farmers is often organised in the township, e.g. at the Agriculture & Forestry Service Center, or the relevant staff would provide training in the village. Occasionally the county officials would join the training events." (Puding Town leader 4; Puding Village leader 3)
> "…If organising training for farmers, you could train the village committee first, as they communicate with farmers more easily." (Puding Village leader 4)

This contrasts with the views of farmers. Whilst government officials were the only linking group identified by smallholder farmers in the questionnaires, this connection was very weak (only 10% of farmers learned from government). Importantly, farmers in their interviews did not remark on any training from these sources, which does not accord with the town and village leader interviews. Additionally, some farmers revealed their doubts about government ability in agricultural knowledge and transparency in the use of training and financial resources (Farmer 1). When linking social capital is concentrated in the hands of a few individuals, they may have access to privileged information which could be used to benefit family and friends (Titeca & Vervisch, 2008). In Puding, training opportunities were limited to a few farmers who were hand-picked by leaders: "You have to be the right person… If you are young, educated, and want to learn the technology (then we'll choose you). But if you're illiterate and old, we can only say sorry" (Puding Village leader 1). While officials must consider practicalities when choosing farmers for training, only a small number may fit their criteria, and some of them may choose not to share knowledge with others (Farmer 10).

Moreover, at the town level, the Agrotech extension and service office, a specialized agency for providing technical training and support for local farming (hereafter, Agrotech Agency), was found to actively share knowledge about sustainable farming methods with farmers. These are referred to as "extension agents" in some studies (e.g., Cui et al., 2018). Due to their limited human resources, they often train a small number of farmer representatives or village leaders to share scientific knowledge with wider groups. Here, the Agrotech Agency served as an important "gatekeeper" or knowledge broker linking farmers and the government, providing direct access to scientific knowledge. A town leader explained it in the case of growing chives:

> "*It is impossible to train all villagers together (for chive growing) as it is too many people and too much work. So… (the Agrotech agents) select two farmers to take training, and they are sent back as two agri-technicians* [i.e. local farmers trained by Agrotechs] *to teach villagers…Although village leaders are very busy, we also ask them to take training… Our office is responsible for training them.*" (Puding Town leader 4).

During interviews, we explored the experiences and receptivity of smallholder farmers and officials to training by "gatekeepers" such as Agrotech officers and/or farmers trained as agri-technicians. Interesting social dynamics emerged. Issues of trust emerged for farmers who are the intended recipients of such training—they felt that farmer representatives such as agri-technicians would be reluctant to teach what they learned from training as "it will increase competition for themselves and take up their own time" (Farmers 3 and 7); this concern was also reflected by some officials suggesting appropriate incentives were necessary to motivate the representatives to provide thorough knowledge sharing. Smallholder farmers' also did not trust their information as half of interviewed farmers were concerned about information accuracy. This is not unsurprising as other studies have found that technical and scientific understandings (i.e., formal knowledge) can be challenged by farmers who sometimes see it as inconsistent with their experiential knowledge (Riley, 2008). They also found the agri-technicians to be unavailable, suggesting a scarcity of resources, "*there are some technicians in town, but they don't give us guidance in villages as they are too busy*" (Puding Village leader 4). This accords with government officials, for example, "*We need Agrotech agents very much, but we don't have any in the village*" (Puding Village leader 4). Greater political attention and financial support from policy-makers to increase the number of Agrotech agents is thus urgently needed.

Farmers also showed distrust in government's transparency in selecting representatives, with some believing that the leaders would unfairly favor their own family to attend training over those who were more suitable as representatives. As one farmer said *"They (the village committee) choose their relatives (to train)*" (Farmer 3). This perceived unfairness in government practice and competition between farmers could influence their trust and willingness to learn from the representatives (He et al., 2016), which compromises KE efficiency and use of government resources. Thus, despite the government trying to increase learning opportunities, such resources were still largely unavailable to most small-holder farmers. These results also clearly show that more research on farmers' (non)-resistance to collaboration and on how to form strong mutual trust (e.g., Fisher, 2013; Riley et al., 2018) could facilitate farmer representatives' or local "champions'" role in learning and collective knowledge co-production (Grainger et al., 2021; Page & Dilling, 2019).

Researchers and research institutes were not an important source of scientific, sustainability or technical knowledge in smallholder farmers' direct learning networks in Puding—none of the farmers reported learning from local colleges or universities. However, government officials indicated that they would attend training courses provided by research institutes (e.g., Guangdong Academy of Agricultural Sciences), and they could organize such training for farmers by inviting the researchers and experts (Puding County leader group interview 2). Therefore, apart from acting as linking capital, the government also offers bridging capital for farmers to connect with researchers. This indirect interaction between researchers and farmers could explain the observed lack of knowledge flow between them, which can hinder the efficiency of agri-environmental science uptake by farmers (Zheng et al., 2019a) and also the flow of local knowledge to scientists (Oliver et al., 2012).

These results show that understanding social dynamics and learning preferences such as those described above and in Oliver et al. (2020) are crucial for scientists looking to develop 3rd generation CZOs and training activities associated with them, so that these programmes co-construct and co-produce outcomes that are seen as legitimate and credible to farmers (Grainger et al., 2021; Morris, 2006) and are relevant to their most pressing needs and adverse environmental impacts such as fertilizer use (e.g., Naylor et al., 2023). This will help improve livelihoods and thus delivery of SDGs. This approach could also help enhance farmers' trust in training and greater uptake of the multiple-forms of knowledge provided (Arnott et al., 2020; Cvitanovic et al., 2021). While such knowledge incorporation may be challenging for the scientific community, it is necessary if co-produced knowledge is to be developed fast enough to overcome the sustainability challenges presented by a rapidly changing world (Norström et al., 2020).

4.3. Regional Variation in Social Capital for Farmers' Learning

The analysis of Yujiang and Changwu reveals the regional similarities and differences in smallholder farmers' knowledge networks compared with those in Puding (Figures 3 and 4). The three major knowledge sources in their learning system, family, friends and peers, and government, were the same, but the strength of bonding and linking networks varied between regions. Bridging networks consisting mainly of farming companies were weak in all counties, assessed by 1%–5% of farmers. In general, family knowledge was most valued by farmers in each county despite the varied strength of connections (see Figure 3). For example, 82% of the Changwu farmers who learned from their family considered the knowledge as "mostly helpful" although it was the least dominant form of knowledge for them.

Government remained as a key "gatekeeper" and linking network for farmers to access scientific knowledge. Having Agrotech Agencies at the town and village levels was a common approach to sharing knowledge with farmers (Figure 4). These agents would improve their professional knowledge by routinely learning from researchers at workshops and meetings, which created an indirect but important pathway for farmers and researchers to interact. Moreover, in all counties, the higher-level government helped establish collaboration with the local agricultural institutes to promote advanced farming practice. For example, Academician Station, a nation-wide

