Moving from measurement to governance of shared groundwater resources

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Meagan E. Schipanski [1], Matthew R. Sanderson[2,3], Linda Estelí Méndez-Barrientos [4], Amy Kremen[1], Prasanna Gowda[5], Dana Porter[6], Kevin Wagner[7], Charles West[8], Charles W. Rice[9], Mark Marsalis[10], Bridget Guerrero[11], Erin Haacker[12], James Dobrowolski[13], Chittaranjan Ray[14] & Brent Auvermann[15]

Global groundwater resources are under strain, with cascading effects on producers, food and fibre production systems, communities and ecosystems. Investments in biophysical research have clarified the challenges, catalysed a proliferation of technological solutions and supported incentivizing individual irrigators to adjust practices. However, groundwater management is fundamentally a governance challenge. The reticence to prioritize building governance capacity represents a critical 'blind spot' contributing to a low return on investment for research funding with negative consequences for communities moving closer towards resource depletion. In this Perspective, we recommend shifts in research, extension and policy priorities to build polycentric governance capacity and strategic planning tools, and to reorient priorities to sustaining aquifer-dependent communities in lieu of maximizing agricultural production at the scale of individual farm operations. To achieve these outcomes, groundwater governance needs to be not only prioritized but also democratized.

Declines in the availability of freshwater that is sufficient in quantity and quality to support the human population and dependent ecosystems is a critical challenge of our time. Globally, groundwater extraction has supported intensification of agriculture and economic development of urban and rural communities, contributing about 42%, 36% and 27% of the annual water used for agriculture, households and manufacturing operations, respectively[1]. For most rural populations in the United States, including more than 43 million people across the Western and High Plains regions, groundwater is the sole domestic water source[2], and 60% of irrigated crop production relies on groundwater[3]. However, the rate of groundwater extraction exceeds recharge rates across many of the world's aquifer systems, threatening the viability of communities and ecosystems.

A common refrain from scientists and water managers is the old adage 'we can't manage what we can't (or don't) measure'. Thus, we continue to measure groundwater declines and focus on the adoption of technological solutions by individual water users without addressing the elephant in the room—that shared groundwater resources are complex socio-ecological systems. Without engaging in the difficult human work of groundwater management, investments in research

[1]Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO, USA. [2]Department of Sociology, Kansas State University, Manhattan, KS, USA. [3]Department of Geography and Geospatial Sciences, Kansas State University, Manhattan, KS, USA. [4]Josef Korbel School of International Studies, University of Denver, Denver, CO, USA. [5]USDA-ARS Southeast Area, Stoneville, MS, USA. [6]Texas A&M AgriLife Extension Service, Biological and Agricultural Engineering, Lubbock, TX, USA. [7]Oklahoma Water Resources Center, Oklahoma State University, Stillwater, OK, USA. [8]Department of Plant and Soil Science, Texas Tech University, Lubbock, TX, USA. [9]Department of Agronomy, Kansas State University, Manhattan, KS, USA. [10]Department of Extension Plant Sciences, New Mexico State University, Agricultural Science Center at Los Lunas, Los Lunas, NM, USA. [11]Department of Agricultural Sciences, West Texas A&M University, Canyon, TX, USA. [12]Department of Earth and Atmospheric Sciences, University of Nebraska, Lincoln, NE, USA. [13]REE-NIFA, USDA, Kansas City, MO, USA. [14]Nebraska Water Center, Daugherty Water for Food Institute, University of Nebraska, Lincoln, NE, USA. [15]Texas A&M AgriLife Research, Biological and Agricultural Engineering, Amarillo, TX, USA. e-mail: meagan.schipanski@colostate.edu

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and financial assistance programmes that aim to encourage adoption of water conservation practices and tools will continue to result in a low return on investment.

Natural resource management is fundamentally a governance challenge, where governance is defined as the processes by which societal rules, norms, relationships and goals inform policy design, implementation and adaptation[4]. Drawing from lessons learned in major US aquifer systems, including the Ogallala-High Plains Aquifer (OHPA) and the California Central Valley Aquifer, we call for a major shift in research, extension and policy priorities to: (1) build polycentric governance capacity and strategic planning tools; and (2) re-orient priorities to facilitate equitable transitions to water and land-use approaches that can sustain aquifer-dependent communities as a

whole, including producer net profitability, in lieu of prioritizing crop production maximization at the scale of individual producers or farm operations.

