Review/

Groundwater-dependent ecosystems are missing from global research and policy agendas

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Abstract

A groundwater-dependent ecosystem (GDE) can be a stream or wetland sustained by groundwater, a terrestrial ecosystem that relies on groundwater for root water uptake, or the biodiversity that lives within aquifers. These ecosystems perform hydrological, ecological, and climate functions, and are meaningful to people through recreational, spiritual, and cultural practices. Traditionally studied at the local scale, GDEs are largely overlooked in global-scale research programmes and lack adequate incorporation in global environmental and sustainability policy agendas, despite holding vast potential to enhance their outcomes. Several global GDE studies have recently emerged, revealing that GDEs are globally prevalent and increasingly under threat. This *Review* synthesises early insights from these studies and argues that this emerging picture of GDE presence must be complemented by a dynamic, process-based understanding of GDE responses under multiple pressures. We outline policy agendas and Earth system frameworks that could be strengthened by the inclusion of GDEs and identify open questions to guide research in support of this shift.

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Groundwater-dependent ecosystem (GDE) scholarship emerged from multiple distinct disciplinary lineages, spanning the documentation of phreatophytes in arid regions,[1] the study of groundwater and surface water interactions in rivers and the hyporheic zone,[2] and the development of groundwater ecology.[3] Collectively, these advances established groundwater as a dynamic component of the critical zone (where rock, soil, water, air and biota interact to sustain terrestrial life)[4] that supports a wide variety of ecosystems and their functions,[5–7] including mediating heat fluxes at the land surface, regulating streamflow and water temperature, and transporting solutes, carbon and nutrients. GDE science further illuminates groundwater not merely as an inert physical resource but as a living ecosystem that nurtures dependent species and facilitates life processes.[8] Groundwater, together with other subterranean ecosystems, contributes to three-quarters of all classified ecosystem services.[9]

Ecological research involving groundwater has advanced alongside a broader embrace of interdisciplinarity in groundwater science.[10–13] Such developments at the interface of groundwater hydrology and ecology have been highly symbiotic. For instance, phreatophyte identification provided boundary conditions used in the early development of regional groundwater flow theory.[14,15] The term 'groundwater-dependent ecosystem'[16] offers an overarching categorisation through which to understand ecological interactions with groundwater. Its introduction encouraged further collaboration among hydrology, ecology, and biology research and practitioner communities,[17] and made significant inroads promoting the awareness and protection of these ecosystems.[18,19] Many GDE advances have also been incentivised by sustainable water laws and policies in jurisdictions worldwide which have required an understanding of GDE locations and their ecological thresholds to inform water decisions.[19]

After a century of groundwater-ecosystem science,[1] and nearly three decades since GDEs were formally recognised,[16] we propose that a meaningful continuation of GDE scholarship lies in pursuing a community-wide and policy-relevant global-scale research agenda on GDEs. Although typically studied at the local scale, advancing a global focus on GDEs is particularly meaningful because: (i) the emergence of continental to global scale hydrology and ecohydrology[20–22] enables analysis at this scale; and (ii) GDEs are profoundly linked to global change and its associated challenges, including biodiversity loss, climate change, and the pursuit of multidimensional sustainability goals,[23] which require global perspectives to be meaningfully addressed.

Here, we (1) provide a synthesis of insights from the first global-scale GDE studies, from which we (2) argue that a more dynamic understanding of GDEs under global change is missing and needed. We then (3) situate GDEs as embedded within the critical zone and social-ecological systems, making (4) addressing policy-relevant knowledge gaps on processes linking global GDEs with biodiversity, climate, and sustainability goals a high-potential priority to guide an impactful future in global GDE science.

Box 1: What are GDEs and why study them at the global scale?

Groundwater-dependent ecosystems (GDEs): An ecosystem that relies on groundwater for some or all of its freshwater needs (see legend of **Figure 1**). There are several types and classifications of GDEs[6,24,25] that include terrestrial GDEs (land-based ecosystems such as fens and dryland woodlands whose vegetation or ecological processes depend on access to groundwater); aquatic GDEs (surface water ecosystems such as rivers, wetlands, and springs that are sustained by groundwater discharge); subterranean GDEs (subsurface ecosystems in aquifers and caves that depend on groundwater as their primary habitat); and coastal and marine GDEs (estuarine and nearshore marine systems such as mangroves and salt marshes that rely on groundwater discharge).