10.1029/2022EF003472

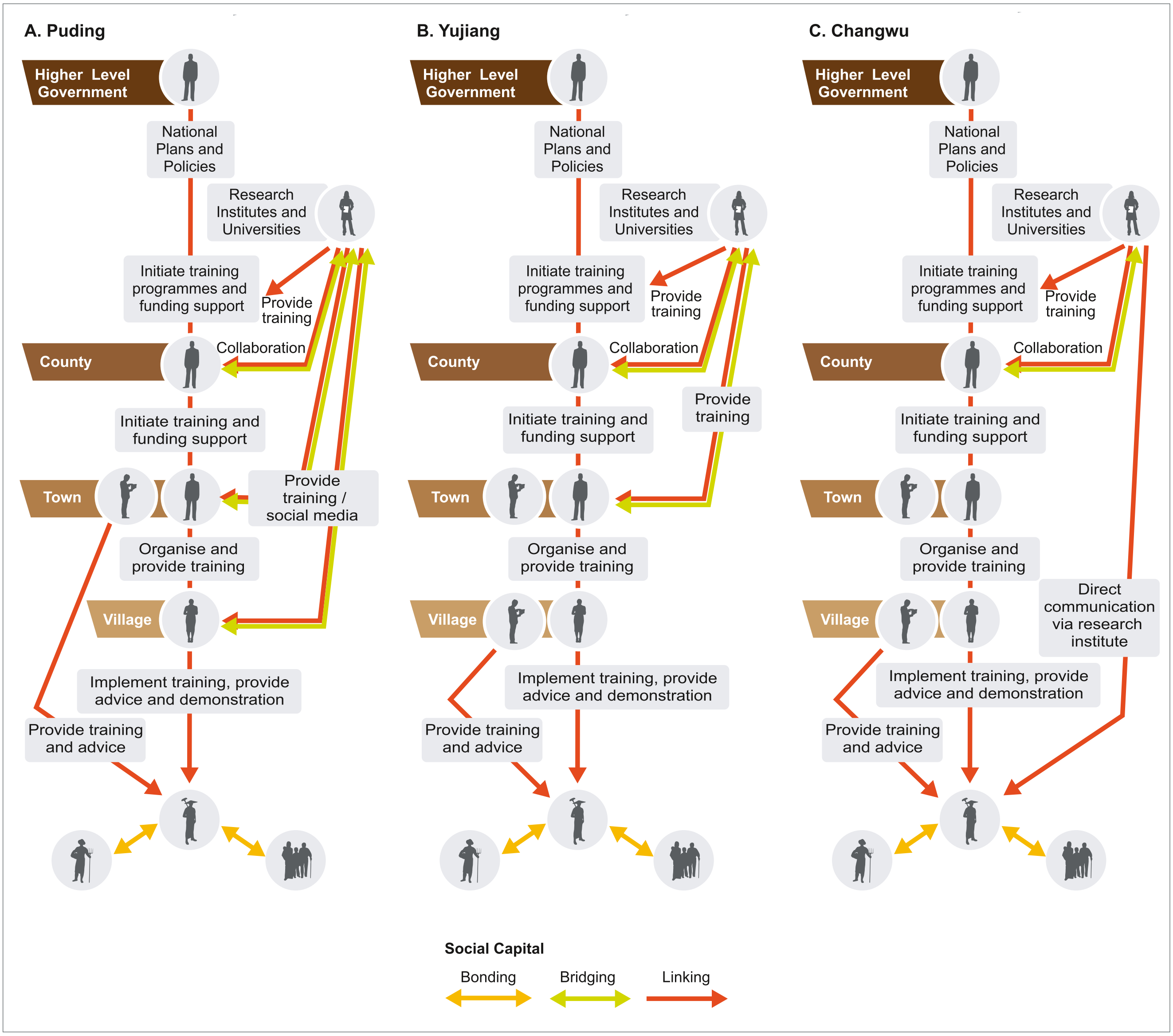

Figure 4. Frameworks of social capital networks for smallholder farmers' learning process in (a) Puding, (b) Yujiang and (c) Changwu Counties with showing regional variations. Arrows represent the direction of connections and knowledge flow in the networks. See Figure 2 for details for an explanation of the different job roles the people in Figure 4 hold.

science-practice program promoted by provincial and city governments, was seen as a good bridge between researchers and farming practitioners. In Yujiang, the county officials told us "*the Academician Station in Jiangxi Province largely helped the development and promotion of rice-fishing cultivation models among local farmers.*"

Our research has shown that the precise knowledge transferred to farmers will be highly dependent upon the sites themselves, understanding the social, cultural and physical geographies of each location including issues of trust and power dynamics are thus fundamental for the design of effective KE programmes and ideally, CZO research questions that align science with local needs to more rapidly improve livelihoods and aid delivery of SDGs. Strong social science understanding and framing is crucial for effective design of locally situated research and KE programmes. For example, use of social science methods in our study allowed identification of the most pressing issues (and thus SDGs) for local people—this allowed us to determine what is most valuable for farmers to learn for to directly improve their livelihoods, environmental outcomes as well as delivery toward SDGs and national policy objectives. Narratives on fertilizer costs gleaned from local farmers can now be usefully combined with the scientific data arising from the CZ projects documenting high nitrogen levels (Naylor et al., 2023), to design a tailored KE program that will help reduce costs for farmers, reduce environmental impacts of excess nitrogen and thus improve their livelihoods by reducing poverty as their farming will become more economically efficient. These measures would also dovetail nicely into national-scale policy shifts, such as no increase in synthetic fertilizer use in agriculture.

Similarly, our research showed that local knowledge was crucial for correct interpretation of CZ science, as local practices to maintain agricultural production in heavily degraded karst landscapes changed soil properties in unexpected ways. CZ scientists conversations with local farmers, made space for this local knowledge to aid interpretation of their unexpected CZ science results (Naylor et al., 2023). Similarly, our study of differential inputs of e coli into the karst aquifers and surface waters from different land uses (Buckerfield et al., 2019b, 2020; Naylor et al., 2023) was greatly situated by being studied within a well-instrumented CZO where social science research methods were also being applied to understand farmers' behavior, learning experiences and willingness to learn). Our combined science and social science showed that there would be improved health and well-being for communities as well as agricultural productivity benefits from practical implementation of these policies. Many of these interventions can be readily applied at the local scale, farm scale.

In contrast to the other two regions, farmers in Changwu had less knowledge shared from their family but more from government and research institutes. This was an interesting finding as while government tends to be the weakest social tie for farmers with the least trust in other studies (e.g., Fisher, 2013), it was accessible by the majority of Changwu farmers (58%) and was their most valued knowledge source. This may be the result of more frequent engagement between farmers and government (i.e., stronger linking capital) which helped them to cultivate greater trust and thus knowledge uptake (Fisher, 2013; Pretty & Ward, 2001).

5. Discussion

With rapid changes in socio-ecological systems due to accelerating global climate change and economic development, efficient KE and co-production are urgently needed to enhance the social-ecological resilience of vulnerable communities, such as smallholder farmers in developing economies (Xu et al., 2020). Improved understanding of social networks and knowledge sources and flows underpinning farmers' learning processes can help identify key KE pathways in the science-policy-practice interface. Our results show that understanding of local contexts and knowledge practices is important for improving two-way knowledge sharing between environmental scientists and local practitioners and governments.

5.1. Insights From Applying a Social Capital Lens

Social capital analysis helps us explore some of the social, political and cultural factors influencing local social capital, allowing us to identify the learning preferences of smallholder farmers' and local officials, and the networks through which learning takes place in the studied CZOs. Underpinned by our data, we produced conceptual frameworks that highlight important trends, complexities and variations in farmers' social relations and knowledge practices between regions (Figure 4). For example, we identified that local and traditional knowledge is the major knowledge source guiding farmers' agri-environmental practice in two of three studied regions, where although there was a strong willingness to learn by all people surveyed (farmer to county government level), issues of trust were seen as key barriers by farmers for the uptake of professional knowledge via linking networks. Within this social system, where traditional knowledge dominates, there is thus a need to understand the social processes, and explore which social mechanisms can enhance incorporation of pluralistic knowledge (Norstrom et al., 2020) and effective sharing (Cash et al., 2003) between farmers and more technical and scientific knowledge. In contrast, a more pluralistic KE pathway was apparent in Changwu. Further social science research could usefully study this region in more detail to understand the willingness of smallholder farmers to trust those outside of their core bonding communities – and thus be open to knowledge sharing and learning from bridging and linking networks, including direct interactions with scientists.

The methods used here can be applied elsewhere to inform farmers' social learning processes in other developing economies facing similar socio-ecological challenges. For national to provincial scale policy makers/practitioners, our research has also highlighted the importance of the local social contexts in which the practical changes (and associated learning) they are seeking to implement varies, within and between communities, helping tailor environmental sustainability interventions and training. For example, funding for sustainable land use/agriculture could be more targeted by providing more funding to regions with fewer existing bridging networks for both building these networks and for building trust between them and the farmers managing the land.