Aquifer-scale analyses have defined potential future trajectories

Groundwater research has mainly focused on two scales—the aquifer and the individual producer. Unsustainable extraction, which occurs when the rate of groundwater extraction exceeds rates of replenishment, is the motivation behind many aquifer-scale studies. Aquiferscale analyses of the biophysical heterogeneity of climate, soil type and hydrology have defined a range of predicted trajectories, hotspots and timelines for groundwater declines under status quo management[5,6]. Critical data infrastructure to support these analyses includes a network of US Geological Survey National Water Information System monitoring wells. Historical well data have also enabled analyses of climate variability impacts on water levels, with increased extraction rates and more rapid declines during dry years, highlighting the vulnerability of groundwater systems to climate change[7].

These analyses have identified three different trajectories for groundwater-dependent regions that we broadly define based on the balance between biophysically defined recharge rates and climatedriven demand on the resource to support irrigated agriculture (Table 1). Trajectory 1 is sustainable use, where relatively high natural recharge rates due to soil type and hydrology are in balance with comparatively lower mean crop water demands due to climatic conditions, such that intensive annual cropping can be sustained with incremental improvements to current water- and crop-management systems. Trajectory 2 is extended use, where economically feasible agricultural systems could be maintained for more than a century into the future if more considerable management changes that reduce water consumption are implemented. Trajectory 3 is the managed depletion of groundwater towards a transition to non-irrigated land use in the coming decades. For example, estimates suggest that 30% of the southern OHPA cannot sustain economic pumping rates to support irrigated agriculture for more than 30 years[8]. In trajectory 3, natural aquifer recharge rates are often orders of magnitude lower than extraction rates required by irrigated agriculture and the very notion of 'sustainable use' is practically moot. While trajectory 3 will experience the most extreme reductions in irrigated land area, all trajectories will require transition plans to accommodate a future with increased water scarcity. Due to spatial heterogeneity, all three trajectories may, and often do, co-occur within a single aquifer system, region or water district, making it more challenging to devise equitable groundwater policy for all water users[9].

Targeting individuals for improved water-use efficiency with limited success

In response to the concerns about groundwater declines outlined by aquifer-scale analyses, applied university research and extension efforts have focused mainly on irrigation technologies and management practices to improve individual field or farm-scale water-use

Table 1 | Three example scenarios (trajectories) of the relative degree of groundwater conservation required to achieve sustainable use and the potential corresponding management changes and scales of governance required to support these changes

Trajectory	Reduction in pumping to sustain groundwater	Management and land-use changes required	Scale of governance response required
(1) Sustainable use	<20%	Improvements in irrigation technology and management with no to minimal land-use change	Changes in practice at the scale of individual producers, supported by federal incentives and training
(2) Extended use	20–40%	Shifts in irrigation technology and land-use changes, including crop shifts and/ or selective irrigation retirement	Locally defined, regionally implemented commitments to achieve specific conservation targets through changes in individual producer management practices; supported by federal- and statelevel incentives and policies, agricultural lending and crop insurance frameworks
(3) Managed depletion and transition	>40% and projected depletion within 100 years	Major land-use transitions and large-scale irrigation retirement	Local engagement in long-term, regional planning and multiscalar public and private investments at state and federal levels to support the development of alternative land uses and economies

The percentage reduction ranges are hypothetical and approximate based on data and analyses focused primarily on the OHPA (for example, refs. 6, 8,61) and the relative potential of irrigation management technologies to improve water-use efficiencies beyond the status quo (for example, refs. 62–65).

efficiency. Federal incentive programmes (for example, US Department of Agriculture (USDA) and Environmental Quality Incentives Program (EQIP); Fig. 1) help defray the costs for individual producers to implement new technologies, such as decision support tools, soil moisture sensors and shifts in irrigation systems[10,11]. Other strategies include the integration of lower-water-use crops into crop rotations[10,12], limiting irrigation amounts during specific crop growth stages[13], and breeding crops for improved drought tolerance and water-use efficiency traits[14]. Recent developments in artificial intelligence, machine learning and Internet of Things technologies promise the solution of real-time automation of irrigation decisions based on sensors linked to data-driven decision support algorithms rather than human observation[15].

