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

Achieving Sustainable Earth Futures in the Anthropocene by Including Local Communities in Critical Zone Science

Larissa A. Naylor[1], Jennifer A. J. Dungait[2,3], Ying Zheng[1], Sarah Buckerfield[4], Sophie M. Green[2,5], David M. Oliver[4], Hongyan Liu[6], Jian Peng[6], Chenglong Tu[7], Gan-lin Zhang[8], Xinyu Zhang[8], Tim A. Quine[2], Susan Waldron[1], and Paul D. Hallett[9]

[1]School of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK, [2]Geography, College of Life and Environmental Science, University of Exeter, Exeter, UK, [3]Carbon Management Centre, SRUC-Scotland's Rural College, Edinburgh, UK, [4]Biological and Environmental Sciences, Faculty of Natural Sciences, University of Stirling, Stirling, UK, [5]Now at School of Natural and Built Environment, Queens University Belfast, Belfast, UK, [6]College of Urban and Environmental Sciences, Peking University, Beijing, China, [7]Toxicity Testing Center, Guizhou Medical University, Guiyang, China, [8]Institute of Soil Science, Chinese Academy of Science (CAS), Nanjing, China, [9]School of Biological Sciences, University of Aberdeen, Aberdeen, UK

Larissa A. Naylor and Jennifer A. J. Dungait are joint first authors.

Key Points:

- Integrating local knowledge with critical zone science can improve interpretation of scientific findings and delivery of Sustainable Development Goals
- Third generation science can improve alignment of research with the practical needs of communities and governments
- A new conceptual diagram for human-modified critical zones is produced to illustrate transdisciplinary Critical Zone Observatories for sustainable Earth futures

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

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Author Contributions:
Conceptualization: Larissa A. Naylor, Jennifer A. J. Dungait, Sarah Buckerfield, David M. Oliver, Susan Waldron, Paul D. Hallett

Abstract

Critical Zone Science (CZS) explores the deep evolution of landscapes from the base of the groundwater or the saprolite-rock interface to the top of vegetation, the zone that supports all terrestrial life. Here we propose a framework for CZS to evolve further as a discipline, building on 1st generation CZOs in natural systems and 2nd generation CZOs in human-modified systems, to incorporate human behaviour for more holistic understanding in a 3rd generation of CZOs. This concept was tested in the China-UK CZO programme (2016–2020) that established four CZOs across China on different lithologies. Beyond conventional CZO insights into soil resources, biogeochemical cycling and hydrology across scales, surveys of farmers and local government officials led to insights into human-environment interactions and key pressures affecting the socio-economic livelihoods of local farmers. These learnings combined with the CZS data identified knowledge exchange (KE) opportunities to unravel diverse factors within the Land-Water-Food Nexus, that could directly improve local livelihoods and environmental conditions, such as reduction in fertilizer use, contributing toward Sustainable Development Goals (SDGs) and environmental policies. Through two-way local KE, the local cultural context and socio-economic considerations were more readily apparent alongside the environmental rationale for policy and local action to improve the sustainability of farming practices. Seeking solutions to understand and remediate CZ degradation caused by human-decision making requires the co-design of CZS that foregrounds human behavior and the opinions of those living in human modified CZOs. We show how a new transdisciplinary CZO approach for sustainable Earth futures can improve alignment of research with the practical needs of communities in stressed environments and their governments, supporting social-ecological and planetary health research agendas and improving capacity to achieve SDGs.

Plain Language Summary

Critical Zone Science (CZS) explores how landscapes evolve from below the Earth's surface to the top of trees, supporting life on Earth. CZS was established by studying pristine landscapes, with little or no human modification of the land, water and soil. These pristine natural systems are rare in our modern world. In this paper, we have proposed a new approach to CZS for studying the human-modified landscapes that dominate our world. To help explain why this is needed, we have re-drawn a diagram explaining how the critical zone works to show the role of humans. We also give examples of research in three regions of China where we learned from local farmers living in our study areas, to improve our scientific understanding and to try to align our research process to address the biggest pressures affecting their lives. This new approach to CZS can help focus research to directly support local people and improve our ability to achieve the United Nations Sustainable Development Goals.

1. Introduction: Incorporating Human Impacts Into Critical Zone Science (CZS)

Humans are ubiquitous modifiers of the environment, especially in terrestrial systems where our surface activities permeate through the soil to the geology deep below and into the local atmosphere above. This can result in substantial impacts from the anthropogenic forcing of natural cycles, such as rates of erosion that drive soil degradation, or nutrient fluxes that pollute water and release greenhouse gases (GHGs) that impact climate (White

Data curation: Sarah Buckerfield, Sophie M. Green, Tim A. Quine, Paul D. Hallett
Formal analysis: Larissa A. Naylor, Jennifer A. J. Dungait, Ying Zheng, Sarah Buckerfield, Sophie M. Green, David M. Oliver
Funding acquisition: Larissa A. Naylor, David M. Oliver, Hongyan Liu, Jian Peng, Chenglong Tu, Gan-lin Zhang, Xinyu Zhang, Tim A. Quine, Susan Waldron, Paul D. Hallett
Investigation: Sarah Buckerfield, Sophie M. Green
Methodology: Larissa A. Naylor, Ying Zheng, Sarah Buckerfield, David M. Oliver, Susan Waldron, Paul D. Hallett
Project Administration: Larissa A. Naylor, Ying Zheng, David M. Oliver, Jian Peng, Chenglong Tu, Gan-lin Zhang, Xinyu Zhang, Tim A. Quine, Susan Waldron, Paul D. Hallett
Resources: Hongyan Liu, Gan-lin Zhang
Supervision: David M. Oliver, Gan-lin Zhang, Xinyu Zhang, Tim A. Quine, Susan Waldron, Paul D. Hallett
Validation: Larissa A. Naylor
Visualization: Larissa A. Naylor
Writing – original draft: Larissa A. Naylor, Jennifer A. J. Dungait, Sophie M. Green, David M. Oliver, Tim A. Quine, Paul D. Hallett
Writing – review & editing: Larissa A. Naylor, Jennifer A. J. Dungait, Ying Zheng, Sophie M. Green, David M. Oliver, Hongyan Liu, Jian Peng, Chenglong Tu, Gan-lin Zhang, Xinyu Zhang, Tim A. Quine, Susan Waldron, Paul D. Hallett

et al., 2015). The proposition by Rockström et al. (2009) that rapid, human-induced alterations of continental- to planetary-scale systems (e.g., climate change, stratospheric ozone, biogeochemical nitrogen and phosphorus cycles, global freshwater use and biodiversity loss) were moving humanity beyond its safe-operating space has generally been confirmed by the findings from Critical Zone Observatories (CZO) (see review by L. Guo and Lin (2016)), and reinforced the standing of human beings as a global-scale influence defining a new Earth epoch, termed the Anthropocene (Crutzen, 2006). The ethos of CZOs is to provide a field experimental platform accessed by diverse disciplines to develop a more holistic scientific understanding of how the critical zone (CZ) functions (Minor et al., 2020; Montanarella & Panagos, 2015). Monitoring CZ processes at CZOs was established initially in "natural" environments but then extended to explicitly human-modified landscapes (see Minor et al., 2020; Richter et al., 2018 for recent reviews), showing an evolution from 1st to 2nd generation CZOs. However, the perspective offered by conventional CZS as a "Gaia-graphic view" of a pristine Earth, for example, global modeling approaches that includes the effect of humans as contributors to geochemical cycles (Arènes et al., 2018), is poorly accessible to inhabitants of CZs and requires translation to human-scale realities and narratives (Latour, 2021) of the lived inhabitants of stressed communities. Seeking solutions to understand and remediate CZ degradation caused by human decision-making requires the co-design of Critical Zone Science (CZS) that incorporates the human dimension, and foregrounds human behaviour and the opinions of those living in human modified CZOs (Latour, 2021).

Knowledge exchange (KE) and feedback activities are often scheduled for the final stages of CZS projects rather than as part of the CZS research process itself. In this paper, we propose that involving local communities more actively as integral collaborators from the outset and then throughout the research process via co-production (Norström et al., 2020) and as research subjects themselves (Latour, 2021) could provide some early "win-win" opportunities for livelihoods in local communities that also support the delivery of policy solutions for planetary health by valuing the human place in CZs (Arènes et al., 2018), aiding delivery of climate resilient rural development pathways (IPCC 6th AR) and the achievement of Sustainable Development Goals (SDGs). Perhaps more importantly, the planning and design of future CZS, CZOs, long-term ecological research networks and scientific study of human-modified landscapes more generally, will prove more beneficial to local communities and accelerate progress on complex global challenges including social cohesion, climate change, environmental quality and food security (Chapin et al., 2022; Thomas et al., 2019). To achieve this, we explored and developed this 3rd Generation CZO idea through a review of literature and a synthesis of social surveys conducted through the China-UK CZO (2016–2020), program and MIDST-UK project (2020–2022). We were motivated by our research experience to incorporate a social science dimension, and we use the China-UK CZO KE research as a case study to describe the development of the 3rd Generation CZO in response. During the China-UK CZO program, we extended our KE research across the different CZOs, allowing comparison between regions to link 2nd Generation science outputs to the livelihoods of the local communities living in the CZs and the achievement of SDGs (see also Naylor et al., 2023b). Based on these developments, we propose a step-change in CZS that explicitly explores these important human dimensions alongside considerations of climate and land use effects on biophysical CZ processes (e.g., Richter et al., 2018) by explicitly including studies of local scale human-behaviours and decision making and their impacts on CZ processes. This new (3rd generation) transdisciplinary form of CZS can explore sustainable Earth futures to address the current ecosystem, climate change and planetary health emergencies.

1.1. Transition From 1st to 2nd Generation CZOs

The aim of CZS is to capture the inputs, outputs and transformations of an environment, and thereby to describe how its evolution over time affects ecosystem processes (L. Guo & Lin, 2016). The initial focus on natural landscapes in 1st Generation CZOs was prompted by fundamental scientific questions about primary geological, biological and atmospheric interactions, and elegantly illustrated by the widely used schematic (Figure 1a) introduced by Chorover et al. (2007). This describes the unique CZS approach that draws on diverse scientific fields to study multi-scale processes from the outer periphery of the vegetation canopy through soil to the underlying geology, exploring how whole ecosystems function and evolve over time. The focus on the connectedness between deep geology and the surface captures processes that discrete scientific approaches miss (Banwart et al., 2011; Chorover et al., 2011). However, a transition has occurred where the legacy of natural processes has been affected to various extents by land use and other direct human interactions with ecosystems (Ellis et al., 2010). Although legacy CZ properties such as palaeotopography (H. Wu et al., 2022) and soil mineralogy (M. Liu et al., 2019b)

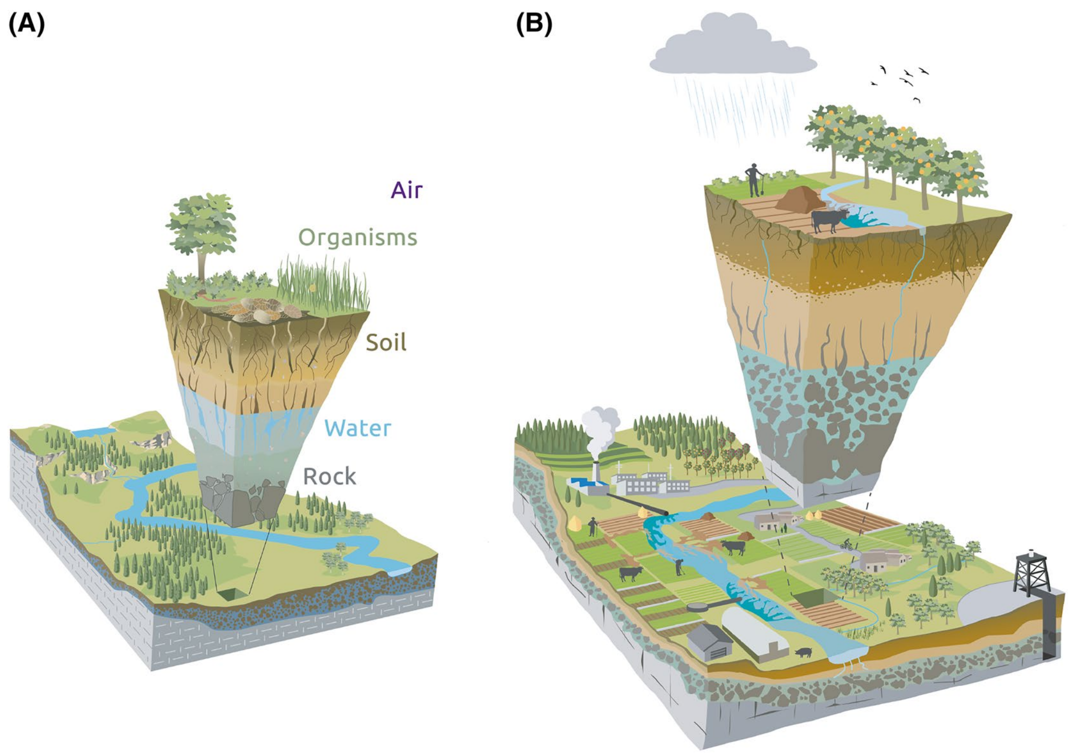

Figure 1. Illustrating Earth's Critical Zone. (a) The Critical Zone without overt consideration of human impact (adapted from original figure in Chorover et al. (2007); modified from artwork by R. Kindlimann; file is licensed under the Creative Commons Attribution-Share Alike 4.0 International license). (b) The 3rd Generation transdisciplinary Critical Zone Observatory for sustainable Earth futures: a novel adaptation of Chorover et al. (2007) to show a wide range of human activities and impacts in human-stressed critical zones (land use impacts on water quality are represented by a darkening of water colour downstream).

fundamentally control the impacts of human interactions with the environment, the equilibrium of the natural environment is increasingly disrupted.