Why a global focus on GDEs? A global perspective on GDEs can be useful because: (1) understanding the distribution of GDEs and their pressures can help place environments within a global context, (2) systematic analysis of GDEs can enable prioritisation and knowledge transfer between regions, (3) GDEs link groundwater to biodiversity, climate, and sustainability processes and policy agendas that operate at the global scale, and (4) global studies help raise awareness about the distributed nature of groundwater and its ecological functions. Many of these purposes align with the general benefits of global scale groundwater science (see full list in ref.[26]).

GDEs are an integrative concept that links research topics with strong research programmes and traditions at the global scale. These include plant-groundwater interactions,[27] groundwater-surface water interactions,[28] groundwater biodiversity,[29] ecosystem services and nature's contributions to people.[5,30] Yet, there remain few studies at the global scale that explicitly work within a GDE framework. Most GDE scholarship to date has been conducted at site-specific scales, although several states and countries have advanced GDE mapping and protection initiatives.[31,32] Advancing global perspectives on GDEs opens distinct research questions that can complement and strengthen (but not supersede) insights produced at local, regional, and biome scales.

GDEs are present across the globe in both humid and arid landscapes

A handful of studies have generated first-order estimates of the distribution of global GDEs.[33–35] Here, we synthesise these first global mapping efforts and summarise GDE distributions across environmental gradients (Figure 1). Existing studies have focused on mapping aquatic and terrestrial GDEs and vary in the granularity with which GDE types are specified, spatial resolution, and methods to detect or model GDE presence (see Supplementary Figure 1).

Subterranean GDEs are synonymous in extent with groundwater presence, for which there are multiple model-based estimates on depth to the water table[36,37] (with uncertainties discussed elsewhere[38]), and global aquifer and karst aquifer maps.[39,40] There are case study compilations and global models of coastal groundwater discharge[41,42] yet no global study to our knowledge explicitly locates marine and coastal GDEs. Other relevant initiatives to understand global GDE distributions include the Springs Geodatabase from the Springs Stewardship Institute,[43] and the Ramsar List of Wetlands of International Importance, but we do not summarise these sources here as their coverage reflects the geography of contributing institutions and the nomination decisions of signatory states rather than a systematic representation of GDE locations.

At our scale of comparison (~55 km grids at the equator), almost every grid cell whose land cover permits GDE occurrence contains at least some GDE fraction (Figure 1a). Although groundwater dependence is predominantly framed as a feature of arid landscapes, GDEs are in fact present in all biomes (Figure 1b). Indeed, aquatic GDEs are considerably more extensive than terrestrial GDEs globally (Figure 1c). This suggests it may be more useful to understand GDEs through their areal density (e.g., sparse versus dense) and landscape composition (i.e., what types of GDEs are present) rather than through a binary presence or absence classification.

GDE extents generally decrease with aridity (Supplementary Figure 3) as reduced precipitation excess limits recharge and deepens water tables. Terrestrial and aquatic GDE distributions generally follow the same density gradients (i.e., landscapes with extensive terrestrial GDEs often co-occur with landscapes with extensive aquatic GDEs), and this coupling is especially strong within Holdridge Life Zones (a bioclimatic ecosystem classification based on precipitation, temperature and evapotranspiration)[44] (Figure 1d). Both aquatic and terrestrial GDEs are most extensive in low elevation, humid environments (e.g., tropical and temperate forests; Figure 1e). Relative distributions of terrestrial and aquatic GDEs differ across environmental gradients and landforms (Figure 1f). For instance, a larger share of aquatic GDEs is present in plain landforms than of terrestrial GDEs, while mountain landforms hold a larger share of terrestrial GDEs than of aquatic GDEs.

These distributions align with plausible process explanations. For instance, in mountainous landscapes with deep water tables, the water table often falls below the depth threshold for surface expression before it exceeds the reach of deep-rooted phreatophytes. Conversely, water table depth is often shallower in humid plains, which are often discharge zones of regional groundwater flow with high permeability geology that supports extensive groundwater-surface water interactions and wetland formation.

GDEs provide social and ecological functions across a range of landscapes, climates, and area densities. For instance, GDEs that are extensive across the landscape (e.g., large wetland complexes such as the Napahai Wetland in Figure 1b) perform functions such as regulating land surface heat fluxes,[45] supporting peat accumulation and anaerobic storage of soil organic carbon,[46] and providing a continuous habitat for biota[47] such as species adapted for constant temperature. Conversely, GDEs that are sparsely located within a landscape perform functions such as buffering microclimates, acting as ecological habitat for specialist fauna and phreatophytes,[48,49] and as refuge for pastoralists.[50] These occur across a range of aridities, from hyper-arid oases (e.g., Blanche Cup Mound Springs, Australia; Figure 1b) and arid phreatophyte patches (e.g., the *Populus euphratica* forests of the Upper Tarim River, China; Figure 1b) to seasonally dry Mediterranean landscapes where GDEs such as coastal woodlands (e.g., *Quercus agrifolia* in Marin County, USA; Figure 1b) support biodiversity hotspots. GDEs in arid climates are typically perceived as the stereotypical form and imagery used to depict GDEs.[18] These GDEs are often named places, sacred sites, or sites of cultural and spiritual significance, such as the role of Mound Springs in the Dreaming stories of Indigenous Australians,[51] and this visual identity and cultural significance aid in motivating the protection of these ecosystems, independent of their limited spatial extent.