Our results show that understanding of social capital networks which facilitate learning is essential for designing KE within the spatial scale of study. CZ scientists must understand the social context in which they are working, and especially the key persons or social group that would be an acceptable conduit for knowledge transfer. Our results show smallholder farmers learn from people they trust, so a social capital analysis can help CZ scientists better allocate scarce resources, and thus create a more tailored, context-specific approach to learning. We found family bonding networks were strongest and issues of trust limited receptivity to other more professional bridging and linking networks. This information can now be used to design sustainable farming training programmes for those who learn primarily from family, where trust in other forms of social capital is weak. For example, future KE programmes in Puding and Yujiang, where recognition and use of formal, scientific knowledge was low, could focus on activities which build trust and increase government and academic engagement with farmers to strengthen trust and with time improve formal knowledge acceptance and uptake (Grainger et al., 2021). This would help build and strengthen bridging and linking networks to facilitate integration of multiple forms of knowledge across power gradients (e.g., government vs. farmers) and social categories (e.g., family vs. government). While the promotion of Agrotech agents can help improve fairness in farmers' learning, more studies to understand trust building between farmers, government and scientists and trust within farming communities could lead to increased use of farmer representatives in knowledge learning and co-production processes (Grainger et al., 2021), as has been found for Catchment Sensitive Farming in the UK (Thomas et al., 2020). A social science research need was identified as part of CZO research programmes, namely, to explore local issues of trust between different groups and regions, for example, farmers and Agrotech experts, scientists and farmers. These findings all firmly attest to the need to understand the social relationships and learning processes first, before designing CZ science projects and KE activities associated with them.

5.1.1. Context-Specific Knowledge Exchange

These results highlight that learning processes vary between different contexts and that KE needs to be reflective (Reed et al., 2010), where spatial variation needs to be considered in the design of KE approaches (Norström et al., 2020). Instead of a universal method, localized design and adoption of multiple innovative ways to facilitate social learning and knowledge sharing will provide better outcomes (Grainger et al., 2020; Leta et al., 2018). Understanding social processes operating in a planned or existing CZO, would allow more localized KE planning for research projects and avoid mismatches and optimize research impacts, and help governments to navigate the science-policy-practice interface as well as policy frameworks (Karcher et al., 2021). Social science research findings can thus usefully inform, shape, research and evaluate the effectiveness of future KE activities. From a KE perspective, this would allow us to better identify context specific mechanisms for the two-way flow of information between CZ researcher and different groups of users, and to tailor this to each CZO being studied. For example, different gatekeepers and issues of trust in different agricultural communities were identified by our research. Insight into these social dynamics can usefully inform the entry point and methods/materials for KE, for example, Agrotech agents are an emerging linking network that were trusted by farmers in some communities. The following questions are posed to further elaborate on our findings, link them to relevant literature and to guide future research on this topic:

- *Are they a good form of linking capital for CZ scientists to engage in these communities, and how would they be trained differently than farmers*? Different learning styles were also identified, where smallholder farmers' primarily wanted farm visits, which was supported by some town and villages leaders in interviews.
- *Could future CZ funding be used to explore if and how demonstration farms and field visits could help build bridging and linking networks in those regions (Puding and Yijang) where family bonding networks were strongest?* Studies from elsewhere have shown that farmers are often more willing to adapt when seeing better results of new technologies and practice through field visits (Page & Dilling, 2019). Demonstration farms have been found to help stimulate stronger social learning and trust within the village, where new and sustainable farming practice can be acquired by observing and imitating the trainers (e.g., Agrotech agents) and other farmers (Keen et al., 2005; Page & Dilling, 2019).
- *Could demonstration farms also stimulate stronger trust in China and lead to more active knowledge co-production and sharing between farming individuals and linking and bridging groups?* Alongside this

10.1029/2022EF003472

social capital research, it is important to design future CZOs so that the effects of these new learnings on the social-ecological resilience of farming communities to pressing environmental issues can be evaluated (Chen et al., 2014; Fazey et al., 2014).

We consider that due to local variability in connections (Figure 5), a one-size-fits-all approach to KE will be inadequate for most sites. Instead, incorporating social science research in the initial research design stage, and further modifying the design iteratively as social and geoscience research advance together will be more able to accurately map out KE planning for sites. The importance of bonding as the primary driver of KE in both Puding and Yujiang has direct policy effects. Bonding, in this case of family members, passes down techniques and knowledge of farming on these particular sites. In such a context, it may be particularly difficult for outside experts, either from higher learning institutes or from government departments to change farmers' practices. In smallholder sites therefore, KE planning must pay particular attention to the issue of trust. In contrast, where linking predominates (the Changwu site contains agri-companies with permanent agri-advisors) KE is significantly easier to initiate and maintain (Figure 4).

While it is important to emphasize the uniqueness of each site in academic contexts, and the need for place-based research on these topics (e.g., Bayne et al., 2016; Chiffoleau, 2005; Skaalvassen et al., 2020) we also acknowledge that government and other bodies have time and funding constraints which mean that this is not always possible. In the Chinese context, and following from the findings of this study, we tentatively suggest that a generalizable KE strategy for future projects may be possible through classifying sites as "smallholder sites" and "agri-company sites." The former are primarily characterized by bonding, and the latter by linking. Our conceptual models of KEprocesses, and interpersonal social networks derived from our qualitative data can also be used as reference points upon which these networks (Figures 3 and 4), their trust, and power dynamics can be further elucidated—especially as rapidly emerging digital communication opportunities (Stroud & Goulding, 2022) continue to develop between small-holder farmers, scientists and other actors.

5.2. Social Science as an Integral Part of Future CZ Science Studies

In order to tailor CZ science programmes to co-deliver results for science and to have human and ecosystem benefits, a firm understanding of the social system in which CZ processes are operating is needed. This requires a re-framing of CZ science so that it is more human-centric, by incorporating local knowledge and study of the social dynamics of the actors shaping CZ processes to build trust with local actors (Karcher et al., 2022) as an integral part of future CZ science (Latour, 2021). In CZOs with large rural populations such as those in China, farmers as stewards of the land (Zhang et al., 2016) are key agents of CZ function, but also have a wealth of local knowledge of their environment, agricultural practices, ecological suitability (e.g., for agroforestry, Rigal et al., 2018; Girard, 2015 for agricultural innovation) and their cultural, social and political context (Naylor et al., 2023; Wu & Pretty, 2004). We describe this integration of local and scientific knowledge as a 3rd generation approach to CZ science (Naylor et al., 2023), in which key stakeholders co-design and co-produce research initiatives that create new dialogs and training opportunities. The outputs of 3rd Generation CZO programmes integrate CZS, social science and local knowledge and should be precursors to the development of fit-for-purpose national policy and locally tailored actions that improve social-ecological livelihoods. We propose a blueprint with specific recommendations that could usefully inform the design of 3rd Generation CZ, planetary boundaries and planetary health research agendas and sampling strategies worldwide that can better achieve these goals. Based on the findings of this research, we have conceptualized how a combined social science, CZ science, local knowledge and KE approach to CZ research could work (Figure 5).

Ideally this social science research would be conducted prior to the development of international collaborative science studies, at Stage 1 in Figure 5, so that the research questions and KE activities are well-tailored to engage different stakeholders and incorporate pluralistic knowledge at the outset of a project—allowing best practice in knowledge co-production and use for sustainability (Grainger et al., 2020; Norström et al., 2020). This approach would allow CZ science to be designed to ensure it is beneficial to the most pressing local needs, whilst achieving goals of funders (e.g., poverty alleviation, climate mitigation or achieving SDGs). For example, smallholder farmers' identified fertilizers as the most expensive component of their farm. Could we usefully design CZ science that could measure both the effects of reduced synthetic and improved organic fertilizer use on the landscape, using conventional CZ science methods alongside social science research evaluating the learning approaches used, the social impacts of the changes, such as improved income and less hunger for farming