This focus on individual producer decisions may be sufficient for trajectory 1 where incremental tweaks to current management systems might be sufficient to sustain groundwater extraction rates to support current

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economic output far into the future (Table 1). However, advances in technologies have not been universally matched with high rates of technology adoption, and the net effect of technology adoption on groundwater conservation is unclear[16] and rarely measured. Furthermore, while irrigation decision support tools have been freely available for more than a decade from many universities, adoption remains at less than 10% (ref. 17). In addition, adoption of more efficient technologies does not always guarantee net conservation of water as more efficient water use can actually lead to an overall increased water consumption at the local or regional scale[18–20]. Thus, while advances in irrigation technologies can contribute to improved water-use efficiency and farm enterprise benefits across all irrigated contexts, the focus on individual producers is an insufficient strategy by itself for many regions, particularly those that fall under trajectories 2 and 3 (Table 1).

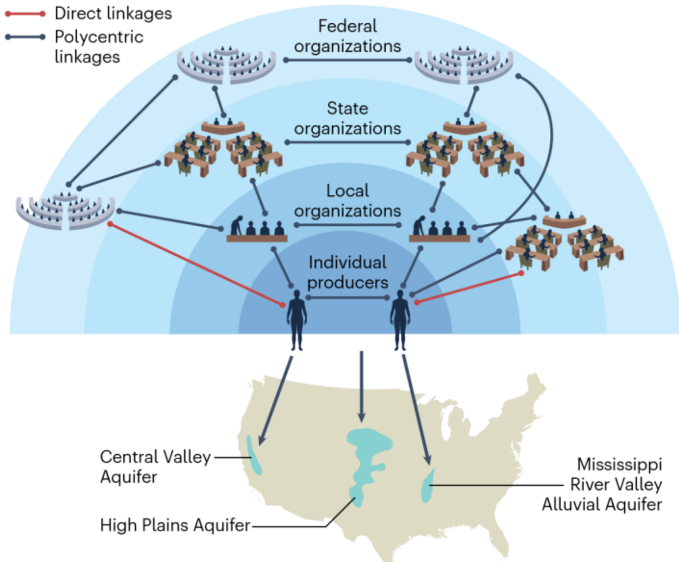

Fig. 1 | Conceptual illustration of the multiple scales of governance that influence groundwater extraction using the United States as an example. Black lines represent polycentric linkages across and within scales that are essential to scaling up collective commitments to groundwater conservation, and red lines represent examples of direct linkages common under status quo governance, such as individual actions incentivized through federal or state programmes. Credit: Erika Peirce.

Communities living and working in areas representing trajectories 2 and 3 require broader and more urgent groundwater governance, particularly in regions where groundwater levels and irrigation well capacities are declining more rapidly. These communities, often rural communities, suffer from recurrent or chronic water insecurity and rely heavily on groundwater not only for irrigated agriculture but also for human consumption. Water insecurity occurs when livelihoods, food production and consumption, and human health and well-being are undermined by water insufficiency and inaccessibility[21–23]. Notably, unincorporated communities, which are not connected to cities' and towns' water provision systems, and are often disadvantaged communities of colour, are disproportionally affected by unsustainable extraction of groundwater as they are reliant on unregulated shallow groundwater wells, deteriorating small water system infrastructure and expensive bottled water[24]. Finally, some communities in trajectories 2 and 3 are already experiencing the effects of a transition from irrigated agricultural to non-irrigated agricultural economies, with little comprehensive land-use planning. For example, in the California Central Valley Aquifer System, it is estimated that more than 200,000 hectares must transition from irrigated to dryland management to balance unsustainable groundwater extraction[25].

Integrating social dimensions to define sustainable water futures

Missing from aquifer-scale analyses and individual producer-scale approaches are larger, more difficult governance questions. How will many communities across the region transition to a future with less available groundwater? What policy strategies and programmes could effectively implement equitable and sustainable transitions?