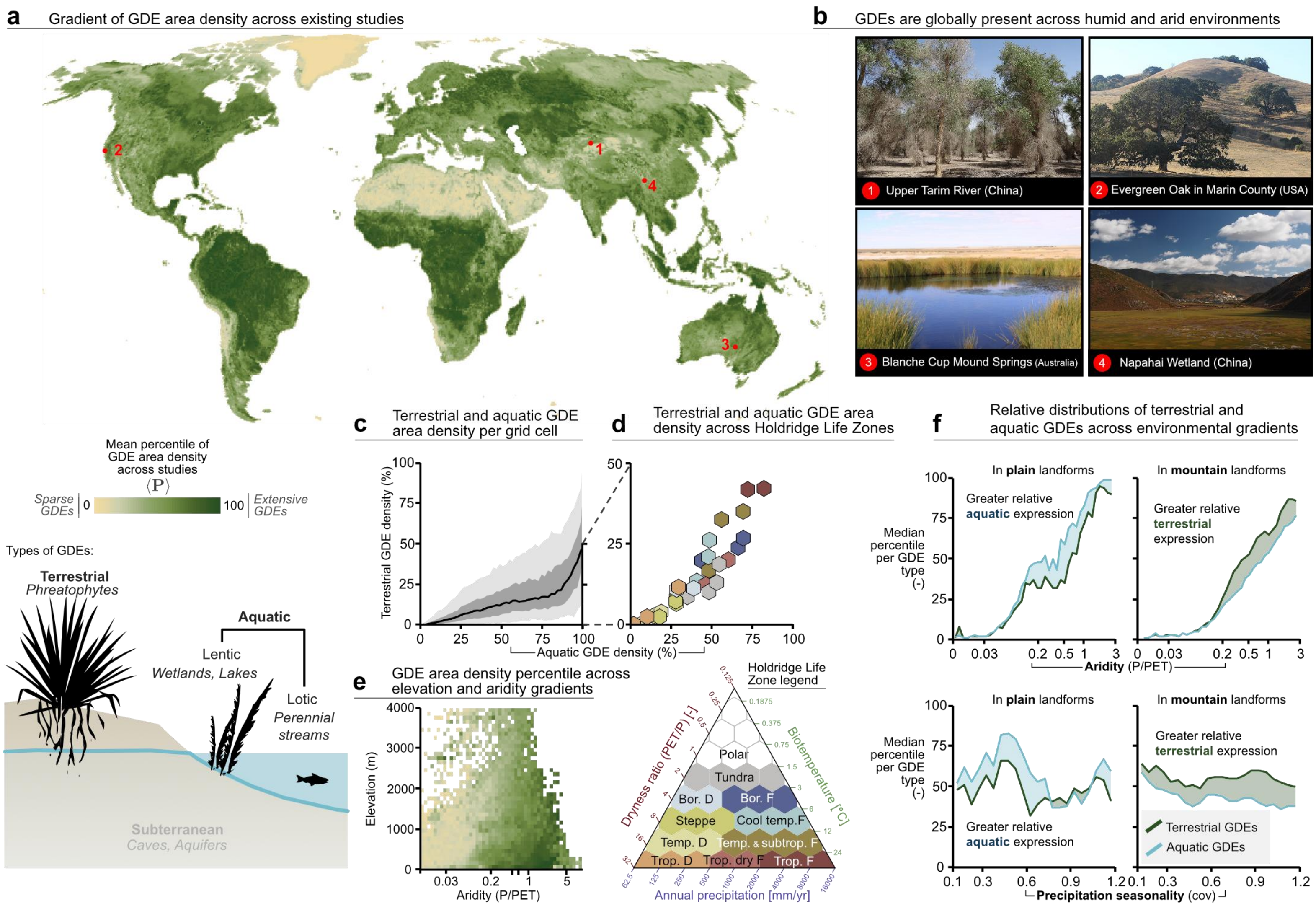

Figure 1: The emerging global picture of GDEs. (a) The mean area density percentile of GDEs across available global GDE distribution studies (see Supplementary Figure 1 for individual study maps). (b) Four environments with GDEs, whose locations are identified in the global map. (c) Global grid-cell comparison of aquatic and terrestrial GDE area densities. (d) Mean terrestrial and aquatic GDE area densities per Holdridge Life Zone. In the Life Zone legend (located below the scatter plot), D. = desert, F. = forest, Temp. = temperate, Trop. = tropical, and Subtrop. = subtropical. (e) Mean GDE area density percentile across aridity (P/PET) and elevation (metres above sea level). This plot uses the same legend as panel a. (f) Relative distributions of terrestrial and aquatic GDE percentiles across gradients in aridity (top row) and precipitation seasonality (bottom row), within plain landforms (left column) and mountain landforms (right column). All landforms are plotted in Supplementary Figure 4. See Acknowledgements for panel (b) image credits.

A dynamic, process-based understanding of global GDEs under multiple pressures

While existing studies provide benchmark estimates regarding the contemporary extent and composition of global GDEs, they are difficult to appraise without the context of a historical baseline. A major limitation of current global GDE studies is the omission of temporal dynamics. Multi-century global wetland extent reconstructions[52] and estimates of potential natural vegetation in the absence of human activities[53] offer useful reference initiatives to build on, yet there remain no global time series that cover the full range of GDE types. Developing such temporally resolved data is a necessary step to generate causal theories on GDE formation in landscape processes and to understand GDE responses under pressures from global change and human activity.

Presently, process-based global hydrological models are being developed to represent surface expressions of groundwater[54] and groundwater-surface water interactions.[55] However, using existing hydrological tools to model GDEs remains a difficult task. Groundwater models typically represent vegetation statically and are unable to represent two-way adaptive coupling, such as between rooting depths of plants and water table fluctuations.[56] Dynamic global vegetation models represent some adaptive vegetation processes but poorly resolve groundwater dynamics. How to best approach embedding ecological knowledge of GDEs into global frameworks to support reliable models is an important priority for the discipline. Given that ecological thresholds for GDEs are specific to regional climate, flora, and habitat types, global GDE modelling efforts could consider aggregating region-specific models, such as has been argued as an opportunity for the broader global groundwater modelling community.[57]