In human-impacted CZOs, local people are direct contributors to CZ function, and act as geomorphic agents of landscape change (Latour, 2021). Thus, 2nd Generation CZO programmes aim to develop a deeper understanding of the impacts of human modification of landscapes, especially the extent to which human activities degrade CZ function, with the intention to inform potential solutions for appropriate remediation, recovery and adaptation (Minor et al., 2020). For example, with the introduction of human influences in 2nd Generation CZOs (Minor et al., 2020), point source pollution and concentrated flow paths driven by agricultural practices and urbanization become more pronounced (e.g., Banwart et al., 2012; White et al., 2015). This has implications for extrapolation from CZOs to the wider landscape and on the design of sampling approaches appropriate to disturbed landscapes. Conceptual diagrams of CZ processes, such as those depicting water, biogeochemical or critical zone processes, are predominately drawn for natural landscapes showing little or no anthropogenic influences on the earth systems being described. Fandel et al. (2018) provided salient suggestions for the refinement of conceptual scientific illustrations to address identified shortcomings, some of which have been incorporated into various revisions to Chorover's original CZ diagram. For example, Chorover's original figure (Figure 1a) has been modified by different authors to introduce themes of the CZ with direct reference to different spatial scales, timescales and ecosystem/CZ services (e.g., Field et al., 2015; Tchakerian & Pease, 2015) and the interrelated sub-systems of human systems (e.g., Ferraro et al., 2018). Here, we have substantively revised and reimagined Chorover's diagram (Figure 1a) to illustrate a range of human activities, human interactions with the landscape and their impacts in human-stressed critical zones (Figure 1b) to highlight these impacts on CZ processes captured using a 3rd generation CZO approach.

1.2. Focus on Agriculture in 2nd Generation CZOs

Recognition of the ubiquitous influence of humans in most terrestrial landscapes led to the development of 2nd Generation CZOs that specifically directed resources toward predicting CZ responses and resilience to human impacts, many related to agriculture (Jordan et al., 2018). Agriculture dominates human land use, accounting for 38% of the Earth's land surface cover (FAO, 2020). The intensification of land use for farming is a major driver of global land cover change, land degradation and GHG emissions. Sustainable solutions to these problems are essential to enable achievement of numerous United Nations SDGs (Table 1). Despite continued human population growth and intensifying pressure on land use to meet the ever-increasing demand for food and non-human-food crops (intensive livestock, fibre, and bioenergy production), urban expansion has reduced the area of global cropland dramatically, from 0.45 to 0.21 ha per capita between 1961 and 2016 (FAO, 2020). Subsequently, pressure to grow more food on less land has strongly contributed to unsustainable agricultural practices that are a principal cause of global land degradation, with direct and indirect consequences for human livelihoods, creating social, political, cultural and economic inequalities (Olsson et al., 2019). Securing domestic food supply is a global priority, but large areas of agricultural land suffer from medium to strong degradation (Nachtergaele et al., 2011). Loss of ecosystem functions due to land degradation has reduced global net primary productivity by 5%, or 10%–17% of global gross domestic product (UNCCD, 2019). However, the implementation of modified management approaches to redress land degradation offers potential co-benefits to improve environmental quality and economic stability (Olsson et al., 2019). Consequently, agriculture's impact on the CZ has become an urgent focus of 2nd Generation CZOs across the world (Banwart et al., 2011; Coughlan et al., 2017; Gaillardet et al., 2018; Gupta et al., 2019; Kumar et al., 2018; Menon et al., 2014; Sekhar et al., 2016; Seyfried et al., 2018; G. Zhang et al., 2019a; Z. C. Zhang et al., 2019b).

The impacts of agriculture on the CZ are diverse and complicated. A recent adaptation of Figure 1a by Kumar et al. (2018) depicted how hydrological processes at the field scale have been radically altered by land use change to intensive agriculture in large-scale (100s of ha) arable monoculture production systems in the prairielands of Mid-West USA. Empirical data outputs from CZOs used to inform land restoration strategies (Green et al., 2019), and develop technological advances and adaptive approaches can provide solutions to improve the sustainability of food production (e.g., Climate Smart Agriculture; Barrett, 2021; Steenwerth et al., 2014). Indeed, although agricultural land use has recently peaked after centuries of expansion, the sustainable intensification of agriculture in industrialized nations has enabled marginal land to be taken out of production via implementation of national scale land abandonment policies with little impact on food production (Navas et al., 2017; Perpiña Castillo et al., 2020; Taylor & Rising, 2021; Xu et al., 2006). However, the majority of agricultural land globally is dominated by subsistence farming systems where the farmers experience extreme challenges due to a range of social, economic and environmental factors. Regions with complex geomorphology also precludes large-scale mechanization. To better accommodate surface process complexity and spatial heterogeneity we present a new modification (Figure 1b) of the original diagram by Chorover et al. (2007) to provide a more generic representation of the wide array of human-environment interactions that resonate through human-stressed landscapes and CZO networks, and pertains to the development of the 3rd Generation approach.

The relevance of 2nd Generation approach to the residents of CZOs is most impactful when it is communicated in a manner that resonates with local communities and supports their needs, helping create positive societal change toward more sustainable livelihoods. Establishing effective KE to share scientific findings in an appropriate way (Karcher et al., 2022) can support optimum human decision-making that meets the economic and social needs of local people by helping them to develop and sustain healthy and productive ecosystems (Yin et al., 2021). For example, in the USA, at the Calhoun CZO, reforested sites previously degraded by agriculture provide information about the potential for the recovery of degraded landscapes, including the specific effects of land use and potential regeneration on fertilizer (phosphorus) transport (Foroughi et al., 2021) and the impact on human livelihoods, adaptation and governance (White et al., 2015). At the Reynolds Creek CZO, dialogue with rangeland stakeholders including local ranchers is a key activity in the application of the outputs of CZS to develop prescribed fire management (McIver et al., 2010). Engagement with local farmers at the Integrated Managed Landscapes CZO in the USA has helped to address the potential to reverse a shift in state from a system that has become dominated by the rapid movement of resources from land to water, to a transformation-dominated system characterized by long residence times of water, carbon and nutrients (Kumar et al., 2018).

Table 1
Relationships Between Chinese Environmental Policy Actions and SDGs[a] Identified at the China Critical Zone Observatory (CZO) Network: (a) Assessment of Delivery of Key Ecosystem Benefits Using a 2nd Generation CZS Approach and (b) Parallel Impacts on the Residents of the China CZOs Using a 3rd Generation CZS Approach

National policy	(a) 2nd Generation CZS approach ecosystem benefits	SDG	(b) 3rd generation CZS approach meeting of human needs	SDG
Grain for Green				
Abandonment of low-yielding sloping farmland (>15°) prone to soil degradation by erosion	*Erosion prevention and maintenance of soil fertility* -Soil structure improves as soil macroaggregates form in regenerating land (M. Liu et al., 2019b)	15	*Stabilization of soil on slopes* -Reduced intensity of runoff and infiltration carrying carbo n, nutrients and pollution	2,6
			- Local adaptations already in place to improve resilience (i.e., abandonment due to demographics) and local measures to improve soil depth/ productivity (e.g., Figure 3c)	11
Allow recovery through natural vegetative regeneration (Li et al., 2018) or afforestation	*Increase and maintain biodiversity* Recolonization of abandoned farmland with diverse species adapted to local conditions (M. Liu et al., 2019a, 2019b; Y. Yang et al., 2022) - Restoration of biological soil function and biodiversity (Z. Guo et al., 2019) - Ecosystem functions persist in "hotspots" of microbial activity next to emergent rocks and at the bottom of the soil profile, even in severely degraded karst exhibiting "rocky desertification" (Y. Tang et al., 2021; Y. Wang et al., 2020).	15	- Local farmer implemented resilience measures (e.g., Figure 3c) improve agricultural productivity	1,2
			Local population faces major challenges from reduced labour availability and demographics (aging population) (Naylor et al., 2023b)	5,8,12
			- Establish/restore agroforestry	5,10
	Carbon sequestration and storage			
	- Massive pools of soil C measured in near surface (0–2 m, 5.85 Pg) and very deep (2–100 m, 10.06 Pg) soils of the Loess Plateau (Jia et al., 2020)	13		
	- Soil C stocks rebuild in the decades following sloping cropland abandonment in karst landscapes (Z. Guo et al., 2021)			
	- Soil C in Karst CZO concentrated in 0–20 cm depth; 10% is inorganic (Qin et al., 2022)			
	- Increase in stable microbial-derived SOC pool (necromass) (Z. Guo et al., 2021)			
Zero-Growth Action Plan for Chemical Fertilizers and Pesticides				
Improve nutrient use efficiency	*Nutrient cycling* Soil N and P explained 13.5% and 12.4% of crop yield variances, respectively, at the Karst CZO (Liang et al., 2020); high risk of environmental pollution prevents increasing crop yield through fertilization (Liang et al., 2021) - Shift from "leaky" to "tight" N-cycling processes (D. Li et al., 2018) - Re-emergence of microbial N-cycling functions in soil after agricultural abandonment (D. Li et al., 2018, 2021a)	15	Farmers in all CZs identified fertilisers as their greatest cost and one of the top three farming challenges they face (Zheng et al,. 2018, this paper) - Reduce N inputs to improve economic livelihoods and well-being	1,2
	- Judicious use of N with crop residue returns increases soil C (X. D. Song et al., 2019a; X. W. Song et al., 2019b)			
	- Reduce fertilizer use to increase crop yields (Liang et al., 2020, 2021)			
Reduce point-source pollution by reducing fertiliser use	*Freshwater supply and regulation of water flow* - Advanced geophysical mapping revealed heterogeneity (Chen et al., 2018) identified fast and slow flow regions (G. Zhang et al., 2019a; Z. C. Zhang et al., 2019b) affecting hydrological cycling, C and nutrient transport, and "hidden" legacy N posing a long-term pollution risk	14	Farmers in Karst and red Soil CZs identified water source availability and quality as a primary challenge (this paper)	3

Table 1
Continued

National policy	(a) 2nd Generation CZS approach ecosystem benefits	SDG	(b) 3rd generation CZS approach meeting of human needs	SDG
	- >90% of soil water stored >5 m depth; inherently fast hydraulic conductivity leads to transfer of N into the deep soil profile at Loess Plateau CZO (Y. J. Zhu et al., 2019a, 2019b) - 80% of >1 Tg N lost via subsurface flow at Karst CZO through epikarst (X. W. Song et al., 2017; X. D. Song et al., 2019a; X. W. Song et al., 2019b; Z. Wang et al., 2022) - < 80% of N (mostly NO_3; H. Wu et al., 2021) from 1 m—bedrock down to 9 m (S. H. Yang et al., 2020a) transported by fast leaching via shrinkage cracks (H. Wu et al., 2019) at Red Soil CZO - <50% of applied N (~100 kg N ha^{-1} $year^{-1}$) accumulated at 0–100 cm depth, posing a significant threat to the wider environment at Red Soil CZO (Dong et al., 2022) - Reduced nitrate pollution of surface- and groundwater (X. W. Song et al., 2017; S. H. Yang et al., 2020b) - Neglected stock (0.2–1.0 Pg) of N measured by deep sampling (50–200 m) at the Loess CZO modeled to reach aquifers more quickly under agricultural land use at regional scale (Turkeltaub et al., 2018)			
Encourage the use of organic fertilisers to replace synthetic fertilisers (Shuqin & Fang, 2018)	- *E. coli* indicators of faecal pathogens - *E. coli* in water (Oliver et al., 2020) from untreated faecal material (human and animal wastes; Buckerfield et al., 2020) transported to wider environment through deep, sub-surface pathways at the Karst CZO (Buckerfield et al., 2019b)	14	Farmers showed strong willingness to learn new sustainable farming practices to manage manure (Naylor et al., 2023b) - Farmers had limited training on how to manage manure wastes, to reduce pathogen and excess N inputs to water and soil	4
			- Raise awareness of potential for waterborne pathogens (Buckerfield et al., 2019a, 2019b, 2020) - Guidance and facilities to manage livestock manures for farmers, and sanitary measures, installing pit toilets in villages (Buckerfield, 2021) Clear routes for CZS to aid the delivery of SDGs relevant to those living in the studied catchments (Buckerfield et al., 2019b; Oliver et al., 2020)	3,11

[a]SGD definitions: SDG 1: No poverty; SDG 2: Zero hunger; SDG 3: Good health and well-being; SDG 4: Quality education; SDG 5: Gender equality; SDG 6: Clean water and sanitation; SDG 7: Affordable and clean energy; SDG 8: Decent work and economic growth; SDG 9: Industry, innovation and infrastructure; SDG 10: Reduced inequalities; SDG 11; Sustainable cities and communities; SDG 12: Responsible consumption and production; SDG 13: Climate Action; SDG 14: Life below water; SDG 15: Life on land; SDG 16: Peace, justice and strong institutions; SDG 17: Partnerships for the Goals.