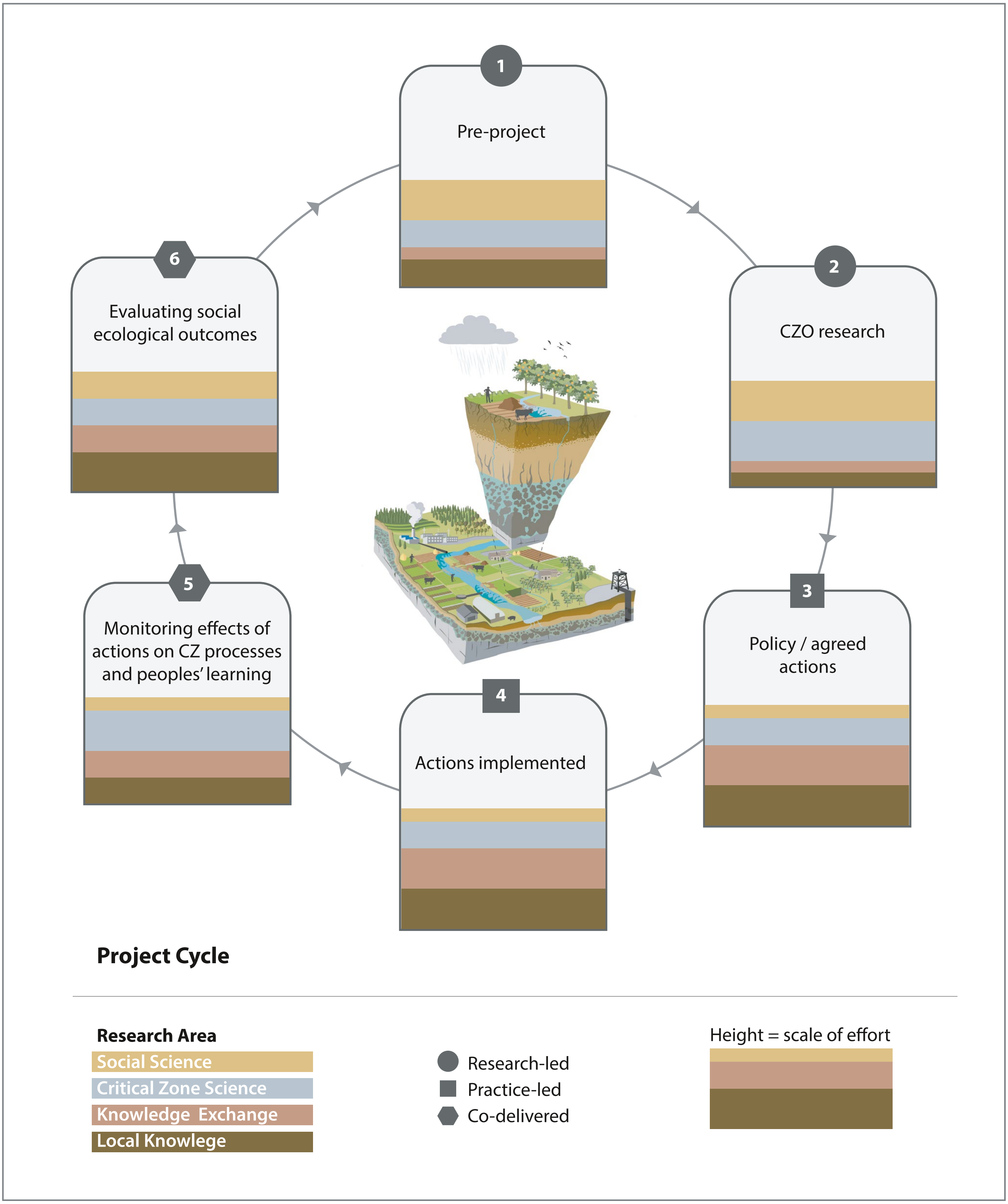

Figure 5. Conceptual diagram illustrating the six stages in a transdisciplinary CZO research project life cycle for sustainable Earth futures to incorporate social science research (SSR), CZ science, local knowledge (LK) and KE activities.

10.1029/2022EF003472

Table 3
Blueprint for Future Transdisciplinary 3rd Generation CZ Science Research and Practice

Funders	Scientists	Both
• Funding social science research (SSR) (and any pilot science) before and during a large interdisciplinary program (Stage 1) • Opportunities for flexible funding during project life (all Stages, e.g., the UK's Economic and Social Research Council's FlexFund) • Funding post-SSR + CZS project to sustain long-term relationships with policy and practice, so that implementation can be measured and evaluated (Stages 4–6) • KE is different than SSR, and both need funding on programmes designed to address planetary boundaries, planetary health, ecosystem services issues and evaluate social-ecological success against metrics (e.g., SDGs). (all Stages) • Funding to support just inclusion of local knowledge. (all Stages)	• Local-scale human behavior is an important driver of CZ function in 2nd and transdisciplinary 3rd generation CZOs • Theories of CZ function from CZOs in more pristine settings may not apply; local (i.e. pluralistic) knowledge can help interpret "noisier" data in human-modified systems[a] • Interdisciplinary research, combining SSR and CZS with KE can co-identify context-specific policy and practical actions. (Stages 2–3) • These actions can then form the basis of combined SSR + CZS that monitors and evaluates the effectiveness of actions on social and environmental outcomes (Stages 5 and 6 in our conceptual model).	• Multi-scale, multi-actor science-policy and science-practice KE goals are required, that is, for both high level policy implementation and local farmer scale actions. (Stages 2–6) • KE ideally needs to be grounded in critical SSR; this requires SSR prior to define CZS research priorities (Stage 1 for critical SSR research) • Co-design of CZS research with local actors and SS researchers is recommended. (Stage 2, informed by Stage 1) • Research process is changed to include pre- and post-CZO science, so that co-design can be most effective, and evaluation of progress to overall social-ecological goals can be evaluated (Stages 5 and 6). • Be open to incorporate other forms of funding for example, for implementation (Stages 3–5)

Note. Stages listed in each column refer to the stages drawn in Figure 5. SSR, social science research; CZO, Critical Zone Observatory; CZS, Critical Zone Science; KE, knowledge exchange; SDG, Sustainable Development Goal.
[a]Naylor et al. (2023).

families? The China-UK CZO projects studied the levels and effects of nitrogen on CZ processes (Li et al., 2021; Liang et al., 2020, 2021; Naylor et al., 2023), and our KE research identified this as a key barrier to achieving SDG1 (Naylor et al., 2023). A social capital analysis framework could also be applied before, during and after this KE project to evaluate if the social networks have changed as well as practical environmental (e.g., improved water or soil quality) or social benefits (e.g., reduce poverty). This could take place at stages 1,2, and 5 and 6 in the conceptualized CZ research project cycle (Figure 5).

5.2.1. Precursor Activity to CZO Project Design and Implementation

Preassessment of local community pressures, needs and potential local scale social context and responses, as well as their learning experiences and preferences is recommended in advance of CZO establishment. This will direct focus to social-ecological systems that accelerate the collective ability to meet policy objectives, to achieve SDGs, avoid ecosystem tipping points and improve planetary health (Figure 5, Table 3). Overall, we recommend that future CZ science funders and project planning involves a priori engagement with local communities, so that local, context specific hypothesis driven research questions can be co-developed from the outset.

5.2.2. Incorporating Local Knowledge, Human Activity and Social Context Into the Design of CZS

Farmer-to-scientist KE can be mutually beneficial but requires these activities to be appropriate to the local social context, with ample time, resource and where required, mediation, to overcome barriers (e.g., sociocultural, language) and to engender trust (Karcher et al., 2022). In CZOs with large rural populations such as those in China, farmers as stewards of the land (Zhang et al., 2016) are key agents of CZ function, but also have a wealth of local knowledge of their environment, agricultural practices, ecological suitability (e.g., for agroforestry, Rigal et al., 2018) and their cultural, social and political context (Wu & Pretty, 2004). Local knowledge is invaluable for interpreting CZS data in heavily human-modified systems, where local adaptation measures to cope with economic and environmental pressure on livelihoods modify CZ processes in unexpected ways (Naylor et al., 2023). Crucially, local human activities to maintain resilience are often innovative with positive effects on the landscape and communities in these CZOs illustrating how the landscape is locally shaped and held together by people as well as living organisms (Latour, 2021). Future CZS programmes would benefit from drawing on this local expertise and practice to co-design CZS questions and use this knowledge to help interpret CZS findings (Naylor et al., 2023; Figure 5).

5.2.3. Funding and Delivering 3rd Generation CZS

Figure 5 outlines what long-term funding of a new CZO, planetary health or social-ecological systems research program would ideally look like, where additional funding streams from government agencies or industry could support the program after the initial phases of SSR and CZS research (Stages 1–2) are completed, whereby stages 3–5 could be co-funded by these organizations alongside academic research councils. Similarly, for places where 2[nd] generation CZO or other planetary health, ecosystem services or social-ecological systems research already provides the foundational knowledge gained in stages 1 and 2, it would be advantageous to co-fund research for stages 3–5 by government funders and/or non-profit organizations, or via commercialization. This would allow the social and ecological impacts of context-specific and suitable management interventions (e.g., Stages 3 and 4) to be robustly evaluated (in Stages 5 and 6), providing key evidence of the impacts of policies and practice changes on environmental and social outcomes—and thus progress toward improving planetary health assessment. Crucial to this is the flexible nature of the funding (Table 3), so that each project has the flexibility for within project double or even triple loop learning (Johannessen et al., 2019), where insights from SSR and local communities can inform and refine CZS studies during the life of a CZ project, and where the social-ecological impacts of national to local scale policies and practice for the lived inhabitants of CZOs and their landscapes can be more effectively evaluated (Stage 6).