Robust global GDE science will rest on the adoption of research practices which recognise that groundwater-ecosystem interactions occur within complex, open systems that exhibit path dependence, emergent behaviour, and potentially multiple stable system states.[13,58] Thus, opportunities for global GDE science include understanding how GDEs interconnect with Earth system processes such as atmospheric moisture recycling;[59] mapping and tracking the extent and condition of GDEs worldwide; and identifying how changes in GDE conditions propagate to impact global social-ecological systems through altered functions and services such as climate buffering, nutrient retention, and pastoral refuge. Further, systematic global perspectives enable comparison of the severity of change across regions and can help identify priority areas for more localised investigation.

Preliminary global studies have considered the risks of groundwater depletion[34,35] and deficiencies in area-based conservation measures.[33,35] These evaluations show that over half of dryland GDEs are facing regional declines in groundwater storage, which can be attributed to both human and climate drivers,[35] and similarly that half of tropical GDEs, a third of arid GDEs, and a fifth of temperate GDEs are located in regions with at least moderate pumping-induced groundwater stress.[34] However, depletion is only one of many pressures facing GDEs worldwide, which include groundwater warming, drought, land use change, groundwater pollution,[60] and their combined impacts. Figure 2a-b highlights the occurrence of three primary pressures for which data are available: regional groundwater depletion,[61] land conversion pressure,[62] and groundwater warming under climate change.[63] These pressures pose distinct risks to GDEs, which are summarised further below.

There are regional patterns in the combined occurrence of these pressures (Figure 2b). The Ganges-Brahmaputra Basin, the southern Ogallala aquifer, the Brazilian Cerrado, the North China Plain, and the Eurasian Steppe all show elevated states of all three pressures. Further, the majority (over 75%) of the terrestrial land surface is facing at least one of these pressures. Thus, despite mapping only a small subset of pressures facing GDEs, the global extent of biophysical challenges facing GDEs is evident. Yet, little is known about how GDEs respond to these pressures, individually or in combination, from catchment to global scales.