1.3. Evolution of the 3rd Generation Transdisciplinary CZO for Sustainable Earth Futures

Engagement in 2nd Generation CZOs has been invaluable for sharing CZS outputs with agricultural communities, but this does not go far enough to achieve a holistic understanding of CZ function. Instead, we propose that such understanding requires that the evaluation of the effects of human-decision making on agricultural and environmental sustainability, from high-level and long-term policy management of national landscapes through to day-to-day plot-scale farmer decisions, is integrated into CZS.

The incorporation of local knowledge is essential to ensure that CZS is relevant to local communities and supports sustainable socio-economic development by improving ecosystem function in degraded landscapes (Yin et al., 2021). Reframing CZS in this way will help co-identify a spectrum of options to modify agricultural practice in ways that are culturally appropriate, context-specific and meet the most pressing social needs (Q. Zhang et al., 2015), thereby hastening the delivery of SDGs. These ideas prompted the development of 3rd Generation CZO approaches described herein that explicitly consider the effects of a wider range of human stressors and their impacts on the entire CZ, using the outputs of both social and biophysical scientific research in human-modified CZOs. Framing CZOs in this way and at this spatial scale also permits the identification of the range of actors (i.e., stakeholders) who live in and/or are directly affected by large-scale policy initiatives (e.g., to deliver sustainable agriculture and food security, and to mitigate climate change), by allowing the capture of local-scale human narratives related to CZ function that are typically overlooked in CZS (Latour, 2021). This opens opportunities for improved dialogue between CZ scientists and those who live in and understand their local landscape, allowing two-way exchange that can benefit CZS and local communities living in CZOs. In doing so, achievement of SDGs will be promoted, ultimately improving the resilience of social-ecological systems in degraded rural landscapes (see Section 3). This is particularly valuable where top-down policy approaches (e.g., national environmental restoration programmes such as China's "Grain for Green" program) deliver environmental benefits but are considered to have reduced local well-being and livelihoods by the local farming communities themselves (You et al., 2022).

Local-scale human decision-making, such as modifying the plot-scale landscape to sustain agricultural productivity, for example, terracing of steeply sloping fields, illustrates local creativity and resilience. However, poor farming decisions disrupt the balance between the inputs and outputs of water, carbon, nutrients and sediment in CZOs, which can change the state of CZ functions and further degrade ecosystem services that support human livelihoods (Green et al., 2019). Therefore, combining CZS with local knowledge has the potential to develop socio-culturally appropriate land management systems with the potential to improve livelihoods over the long term, by sustaining economic productivity and benefitting the environment. Thus, the integration of social science research into CZO scientific research programmes is a critical component of the 3rd Generation CZ approach, because it enables the capture of robust information about the opinions, practices, social dynamics and/or power relations of local people living and working in CZOs. Latour (2021, pp. 14) contends that "each critical zone offers a smaller but just as complicated scaled model of the question as to how living organisms elaborate their own environment and hold it together". This perspective offers a missing facet to CZS and its value to promote cross-disciplinarity and wider public conversations on human-landscape interactions in the Anthropocene (Latour, 2014). In this paper, we present what we have learned by applying this 3rd Generation CZO approach in the China-UK CZO program as a case study to illustrate its value and application.

2. The China-UK CZO Network: Demonstrating a Shift From a 2nd to a 3rd Generation CZO Approach

Large-scale modification of land for farming has affected landscapes in China for millennia, including long-standing practices to support paddy rice production by terracing slopes or flooding. Through these local-scale human interventions, people in China have attempted to manipulate CZ processes for economic and societal gain, but not without environmental impacts (H. Zhao et al., 2021). Driven by rapid economic expansion and historic population growth, much of the 500 Mha of China's agricultural land is severely degraded by intensive agricultural production (FAO, 2020). Consequently, bold national scale policy had been implemented to restore degraded ecosystems in China through a series of environmental restoration programmes (see Q. Zhang et al., 2015 for a chronology). For example, the regional "Grain for Green" program was initiated in 1999 to control erosion and increase vegetation cover, and is the largest ecological restoration project in central and western China (Persson et al., 2013; X. Song et al., 2014). More recently, China's national "Zero-Growth Action Plan for Chemical Fertilizers and Pesticides" was implemented in 2015 (Ding et al., 2022; Shuqin & Fang, 2018) to rationalize historic overuse of synthetic fertilizers, and to substantially increase the recycling of organic fertilizers, including livestock manures, to farmlands from 2020 onwards (Buckerfield et al., 2019a).

Understanding the impact of national land-use policy on CZ function is essential to provide feedback on its goal-framing and implementation. Thus, the China-UK CZO network was established with these policy goals in mind and was designed to determine the effectiveness of recommended changes to agricultural practice to remediate the impacts of land degradation in fragile ecosystems. The collection of CZOs provided diverse environments due to both their inherent properties (1st Generation CZO approach) and the anthropogenic modification of these properties (2nd Generation CZO approach). All sites had severely degraded landscapes with active restoration programmes in place. Underpinning the human-landscape interactions were differences in geology, climate, hydrology and soil properties between the CZOs (Section 2.1). Using a 2nd Generation CZS approach, the network aided the evaluation of the effectiveness of national environmental policies in delivering benefits for CZ function in the studied CZOs, provided key outputs of 2nd Generation CZS for key environmental policy objectives, and evaluated their implementation using measurable changes in CZ functions (Section 2.2, Table 1a). It also aimed to use the results to inform improved farm management and related policy development via KE and to support delivery of SDGs using a 3rd Generation CZS approach (Table 1b). In Section 2.3, we introduce and present findings from our KE research, which combined conventional CZS with social science using a 3rd Generation CZS approach.

2.1. China-UK CZO Sites and Characteristics

The China-UK CZO network encompassed four of the major contrasting geomorphological regions of China where land use is predominantly intensive agriculture (Figure 2a, inset) (G. L. Zhang et al., 2021). Four sites located in vulnerable landscapes were selected to allow targeted hypotheses to be tested about the impacts of farming of the land surface on deeper subsurface geological properties and biogeochemical processes in the context of national land management policy.

- The Sunjia catchment that formed the Red Soil CZO (S. H. Yang et al., 2020a) had multiple land uses in a single area, ranging from different cropping practices to semi-natural land. Here, some of China's most weathered soils had developed in the subtropical climate (Tahir et al., 2016).
- The Loess Plateau CZO featured China's deepest soils, formed from the deposition of wind-blown soils (Jin et al., 2018), and consisted of a longitudinal series of monitoring sites rather than a single observatory subcatchment (Jia et al., 2020). This larger scale, multi-catchment approach facilitated a regional understanding that encompassed spatial variations in landscape properties and land management.
- The Zhangxi catchment at Ningbo that formed the Peri-Urban CZO incorporated more fertile soils, but the landscape was recently strongly modified by human interventions (Y. G. Zhu et al., 2017). It was the most urbanized landscape studied, incorporating different established land uses; field experiments investigating the effects of increased organic fertilizer loadings were carried out here (J. F. Tang et al., 2020; Y. G. Zhu et al., 2017).
- The Houzhai catchment that formed the Karst CZO (Qin et al., 2022) encompassed China's shallowest soils, formed over limestone containing cavernous channels (H. Liu et al., 2019c).

2.2. 2nd Generation CZS and Key Outputs to Policymakers

The 2nd Generation CZ approach applied in the Chinese CZO network revealed the consequences of unsustainable land management on soil and water quality that are ubiquitous to intensive agriculture scenarios across the world, that is, (a) soil erosion (B. Liu et al., 2020; X. Wang et al., 2016) and loss of soil organic carbon (G. H. Song et al., 2005), (b) overuse of nitrogen fertilizers (Gu et al., 2015), and water pollution by (c) nutrients and (d) pathogens (Sun et al., 2018; Tao et al., 2005). The key 2nd Generation CZO outputs are summarized in Table 1a, and were disseminated using a commissioned "art-science" approach as on-line animations in Chinese (https://www.youtube.com/watch?v=Y2ILx25nx4A) and English (https://www.youtube.com/watch?v=DcAmNUtZC04).

Strong scientific evidence for the potential for positive changes in land use in the studied CZOs was provided for policymakers that could lead to better informed recommendations to manage and accelerate ecosystem regeneration (e.g., D. Li et al., 2021a, 2021b). For example, considering the CZS outputs across the China-UK network, Table 1 suggests that the Grain to Green land abandonment policies were having positive effects on key indicators of soil restoration, including increased soil organic carbon and improved soil structure (Z. Guo et al., 2021; M. Liu et al., 2019a, 2019b) and soil microbial function (Z. Guo et al., 2019; D. Li et al., 2018) (Table 1a). This demonstrated that innovative CZS approaches can advance our scientific understanding of environmental processes with global significance (e.g., deep soil coring in the Loess Plateau, and combined soil and water research in the Karst CZO), and usefully assess the impacts of national environmental policies related to agricultural practices on CZ ecosystem function (Table 1a). Novel insights into CZ functions with a large global impact were a common theme

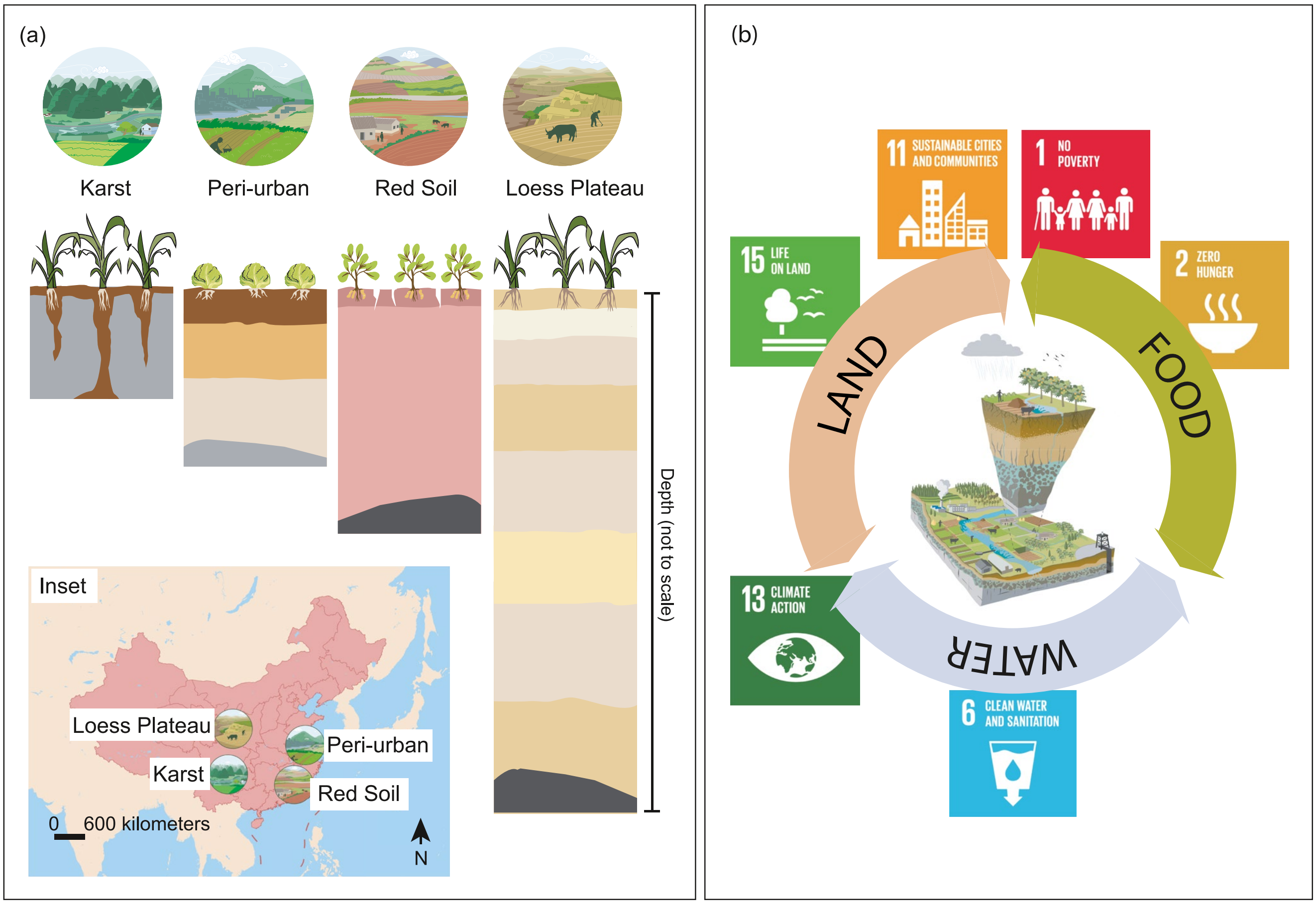

Figure 2. (a) Contrasting geomorphologies at each CZO: Karst (Houzhai catchment, Puding County, Guizhou province) which are China's shallowest soils formed over carbonate rich limestone, Peri-Urban (Zhangxi catchment, Yangtze delta, Eastern China) with more fertile soils formed from river alluvium in heavily human-modified landscapes; Red Soil (Sunjia catchment, Yujiang County, Jiangxi province) which are China's most weathered soils derived from weathered sandstone; and Loess Plateau (Changwu catchment in Shaanxi province) which are China's deepest soils, formed from the deposition of wind-blown soils. Inset: locations of four sites of the China-UK Critical Zone Observatory (CZO) Network. (b) The relationship of the four CZOs, the Land-Water-Food Nexus and six UN Sustainable Development Goals [SDG 1, No poverty; SDG 2, Zero hunger; SDG 6, Clean water and sanitation; SDG 11, Sustainable cities and communities; SDG 13, Climate action; SDG 15, Life on land].

between the research outputs of the Chinese CZOs and provided feedback on the effectiveness of regional to national scale environmental policies. Set in the context of national restoration projects (i.e., Zero-Growth Action Plan for Chemical Fertilizers and Pesticides, and Grain for Green programme), this also provided feedback on the impacts of changing management (Table 1a). Overall, the 2nd Generation CZS provided valuable insights into the biophysical effects of existing and recent shifts in land use due to top-down policy changes in the Chinese CZO network. However, this approach cannot elucidate the impacts of policy implementation on the lived inhabitants of the CZOs, or show how the inhabitants' understanding of their environment impacts the CZ and ultimately informs the specific management actions they need take to sustain and improve their livelihoods.