Who might integrate decision-making platforms that influence the type and extent of groundwater management strategies? Importantly, who might win or lose with the implementation of reforms aimed at ensuring more sustainable futures? Further, what are society's goals of groundwater governance in light of current and future social and economic values of groundwater[26–29]? For some regions, the goal may be achieving sustainability by balancing extraction with recharge. In other regions, the goal may be maintaining community livelihoods and well-being in a future with less water, which can include extending the timeframe of groundwater resources via conservation and identifying alternative livelihoods that can sustain communities. While still other regions may be focused solely on current economic output without regard to future water users.

Addressing these important questions will require strong democratic governance processes that facilitate access and opportunity to diverse users, especially those who have not historically been included in water governance processes as well as future unknown water users that do not have the ability to voice their opinion[29,30]. In addition, this will require coordination across multiple public and private governance venues from farm to county, state, region and federal levels of governance to develop a shared understanding and urgency of the issues and implement transitions to water and land-use approaches that sustain shared water futures[31–34]. In short, a polycentric governance approach that integrates diverse stakeholders and governance systems across multiple scales will be a key implementation vehicle for these transitions[35].

But how can the re-organization of social, economic, political and ecological interactions at multiple scales be facilitated? Recent surveys of irrigated producers in the OHPA and California Central Valley regions highlighted broad concern about declining groundwater levels. However, many producers feel that they are already doing all they can to conserve water[36,37]. In the OHPA, producers value groundwater for its ability to buffer the effects of drought and support future generations of farms and communities. Nevertheless, concerns about reducing crop yields, risks associated with changing practices, and costs of technology adoption and maintenance remain barriers to adopting water conservation practices[36]. Moreover, farmers prefer voluntary, incentive-based approaches at the individual producer scale over top-down, state-led policy approaches such as pumping fees or regulations, even though incentive programmes focused on individual producer decisions have not been particularly effective in reducing depletion[37]. These findings support our contention that a combination of strategies at various levels of governance and across diverse types of organization may be more effective than singular approaches at singular scales.

Current practice-based incentive approaches for agriculture may also be insufficient without also considering broader social and economic drivers[38]. For example, there is insufficient economic incentive to shift away from water-intensive crops, such as maize and alfalfa (*Medicago sativa*), to lower-water-use crops that may extend the timeline of groundwater availability, but that may also be less lucrative or stable under current markets[39]. In addition, quantifying the social and economic value of future water resources is challenging, and myopic incentive systems contribute to policy and practices that prioritize using the groundwater today over conservation for an uncertain future. Financial lenders and insurers, in turn, are beginning to consider the broader benefits of conservation practices implemented today but may lack technical awareness and knowledge to recognize and reward this behaviour. Recently proposed federal guidance for banks to review their lending based on climate risk will contribute to the development of new or revised agricultural lending products to recognize field and farm-level conservation-oriented management shifts as climate-smart investments. In short, integrating the broader societal value of water to producers and groundwater-dependent communities is critical for defining shared policy strategies and programmes that support water conservation. Centring the focus on enhancing polycentric governance capacity may increase the effectiveness of current research and other water conservation focused investments.

Lessons learned at multiple governance scales

The urgent need to improve governance systems for groundwater management was recently highlighted by a global network of more than 1,300 water experts (www.groundwaterstatement.org). This call for polycentric governance is not new (for example, ref. 40), yet implementation has been difficult to achieve. Here we highlight current and historical approaches to groundwater governance at national, state and local scales within the United States.

At the national scale, agricultural policies have not prioritized water conservation and have often incentivized the accelerated extraction of groundwater. Federal Farm Bill programmes, which provide critical financial safety net programmes for producers, incentivize maximizing production over conserving scarce resources[39]. Similarly, agricultural funding has prioritized research that will increase agricultural productivity by 40% and cut environmental impacts in half by 2050[41]. This productivity-focused priority does not address the needs or reality facing resource-limited regions, such as those in trajectories 2 or 3. A shift in federal funding priorities is needed. Revising priorities to support groundwater-dependent communities should include incentives for the diversification of regional-local economic activities, including emerging ecosystem services markets, renewable energy and expanding markets for lower-water-use crops, among others. In addition, federal incentives should be linked to state and local governance efforts to build capacity and strengthen stakeholder engagement in local and regional governance. Importantly, the recent investments in climate-smart agriculture research needs to balance investments in soil carbon with investments in water conservation[42]. Aligning federal dollars with sustainability priorities is key to the design and implementation of more sustainable water futures.