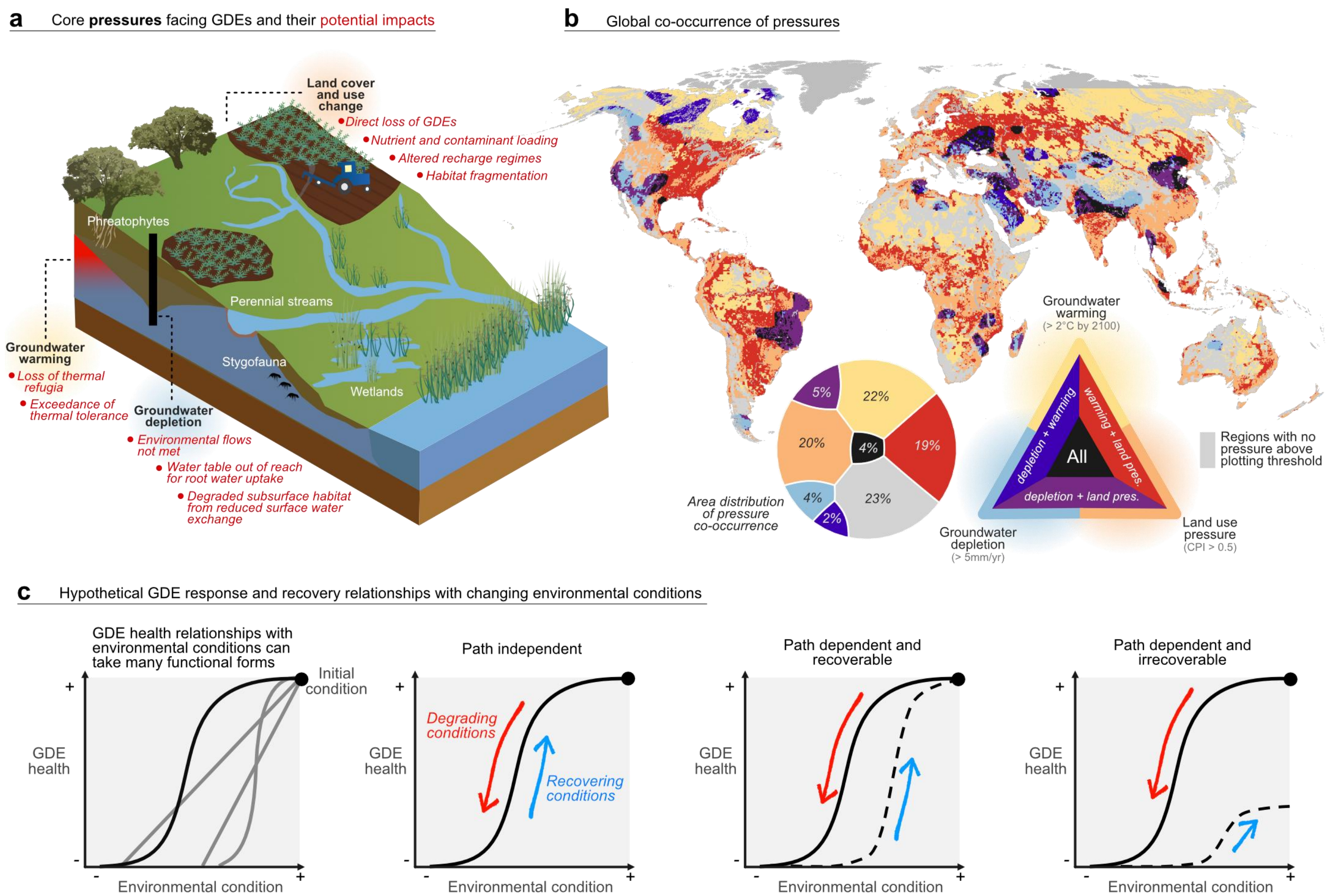

Figure 2: Global pressures and uncertain responses from GDEs and groundwater biodiversity. (a) Some of the global pressures and their potential impacts on GDEs and groundwater biodiversity. (b) The co-occurrence of these pressures. The Voronoi tree reveals the area distribution of pressure combinations across the terrestrial land surface. For the land conversion pressure legend, CPI represents the conversion pressure index.[62] See the Supplementary Information for the data handling steps used to produce the map. (c) Potential relationships in GDE health as a function of environmental conditions,[64] which are likely path dependent and in some cases irrecoverable. One curve in the leftmost panel is highlighted to denote its use, among the others, in the subsequent plots in panel c.