2.3. Development of a 3rd Generation Transdisciplinary CZO Approach

The China-UK CZO program allocated resources to KE and impact research activities across the four studied CZOs (Figure 2; Zheng et al., 2018) in tandem with the conventional CZS approach (Section 2.2). This allowed feedback to policy stakeholders on the consequences of national restoration projects (Table 1a; Zheng et al., 2018) and human activities (Figure 1b) for CZ function. Before KE activities could be designed and implemented for the four projects, KE research was carried out to provide complementary information about the influence of human decision making on CZ function at both high level (policy and practices encouraged by government) and local scale (human behaviour and dynamics, e.g., demographics, power relations, social capital, farming methods used). Incorporating local knowledge into regional scale policy planning is essential because local-scale human behaviours in rural CZOs are largely driven by economic imperatives focussed on sustaining subsistence livelihoods in stressed, degraded environments (Y. Liu et al., 2017), and local community engagement with restoration programmes is likely to increase (Q. Zhang et al., 2015). We adopted a CZS approach (after Field et al., 2016) which incorporated parallel research into human behaviours and local knowledge, combining KE practice and social research methodology. The knowledge and concerns of smallholder farmers in the CZOs were sought to facilitate links between CZ scientists, their outputs and the key environmental and economic pressures experienced by rural residents of the CZOs. Knowledge was gained about how local people are affected directly by the changing environment, whether policy recommendations would be understood and implemented by farmers, and the potential impact on local livelihoods (e.g., You et al., 2022).

As described above, 2nd Generation CZOs focus on assessing the impacts of land use, including agriculture, on CZ function. However, large-scale changes in land use arising from top-down policy decisions, such as the complete abandonment of farming in the Green for Grain programme, are not described by the effects of local-scale, farmer-community scale activities on mediating CZ function. However, a transdisciplinary approach (i.e., natural and social sciences researchers, alongside practitioners and local farming communities; Field et al., 2016) can provide novel insights into the integral roles of local human behaviour in CZ processes that facilitate the understanding of ecosystem states in stressed and degraded human-modified environmental systems. Understanding these motivations is critical to supplement CZS outputs communicated to policymakers who require feedback to understand progress toward national targets for sustainable rural communities, food security, and high air and water quality (J. Liu et al., 2021). Perhaps more importantly, inviting local populations to share their understanding of place within the CZO using a 3rd Generation CZ approach can create spaces of enquiry where transformative, socially and ecologically impactful research and KE outcomes can emerge. Thus, in one of the four CZ projects, KE activities were designed to run concurrently with the biophysical CZS during the project rather than the conventional approach of performing KE as a means of sharing outcomes at the end of the project. The CZS team quickly recognized that research was needed to better understand the human behaviour elements of the social-ecological system (Ostrom, 2009) to devise policies and KE strategies best suited to the local social context (Karcher et al., 2022; Q. Zhang et al., 2015). The KE research process would, at the same time, help build relationships and trust which are known to underpin successful KE (Karcher et al., 2022; Reed et al., 2014). The research reported in this paper was carried out using established social science survey methods (Section 2.3.1; e.g., as used by Oliver et al., 2020; Naylor et al., 2023a) and produced KE outputs (e.g., Zheng et al., 2018) that were delivered to local government (county to village level) prior to COVID-19. (The restrictions during the pandemic prevented more widespread sharing and two-way KE in 2020 and 2021.)

2.3.1. Knowledge Exchange (KE) Research Design

Phase 1 of KE research in the China-UK CZO program was carried out in the Karst CZO, one of the poorest regions of China (Figure 2a) where underlying physical geography, resource scarcity, ecosystem degradation and population pressures are key drivers of poverty (Buckerfield et al., 2019a; Y. Liu et al., 2017). This was extended to the Red Soil CZO and Loess Plateau CZO (Figure 2a) allowing comparison between regions. Formal data collection was conducted between researchers and smallholder farmers, and village, town and county leaders, with the support of Chinese students from farming families (for full methods and details see Naylor et al., 2023b; Oliver et al., 2020). The knowledge, opinions and aspirations of CZ residents and information about the challenges they faced, and from who and how they learned, were gathered using a mixed method approach combining primary semi-structured interviews and questionnaire surveys (Naylor et al., 2023a; Oliver et al., 2020; Zheng et al., 2019b; all the data is held in freely accessible depositories). The survey questions were based on knowledge gaps arising from major CZS themes, that is, soil erosion and carbon, nitrogen cycling and water quality, to align with CZ scientific objectives. Importantly, this activity motivated biophysical CZ researchers to consider the importance of human residents' experiences of living in CZOs as major contributors to CZ processes. The questions included: (a) how CZ residents understood human impacts on the environment (this paper); (b) the greatest pressures on farmers' livelihoods (e.g., Oliver et al., 2020); (c) experiences of sustainable farming practices (e.g., Buckerfield et al., 2019a), including social processes of learning, learning preferences and barriers to learning new farming practices (Naylor et al., 2023b; Zheng et al., 2019a); and (d) management strategies to support crop yields in increasingly degraded ecosystems. Crucially, and rather unexpectedly, these two-way interactions between CZ researchers and farmers also aided the interpretation of CZS outputs (Section 2.3.2), showing the value of including local knowledge in nature-based systems (Welden et al., 2021) and sustainability-oriented

CZ research (Norström et al., 2020). The shift in understanding engendered by this research informed Figure 1b illustrating a range of human activities and impacts in human-stressed environments that dominate terrestrial landscapes worldwide.

2.3.2. Knowledge Exchange Research Findings

Exploitation of CZS in the context of local communities' experience could promote resilience in social-ecological systems, and identify local-scale, bottom-up mechanisms that can improve delivery of both environmental and human-centered SDGs. In this section, we describe the results from our KE research on the awareness of human impacts on the environment and the key pressures and challenges CZ residents face in their day-to-day lives. We incorporated social science research methods as "knowledge exchange research" to more closely align the CZS goals to local livelihoods and SDGs as part of a developing 3rd generation CZO approach. By changing the perspective of the CZ study to encompass social science methods, clear routes for CZS to aid the delivery of SDGs relevant to those living in the studied catchments (Buckerfield et al., 2019b; Oliver et al., 2020) were identified, providing a human context to the national environmental restoration programmes.

The KE research in the China-UK program revealed that dialogue with people living and farming within the CZOs could benefit scientists by helping them to better understand their data, and pointed to direct action to accelerate toward policy objectives to achieve resilience using a combination of physical and social science data. Below, we provide specific examples to illustrate how (a) gathering knowledge on human behaviour can improve scientists' understanding of local farmers' needs and their environmental understanding; (b) interpretation of CZS in messy, human-modified CZOs (Figure 1b) was enhanced by using the experience gained from CZS research; and (c) local scale management actions could directly improve local livelihoods and make progress toward both environmental and human-centred SDGs using CZS outputs. This approach allows human-nature/landscape interactions to be at the heart of understanding how CZs function (Welden et al., 2021). In doing so, it showed the power of human ingenuity including resilience measures already employed to sustain livelihoods in the studied CZOs and how this in turn can help interpret CZS data. These actions, especially if also supported financially (You et al., 2022), can accelerate delivery of environmental, but also human-centered SDGs (Table 1b).

2.3.2.1. Local Farmers' Pressures, Perceptions and Understanding of Human-Environment Interactions

Poor farming decisions can promote land degradation and reduce water quality with negative consequences for livelihoods in regions where farmers already suffer from poverty (Oliver et al., 2020). Overall, the KE research revealed that local farmer understanding of human impacts on the wider environment in three CZOs (Karst, Red Soil, and Loess Plateau) was sparse and varied significantly between regions (chi square test, $p < 0.001$, $\varphi c = 0.37$). Farmers were asked, "Do you think any of the farm activities (e.g., tillage, fertilizer, or chemical use) you do on your land affect other farmland nearby?". Most farmers in the Loess Plateau CZO and Red Soil CZO did not recognize any risk, whereas a small proportion of farmers in the Karst CZO recognized potential risk. Here, farmers had a generally limited and spatially variable understanding of human impacts on their local environment, or of the value of the natural environment for their well-being. Notable exceptions were observed phenomena that directly affected subsistence livelihoods, for example, flooding and droughts, soil erosion (see Sections 2.3.2 and 2.3.2.2, below), landslides and wildfire (Oliver et al., 2020). Further surveys of 478 farmers in the Karst CZO, Red Soil CZO and Loess Plateau CZO revealed that labour, fertilizer costs and water availability were the greatest perceived challenges for all surveyed across the three regions (Zheng et al., 2018).

2.3.2.2. How Local Knowledge Improved Interpretation of CZS Data on Soil Erosion

CZS had revealed the negative consequences of poorly managed tillage on steeply sloping fields for the environment (Green et al., 2019; Quine et al., 2017; Zheng et al., 2018) and farmer livelihoods (M. Liu et al., 2019a; X. D. Song et al., 2019a; X. W. Song et al., 2019b) (Figure 3a). The Grain for Green programme promoted the abandonment of very degraded, sloping agricultural land and natural recolonization by diverse species (M. Liu et al., 2019a, 2019b; Y. Yang et al., 2022), or change to conservation management (X. D. Song et al., 2019a; X. W. Song et al., 2019b). Both land use changes led to reduced erosion rates and restored soil organic carbon (Z. Guo et al., 2021) and were associated with improvements in soil structure (M. Liu et al., 2019b) (Table 1a).

Application of KE research with farmers in the Karst, Red Soil, and Loess Plateau regions of China revealed their interest in learning about soil erosion, which varied between CZO and was strongest in the Karst region where all farmers were interested ($p < 0.001$, $\varphi_c = 0.32$). From a biophysical perspective, the legacy of soil erosion and loss from the steeply sloping fields was investigated using ^{137}Cs activity in soil samples taken in soil profiles from the surface to the bedrock (Quine et al., 2017) (Figure 3b). On these inherently shallow soils, severe erosion of topsoil was evident that was caused by the removal of natural vegetation followed by repeated tillage of soils for food production. In the Karst region, soil washing from sloping fields during rainstorms had been witnessed by the farmers living in Puding village in the Chenqi catchment and described to the CZS team by the village leader in June 2016. The village leader said that farmers had taken remedial action to preserve the soil resource, including blocking pathways of soil loss between emergent rocks and physically moving eroded soil upslope into rockbound terraces (see Figure 3c above). This direct farmer-scientist interaction provided vital information that facilitated the interpretation of ^{137}Cs data from soil profiles, indicating burial of eroded topsoil in abandoned farmland affected by rocky desertification (Figures 3a and 3b). Thus, local, farmer-led land management practices to maintain agricultural capacity in degraded landscapes explained the ^{137}Cs data, elegantly illustrating the capacity of local farmers to innovate in the face of environmental challenges, and why local knowledge of the environment and human modifications (i.e., the context and pluralistic knowledge described in Norström et al. (2020)) within it may be vital for interpreting apparent data anomalies in human-modified CZOs. Using an arts-science approach, a "comic strip" was developed to illustrate this example of positive interaction and knowledge co-production between farmers and CZ scientists (Figure 3c). This easily accessible format as a KE tool for both CZ scientists and farmers creates a readily understandable human-scale narrative (sensu Latour, 2021) that makes explicit the value of place-based local knowledge in environmental science (Welden et al., 2021). Feeding back the benefits of data "co-production" between scientists and farmers to both parties in forms that transcend language barriers is essential to exchange knowledge and engender trust (Fazey et al., 2014). This example also emphasizes the crucial role local/tacit knowledge can play (Welden et al., 2021) in interpretation of scientific findings in human-modified landscapes.

2.3.2.3. Potential Benefits of Land Use Change to Agroforestry for Local Population and Environment

CZS investigation of the biological processes in the Karst soils under the Grain for Green programme suggested that the existing policy of abrupt abandonment of agricultural management was not an optimal approach to regenerate soil functions (e.g., Z. Guo et al., 2019; D. Li et al., 2018). Instead, it revealed that active management of nutrients (nitrogen and phosphorus) can accelerate landscape restoration to secondary forest, with benefits including carbon sequestration (Z. Guo et al., 2021; D. Li et al., 2021a; Xue et al., 2020). The pursuit of forest regeneration for the improvement of ecosystem services is appropriate where trees are uniquely adapted to environmental conditions in the Karst environment, that is, deep-rooting, H. J. Li et al., 2019 and mycorrhizal associations (Y. Yang et al., 2022). These CZS findings are serendipitous as bringing suitable trees into cultivation, as part of agroforestry or silvopastoral systems, could provide both environmental and economic benefits, and better suit the local aging demographics.