6. Conclusions

Ultimately, the successful delivery of national policy requires both high level policy implementation support tools and local scale actions that are co-designed with local actors. In order to support long term change, even after project funding has dried up, local actors must perceive change as positive, and integrate this change into their everyday practice. Our analysis shows that using a social capital lens helps us to consider the social relationships influencing learning, that can improve KE practitioners' and CZ scientists' understanding of the social relationships within which our KE activities can take place. This understanding ultimately improves the allocation of scarce resources to support local farmers as they change their farming practices. Through a social capital lens, we were able to gain insight about the studied communities, helping identify opportunities and difficulties of how to bring knowledge in, how and with whom to build trust.

The application of this social capital lens specifically, and social science more generally into the later stages of this project at the KE phase limited the applied value of the project, in terms of helping to deliver science that could directly support changes in and thus benefit the smallholder farmers to help improve their livelihoods. However the work here also shows the value of flexible, adaptable funding (Naylor et al., 2023), and how it can be harnessed to adopt a practice-based research approach to KE in CZ projects. Through learning by doing, we gradually enhanced our understanding of the human behaviors and relationships in the studied communities. Crucially, this work has shown the importance of moving beyond "if" and "how" local people want to learn, to better understand the social context in which they learn—the relationships between different actors in the community and local governance systems, their power dynamics, social capital stocks and trust flows and how these operate in each local context (Fielke et al., 2022). Funding CZ projects without this knowledge is liable to result in allocating resources in sub-optimal ways. In practical terms, this means issues such as corruption, local distrust and intransigence, and ultimately reverting to harmful farming practices.

A focus on local community relationships has allowed us to show there are geographical variations in learning experiences and preferences, and degrees of trust between smallholder farmers, government officials and scientific researchers between regions. These spatial variations highlight the critical importance of understanding the local environmental and social contexts (Thomas et al., 2020) when designing and executing KE in human-modified landscapes. Interesting social science research questions emerge from this research process such as understanding why these spatial differences exist and to explore if and how some of the barriers (e.g., lack of trust) to information flows and learning can be overcome. For example, our findings have demonstrated that one location (Changwu) would is particularly useful for further social science study on why and how linking networks have emerged and gained trust of small-holder farmers, to identify generalizable trends. Moving forward, we recommend that large-scale research programmes, such as those addressing planetary health and/or CZ science, fund both science and social science research, as well as two-way KE activities that draw together local and more formal knowledges and exchange mechanisms.

Data Availability Statement

Data sets that report on farmer and village/county official knowledge learning dynamics and preferences for Puding county are reported in Oliver et al. (2020) and Buckerfield et al. (2019a). The data for Puding as well as the other two regions studied are fully available via the Environmental Information Date Centre repositories at: https://doi.org/10.5285/9c14948d-cf58-4194-9fef-c2cb56818667 and https://doi.org/10.5285/e674e08c-fbf5-411b-940c-7e31014f0e76.

Acknowledgments

The UK team were supported by the Natural Environmental Research Council China CZO and MIDST-CZO projects (NE/S009167/1, NE/S009175/1, NE/S009140/1). The team also appreciate the research outputs of and discussions with the entire UK-China research team at whole programme meetings. The authors appreciate the generous support for fieldwork from local field stations, local communities, and university students in conducting the social science surveys in China. The team also appreciate C. Gu for transcription and translation of interview data, L. Comber for establishing connections with the field station and local government staff in Changwu and Shaun Pimlott Design for the figures.

References

Arnott, J. C., Neuenfeldt, R. J., & Lemos, M. C. (2020). Co-producing science for sustainability: Can funding change knowledge use? *Global Environmental Change*, *60*, 101979. https://doi.org/10.1016/j.gloenvcha.2019.101979

Baars, T. (2011). Experiential science; towards an integration of implicit and reflected practitioner-expert knowledge in the scientific development of organic farming. *Journal of Agricultural and Environmental Ethics*, *24*(6), 601–628. https://doi.org/10.1007/s10806-010-9281-3

Baker, Z., Ekstrom, J. A., Meagher, K. D., Preston, B. L., & Bedsworth, L. (2020). The social structure of climate change research and practitioner engagement: Evidence from California. *Global Environmental Change*, *63*, 102074. https://doi.org/10.1016/j.gloenvcha.2020.102074

Bayne, K., Moore, J., & Fielke, S. (2016). Structural and relational support for innovation-formal versus informal knowledge exchange mechanisms in forest-sector learning. *The Forestry Chronicle*, *92*(04), 432–440. https://doi.org/10.5558/tfc2016-078

Buckerfield, S. J., Quilliam, R. S., Bussiere, L., Waldron, S., Naylor, L. A., Li, S., & Oliver, D. M. (2020). Chronic urban hotspots and agricultural drainage drive microbial pollution of karst water resources in rural developing regions. *Science of the Total Environment*, *744*, 140898. https://doi.org/10.1016/j.scitotenv.2020.140898

Buckerfield, S. J., Quilliam, R. S., Waldron, S., Naylor, L. A., Li, S., & Oliver, D. M. (2019a). Rainfall-driven *E. coli* transfer to the stream-conduit network observed through increasing spatial scales in mixed land-use paddy farming karst terrain. *Water Research X*, *5*, 100038. https://doi.org/10.1016/j.wroa.2019.100038

Buckerfield, S. J., Waldron, S., Quilliam, R. S., Naylor, L. A., Li, S., & Oliver, D. M. (2019b). How can we improve understanding of faecal indicator dynamics in karst systems under changing climatic, population, and land use stressors? Research opportunities in SW China. *Science of the Total Environment*, *646*, 438–447. https://doi.org/10.1016/j.scitotenv.2018.07.292

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., et al. (2003). Knowledge systems for sustainable development. *Proceedings of National Academy of Science*, *100*(14), 8086–8091. https://doi.org/10.1073/pnas.1231332100

Chen, H., Wang, J., & Huang, J. (2014). Policy support, social capital, and farmers' adaptation to drought in China. *Global Environmental Change*, *24*, 193–202. https://doi.org/10.1016/j.gloenvcha.2013.11.010

Chiffoleau, Y. (2005). Learning about innovation through networks: The development of environment-friendly viticulture. *Technovation*, *25*(10), 1193–1204. https://doi.org/10.1016/j.technovation.2004.04.003

Cofré-Bravo, G., Klerkx, L., & Engler, A. (2019). Combinations of bonding, bridging, and linking social capital for farm innovation: How farmers configure different support networks. *Journal of Rural Studies*, *69*, 53–64. https://doi.org/10.1016/j.jrurstud.2019.04.004

Cui, J., Zhou, J., Peng, Y., Hea, Y., Yange, H., & Mao, J. (2014). Atmospheric wet deposition of nitrogen and sulfur to a typical red soil agroecosystem in Southeast China during the ten-year monsoon seasons (2003-2012). *Atmospheric Environment*, *82*, 121–129. https://doi.org/10.1016/j.atmosenv.2013.10.023

Cui, Z., Zhang, H., Chen, X., Zhang, C., Ma, W., Huang, C., et al. (2018). Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, *555*(7696), 363–366. https://doi.org/10.1038/nature25785

Cvitanovic, C., Shellock, R. J., Mackay, M., van Putten, E. I., Karcher, D. B., Dickey-Collas, M., & Ballesteros, M. (2021). Strategies for building and managing 'trust' to enable knowledge exchange at the interface of environmental science and policy. *Environmental Science & Policy*, *123*, 179–189. https://doi.org/10.1016/j.envsci.2021.05.020

Diver, S. (2017). Negotiating indigenous knowledge at the science policy-interface: Insights from the Xáxli'p community forest. *Environmental Science & Policy*, *73*, 1–11. https://doi.org/10.1016/j.envsci.2017.03.001