To stimulate broader consideration of system interactions with GDEs, we discuss here plausible GDE responses to these pressures. Previous work has emphasised that groundwater quantity, timing, and quality all affect GDE health, with response curves specific to organism age, species, and ecosystem type.[64] We raise the need to consider path dependence and recoverability (i.e., resilience[65]) in these functional relationships between ecological conditions and GDE health (Figure 2c), as few (if any) ecosystems exhibit path independence.[66]

The plausible relationships we summarise below are informed by studies typically conducted at site-specific scales. However, as local response functions do not scale linearly across heterogeneous landscapes, we do not assume the same relationships necessarily hold at coarser resolutions. For example, negative ecological responses to altered streamflow regimes are well documented at the reach scale[67] yet initial efforts have so far been unable to identify these same relationships at basin and global scales.[68]

Groundwater depletion, which results from both natural variability and human-caused climate change and pumping,[69] has extensively documented GDE impacts across scales. These include: reducing perennial stream networks[70], springs[71], and their flow; transgressing environmental flow needs;[72] driving transitions in community composition and tree health once drawdown thresholds are surpassed;[56,73,74] and degrading and eliminating[75] subsurface habitat through weakened exchange with surface water, which reduces food and oxygen for groundwater biota.[76] During groundwater depletion, GDEs may remain relatively stable in extent and community composition until a threshold is crossed, such as a maximum rooting depth, a rate of change exceeding root zone adaptation rates, or a stream stage resulting in a change from a gaining to losing stream. Once crossed, groundwater-dependent vegetation may die off, soil desiccation may alter soil texture and organic matter and lead to compaction and subsidence, and invasive species may alter community composition.[19] Recovery processes are likely path dependent where water table recovery occurs on faster timescales than ecosystems can re-establish their structure, composition, and function, particularly if groundwater depletion resulted in further changes in soil structure or hydraulic conductivity. In some cases, such as land subsidence resulting from irreversible aquifer compaction, ecological recovery may be impossible even if groundwater levels recover (Figure 2c).

Land use change, which includes threats such as forestry and the drainage of peatlands, directly results in the loss and conversion of GDEs to other land cover types and carries further impacts through altered groundwater recharge regimes,[77] nutrient and contaminant loading, habitat fragmentation, and soil compaction. In the case of land cover change where GDEs were present, this represents a direct loss of GDE area. How this aggregates regionally is difficult to anticipate, as many drivers and response thresholds act asynchronously across large areas, and thus individual thresholds may not be discernible in aggregate regional responses. Legacy effects of landscape conversion such as entrenched invasive species and altered recharge pathways may sustain a degraded GDE condition after land use pressures are reduced.

The evidence base of groundwater warming impacts on GDEs is small, but initial work shows that faunal diversity decreases with warming temperatures[78] as environments exceed the thermal tolerance of groundwater biota. Studies have revealed non-linear thermal tolerance mortality frequencies in groundwater crustaceans[79] and potential regional extinction of cold-temperature specialist macroinvertebrates with warming groundwater temperatures.[80] We do not hypothesise recovery curves for groundwater warming as reversal of temperature increases is unlikely over human timescales. Warmer groundwater will also likely impact riverine ecosystems sustained by groundwater discharge[81] by increasing microbial metabolic rates and altering nutrient cycling,[82] and by eroding cool-water refugia.[83]

Incorporating GDEs can enhance global-scale science and policy agendas

GDE science and policy are inherently interdisciplinary as they require the integrated consideration of geological, hydrological, biological, ecological, and social systems in diverse environments. A global GDE perspective can therefore offer new and needed contributions to several existing priority agendas in science and policy. Yet, GDEs remain largely absent from these agendas despite their potential to make each more robust. We highlight a subset of these opportunities below through *prima facie* comparisons of global datasets (Figure 3), yet these comparisons do not substitute for rigorous analyses that we leave for future work.

GDEs can further enhance our understanding of groundwater-climate interactions (Figure 3a). Flux partitioning is a fundamental dynamic of the global water cycle,[84] and groundwater-climate interactions are a core Earth system process.[85] Globally, the mode of these interactions has been analytically modelled,[86] and process-based models estimate these interactions based on root water uptake modules.[27] However, a direct comparison of terrestrial and aquatic GDE locations with analytically modelled groundwater-climate interactions reveals many contiguous regions with extensive GDEs in areas estimated to have limited groundwater evapotranspiration potential.[86] These regions (red areas in Figure 3a) may be starting points to investigate whether groundwater evapotranspiration is being under-accounted due to neglected consideration of GDE processes, or equally starting points to refine frameworks to assess groundwater-climate interactions through the incorporation of ecohydrogeological variables.