Challenges in securing on-farm labour were associated statistically with the Karst CZO (and Loess Plateau CZO) ($p < 0.001$, $\varphi_c = 0.26$) and perceived as the biggest challenge to farming. KE research also revealed that the aging demographic of the local community was not suited to the physical demands of farming on steep slopes: more than 80% of farmers in Karst CZO were 40+ years, half of those were 60+ years, and 70% were female (Oliver et al., 2020) (with similar demographic profiles for Red Soil CZO and Loess Plateau CZO; Naylor et al., 2023b). Local farmers at Chenqi suggested that re-establishment of traditional fruit orchards (M. Zhao et al., 2010) would be appropriate for older people. Therefore, a renewed shift toward less intensive agroforestry on steeply sloping farmland could help address local labour shortages, suit demographic trends and thus help improve local livelihoods, whilst at the same time achieving top-down policy goals to improve the resilience of fragile sloping karst environments through ecologically sensitive local management (Table 1b). Thus, feedback to policymakers can be augmented: afforestation for food and fibre production (agroforestry) including judicious nutrient management, rather than uncontrolled recolonization, can continue to provide income for rural populations, and is appropriate to the demographic challenges in rural areas, i.e., an aging population, and deliver ecosystem benefits for soil regeneration.

2.3.2.4. Mutual Benefits From Synthetic Nitrogen Fertilizer Reduction for Farmers and Environment

Fertilizer was the most expensive operational cost for 77% of Karst farmers, 88% of Red Soil farmers and 95% of Loess Plateau farmers in China, creating a primary pressure for farmers and an obstacle to sustainable land management (e.g., Buckerfield et al., 2019a). In tandem, CZS data clearly identified negative impacts of excess

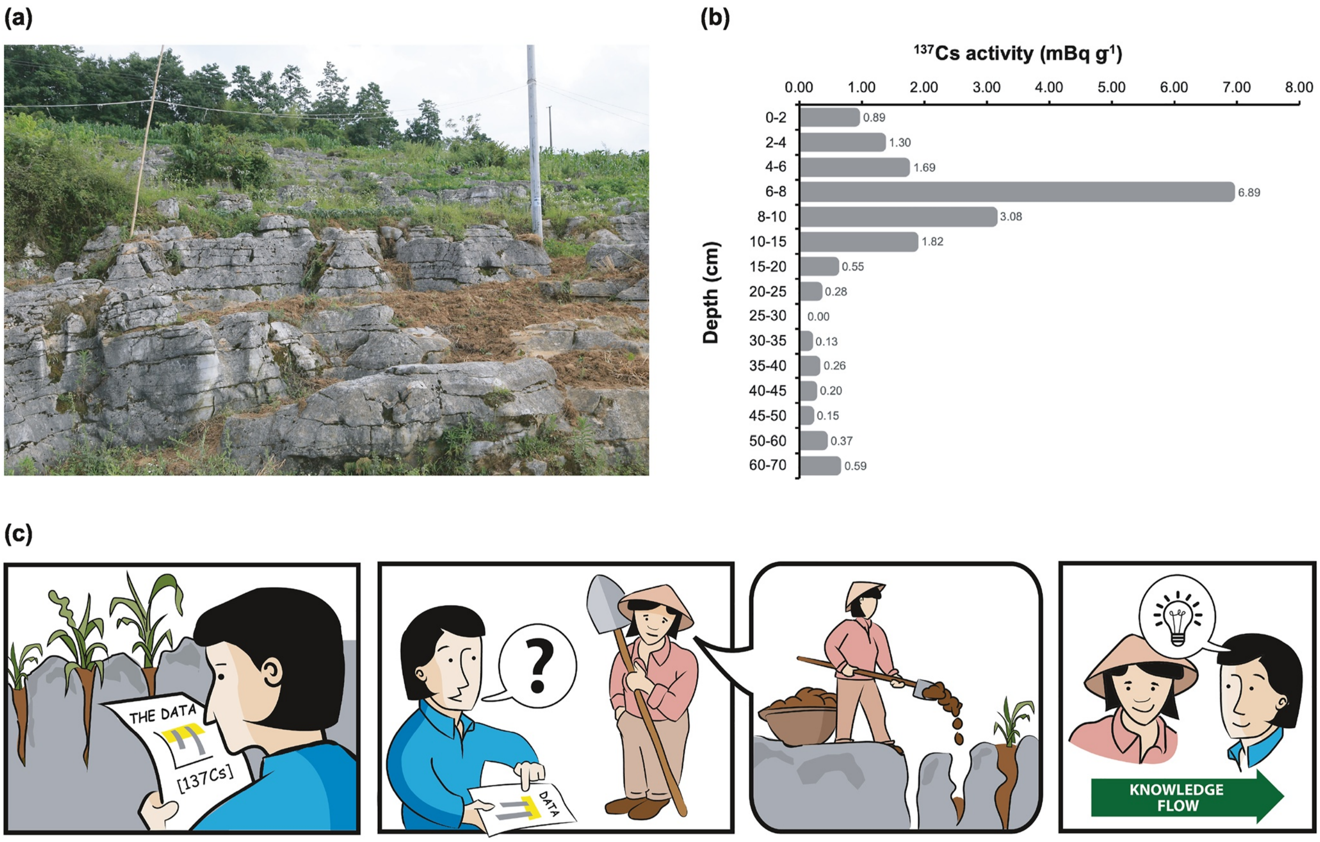

Figure 3. (a) Photographs of land suffering from severe soil loss and "rocky desertification" at the Karst CZO (credit: Tim Quine). (b) ^{137}Cs inventories measured in soil profiles from abandoned farmland at the Chinese Karst CZO indicating buried, eroded topsoil. (c) "Comic strip" created to show benefits of data co-production and knowledge exchange between scientists and farmers, where local knowledge and local farming practices to manage soil loss and conserve eroded soil resources was crucial to interpret CZS results which did not conform to typical profiles from mechanized agricultural landscapes.

inorganic fertilizer use by farmers, (e.g., water pollution by leached nitrates; Gu et al., 2015; Tao et al., 2005; see also details about the magnitude and threats of excess nitrogen in each CZO in Sections 2.2.2–2.2.3 above) creating a point of synergy between economic pressure faced by farmers, a top-down environmental restoration policy goal and CZS (Qin et al., 2020; X. W. Song et al., 2017; H. Wu et al., 2019, 2021; S. H. Yang et al., 2020b; Z. Zhang et al., 2020). Working more closely with local farmers to reduce nitrogen fertilizer loadings through KE activities (e.g., to monitor and reduce reactive nitrogen loading from inorganic and organic fertilizers; Sutton et al., 2013) raises the potential for direct benefits for local livelihoods (by reducing the expensive outlay on synthetic fertilizers) whilst at the same time reducing the threat identified by the overuse of nitrogen fertilizers for CZ functions, thereby hastening the achievement of key policy objectives of the Zero-Growth Action Plan for Chemical Fertilizers and Pesticides (Cui et al., 2018; Shuqin & Fang, 2018) and SDG 6 (Figure 2b).

2.3.2.5. Hidden Risks of Increased Use of Organic Fertilizers for Water Quality

The recycling of nutrients in organic manures back to land is tenet of sustainable farming practice, which has increased soil organic carbon and crop yields in farmed soils of north China in recent decades (Z. Zhang et al., 2011). The use of animal waste management practice is, therefore, advocated as a solution to relieve economic pressure on farmer livelihoods and achieve key policy objectives of the Zero-Growth Action Plan for Chemical Fertilizers and Pesticides (Y. Wang et al., 2018; T. Zhang et al., 2022; Table 1), specifically via the related national Action Plan for Organic-Substitute-Chemical-Fertilizer (OSCF) for Fruits, Vegetables and Tea (OSCF Policy) (Yi et al., 2021). The shift in policy to reduce synthetic nitrogen fertilizer use creates new risks from diffuse pollution in run-off from manure-treated soils that may present risks for human and environmental health. Poor water quality caused by farming practices based on inadequate evidence or guidance on best practice

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has negative consequences for livelihoods in regions of China where farmers already suffer from poverty (Oliver et al., 2020).

The established China CZO network plus a flexible funding approach provided an opportunity to investigate the hydrological pathways of faecal indicator organisms (*Escherichia coli*) during monsoonal rainfall to elucidate links between human activities and impacts on receiving waters. This targeted project benefitted from the existing wider instrumental set-up and derived data at the CZOs but studied the CZ in a novel way. It identified that *E. coli* from untreated faecal material were transported to the wider environment through deep, sub-surface pathways at the Karst CZO (Buckerfield et al., 2019b) (Table 1a). *E. coli* loadings in water generated from human use of the landscape varied by land use (Figure 4), and the dominant pollutant stressor and risk of faecal pollution in receiving waters was determined as poorly managed human wastes, followed by livestock manure inputs (Buckerfield et al., 2020). Using this example of risks of water pollution, we conclude that the scientific hypotheses tested by 2nd Generation CZS that was driven by the higher-level priorities of policymakers could not address local community needs directly within the CZ, including as a consequence of policy implementation, nor address multi-sector or multi-agency changes: 3rd Generation CZOs are needed for this purpose.

Our KE research revealed that only 40% of 312 surveyed farmers in the Karst CZO were aware of contaminant risks from nitrogen or pathogens in manures for water supplies. Manure management arrangements aligned with contaminant awareness. Less than half of farmers surveyed in the Karst CZO had any infrastructure to contain stored manures, with most manures stored as field heaps increasing the potential for mobilization of faecal pollutants following rainfall events (Buckerfield et al., 2019b; Oliver et al., 2020). However, the farmers identified a general lack of resources (labour shortages and materials availability) combined with high poverty rates as critical obstacles to increasing farm productivity, which likely includes the capacity to develop on-farm systems for optimum manure management.

CZS monitoring of the impacts of changing fertilizer management could assist with the implementation of policy to improve human and environmental health outcomes. Complementary KE research provided understanding of how farmers manage manure wastes, prefer to learn, and the training provision needed to improve manure management. Surveys of farmers at the Karst CZO, Red Soil CZO and Loess Plateau CZOs recorded a strong and significant association ($p < 0.001$, $\varphi_c = 0.17$) between region and the likelihood of completion of manure/fertiliser management plans by farmers. Regions with policy that encouraged farmers to complete a plan clearly differentiated from those that did not, that is, Red Soil CZO. Whilst at the Karst CZO, fewer than 50% of farmers had completed a manure management plan in six villages surveyed (Oliver et al., 2020; see Section 2.3.2.5). Interviews with village leaders also illustrated spatial variations in development of more advanced manure management mechanisms (e.g., biodigesters; Table 1), further highlighting how understanding local practices can both inform the interpretation of CZO science (e.g., the measurement of faecal indicator organisms from organic manures in waterways; Figure 3), and feedback to policy about education, training and financial support pathways that incorporate local knowledge in the design of actions to improve agricultural sustainability.

The example in Section 2.3.2.5 illustrates well how CZS informed by KE research led to enhanced identification of recommendations for prioritization of policy and practical actions (e.g., provision of training, financial support and facilities to manage livestock manures for farmers), and sanitary measures in villages such as installing pit toilets (Buckerfield, 2021). It also illustrates how multi-land use studies can help identify multiple policy routes (e.g., public health, agriculture and ecosystems/CZ function) to improve outcomes for society and the environment (Buckerfield, 2021). We recommend that future CZ approaches considering source apportionment of key pollutants should use a combined multiple land management hypothesis-driven sampling frame (Figure 3) across multiple landscape types in CZOs (Granados Aguilar et al., 2020), so that spatial and/or temporal variations in human activity to manage inputs to the environment (e.g., manure management methods) can be measured and their effectiveness evaluated via reflective practices (Dunkley & Franklin, 2017). Similarly, CZS sampling designs can be usefully informed by local/tacit knowledge, such as measuring the effects of adaptations to farming practices to maintain production in degraded landscapes described in Section 2.3.2 on CZ function, and crucially using social science research to assess the impacts on the livelihoods of farmers and their communities.