Edelenbos, J., van Buuren, A., & van Schie, N. (2011). Co-producing knowledge: Joint knowledge production between experts, bureaucrats and stakeholders in Dutch water management projects. *Environmental Science & Policy*, *14*(6), 675–684. https://doi.org/10.1016/j.envsci.2011.04.004

Fazey, I., Bunse, L., Msika, J., Pinke, M., Preedy, K., Evely, A. C., et al. (2014). Evaluating knowledge exchange in interdisciplinary and multi-stakeholder research. *Global Environmental Change*, *25*, 204–220. https://doi.org/10.1016/j.gloenvcha.2013.12.012

Fielke, S., Taylor, B. M., Coggan, A., Jakku, E., Davis, A. M., Thorburn, P. J., et al. (2022). Understanding power, social capital and trust alongside near real-time water quality monitoring and technological development collaboration. *Journal of Rural Studies*, *92*, 120–131. https://doi.org/10.1016/j.jrurstud.2022.03.022

Fisher, R. (2013). 'A gentleman's handshake': The role of social capital and trust in transforming information into useable knowledge. *Journal of Rural Studies*, *31*, 13–22. https://doi.org/10.1016/j.jrurstud.2013.02.006

Fry, P., & Theime, S. (2019). A social learning video method: Identifying and sharing successful transformation knowledge for sustainable soil management in Switzerland. *Soil Use & Management*, *35*(1), 185–194. https://doi.org/10.1111/sum.12505

Fu, B., Wang, S., Liu, Y., Liu, J., Liang, W., & Miao, C. (2017). Hydrogeomorphic ecosystem responses to natural and anthropogenic changes in the Loess Plateau of China. *Annual Review of Earth and Planetary Sciences*, *45*(1), 223–243. https://doi.org/10.1146/annurev-earth-063016-020552

Girard, N. (2015). Knowledge at the boundary between science and society: A review of the use of farmers' knowledge in agricultural development. *Journal of Knowledge Management*, *19*(5), 949–967. https://doi.org/10.1108/JKM-02-2015-0049

Gonzalez, R. M. (2002). Joint learning with GIS: Multi-actor resource management. *Agricultural Systems*, *73*(1), 99–111. https://doi.org/10.1016/S0308-521X(01)00102-0

Grainger, S., Murphy, C., & Vicente-Serrano, S. M. (2021). Barriers and opportunities for actionable knowledge production in drought risk management: Embracing the frontiers of co-production. *Frontiers in Environmental Science*, *9*. https://doi.org/10.3389/fenvs.2021.602128

Grainger, S., Ochoa-Tocachi, B. F., Antiporta, J., Dewulf, A., & Buytaert, W. (2020). Tailoring infographics on water resources through iterative, user-centered design: A case study in the Peruvian Andes. *Water Resources Research*, *56*(2), e2019WR026694. https://doi.org/10.1029/2019WR026694

Green, S. M., Dungait, J. A. J., Tu, C., Buss, H. L., Sanderson, N., Hawkes, S. J., et al. (2019). Soil functions and ecosystem services research in the Chinese karst Critical Zone. *Chemical Geology*, *527*, 119107. https://doi.org/10.1016/j.chemgeo.2019.03.018

He, K., Zhang, J., Feng, J., Hu, T., & Zhang, L. (2016). The impact of social capital on farmers' Willingness to reuse agricultural waste for sustainable development. *Sustainable Development*, *24*(2), 101–108. https://doi.org/10.1002/sd.1611

Huang, J., Qiu, H., & Wang, X., & International Institute for Environment and Development. (2012). *Small-scale farmers in China in the face of modernisation and globalisation*. International Institute for Environment and Development.

Hurley, R. (2017). *Bonding & bridging social capital in family & school relationships*. University of Wisconsin.

Johannessen, A., Swartling, A. G., Wamsler, C., Andersson, K., Arran, J. T., Hernández Vivas, D. I., & Strenström, T. A. (2019). Transforming urban water governance through social (triple-loop) learning. *Environmental Policy and Governance*, *29*(2), 144–154. https://doi.org/10.1002/eet.1843

Karcher, D. B., Cvitanovic, C., Colvin, R. M., van Putten, I. E., & Reed, M. S. (2021). Is this what success looks like? Mismatches between the aims, claims, and evidence used to demonstrate impact from knowledge exchange processes at the interface of environmental science and policy. *Environmental Science & Policy*, *125*, 202–218. https://doi.org/10.1016/j.envsci.2021.08.012

Karcher, D. B., Cvitanovic, C., van Putten, I. E., Colvin, R. M., Armitage, D., Aswani, S., et al. (2022). Lessons from bright-spots for advancing knowledge exchange at the interface of marine science and policy. *Journal of Environmental Management*, *314*, 114994. https://doi.org/10.1016/j.jenvman.2022.114994

Karubanga, G., Kibwika, P., Okry, F., & Sseguya, H. (2017). How farmer videos trigger social learning to enhance innovation among smallholder rice farmers in Uganda. *Cogent Food & Agriculture*, *3*(1), 1368105. https://doi.org/10.1080/23311932.2017.1368105

Keen, M., Brown, V. A., & Dyball, R. (2005). *Social learning in environmental management: Towards a sustainable future* (2005th ed.). Routledge.

Klerkx, L., & Proctor, A. (2013). Beyond fragmentation and disconnect: Networks for knowledge exchange in the English land management advisory system. *Land Use Policy*, *30*(1), 13–24. https://doi.org/10.1016/j.landusepol.2012.02.003

Koskinen, I., Zimmerman, J., Binder, T., Redstrom, J., & Wensveen, S. (2012). *Design research through practice: From the lab, field, and showroom*. Morgan Kaufmann. https://doi.org/10.1016/C2010-0-65896-2

Krzywoszynska, A. (2019). Making knowledge and meaning in communities of practice: What role may science play? The case of sustainable soil management in England. *Soil Use & Management*, *35*(1), 160–168. https://doi.org/10.1111/sum.12487

Kumar, P., Le, P. V., Papanicolaou, A. T., Rhoads, B. L., Anders, A. M., Stumpf, A., et al. (2018). Critical transition in critical zone of intensively managed landscapes. *Anthropocene*, *22*, 10–19. https://doi.org/10.1016/j.ancene.2018.04.002

Laflen, J. M., Tian, J., & Huang, C. H. (Eds.) (2000). *Soil erosion and dryland farming*. CRC Press.

Latour. (2021). Is Geo-logy the New Umbrella for all the sciences? Hints for a Neo-Humboldtian University. P. 9-23 In R.Barnacle, & D.Cuthbert (Eds.) *The PhD at the End of the World: Provocations for the Doctorate and a future contested –introduction*. Springer Link.

Lefebvre, V. M., Sorenson, D., Henchion, M., & Gellynck, X. (2016). Social capital and knowledge sharing performance of learning networks. *International Journal of Information Management*, *36*(4), 570–579. https://doi.org/10.1016/j.ijinfomgt.2015.11.008

Leitgeb, F., Funes-Monzote, F. R., Kummer, S., & Vogl, C. R. (2011). Contribution of farmers' experiments and innovations to Cuba's agricultural innovation system. *Renewable Agriculture and Food Systems*, *26*(4), 354–367. https://doi.org/10.1017/S1742170511000251

Leta, G., Stellmacher, T., Kelboro, G., Van Assche, K., & Hornidge, A.-K. (2018). Social learning in smallholder agriculture: The struggle against systemic inequalities. *Journal of Workplace Learning*, *30*(6), 469–487. https://doi.org/10.1108/JWL-12-2017-0115

Li, D., Zhang, X., Dungait, J. A., Wen, X., Quine, T. A., & Wang, Q. (2021). Changes in the biological N_2-fixation rates and diazotrophic community as vegetation recovers on abandoned farmland in a karst region of China. *Applied Soil Ecology*, *158*, 103808. https://doi.org/10.1016/j.apsoil.2020.103808

Liang, B.-Y., Liu, H.-Y., Quine, T. A., Chen, X.-Q., Hallett, P. D., Cressey, E. L., et al. (2020). Analysing and simulating spatial patterns of crop yield in Guizhou Province based on artificial neural networks. *Progress in Physical Geography*, *45*(1), 33–52. https://doi.org/10.1177/0309133320956631

