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EDITORIAL

Focus on the future of water-limited agricultural landscapes

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Abstract

Water scarcity and related climate volatility are growing constraints on agricultural production landscapes around the world. While the adaptation options available are often dictated by system context, in many places broad-scale transformations are occurring in response to water-related pressures. We sought contributions from across regions, agricultural system types, and scientific disciplines to examine agricultural land use transitions driven by water scarcity, including the tradeoffs associated with alternative land uses; impacts on food production, environment, and society; innovations that can buffer risk; and considerations for planning and implementation. The research presented in this collection highlights the spectrum of policy and practice changes that are needed to facilitate beneficial land use transitions and system transformations, from quantifying risks, to evaluating multidimensional tradeoffs, to developing socio-technical policy bundles to maximize co-benefits.

1. Introduction

Water scarcity in agricultural landscapes is an issue of global scope. Irrigated agriculture contributes to 40% of the global food supply and accounts for most of the world's anthropogenic freshwater consumption (90%; Rosa 2022). As a result, the agricultural sector is on the front lines of growing scarcity and volatility in water supplies (D'Odorico *et al* 2018). Agricultural adaptation to water scarcity can take many forms, from efforts to increase the efficiency of water delivery systems, to supply augmentation via aquifer recharge or water storage investments. Adaptation can also involve cropland expansion or crop switching to account for changing water availability. In many places, however, adaptation is playing out in the form of broad-scale system transformations, including irrigated systems transitioning to dryland crop production, mixed crop-livestock production, or livestock grazing; dryland subsistence systems adopting sustainable irrigation as a climate hedge; and wholesale conversion to other enterprises, such as renewable energy.

This focus issue brings together research from across system types, regions, and disciplines to examine water-driven agricultural land use transitions. Specifically, it looks at a series of questions revolving around the future of agricultural systems that can no longer rely on as much water from precipitation or irrigation as in the past. In these water-limited agricultural landscapes:

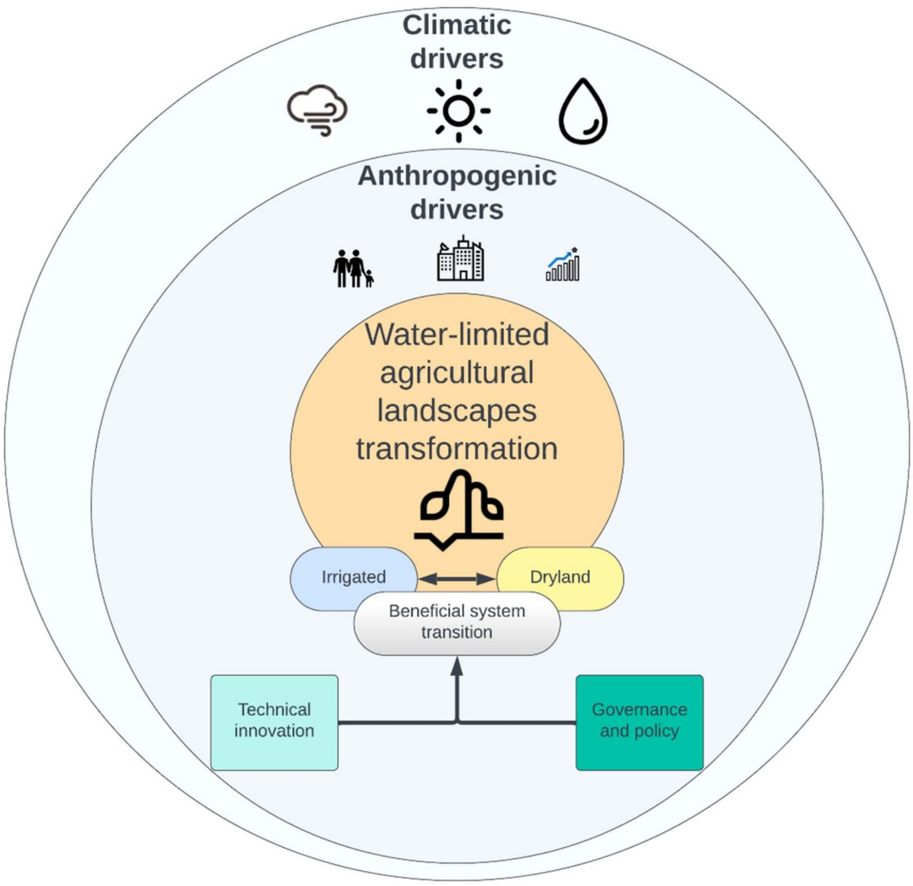

Figure 1. Land use transitions and system transformations in water-limited agricultural landscapes. Both climatic drivers (e.g. increasing temperatures, more intense droughts) and anthropogenic drivers (e.g. increased water demand) are behind shifts in water-limited landscapes, such as the transition from irrigated to dryland crop production. But technical innovations and good governance and policy can help ensure that these transitions result in beneficial outcomes for stakeholders.