2.3.3. Benefits of Farmer-Scientist Interactions in CZOs

Interdisciplinary, multi-sector science-policy-practice solutions are needed to support policy and governance frameworks that use CZS to achieve SDGs by providing a multi-faceted understanding of the response of CZ

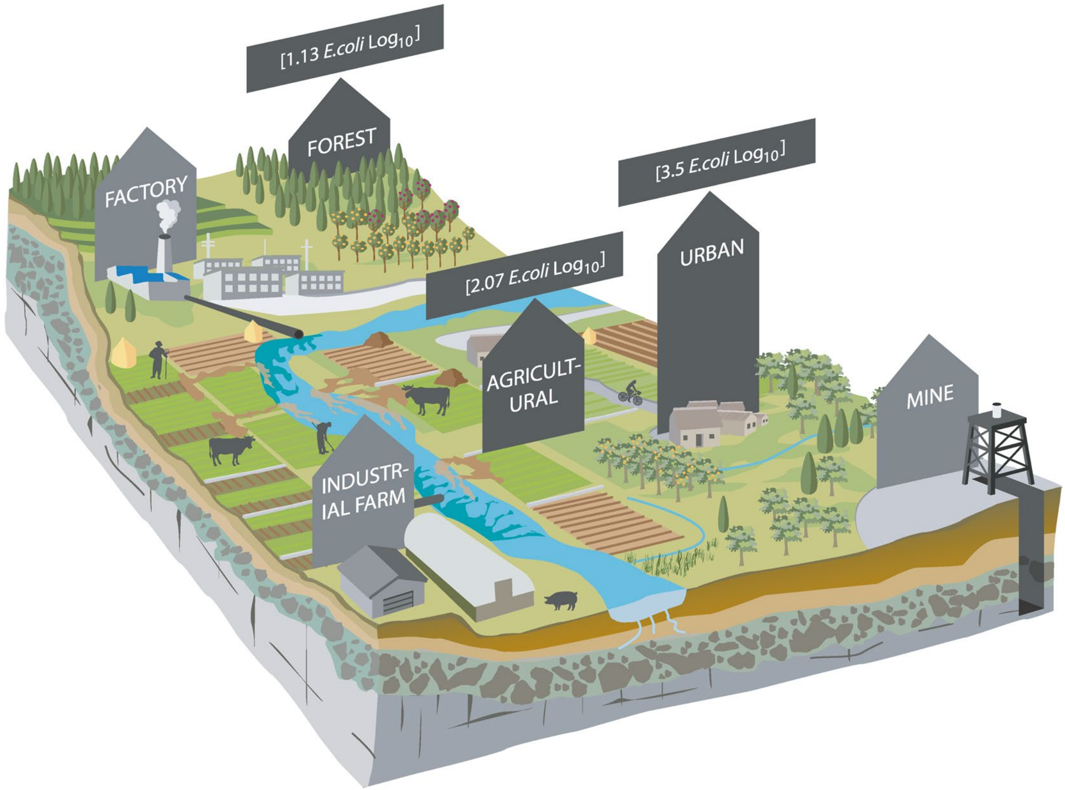

Figure 4. Annotated version of the transdisciplinary Critical Zone Observatory for sustainable Earth futures diagram to illustrate the effects of multiple human impacts on the environment, using the example (dark grey labels) of the measured impacts of manure management on faecal pollution and water quality using counts of faecal indicator organisms (*E. coli*; numbers in the figure represent concentration with units of CFU/100 mL). Light grey labels denote other likely sources of pollutants into the CZ.

processes to managed change. The 3rd Generation CZ approach described above created opportunities for CZS data co-production and co-learning situated in a social-ecological system context that allowed for pluralistic (i.e., combined local and scientific knowledge of a place) and interactive knowledge (Norström et al., 2020). Eagerness to learn and develop connections between CZ scientists and farmers in the CZOs (Oliver et al., 2020; Zheng et al., 2018) could further accelerate the achievement of national and global policy objectives (Figure 3), as previously recognized in China, for example, the Science and Technology Backyard platform (Jiao et al., 2019).

Previously, Banwart et al. (2012) used the Drivers-Pressures-State-Impact-Response (DPSIR) framework to assess trade-offs between policy and soil management interventions in European CZs in the SoilTrec project. Musche et al. (2019) developed this approach, recommending that whole-systems approaches were needed to address the complexity of biotic, abiotic and socio-economic issues that affect CZs. Stakeholder engagement in socio-ecological research that encompassed synthetic, network-based and transdisciplinary approaches to address emerging ecosystem services and social-ecological systems research themes was emphasized. Integral to the proposed 3rd Generation CZS approach, the incorporation of local community knowledge in informing the DPSIR "Pressures" and "Response" components was intended to improve the quality of social-ecological systems to achieve SDGs through the development of co-designed multi-scale, multi-sector policy and management interventions. For example, scientifically sound and evidence-based technologies combined with building trust, participatory innovation, developing human capacity and strengthening the coherence of farming communities are necessary to promote the changes in farmer behaviour required to achieve reductions in nitrogen use across China (Cui et al., 2018). The work on water quality in the Chinese CZO network (Sections 2.3.2 and 2.3.2.5) is also a case in point. Without KE, the "Driver" focus for CZS in the CZOs, that is, agriculture, would have ignored a dominant "Impact" on water quality: the potential contamination of deep hydrological pathways by human waste in rural communities (Buckerfield et al., 2020). This approach exemplifies the integration of CZS outcomes

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across earth science disciplines: faecal indicator organisms (*E. coli*) are microfauna which are part of the carbon cycle ("State"), and high *E. coli* loadings in receiving waters ("State") adversely affect water quality ("Impact") as a potential consequence of managing the nitrogen cycle ("Driver"/"Pressure") in agricultural and human settings. Our findings provide further evidence of how a combined science and social-science approach can help inform sustainable implementation of policy shifts (e.g., toward organic fertilizers) to avoid maladaptation (i.e., lack of context-suitable training, awareness, and funding for organic waste management practices) and improve the "State" of social-ecological livelihoods in CZOs.

3. Conclusions and Recommendations

Adopting a transdisciplinary CZO for sustainable Earth futures (3rd generation) approach to agricultural or other heavily human modified landscapes (summarized in the updated CZO model in Figures 1b and 3) as part of funding calls and at the project design stage should allow identification of people-centred recommendations that are initiated by new dialogues, training and co-produced research initiatives. Further, the outputs of 3rd Generation transdisciplinary CZO programmes for sustainable Earth futures that integrate CZS, social science and draw on local knowledge experience should be precursors to the development of fit-for-purpose national policy and locally tailored actions that improve local livelihoods in social-ecological systems, such as increased use of nature-based solutions. Ultimately, the successful implementation of national policy requires both high level (e.g., decision support tools (DSTs)) policy implementation support tools and local scale actions that are co-designed with local actors (i.e., practitioners, such as smallholder farmers in the China CZOs) to develop the necessary behaviours and changes in practice that will only propagate and persist if the local impact of high-level policy goals is positive. Based on our experience accumulated during the China-UK CZO program, we make the following four recommendations:

1. *Precursor activity to CZO project design and implementation*.
   We recommend that future CZS 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. Preassessment of local community pressures, needs and potential local-scale social context and responses, as well as their learning experiences and preferences (Naylor et al., 2023b) is recommended in advance of CZO establishment to 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 (Table 1).
2. *Incorporate local knowledge, human activity and social context into the design of CZS*.
   We recommend that future CZS programmes should draw on local expertise and practice to co-design CZS questions and use this knowledge to help interpret CZS findings. Practitioner-to-scientist KE (e.g., with farmers, industry, water suppliers and/or energy companies) 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 (W. 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 (B. Wu & Pretty, 2004; Naylor et al., 2023b). 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 (Figure 3c). 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 and other living organisms (Latour, 2021).
3. *Put CZS into practice across scales and sectors*.
   We recommend that dedicated funding is invested in social science research to establish the optimal (context-specific) mechanisms for the flow of information from CZ research to different groups of users (see Naylor et al., 2023b) and explores the benefits of innovative interactive learning tools such as reality-based games (Seysel, 2017). Different approaches are required to share CZS into practice across scales and for different sectors of society, for example, policy-scale and practice-scale (Table 1). At the policy scale, on-line connectivity and social media provide opportunities for DSTs informed by CZS to be created and shared with practitioners and policy makers designing policies to improve agricultural sustainability. At the practice scale,

using social science methods to identify social, political and cultural factors influencing local social capital (Naylor et al., 2023b), and how these influence learning preferences of lived inhabitants in CZOs (Naylor et al., 2023b; B. Wu & Pretty, 2004), can usefully guide research co-design and knowledge mobilization and exchange during CZ research projects.

4. *Flexible funding approaches informed by iterative review milestones*.

   We recommend that a longer-term perspective (minimum 10 years) is required to gain sufficiently comprehensive understanding of CZ processes at scales appropriate to both biophysical and socio-cultural contexts. Both scientists and CZ residents should be involved in cycles of data gathering, review, and implementation of evidence-based management change and monitoring, to develop strategies to support ecosystem function and regeneration, while providing roadmaps for sustainable economic development. Funding streams from government agencies, non-profit organizations and industry should be sought to support longer term programmes that capture changes in livelihoods alongside use of innovative sensor technologies to monitor CZ processes more efficiently, to evaluate and inform the implementation and progress of national and international policy goals (e.g., SDGs), and local livelihood impacts, for both ecological and social parameters. Crucial to this is the flexible nature of funding to respond to changes in priorities based on knowledge gaps identified within the project and/or external drivers, for example, policy change. To enable flexibility, CZ projects should build in milestones for iterative learning and review, where insights from social science research and local communities can inform and refine CZS studies during the lifetime 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.

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. (2019b). 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/e674e08c-fbf5-411b-940c-7e31014f0e76 and https://doi.org/10.5285/9c14948d-cf58-4194-9fef-c2cb56818667.

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References

Arènes, A., Latour, B., & Gaillardet, J. (2018). Giving depth to the surface: An exercise in the Gaia-graphy of critical zones. *The Anthropocene Review*, *5*(2), 120–135. https://doi.org/10.1177/2053019618782257

Banwart, S., Bernasconi, S. M., Bloem, J., Blum, W., Brandao, M., Brantley, S., et al. (2011). Soil processes and functions in critical zone observatories: Hypotheses and experimental design. *Vadose Zone Journal*, *10*(3), 974–987. https://doi.org/10.2136/vzj2010.0136

Banwart, S., Menon, M., Stefano, M., Bloem, J., Blum, W. E., de Souza, D. M., et al. (2012). "Soil processes and functions across an international network of critical zone observatories: Introduction to experimental methods and initial results". *Comptes Rendus Geoscience*, *344*(11–12), 758–772. https://doi.org/10.1016/j.crte.2012.10.007

Barrett, C. B. (2021). Overcoming global food security challenges through science and solidarity. *American Journal of Agricultural Economics*, *103*(2), 422–447. https://doi.org/10.1111/ajae.12160

Buckerfield, S. J. (2021). Understanding hydrological and land-use controls on microbial pollution & human health risks in the South West China karst region. PhD thesis. University of Stirling.

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. (2019b). 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. (2019a). 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

Chapin, F. S., Weber, E. U., Bennett, E. M., Biggs, R., van den Bergh, J., Adger, W. N., et al. (2022). Earth stewardship: Shaping a sustainable future through interacting policy and norm shifts. *Ambio*, *51*(9), 1907–1920. https://doi.org/10.1007/s13280-022-01721-3

Chen, X., Zhang, Z. C., Soulsby, C., Cheng, Q. B., Binley, A., Jiang, R., & Tao, M. (2018). Characterizing the heterogeneity of karst critical zone and its hydrological function: An integrated approach. *Hydrological Processes*, *32*(19), 2932–2946. https://doi.org/10.1002/hyp.13232

Chorover, J., Kretzschmar, R., Garcia-Pichel, F., & Sparks, D. L. (2007). Soil biogeochemical processes in the critical zone. *Elements*, *3*(5), 321–326. https://doi.org/10.2113/gselements.3.5.321

Chorover, J., Troch, P. A., Rasmussen, C., Brooks, P. D., Pelletier, J. D., Breshears, D. D., et al. (2011). How water, carbon, and energy drive critical zone evolution: The Jemez–Santa Catalina Critical Zone Observatory. *Vadose Zone Journal*, *10*(3), 884–899. https://doi.org/10.2136/vzj2010.0132

Coughlan, M. R., Nelson, D. R., Lonneman, M., & Block, A. E. (2017). Historical land use dynamics in the highly degraded landscape of the Calhoun Critical Zone Observatory. *Land*, *6*(2), 32. https://doi.org/10.3390/land6020032

Crutzen, P. J. (2006). The "Anthropocene". In *Earth system science in the Anthropocene* (pp. 13–18). Springer. https://doi.org/10.1007/3-540-26590-2_3v

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

Ding, J., Jia, X., Zhang, W., & Klerkx, L. (2022). The effects of combined digital and human advisory services on reducing nitrogen fertilizer use: Lessons from China's national research programs on low carbon agriculture. *International Journal of Agricultural Sustainability*, *20*(6), 1–14. https://doi.org/10.1080/14735903.2022.2057643

Dong, Y., Yang, J. L., Zhao, X. R., Yang, S. H., Mulder, J., Dorsch, P., & Zhang, G. L. (2022). Nitrate leaching and N accumulation in a typical subtropical red soil with N fertilization. *Geoderma*, *407*, 115559. https://doi.org/10.1016/j.geoderma.2021.115559

Dunkley, R. A., & Franklin, A. (2017). Failing better: The stochastic art of evaluating community-led environmental action programs. *Evaluation and Program Planning*, *60*, 112–122. https://doi.org/10.1016/j.evalprogplan.2016.11.005

Ellis, E. C., Klein Goldewijk, K., Siebert, S., Lightman, D., & Ramankutty, N. (2010). Anthropogenic transformation of the biomes, 1700 to 2000. *Global Ecology and Biogeography*, *19*(5), 589–606. https://doi.org/10.1111/j.1466-8238.2010.00540.x

Fandel, C. A., Breshears, D. D., & McMahon, E. E. (2018). Implicit assumptions of conceptual diagrams in environmental science and best practices for their illustration. *Ecosphere*, *9*, 1–15. https://doi.org/10.1002/ecs2.2072

FAO. (2020). Land use in agriculture by the numbers. Retrieved from https://www.fao.org/sustainability/news/detail/en/c/1274219/

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

Ferraro, J. V., Hoggarth, J. A., Zori, D., Binetti, K. M., & Stinchcomb, G. (2018). Integrating human activities, archeology, and the Paleo-critical zone paradigm. *Frontiers in Earth Science*, *6*, 84. https://doi.org/10.3389/feart.2018.00084

Field, J. P., Breshears, D. D., Law, D. J., Villegas, J. C., López-Hoffman, L., Brooks, P. D., et al. (2015). Critical zone services: Expanding context, constraints, and currency beyond ecosystem services. *Vadose Zone Journal*, *14*(1), 1–7. https://doi.org/10.2136/vzj2014.10.0142

Field, J. P., Breshears, D. D., Law, D. J., Villegas, J. C., López-Hoffman, L., Brooks, P. D., et al. (2016). Understanding ecosystem services from a geosciences perspective. *Eos*, *97*(5), 10–11. https://doi.org/10.1029/2016eo043591