GDEs can help enhance groundwater representation in Earth system change and resilience frameworks (Figure 3b). Groundwater has long been a challenging Earth system element to include in Earth system resilience initiatives, such as the Planetary Boundaries[87] and the safe and just Earth system boundaries.[88] These challenges arise as groundwater is a fundamentally local resource[89] with minimal mixing and connectivity across continental to global scales in comparison to other Earth system elements. In these frameworks, a simple accounting of groundwater use is insufficient to represent functional impacts on hydroclimatic and hydroecological regulation, and on nutrient transport.[85] Misrepresenting groundwater dynamics may lead to counterproductive policy recommendations that are inconsistent with Earth system resilience, sustainability, and justice goals.[90] Rather than aggregating groundwater stores or consumption fluxes, incorporating GDE condition as a response variable might offer a pragmatic way to better represent groundwater's hydroecological and hydroclimatic functions in these frameworks. For instance, the proportion of present-day GDE areas facing meteorological drought now exceeds a range of natural variability, characterised here for illustrative purposes using a 1970–2000 reference period (Figure 3b). Yet incorporating GDEs into such frameworks depends not only on selecting the right control variable, but also on understanding the causal processes linking environmental controls to GDE condition, which, as argued above, remains poorly understood at the global scale.

GDEs warrant dedicated protection targets in global conservation initiatives (Figure 3c). Only one-fifth of dryland GDEs benefit from some form of legal protection, and 85% of GDEs inside protected areas are vulnerable to human impacts occurring outside of protection boundaries from exposure through lateral groundwater flow.[33,35] Many ecosystems receive protections from dedicated international policy, such as through conventions or international assembly resolutions, some of which overlap with GDE types (the Ramsar Convention on Wetlands or the United Nations Environmental Assembly Resolution 4/16 on peatlands). Yet, given that an estimated three-quarters of the global land surface, excluding deserts and high mountains, have medium-to-high interactions with groundwater,[29] direct conservation of global GDEs is warranted. Presently, high-aridity GDEs are less protected than GDEs in humid climates despite being typically more vulnerable to environmental pressures (Figure 3c). Indeed, aside from humid regions with extensive GDEs, GDE protection is presently falling short of reaching the Kunming-Montreal Global Biodiversity Framework target to conserve and manage 30% of land area by 2030.[91,92] While there are several guidelines for effective GDE protection,[19,93,94] it remains that too few GDEs are sufficiently protected.

GDE conservation can support global carbon policy (Figure 3d). There are many regions worldwide with high levels of soil organic carbon and extensive GDE presence (Figure 3d), including the Amazonian headwaters, coastal tropical western Africa, island southeast Asia, the Baltics, Siberia, and central boreal Canada. In many of these regions, the carbon is held in waterlogged organic soils sustained by groundwater levels. GDE conservation and management in these areas not only supports their hydrological, ecological, and social functions but doubles as a measure to prevent soil organic carbon mineralisation. Drained peatlands alone contribute 5% of global anthropogenic carbon emissions from only 0.4% of land area.[95] It may prove strategic to embed GDE protection within existing carbon policy initiatives since peatlands and wetlands (a subset of which are GDEs) are already recognised in international carbon accounting frameworks.[96] Making this conceptual link between carbon-rich ecosystems and GDEs may generate broader awareness about the value of conserving and managing GDEs while simultaneously encouraging the integrated, landscape-scale considerations inherent to GDE management.[94]

Given the widespread omission of GDEs from global policy agendas, advancing research questions tailored to connect GDE insights to existing policy priorities may prove an effective strategy for their broader recognition, protection, and inclusion in these agendas. Several open questions remain unexplored in the global GDE literature, which we list in Table 1 to stimulate their further consideration and uptake by the broader research community. Many of these directions may equally be pursued at finer scales, and aggregating regional assessments into global databases will likely prove useful given the heterogeneity of GDEs across diverse biomes. Yet, closing knowledge gaps at the global scale is necessary to more fully quantify GDE interactions with the Earth system, to incorporate GDEs into Earth system change frameworks and global-scale policy, and because certain phenomena, such as teleconnections and cross-scale interactions, require an understanding of global processes to fully resolve.