At state levels, groundwater governance systems and water laws are highly variable and have had mixed success in slowing groundwater depletion. Historical ‘use it or lose it’ water laws in many states discourage water conservation. State-level responses to declining groundwater also vary considerably. For example, several High Plains states have long accepted that the OHPA is a non-renewable resource and, therefore, have focused on setting targets for the planned depletion of groundwater rather than sustaining the resource[43]. In contrast, California recently passed the Sustainable Groundwater Management Act (SGMA) in an effort to develop new groundwater agencies and sustainability plans to tackle the state’s groundwater overdraft issue[44,45].

Looking at successes and failures of state efforts to support voluntary groundwater conservation over the past 40 years yields important insights. Groundbreaking at the time, Arizona’s Groundwater Management Act (GMA) of 1980 established groundwater management goals by management areas, reduced sole reliance on groundwater sources for several areas and effectively curbed new municipal development that could not document availability of a 100-year supply of water. However, there were no penalties for non-compliance, and while the GMA likely slowed groundwater depletion, groundwater declines have persisted[46]. Similarly, Texas has engaged water-user groups in defining 50-year water plans that are enforceable by locally elected board members of groundwater conservation districts, such that the enforcers are also the water users[47]. Although Nebraska lies over the most productive part of the OHPA, natural resource districts in areas experiencing groundwater depletion define district pumping limits, while also offering flexible options for meeting these limits[48]. As groundwater has continued to decline across western US aquifer systems, Arizona and Kansas have changed water laws to reduce legal disincentives to conservation and increase local governance flexibility[49,50].

Recent changes in Kansas demonstrate how state laws can support local governance and agency for conservation efforts. For example, in 2013, Kansas empowered Groundwater Management Districts (GMDs) to voluntarily establish locally enhanced management areas (LEMAs) and smaller groups to develop Water Conservation Areas (WCAs) in which voluntary, collectively defined limits on groundwater use are defined by producers and sanctioned by the state for designated periods of time[50]. Producers in the state’s first LEMA in Sheridan District 6 (SD6) (2013–2018) maintained production returns while reducing pumping rates by 31%, exceeding their 20% reduction target, without any financial incentives[51]. This was achieved through increased irrigation efficiency, a focus on reducing input costs, shifts to less-waterconsuming crops, and effective marketing opportunities through feed and forage buyers. By opting to renew the LEMA for an additional five years (2018–2022), SD6 producers confirmed that the perceived conservation benefits—slowing aquifer decline, extending the aquifer’s productive life—outweighed the costs and effort associated with participating in the LEMA. As of early 2022, more than 86,500 acres (35,000 ha) were actively enroled in WCAs, with nearly 12,000 acre-feet (0.015 km^3) in annual water savings projected relative to previous water use on that area. The Sheridan LEMA provides an example of polycentric governance systems with multiple organizations contributing across multiple scales to achieve groundwater conservation goals[40]. Changes in state water governance enabled local governance authority, and local businesses and markets enabled water users to achieve collectively defined pumping limits while maintaining profitability, and individual producers also received support from federal incentives payment programmes.

More recently, California opted for a stronger regulatory mandate that requires groundwater basins to manage overdraft by 2040[29,52]. After two failures to voluntarily manage groundwater (AB3030 and SB1938)[28,53], the implementation of the 2014 SGMA will require major land- and water-use changes especially in the South Central Valley[25]. The SGMA proposed the formation of new, local governance agencies known as groundwater sustainability agencies (GSAs), using pre-existing local agencies as the point of departure for local governance structures[29,44]. Once GSAs were established, it required the development of aquifer management plans known as groundwater sustainability plans (GSPs). While the SGMA provided a framework to guide the implementation of the reform, it left key decisions to local actors. Unsurprisingly, the experience of SGMA has been diverse in California. While GSPs are still being developed, preliminary analysis on the development of GSAs have shown that the type of governance structure chosen by local actors matters for equity and inclusion of disadvantaged groups[54]. The newly created GSA institutional set-up will be as important for the types of rule chosen under the new plans[44,55].