Liang, B.-Y., Quine, T. A., Liu, H.-Y., Cressey, E. L., & Bateman, I. (2021). How can we realize sustainable development goals in rocky desertified regions by enhancing crop yield with reduction of environmental risks? *Remote Sensing*, *13*(9), 1614. https://doi.org/10.3390/rs13091614

Liu, C., & Zheng, H. (2021). How social capital affects willingness of farmers to accept low-carbon agricultural technology (LAT)? A case study of Jiangsu, China. *International Journal of Climate Change Strategies and Management*, *13*(3), 286–301. https://doi.org/10.1108/ijccsm-09-2020-0100

Liu, X., Zhang, Y., Han, W., Tang, A., Shen, J., Cui, Z., et al. (2013). Enhanced nitrogen deposition over China. *Nature*, *494*(7438), 459–462. https://doi.org/10.1038/nature11917

Liu, Z., Ma, J., Wei, G., Liu, Q., Jiang, Z., Ding, X., et al. (2017). Magnetism of a red soil core derived from basalt, northern Hainan Island, China: Volcanic ash versus pedogenesis. *Journal of Geophysical Research: Solid Earth*, *122*, 1677–1696. https://doi.org/10.1002/2016JB013834

Lucey, J. M., Palmer, G., Yeong, K. L., Edwards, D. P., Senior, M. J. M., Scriven, S. A., et al. (2017). Reframing the evidence base for policy-relevance to increase impact: A case study on forest fragmentation in the oil palm sector. *Journal of Applied Ecology*, *54*(3), 731–736. https://doi.org/10.1111/1365-2664.12845

Luckasiewicz, K., Bahar, O. S., Ali, S., Gopalan, P., Parker, G., Hawkins, R., et al. (2019). Getting by in New York City: Bonding, bridging and linking capital in poverty-impacted neighborhoods. *City & Community*, *18*(1), 280–301. https://doi.org/10.1111/cico.12373

Lv, M. X., Ma, Z. G., Li, M. X., & Zheng, Z. Y. (2019). Quantitative analysis of terrestrial water storage changes under the Grain for Green Program in the Yellow River basin. *Journal of Geophysical Research - Atmosphere*, *124*, 1336–1351. https://doi.org/10.1029/2018JD029113

Montana, J., Elliott, L., Ryan, M., & Wyborn, C. (2020). The need for improved reflexivity in conservation science. *Environmental Conservation*, *47*(4), 217–219. https://doi.org/10.1017/S0376892920000326

Morgan, S. L. (2011). Social learning among organic farmers and the application of the communities of practice framework. *The Journal of Agricultural Education and Extension*, *17*(1), 99–112. https://doi.org/10.1080/1389224X.2011.536362

Morris, C. (2006). Negotiating the boundary between state-led and farmer approaches to knowing nature: An analysis of UK agri-environment schemes. *Geoforum, Geographers in Guatemala: Fieldwork in a Conflicted Landscape*, *37*(1), 113–127. https://doi.org/10.1016/j.geoforum.2005.01.003

Narayan, D. (2002). Bonds and bridges: Social capital and poverty. In *Social capital and economic development: Well-being in developing countries* (pp. 58–81). Edward Elgar.

Naylor, L. A., Dungait, J. A. J., Zheng, Y., Buckerfield, S., Green, S. M., Oliver, D. M., et al. (2023). Achieving sustainable Earth futures in the Anthropocene by including local communities in critical zone science. *Earth's Future*, *11*, e2022EF003448.

Nocco, M. A., Feinstein, N. W., Stock, M. N., McGill, B. M., & Kucharik, C. J. (2020). Knowledge co-production with agricultural trade associations. *Water*, *12*, 1–15. https://doi.org/10.3390/w12113236

Norström, A. V., Cvitanovic, C., Löf, M. F., West, S., Wyborn, C., Balvanera, P., et al. (2020). Principles for knowledge co-production in sustainability research. *Nature Sustainability*, *3*, 182–190. https://doi.org/10.1038/s41893-019-0448-2

Oliver, D. M., Fish, R. D., Winter, M., Hodgson, C. J., Heathwaite, A. L., & Chadwick, D. R. (2012). Valuing local knowledge as a source of expert data: Farmer engagement and the design of decision support systems. *Environmental Modelling & Software*, *36*, 76–85. https://doi.org/10.1016/j.envsoft.2011.09.013

Oliver, D. M., Zheng, Y., Naylor, L. A., Murtagh, M., Waldron, S., & Peng, T. (2020). How does smallholder farming practice and environmental awareness vary across village communities in the karst terrain of southwest China? *Agriculture, Ecosystems & Environment*, *288*, 106715. https://doi.org/10.1016/j.agee.2019.106715

Page, R., & Dilling, L. (2019). The critical role of communities of practice and peer learning in scaling hydroclimatic information adoption. *Weather, Climate, and Society*, *11*(4), 851–862. https://doi.org/10.1175/WCAS-D-18-0130.1

Pretty, J., & Ward, H. (2001). Social capital and the environment. *World Development*, *29*(2), 209–227. https://doi.org/10.1016/S0305-750X(00)00098-X

Putnam, R. D., Leonardi, R., & Nanetti, R. (1994). *Making democracy work: Civic traditions in modern Italy*. Princeton University Press.

Qin, C., Ding, H., Li, S. L., Yue, F. J., Wang, Z. J., & Zeng, J. (2020). Hydrogeochemical dynamics and response of karst catchment to rainstorms in a Critical Zone Observatory (CZO), southwest China. *Frontiers in Water*, *2*, 52. https://doi.org/10.3389/frwa.2020.577511

Reed, M., Evely, A., Cundill, G., Fazey, I., Glass, J., Laing, A., et al. (2010). What is social learning? *Ecology and Society*, *15*(4), resp1. https://doi.org/10.5751/ES-03564-1504r01

Ren, Y., Lü, Y., Fu, B., Comber, A., Li, T., & Hu, J. (2020). Driving factors of land change in China's Loess Plateau: Quantification using geographically weighted regression and management implications. *Remote Sensing*, *12*(3), 453. https://doi.org/10.3390/rs12030453

Rigal, C., Vaast, P., & Xu, J. (2018). Using farmers' local knowledge of tree provision of ecosystem services to strengthen the emergence of coffee-agroforestry landscapes in southwest China. *PLoS One*, *13*(9), e0204046. https://doi.org/10.1371/journal.pone.0204046

Riley, M. (2008). Experts in their fields: Farmer — Expert knowledges and environmentally friendly farming practices. *Environment & Planning A*, *40*(6), 1277–1293. https://doi.org/10.1068/a39253

Riley, M., Sangster, H., Smith, H., Chiverrell, R., & Boyle, J. (2018). Will farmers work together for conservation? The potential limits of farmers' cooperation in agri-environment measures. *Land Use Policy*, *70*, 635–646. https://doi.org/10.1016/j.landusepol.2017.10.049

Rist, S., Chidambaranathan, M., Escobar, C., Wiesmann, U., & Zimmermann, A. (2007). Moving from sustainable management to sustainable governance of natural resources: The role of social learning processes in rural India, Bolivia and Mali. *Journal of Rural Studies*, *23*(1), 23–37. https://doi.org/10.1016/j.jrurstud.2006.02.006

Saint Ville, A. S., Hickey, G. M., Locher, U., & Phillip, L. E. (2016). Exploring the role of social capital in influencing knowledge flows and innovation in smallholder farming communities in the Caribbean. *Food Security*, *8*(3), 535–549. https://doi.org/10.1007/s12571-016-0581-y

Sewell, A. M., Gray, D. I., Blair, H. T., Kemp, P. D., Kenyon, P. R., Morris, S. T., & Wood, B. A. (2014). Hatching new ideas about herb pastures: Learning together in a community of New Zealand farmers and agricultural scientists. *Agricultural Systems*, *125*, 63–73. https://doi.org/10.1016/j.agsy.2013.12.002

Shen, J., Cui, Z., Miao, Y., Mi, G., Zhang, H., Fan, M., et al. (2013). Transforming agriculture in China: From solely high yield to both high yield and high resource use efficiency. *Global Food Security*, *2*, 1–8. https://doi.org/10.1016/j.gfs.2012.12.004

Skaalsveen, K., Ingram, J., & Urquhart, J. (2020). The role of farmers' social networks in the implementation of no-till farming practices. *Agricultural Systems*, *181*, 102824. https://doi.org/10.1016/j.agsy.2020.102824