1. How and to what extent can agricultural lands adapt to water scarcity?
2. How do water-driven land use transitions play out for those whose lives and livelihoods are directly impacted, and what enables optimal outcomes for stakeholders?
3. How can transitioning lands become liabilities or assets depending on the balance of environmental conditions and management choices?
4. What are the success stories that can serve as guideposts for regions undergoing similar transitions?

Farmers, allied industries, and downstream sectors all benefit from reducing uncertainties about how the agricultural industry will evolve under increasing water limitations. This collection explores the human and ecosystem level implications of land use transitions in production landscapes, including the tradeoffs associated with alternative land uses and land abandonment; impacts on food production, environment, and society; innovations that can buffer risk; and considerations for planning and implementation of multi-benefit landscapes in the face of water scarcity (figure 1). In this editorial, we review some of the key biophysical and sociological findings from the collection and provide an outlook on future research needs and priorities for this growing area of scientific inquiry.

2. Irrigated and dryland agricultural system transitions

In the semi-arid and arid regions of the world, the advent of irrigation drastically changed the crop profile and extent of the agricultural landscape. However, climatic changes have spurred new shifts that challenge both currently irrigated and traditionally dryland systems' capacity to cope with growing scarcity of water supplies. This is evident in practices such as the increased emphasis on wet season cropping in the Aral Sea basin (Rufin *et al* 2022), or the redesign of viable cropping strategies prompted by irrigation retirement in the Great Plains region of the US (Núñez *et al* 2022). In areas where agriculture depends heavily on irrigation, looming cutbacks in water availability underscore the need to understand how the transition from irrigated to non-irrigated systems will play out, along with its economic and environmental implications. For example, when previously irrigated land is retired or fallowed and tilled for weed management over long periods, the effects on soil biology can be profound (Núñez *et al* 2022). Transitioning to dryland or water-limited cropping systems can keep these lands productive while mitigating some of the negative impacts of irrigation retirement on soil health and microbial activity.

In regions where production costs—including the cost of water—have historically been high, water-limited cropping systems can prove to be a high-value use of water relative to thirstier crops (Peterson and Hanak 2022). However, dryland crop production can be risky, and not economically viable in the lowest rainfall areas. A potentially lucrative alternative land use that could capitalize on acreage coming out of irrigated production is renewable energy development, particularly solar farms. In the US, a large share of planned utility-scale solar energy development targets working lands (Biggs *et al* 2022). Where solar developments ultimately occur will be influenced by incentives and landowner decision-making factors, which tend to differ among types of landowners (e.g. ranchers or intensive crop growers).

Climate change is altering drought patterns globally, including changes in frequency, intensity, and duration of drought (Prudhomme *et al* 2014, Satoh *et al* 2022). In this context, historically dryland regions, which predominantly support subsistence agriculture, are facing heightened threats to food security. Regions that are already at the margins of suitability for dryland crop production are particularly exposed to these climatic changes. Across Africa, for example, the margins of dryland crop production areas are expected to retreat and be replaced by pastoral systems, raising concerns about the region's ability to produce adequate food under future climates (Nidumolu *et al* 2022). Likewise, droughts in Australia have the potential to significantly impact global food supply; the country's dryland production systems are highly sensitive to water limitations, and yet supply 10%–40% of the world's grain (Grundy *et al* 2016).

In contexts where irrigated agriculture has been limited less by water availability than by socioeconomic factors, poor access to technologies, or lack of investment, research has focused on how developing the capacity to irrigate can help secure food production. Sustainable irrigation is highlighted by some as a measure to build resilience to climate change and avoid further environmental externalities from agricultural expansion, particularly in marginalized, food insecure populations (Rosa *et al* 2020). However, irrigation expansion must be done carefully to avoid falling into the same water scarcity traps that are afflicting currently irrigated lands, and to avoid creating new problems and unexpected consequences such as soil salinization or increased energy expenditures (Rosa 2022). Socioeconomic factors must also be considered because they can considerably reduce the scope for sustainable irrigation relative to the biophysical potential (Van Maanen *et al* 2022).