Foroughi, M., Mallard, J. M., Nelson, D. R., Sutter, L. A., & Markewitz, D. (2021). The impacts of historical land-use on phosphorus movement in the Calhoun Critical Zone Observatory in the southeastern US Piedmont. *Biogeochemistry*, *154*(1), 17–35. https://doi.org/10.1007/s10533-021-00794-8

Gaillardet, J., Braud, I., Gandois, L., Probst, A., Probst, J. L., Sanchez-Pérez, J. M., et al. (2018). OZCAR: The French network of critical zone observatories. *Vadose Zone Journal*, *17*(1), 1–24. https://doi.org/10.2136/vzj2018.04.0067

Granados Aguilar, R., Owens, R., & Giardino, J. R. (2020). The expanding role of anthropogeomorphology in critical zone studies in the Anthropocene. *Geomorphology*, *366*, 107165. https://doi.org/10.1016/j.geomorph.2020.107165

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

Gu, B., Ju, X., Chang, J., Ge, Y., & Vitousek, P. M. (2015). Integrated reactive nitrogen budgets and future trends in China. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(28), 8792–8797. https://doi.org/10.1073/pnas.1510211112

Guo, L., & Lin, H. (2016). Critical zone research and observatories: Current status and future perspectives. *Vadose Zone Journal*, *15*(9), 1–14. https://doi.org/10.2136/vzj2016.06.0050

Guo, Z., Zhang, X., Dungait, J. A., Green, S. M., Wen, X., & Quine, T. A. (2021). Contribution of soil microbial necromass to SOC stocks during vegetation recovery in a subtropical karst ecosystem. *Science of the Total Environment*, *761*, 143945. https://doi.org/10.1016/j.scitotenv.2020.143945

Guo, Z., Zhang, X., Green, S. M., Dungait, J. A. J., Wen, X., & Quine, T. A. (2019). Soil enzyme activity and stoichiometry along a gradient of vegetation restoration at the Karst Critical Zone Observatory in Southwest China. *Land Degradation & Development*, *30*(16), 1916–1927. https://doi.org/10.1002/ldr.3389

Gupta, S., Karumanchi, S. H., Dash, S. K., Adla, S., Tripathi, S., Sinha, R., et al. (2019). Monitoring ecosystem health in India's food basket. *Eos*, *100*. https://doi.org/10.1029/2019EO117683

Jia, X. X., Wu, H. M., Shao, M. A., Huang, L. M., Wei, X. R., Wang, Y. Q., & Zhu, Y. J. (2020). Re-evaluation of organic carbon pool from land surface down to bedrock on China's Loess Plateau. *Agriculture, Ecosystems & Environment*, *293*, 106842. https://doi.org/10.1016/j.agee.2020.106842

Jiao, X. Q., Zhang, H. Y., Chong, W. A. N. G., Li, X. L., & Zhang, F. S. (2019). Science and technology backyard: A novel approach to empower smallholder farmers for sustainable intensification of agriculture in China. *Journal of Integrative Agriculture*, *18*(8), 1657–1666. https://doi.org/10.1016/S2095-3119(19)62592-X

Jin, X. X., Zhu, Y. J., Huang, L. M., Wei, X. R., Fang, Y. T., Wu, L. H., et al. (2018). Mineral N stock and nitrate accumulation in the 50 to 200 m profile on the Loess Plateau. *Science of the Total Environment*, *633*, 999–1006. https://doi.org/10.1016/j.scitotenv.2018.03.249

Jordan, N. R., Mulla, D. J., Slotterback, C., Runck, B., & Hays, C. (2018). Multifunctional agricultural watersheds for climate adaptation in Midwest USA: Commentary. *Renewable Agriculture and Food Systems*, *33*(3), 292–296. https://doi.org/10.1017/S1742170517000655

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

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

Latour, B. (2021). Is geology the New Umbrella for all the sciences? Hints for a Neo-Humboldtian University. In R. Barnacle, & D. Cuthbert (Eds.), *The PhD at the end of the world: Provocations for the doctorate and a future contested—Introduction* (pp. 9–23). Springer Link.

Latour, B. (2014). Some advantages of the notion of "critical zone" for geopolitics. *Procedia Earth and Planetary Science*, *10*, 3–6. https://doi.org/10.1016/j.proeps.2014.08.002

Li, D., Zhang, X., Dungait, J. A., Green, S. M., Wen, X., Quine, T. A., & Wang, Q. (2021b). Main controls on the denitrification rates during cropland revegetation in the southwest China Karst Critical Zone Observatory. *Agriculture, Ecosystems & Environment*, *308*, 107228. https://doi.org/10.1016/j.agee.2020.107228

Li, D., Zhang, X., Dungait, J. A., Wen, X., Quine, T. A., & Wang, Q. (2021a). 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

Li, D., Zhang, X., Green, S. M., Dungait, J. A. J., Wen, X., Tang, Y., et al. (2018). Nitrogen functional gene activity in soil profiles under progressive vegetative recovery after abandonment of agriculture at the Puding Karst Critical Zone Observatory, SW China. *Soil Biology and Biochemistry*, *125*, 93–102. https://doi.org/10.1016/j.soilbio.2018.07.004

Li, H. J., Si, B. C., Wu, P. T., & McDonnell, J. J. (2019). Water mining from the deep critical zone by apple trees growing on loess. *Hydrological Processes*, *33*(2), 320–327. https://doi.org/10.1002/hyp.13346

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, B., Xie, Y., Li, Z., Liang, Y., Zhang, W., Fu, S., et al. (2020). The assessment of soil loss by water erosion in China. *International Soil and Water Conservation Research*, *8*(4), 430–439. https://doi.org/10.1016/j.iswcr.2020.07.002

Liu, H., Jiang, Z., Dai, J., Wu, X., Peng, J., Wang, H., et al. (2019c). Rock crevices determine woody and herbaceous plant cover in the karst critical zone. *Science China Earth Sciences*, *62*(11), 1756–1763. https://doi.org/10.1007/s11430-018-9328-3

Liu, J., Wang, J., Li, Z., & Du, Y. (2021). Exploring impacts of the Grain for Green program on Chinese economic growth. *Environment, Development and Sustainability*, *23*(4), 5215–5232. https://doi.org/10.1007/s10668-020-00810-1

Liu, M., Han, G., Li, Z., Zhang, Q., & Song, Z. (2019b). Soil organic carbon sequestration in soil aggregates in the karst Critical Zone Observatory, Southwest China. *Plant Soil and Environment*, *65*(5), 253–259. https://doi.org/10.17221/602/2018-PSE

Liu, M., Han, G., Zhang, Q., & Song, Z. (2019a). Variations and indications of $\delta^{13}C_{SOC}$ and $\delta^{15}N_{SON}$ in soil profiles in karst critical zone observatory (CZO), southwest China. *Sustainability*, *11*(7), 2144. https://doi.org/10.3390/su11072144

Liu, Y., Liu, J., & Zhou, Y. (2017). Spatio-temporal patterns of rural poverty in China and targeted poverty alleviation strategies. *Journal of Rural Studies*, *52*, 66–75. https://doi.org/10.1016/j.jrurstud.2017.04.002

McIver, J., Brunson, M., Bunting, S., Chambers, J., Devo, N., Doescher, P., et al. (2010). *The sagebrush steppe treatment evaluation project (SageSTEP): A test of state-and-transition theory*. General Technical Report RMRS-GTR-237. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. https://doi.org/10.2737/RMRS-GTR-237

Menon, M., Rousseva, S., Nikolaidis, N. P., van Gaans, P., Panagos, P., de Souza, D. M., et al. (2014). SoilTrEC: A global initiative on critical zone research and integration. *Environmental Science and Pollution Research*, *21*(4), 3191–3195. https://doi.org/10.1007/s11356-013-2346-x

Minor, J., Jessie, K., Mallory, P., Barnes, L., Colella, T. R., Murphy, P. C., et al. (2020). Critical Zone Science in the Anthropocene: Opportunities for biogeographic and ecological theory and praxis to drive earth science integration. *Progress in Physical Geography: Earth and Environment*, *44*(1), 50–69. https://doi.org/10.1177/0309133319864268

Montanarella, L., & Panagos, P. (2015). Policy relevance of critical zone science. *Land Use Policy*, *49*, 86–91. https://doi.org/10.1016/j.landusepol.2015.07.019

Musche, M., Adamescu, M., Angelstam, P., Bacher, S., Bäck, J., Buss, H. L., et al. (2019). Research questions to facilitate the future development of European long-term ecosystem research infrastructures: A horizon scanning exercise. *Journal of Environmental Management*, *250*, 109479. https://doi.org/10.1016/j.jenvman.2019.109479

Nachtergaele, F., Petri, M., & Biancalani, R. (2011). Land degradation. SOLAW background thematic report, *3*. https://www.fao.org/fileadmin/templates/solaw/files/thematic_reports/SOLAW_thematic_report_3_land_degradation.pdf

Navas, A., Quine, T. A., Walling, D. E., Gaspar, L., Quijano, L., & Lizaga, I. (2017). Relating intensity of soil redistribution to land use changes in abandoned Pyrenean fields using fallout caesium-137. *Land Degradation & Development*, *28*(7), 2017–2029. https://doi.org/10.1002/ldr.2724

Naylor, L. A., Dungait, J. A. J., Zheng, Y., Buckerfield, S., Green, S. M., Oliver, D. M., et al. (2023a). Achieving sustainable Earth futures in the Anthropocene by including local communities in critical zone science. *Earth's Future*, *11*, e2022EF003448. https://doi.org/10.1029/2022EF003448

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

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*(3), 182–190. https://doi.org/10.1038/s41893-019-0448-2

Oliver, D. M., Zheng, Y., Naylor, L. A., Murtagh, M., Waldron, S., & Peng, T. (2020). How does smallholder framing 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

Olsson, L., Barbosa, H., Bhadwal, S., Cowie, A., Delusca, K., Flores-Renteria, D., et al. (2019). Land degradation in IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems. In *Intergovernmental panel on climate change (IPCC)* (pp. 345–436).

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science*, *325*(5939), 419–422. https://doi.org/10.1126/science.1172133

Perpiña Castillo, C., Coll Aliaga, E., Lavalle, C., & Martínez Llario, J. C. (2020). An assessment and spatial modelling of agricultural land abandonment in Spain (2015–2030). *Sustainability*, *12*(2), 560. https://doi.org/10.3390/su12020560

Persson, M., Moberg, J., Ostwald, M., & Xu, J. (2013). The Chinese Grain for Green Programme: Assessing the carbon sequestered via land reform. *Journal of Environmental Management*, *126*, 142–146. https://doi.org/10.1016/j.jenvman.2013.02.045

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

Qin, C., Li, S.-L., Yu, G.-H., Bass, A. M., Yue, F.-J., & Xu, S. (2022). Vertical variations of soil carbon under different land uses in a karst critical zone observatory (CZO), SW China. *Geoderma*, *412*, 115741. https://doi.org/10.1016/j.geoderma.2022.115741. https://www.sciencedirect.com/science/article/pii/S0016706122000489

Quine, T., Guo, D., Green, S. M., Tu, C., Hartley, I., Zhang, X., et al. (2017). Ecosystem service delivery in Karst landscapes: Anthropogenic perturbation and recovery. *Acta Geochimica*, *36*(3), 416–420. https://doi.org/10.1007/s11631-017-0180-4

Reed, M., Stringer, L. C., Fazey, I., Evely, A. C., & Kruijsen, J. (2014). Five principles of knowledge exchange in environmental management. *Journal of Environmental Management*, *146*, 337–345. https://doi.org/10.1016/j.jenvman.2014.07.021

Richter, D. D., Billings, S. A., Groffman, P. M., Kelly, E. F., Lohse, K. A., McDowell, W. H., et al. (2018). Ideas and perspectives: Strengthening the biogeosciences in environmental research networks. *Biogeosciences*, *15*, 4815–4832. https://doi.org/10.5194/bg-15-4815-2018

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

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., III., Lambin, E., et al. (2009). Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, *14*(2). https://doi.org/10.5751/es-03180-140232

Sekhar, M., Riotte, J., Ruiz, L., Jouquet, P., & Braun, J. J. (2016). Influences of climate and agriculture on water and biogeochemical cycles: Kabini critical zone observatory. *Proceedings of the National Academy of Sciences of the United States America*, *82*(3), 833–846. https://doi.org/10.5814/j.issn.1674-764x.2018.01.006

Seyfried, M., Lohse, K., Marks, D., Flerchinger, G., Pierson, F., & Holbrook, W. S. (2018). Reynolds creek experimental watershed and critical zone observatory. *Vadose Zone Journal*, *17*(1), 1–20. https://doi.org/10.2136/vzj2018.07.0129

Seysel, A. K. (2017). Role of information feedback in soil nitrogen management: Results from a dynamic simulation game. *Systems Research and Behavioral Science*, *34*(4), 424–439. https://doi.org/10.1002/sres.2466

Shuqin, J., & Fang, Z. (2018). Zero growth of chemical fertilizer and pesticide use: China's objectives, progress and challenges. *Journal of Resources and Ecology*, *9*(1), 50–58. https://doi.org/10.5814/j.issn.1674-764x.2018.01.006

Song, G. H., Li, L. Q., Pan, G., & Zhang, Q. (2005). Topsoil organic carbon storage of China and its loss by cultivation. *Biogeochemistry*, *74*(1), 47–62. https://doi.org/10.1007/s10533-004-2222-3