Storr, V. H., Haeffele-Balch, S., & Grube, L. E. (2017). Social capital and social learning after Hurricane Sandy. *The Review of Austrian Economics*, *30*(4), 447–467. https://doi.org/10.1007/s11138-016-0362-z

Stringer, L. C., Fraser, E. D. G., Harris, D., Lyon, C., Pereira, L., Ward, C. F. M., & Simelton, E. (2020). Adaptation and development pathways for different types of farmers. *Environmental Science & Policy*, *104*, 174–189. https://doi.org/10.1016/j.envsci.2019.10.007

Stroud, J. L., & Goulding, K. W. T. (2022). Science and user-based co-development of a farmland earthworm survey facilitated using digital media: Insights and policy implications. *Annals of Applied Biology*, *181*(1), 70–79. https://doi.org/10.1111/aab.12766

Tang, L., Ma, X., Zhou, Y., Shi, X., & Ma, J. (2019). Social relations, public interventions and land rent deviation: Evidence from Jiangsu Province in China. *Land Use Policy*, *86*, 406–420. https://doi.org/10.1016/j.landusepol.2019.05.025

Thomas, D. R. (2006). A general inductive approach for analyzing qualitative evaluation data. *American Journal of Evaluation*, *27*(2), 237–246. https://doi.org/10.1177/1098214005283748

Thomas, E., Riley, M., & Spees, J. (2020). Knowledge flows: Farmers' social relations and knowledge sharing practices in 'Catchment Sensitive Farming'. *Land Use Policy*, *90*, 104254. https://doi.org/10.1016/j.landusepol.2019.104254

Titeca, K., & Vervisch, T. (2008). The dynamics of social capital and community associations in Uganda: Linking capital and its consequences. *World Development*, *36*(11), 2205–2222. https://doi.org/10.1016/j.worlddev.2007.10.021

Tregear, A., & Cooper, S. (2016). Embeddedness, social capital and learning in rural areas: The case of producer cooperatives. *Journal of Rural Studies*, *44*, 101–110. https://doi.org/10.1016/j.jrurstud.2016.01.011

Tsouvalis, J., Seymour, S., & Watkins, C. (2000). Exploring knowledge-cultures: Precision farming, yield mapping, and the expert–farmer interface. *Environment & Planning A: Economy and Space*, *32*(5), 909–924. https://doi.org/10.1068/a32138

Vogl, C., Kummer, S., Leitgeb, F., Schunko, C., & Aigner, M. (2015). Keeping the actors in the organic system learning: The role of organic farmers' experiments. *Sustainable Agriculture Research*, *4*(3), 140. https://doi.org/10.5539/sar.v4n3p140

Weichselgartner, J., & Kasperson, R. (2010). Barriers in the science-policy-practice interface: Toward a knowledge-action-system in global environmental change research. *Global Environmental Change*, *20*(2), 266–277. https://doi.org/10.1016/j.gloenvcha.2009.11.006

Whatmore, S. J. (2009). Mapping knowledge controversies: Science, democracy and the redistribution of expertise. *Progress in Human Geography*, *33*(5), 587–598. https://doi.org/10.1177/0309132509339841

White, T., Brantley, S., Banwart, S., Chorover, J., Dietrich, W., Derry, L., et al. (2015). The role of critical zone observatories in critical zone science. *Developments in Earth Surface Processes*, *19*, 15–78. https://doi.org/10.1016/B978-0-444-63369-9.00002-1

Woolcock, M. (1998). Social capital and economic development: Toward a theoretical synthesis and policy framework. *Theory and Society*, *27*(2), 151–208. https://doi.org/10.1023/a:1006884930135

Woolcock, M., & Narayan, D. (2000). Social capital: Implications for development, theory, and policy. *World Bank Research Observer*, *15*, 225–249. https://doi.org/10.1093/wbro/15.2.225

Wu, B., & Pretty, J. (2004). Social connectedness in marginal rural China: The case of farmer innovation circles in Zhidan, North Shaanxi. *Agriculture and Human Values*, *21*(1), 81–92. https://doi.org/10.1023/b:ahum.0000014025.47576.72

Wu, Y., Xi, X., Tang, X., Luo, D., Gu, B., Lam, S. K., et al. (2018). Policy distortions, farm size, and the overuse of agricultural chemicals in China. *Proceedings of the National Academy of Sciences of the United States of America*, *115*(27), 7010–7015. https://doi.org/10.1073/pnas.1806645115

Wyckhuys, K. A. G., Bentley, J. W., Lie, R., Nghiem, L. T. P., & Fredrix, M. (2018). Maximizing farm-level uptake and diffusion of biological control innovations in today's digital era. *BioControl*, *63*(1), 133–148. https://doi.org/10.1007/s10526-017-9820-1

Xu, X., Wang, L., Sun, M., Fu, C., Bai, Y., Li, C., & Zhang, L. (2020). Climate change vulnerability assessment for smallholder farmers in China: An extended framework. *Journal of Environmental Management*, *276*, 111315. https://doi.org/10.1016/j.jenvman.2020.111315

Ye, J. (2015). Land transfer and the pursuit of agricultural modernization in China: Land transfer and agricultural modernization in China. *Journal of Agrarian Change*, *15*(3), 314–337. https://doi.org/10.1111/joac.12117

Yue, F.-J., Li, S.-L., Waldron, S., Wang, Z.-J., Oliver, D. M., Chen, X., & Liu, C.-Q. (2020). Rainfall and conduit drainage combine to accelerate nitrate loss from a karst agroecosystem: Insights from stable isotope tracing and high-frequency nitrate sensing. *Water Research*, *186*, 116388. https://doi.org/10.1016/j.watres.2020.116388

Zhang, J., Zhu, T., Meng, T., Zhang, Y., Yang, J., Yang, W., et al. (2013). Agricultural land use affects nitrate production and conservation in humid subtropical soils in China. *Soil Biology and Biochemistry*, *62*, 107–114. https://doi.org/10.1016/j.soilbio.2013.03.006

Zhang, W., Cao, G., Li, X., Zhang, H., Wang, C., Liu, Q., et al. (2016). Closing yield gaps in China by empowering smallholder farmers. *Nature*, *537*(7622), 671–674. https://doi.org/10.1038/nature19368

Zhang, Z., Chen, X., Cheng, Q., Li, S., Yue, F., Peng, T., et al. (2020). Coupled hydrological and biogeochemical modelling of nitrogen transport in the karst critical zone. *Science of the Total Environment*, *732*, 138902. https://doi.org/10.1016/j.scitotenv.2020.138902

Zhao, D., & Seip, H. M. (1991). Assessing effects of acid deposition in Southwestern China using the magic model. *Water, Air, and Soil Pollution*, *60*(1–2), 83–97. https://doi.org/10.1007/BF00293967

Zhao, G., Mu, X., Wen, Z., Wang, F., & Gao, P. (2013). Soil erosion, conservation, and eco-environment changes in the Loess Plateau of China. *Land Degradation & Development*, *24*(5), 499–510. https://doi.org/10.1002/ldr.2246

Zheng, Y., Naylor, L., Waldron, S., & Oliver, D. (2019b). Stakeholder surveys to local farmers and officials in Chinese villages to understand knowledge management dynamics. [Dataset]. NERC Environmental Information Data Centre. https://doi.org/10.5285/9c14948d-cf58-4194-9fef-c2cb56818667

Zheng, Y., Naylor, L. A., Waldron, S., Oliver, D., & Gu, C. (2022). Social surveys to environmental scientists and local stakeholders in Chinese villages to understand knowledge management dynamics. [Dataset]. NERC EDS Environmental Information Data Centre. https://doi.org/10.5285/e674e08c-fbf5-411b-940c-7e31014f0e76

Zheng, Y., Naylor, L. A., Waldron, S., & Oliver, D. M. (2018). Summary report of China-UK knowledge exchange project for their critical zone programme.

Zheng, Y., Naylor, L. A., Waldron, S., & Oliver, D. M. (2019a). Knowledge management across the environment-policy interface in China: What knowledge is exchanged, why, and how is this undertaken? *Environmental Science & Policy*, *92*, 66–75. https://doi.org/10.1016/j.envsci.2018.09.021