3. Innovations to mitigate risk from climate extremes

Under any of these scenarios, innovation and new strategies in genetics, agronomy, management systems, and crop modeling and simulation tools are all needed to facilitate beneficial transitions in response to water scarcity. Precipitation extremes in either direction can result in prevented planting or a failed crop, and climate change projections indicate more frequent extremes in many important agricultural regions (IPCC 2022). Adaptive innovations often revolve around quantifying risk—particularly changes in precipitation regimes—as a way to account for increased climate variability in management plans. Improved climate and productivity forecasting, for example, can serve an important role in understanding the risk of crop loss or prevented planting. This is the case for both managing rainfall scarcity, as in dryland contexts where both rainfall distribution and quantity are critical, and managing over-abundance or extreme rainfall events (Lee and Abatzoglou 2023).

Management system innovations that embrace biological diversity and redundancy have been shown to improve the resilience of crop production to climate and weather extremes at the field level (Renwick *et al* 2021), but crop diversity also has implications for resilience at larger scales. Country-level food systems, for instance, are less vulnerable to weather extremes and display a greater ability to recover from shocks when they have a more diverse crop portfolio, especially one that includes more minor and drought-resistant crops (Renard *et al* 2023). Water systems also benefit from diversification; efforts to diversify water supply sources, e.g. irrigating with reclaimed water (Ballesteros-Olza *et al* 2022), can improve the system's ability to cope with shortages and reduce the overexploitation of existing supplies.

Refinement of crop genetics to improve baseline resistance to extremes like drought and high temperature and to enable climate-adaptive management systems will also help with system adaptation and transformation. In Australian dryland systems, for instance, long-coleoptile wheat genotypes have allowed for deeper planting into subsurface soil moisture, which can lengthen the time window for sowing and decrease reliance on ever-shifting seasonal precipitation events (Stummer *et al* 2023). Development of crop varieties that perform well in novel dryland contexts will be important in easing cropping system transitions by reducing agronomic risk and improving financial incentives to adapt.

4. Governance and policy for water-limited agricultural regions

Water scarcity-driven agricultural land use transitions can be fraught with tradeoffs, and good policies and governance systems are essential for enabling beneficial transitions for possible stakeholders, including farmers, communities, and other water users. For instance, recent work in the San Joaquin Valley of California has shown that building flexible, transparent water markets and fast-tracking efforts to repurpose transitioning agricultural land can help avoid undesirable economic and environmental outcomes (Hanak *et al* 2023). In India's cereal producing regions, policy scenario development showed that energy pricing tools could reduce agricultural demand for water with minimal impacts on production, resulting in the same outcomes as water withdrawal quotas by the year 2050 (Singh *et al* 2023). However, in the stressed Ganges–Brahmaputra–Meghna river basin, emphasizing sustainable development goals related to agricultural profitability over those related to food production goals would reduce the number of people fed by an estimated two-thirds (Siderius *et al* 2022).

Recent studies have highlighted the importance of considering the increasing complexity in the interaction of natural and human processes, particularly as water supplies decrease in situations like prolonged droughts. While short-term measures (e.g. drought coping mechanisms or emergency responses like reducing water use, increasing groundwater pumping, or switching water sources) might be beneficial initially, they could lead to more significant challenges in the future (Fernández *et al* 2023). Governance systems must therefore be adaptable and consider both social and environmental contexts, especially in areas facing severe water scarcity.

The various ways in which policy decisions can manifest in different contexts highlight the importance of 'fit' in water governance systems, e.g. for groundwater use in heavily stressed aquifers (Marston *et al* 2022). This is especially true for developing bottom–up governance systems, which have struggled to gain traction in industrialized agricultural settings but offer the potential for resilient and adaptable solutions when the relevant social and environmental contexts are considered.

5. Research needs and priorities

The research presented in this collection highlights the spectrum of needs and priorities that will be critical for adaptation to water limitations. The measures proposed are both policy and practice changes. These priorities include:

(1) **Quantifying the current and future states/risks of water scarcity in agricultural lands**, e.g. mapping the shifting margins of arid/semi-arid agricultural production zones, or improving prediction of precipitation-related crop losses;
(2) **Evaluating the multidimensional tradeoffs or co-benefits of future land use alternatives,** e.g. documenting the biophysical impacts of irrigation retirement on soil functionality, considering sustainable irrigation expansion where relevant for food security, or developing crop varieties and management systems that are adapted to shifting climate baselines and frequent precipitation extremes;
(3) **Developing socio-technical policy bundles to maximize co-benefits of land use transitions or system transformations**, e.g. discerning effective policies and governance strategies for different scarcity contexts.

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