Implementing polycentric governance of groundwater resources

Locally defined collective efforts across states and aquifer systems that have successfully slowed groundwater depletion rates seem to share key components: (1) defining a shared level of concern and understanding of the issue[56]; (2) establishing a collective commitment to conservation achieved through stakeholder engagement rather than a reliance on voluntary, individualized action[57]; (3) strong local leadership[58]; and (4) supportive state- and national-level policies that also support local governance authority[57]. Within the US context, states play a central role in defining and regulating water rights. The Kansas SD6 LEMA example of state enabled, locally defined governance demonstrates that once a shared future water vision and collective commitments to limit pumping are established, individual producers tended to shift behaviour much more rapidly and at scale, with or without short-term financial incentives, especially in contrast to individual(ized) voluntary resource management[57].

Scaling up locally defined, collective commitments to groundwater conservation requires strong local leadership and flexible but targeted policy mechanisms at state and higher levels of government, technical support and often, federally or state-supported economic incentives (Fig. 1). More importantly, this implementation requires a critical examination of who shapes groundwater policy at each governance scale. Polycentric governance requires cooperation, adaptation and coordinating multiple actors, at multiple venues and timescales. This work can be slow, nonlinear and challenging, which is probably why it has not received the same level of priority and funding as measuring groundwater and developing new water-management technologies.

Normalizing polycentric aquifer governance systems that leverage and engage critical social, political and financial capital (both farmer/industry investment and government funding) is a strategic necessity for addressing water-related challenges in stressed regions. Recent aquifer-wide initiatives in the OHPA, such as the Ogallala Water Coordinated Agricultural Project (www.ogalallawater.org), have demonstrated that linking local initiatives with state and federal resources can help define future water visions and catalyse new social networks and policy developments focused on optimizing groundwater use. However, there is no mechanism to sustain cross-scale efforts. Prioritization of building polycentric governance capacity could improve the effectiveness of federal investments in research, extension and incentive programmes, in part through identifying and linking research and diverse stakeholder needs to more coordinated and targeted federal cost-share programmes. It may be, moreover, that federal subsidies should flow towards the development of innovative governance structures rather than conservation practices per se. Enhancing governance capacity would also improve the regional capacity to adapt to other critical, unforeseen stressors such as a pandemic or economic depression.

The development of new programmes and governance approaches at local, state and regional levels will require a critical lens towards equity as the voices of larger water users have historically had more privilege than others despite the broad, community-wide and often unaddressed future impacts of groundwater depletion[29,54,59]. This includes how resource board members at local and state levels are selected among many other factors. Developing a more inclusive approach to groundwater governance would also require major shifts in how land-grant universities, USDA research priorities, and state and federal policies define their key stakeholders and broader programme objectives as they have historically prioritized technological and individual-producer-focused solutions rather than the more difficult social and governance-focused solutions.

The geophysical heterogeneity of groundwater levels presents challenges as water users can be unevenly impacted by the same policies. However, policies that define the end goal of conservation rather than imposing specific fees or incentivizing specific practices allow producers to adapt production and conservation goals to local conditions[60]. The combination of collaborative, regional governance that defines goals and manages conservation commitments with local flexibility tailored to local issues have the greatest potential to slow groundwater depletion, and perhaps even stabilize groundwater levels in some regions.

For areas in trajectory 3 facing imminent transitions to non-irrigated land management, coordinated governance is needed to support strategic enterprise planning, such as reversion to perennial grasslands, dryland cropping, integration of renewable energy production, and other innovations to support rural economies. This is the trajectory with the greatest need, but the fewest positive examples to follow. There are limited success stories of transitions away from resourceextractive economies, but there is a pressing global need in this space to shift communities away from dependency on non-sustainable resource extraction.

Stressed aquifer-dependent communities and ecosystems are not destined for failure. It is possible to leverage widespread social will for engagement and application of emerging science-based technologies related to water conservation to improve management of globally important aquifers. By doing so, these aquifer regions can remain a critical part of the global food production system to meet growing food demand while supporting broader ecosystem services and local communities. It is time to pivot away from measuring how fast the sky is falling towards building coordinated forms of governance that engage the wide range of individuals and groups impacted by groundwater declines.

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Competing interests

The authors declare no competing interests.

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Additional information

Correspondence should be addressed to Meagan E. Schipanski.

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