Song, X., Peng, C., Zhou, G., Jiang, H., & Wang, W. (2014). Chinese grain for green program led to highly increased soil organic carbon levels: A meta-analysis. *Scientific Reports*, *4*(1), 1–7. https://doi.org/10.1038/srep0446

Song, X. D., Wu, H. Y., Liu, F., Tian, J., Cao, Q., Yang, S. H., et al. (2019a). Three-dimensional mapping of organic carbon using piecewise depth functions in the red soil critical zone observatory. *Soil Science Society of America Journal*, *83*(3), 687–696. https://doi.org/10.2136/sssaj2018.11.0447

Song, X. W., Gao, Y., Green, S. M., Dungait, J. A. J., Peng, T., Quine, T. A., et al. (2017). Nitrogen loss from karst area in China in recent 50 years: An in-situ simulated rainfall experiment's assessment. *Ecology and Evolution*, *7*(23), 10131–10142. https://doi.org/10.1002/ece3.3502

Song, X. W., Gao, Y., Green, S. M., Wen, X., Dungait, J. A. J., Xiong, B., et al. (2019b). Rainfall driven transport of carbon and nitrogen along karst slopes and associative interaction characteristic. *Journal of Hydrology*, *573*, 246–254. https://doi.org/10.1016/j.jhydrol.2019.03.083

Steenwerth, K. L., Hodson, A. K., Bloom, A. J., Carter, M. R., Cattaneo, A., Chartres, C. J., et al. (2014). Climate-smart agriculture global research agenda: Scientific basis for action. *Agriculture & Food Security*, *3*(1), 1–39. https://doi.org/10.1186/2048-7010-3-11

Sun, J., Pan, L., Tsang, D. C., Zhan, Y., Zhu, L., & Li, X. (2018). Organic contamination and remediation in the agricultural soils of China: A critical review. *Science of the Total Environment*, *615*, 724–740. https://doi.org/10.1016/j.scitotenv.2017.09.271

Sutton, M. A., Bleeker, A., Howard, C. M., Bekunda, M., Grizzetti, B., de Vries, W., et al. (2013). Our Nutrient World: The challenge to produce more food and energy with less pollution. In *Global overview of nutrient management. Centre for ecology and hydrology, Edinburgh on behalf of the global partnership on nutrient management and the international nitrogen initiative*. Retrieved from https://www.unep.org/resources/report/our-nutrient-world-challenge-produce-more-food-and-energy-less-pollution

Tahir, M., Lv, Y., Gao, L., Hallett, P. D., & Peng, X. (2016). Soil water dynamics and availability for citrus and peanut along a hillslope at the Sunjia Red soil critical zone observatory (CZO). *Soil and Tillage Research*, *163*, 110–118. https://doi.org/10.1016/j.still.2016.05.017

Tang, J. F., Wang, W. D., Yang, L., Qiu, Q. L. L., Lin, M. X., Cao, C. L., & Li, X. H. (2020). Seasonal variation and ecological risk assessment of dissolved organic matter in a peri-urban critical zone observatory watershed. *Science of the Total Environment*, *707*, 136093. https://doi.org/10.1016/j.soilbio.2021.108286

Tang, Y., Tian, J., Li, X., Yao, M., Wang, S., Kuzyakov, Y., & Dungait, J. A. J. (2021). Higher free-living N_2 fixation at rock-soil interfaces than topsoils during vegetation recovery in karst soils. *Soil Biology and Biochemistry*, *159*, 108286. https://doi.org/10.1016/j.soilbio.2021.108286

Tao, F., Yokozawa, M., Hayashi, Y., & Lin, E. (2005). A perspective on water resources in China: Interactions between climate change and soil degradation. *Climatic Change*, *68*(1), 169–197. https://doi.org/10.1007/s10584-005-6013-1

Taylor, C. A., & Rising, J. (2021). Tipping point dynamics in global land use. *Environmental Research Letters*, *16*(12), 125012. https://doi.org/10.1088/1748-9326/ac3c6d

Tchakerian, V., & Pease, P. (2015). The critical zone in desert environments. *Developments in Earth Surface Processes*, *19*, 449–472. https://doi.org/10.1016/B978-0-444-63369-9.00014-8

Thomas, Z., Rousseau-Gueutin, P., Abbott, B. W., Kolbe, T., Le Lay, H., Marçais, J., et al. (2019). Long-term ecological observatories needed to understand ecohydrological systems in the Anthropocene: A catchment-scale case study in Brittany, France. *Regional Environmental Change*, *19*(2), 363–377. https://doi.org/10.1007/s10113-018-1444-1

Turkeltaub, T., Jia, X., Zhu, Y., Shao, M. A., & Binley, A. (2018). Recharge and nitrate transport through the deep Vadose Zone of the Loess Plateau: A regional-scale model investigation. *Water Resources Research*, *54*(7), 4332–4346. https://doi.org/10.1029/2017WR022190

UNCCD. (2019). Land-based adaptation and resilience: Powered by nature. Retrieved from https://www.eld-initiative.org/fileadmin/pdf/Land_Based_Adaptation_ENG_Sall_web.pdf

Wang, X., Zhao, X., Zhang, Z., Yi, L., Zuo, L., Wen, Q., et al. (2016). Assessment of soil erosion change and its relationships with land use/cover change in China from the end of the 1980s to 2010. *Catena*, *137*, 256–268. https://doi.org/10.1016/j.catena.2015.10.004

Wang, Y., Dungait, J. A. J., Xing, K., Green, S. M., Hartley, I., Tu, C., et al. (2020). Persistence of soil microbial function at the rock-soil interface in degraded karst topsoils. *Land Degradation & Development*, *31*(2), 251–265. https://doi.org/10.1002/ldr.3445

Wang, Y., Zhu, Y., Zhang, S., & Wang, Y. (2018). What could promote farmers to replace chemical fertilizers with organic fertilizers? *Journal of Cleaner Production*, *199*, 882–890. https://doi.org/10.1016/j.jclepro.2018.07.222

Wang, Z., Han, R. X., Muhammad, A., Guan, D. X., Zama, E., & Li, G. (2022). Correlative distribution of DOM and heavy metals in the soils of the Zhangxi watershed in Ningbo city, East of China. *Environmental Pollution*, *299*, 118811. https://doi.org/10.1016/j.envpol.2022.118811

Welden, E. A., Chausson, A., & Melanidis, M. S. (2021). Leveraging nature-based solutions for transformation: Reconnecting people and nature. *People and Nature*, *3*(5), 966–977. https://doi.org/10.1002/pan3.10212

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. In *Developments in earth surface processes* (Vol. 19, pp. 15–78). Elsevier. https://doi.org/10.1016/B978-0-444-63369-9.00002-1

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, H., Dong, Y., Gao, L., Song, X., Liu, F., Peng, X., & Zhang, G. L. (2021). Identifying nitrate sources in surface water, regolith and groundwater in a subtropical red soil Critical Zone by using dual nitrate isotopes. *Catena*, *198*, 104994. https://doi.org/10.1016/j.geoderma.2018.11.019

Wu, H., Song, X., Liu, F., Li, D., & Zhang, G. L. (2022). Geophysical and geochemical characterization reveals topography controls on critical zone structure in a low hilly region. *Earth Surface Processes and Landforms*, *47*(11), 2796–2810. https://doi.org/10.1002/esp.5424

Wu, H., Song, X., Zhao, X., Peng, X., Zhou, H., Hallett, P. D., et al. (2019). Accumulation of nitrate and dissolved organic nitrogen at depth in a red soil Critical Zone. *Geoderma*, *337*, 1175–1185. https://doi.org/10.1016/j.geoderma.2018.11.019

Xu, Z., Xu, J., Deng, X., Huang, J., Uchida, E., & Rozelle, S. (2006). Grain for green versus grain: Conflict between food security and conservation set-aside in China. *World Development*, *34*(1), 130–148. https://doi.org/10.1016/j.worlddev.2005.08.002

Xue, Y., Tian, J., Quine, T. A., Powlson, D., Kuzyakov, Y., Dungait, J. A. J., et al. (2020). The persistence of bacterial diversity and ecosystem multifunctionality along a disturbance intensity in karst soil. *Science of the Total Environment*, *748*, 142381. https://doi.org/10.1016/j.scitotenv.2020.142381

Yang, S. H., Wu, H., Dong, Y., Zhao, X., Song, X., Yang, J., et al. (2020b). Deep nitrate accumulation in a highly weathered subtropical critical zone depends on the regolith structure and planting year. *Environmental Science & Technology*, *54*(21), 13739–13747. https://doi.org/10.1021/acs.est.0c04204

Yang, S. H., Wu, H. Y., Song, X. D., Dong, Y., Zhao, X. R., Cao, Q., et al. (2020a). Variation of deep nitrate in a typical red soil Critical Zone: Effects of land use and slope position. *Agriculture, Ecosystems & Environment*, *297*, 106966. https://doi.org/10.1016/j.agee.2020.106966

Yang, Y., Zhang, X., Hartley, I. P., Dungait, J. A. J., Wen, X., Li, D., et al. (2022). Contrasting rhizosphere soil nutrient economy of plants associated with arbuscular mycorrhizal and ectomycorrhizal fungi in karst forests. *Plant and Soil*, *470*(1–2), 81–93. https://doi.org/10.1007/s11104-021-04950-9

Yi, X., Yu, L., Yin, C., Wang, H., & Zhang, Z. (2021). The effects of China's Organic-Substitute-Chemical-Fertilizer (OSCF) policy on greenhouse vegetable farmers. *Journal of Cleaner Production*, *297*, 126677. https://doi.org/10.1016/j.jclepro.2021.126677

Yin, C., Zhao, W., Cherubini, F., & Pereira, P. (2021). Integrate ecosystem services into socio-economic development to enhance achievement of sustainable development goals in the post-pandemic era. *Geography and Sustainability*, *2*(1), 68–73. https://doi.org/10.1016/j.geosus.2021.03.002

You, Z., Wu, T., Gong, M., Zhen, S., & Cheng, J. (2022). The impact of the grain for green program on farmers' well-being and its mechanism—Empirical analysis based on CLDS data. *Frontiers in Ecology and Evolution*, *10*. https://doi.org/10.3389/fevo.2022.771490

Zhang, F., Cui, Z., Fan, M., Zhang, W., Chen, X., & Jiang, R. (2011). Integrated soil–crop system management: Reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. *Journal of Environmental Quality*, *40*(4), 1051–1057. https://doi.org/10.2134/jeq2010.0292

Zhang, G., Zhu, Y., & Shao, M. A. (2019a). Understanding sustainability of soil and water resources in a critical zone perspective. *Science China Earth Sciences*, *62*(11), 1716–1718. https://doi.org/10.1007/s11430-019-9368-7

Zhang, G. L., Song, X. D., & Wu, K. N. (2021). A classification scheme for Earth's critical zones and its application in China. *Science China Earth Sciences*, *64*(10), 1709–1720. https://doi.org/10.1007/s11430-020-9798-2

Zhang, Q., Xiao, H., Duan, M., Zhang, X., & Yu, Z. (2015). Farmers' attitudes towards the introduction of agri-environmental measures in agricultural infrastructure projects in China: Evidence from Beijing and Changsha. *Land Use Policy*, *49*, 92–103. https://doi.org/10.1016/j.landusepol.2015.07.021

Zhang, T., Meng, T., Hou, Y., Huang, X., & Oenema, O. (2022). Which policy is preferred by crop farmers when replacing synthetic fertilizers by manure? A choice experiment in China. *Resources, Conservation and Recycling*, *180*, 106176. https://doi.org/10.1016/j.resconrec.2022.106176

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

Zhang, Z. C., Chen, X., Cheng, Q. B., & Soulsby, C. (2019b). Storage dynamics, hydrological connectivity and flux ages in a karst catchment: Conceptual modelling using stable isotopes. *Hydrology and Earth System Sciences*, *23*(1), 51–71. https://doi.org/10.5194/hess-23-51-2019

Zhao, H., Chang, J., Havlík, P., van Dijk, M., Valin, H., Janssens, C., et al. (2021). China's future food demand and its implications for trade and environment. *Nature Sustainability*, *4*(12), 1042–1051. https://doi.org/10.1038/s41893-021-00784-6

Zhao, M., Zeng, C., Liu, Z., & Wang, S. (2010). Effect of different land use/land cover on karst hydrogeochemistry: A paired catchment study of Chenqi and Dengzhanhe, Puding, Guizhou, SW China. *Journal of Hydrology*, *388*(1–2), 121–130. https://doi.org/10.1016/j.jhydrol.2010.04.034

Zheng, Y., Naylor, L. A., 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. M. (2018). Summary report of China-UK knowledge exchange project for their critical zone programme. Retrieved form osf.io/hw2es

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

Zhu, Y. G., Reid, B. J., Meharg, A. A., Banwart, S. A., & Fu, B. J. (2017). Optimizing Peri-URban Ecosystems (PURE) to re-couple urban-rural symbiosis. *Science of the Total Environment*, *586*, 1085–1090. https://doi.org/10.1016/j.scitotenv.2017.02.094

Zhu, Y. J., Jia, X. X., Qiao, J. B., Binley, A., Horton, R., Hu, W., et al. (2019b). Capacity and distribution of water stored in the Vadose Zone of the Chinese Loess Plateau. *Vadose Zone Journal*, *18*(1), 180203. https://doi.org/10.2136/vzj2018.11.0203

Zhu, Y. J., Jia, X. X., Qiao, J. B., & Shao, M. A. (2019a). What is the mass of loess in the Loess Plateau of China? *Science Bulletin*, *64*(8), 534–539. https://doi.org/10.1016/j.scib.2019.03.021