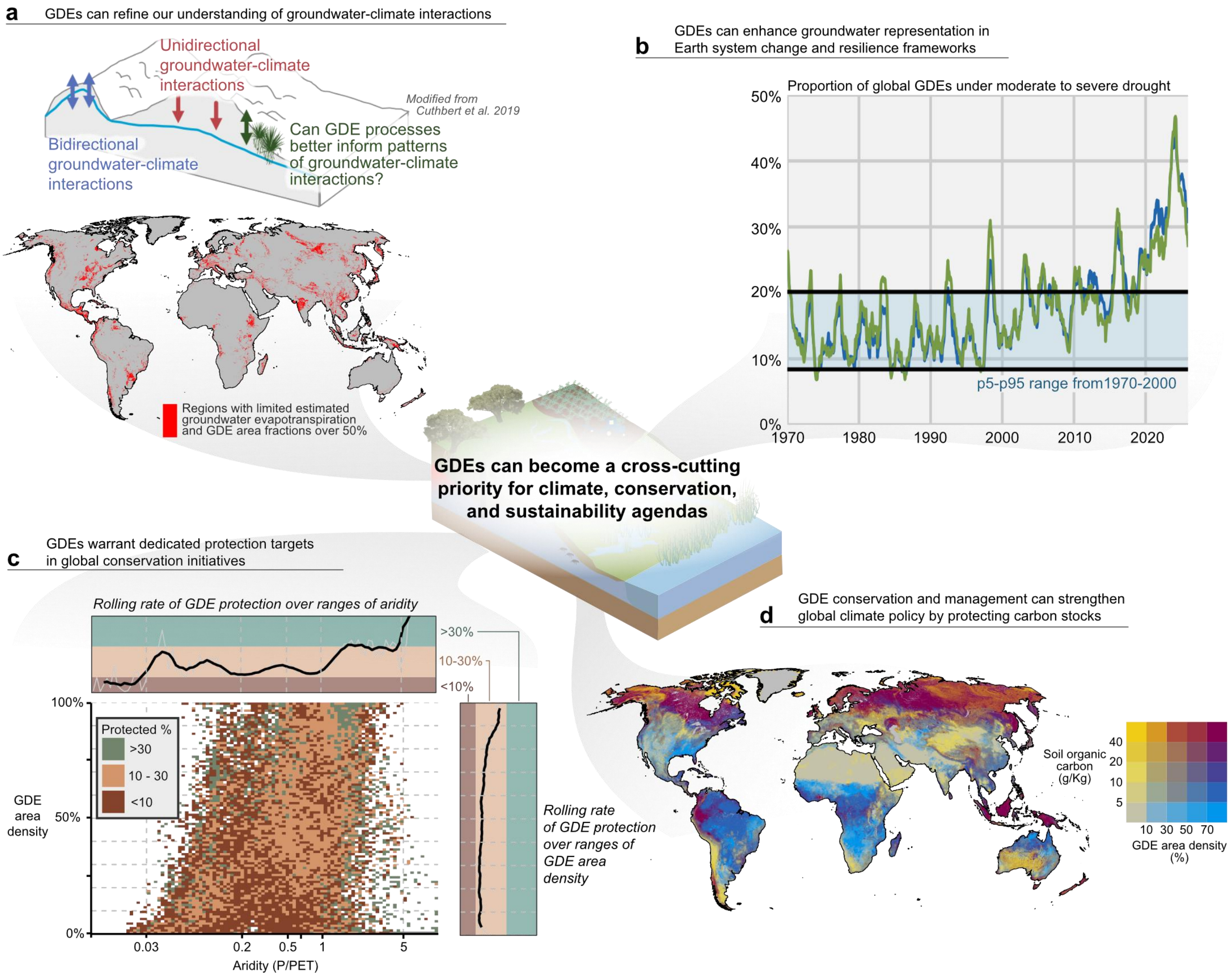

Figure 3: Global GDE perspectives can strengthen existing global science and policy priorities. (a) Relationship between aquatic and terrestrial GDE presence and groundwater-climate modes of interaction. (b) Time series of the fraction of present-day aquatic (green) and terrestrial (blue) GDEs experiencing meteorological drought over the past 5 decades. (c) The area-based formal protection status of aquatic and terrestrial GDEs worldwide across aridity and GDE area density. Rolling windows of protected fraction are shown above and to the right of the plot. (d) Bivariate global map of soil organic carbon (SOC) stores within the upper 2m of the soil column and combined aquatic and terrestrial GDE area density.

Table 1: Research opportunities for advancing global GDE science to embed GDEs within global policy and Earth system frameworks.

Policy-relevant questions	Research directions that address these needs
Where do GDEs exist, and how has this changed?	• High-resolution GDE maps across diverse environments beyond drylands • Historical reconstructions of GDE extents • Projections of future GDE states under interacting climate and land use scenarios
What functions do GDEs perform, and how can they be managed?	• Spatially explicit understanding of GDE ecosystem services and service bundles • Identification of pressure-response thresholds in GDEs across all scales
How do GDEs support biodiversity at regional and global scales?	• Groundwater quantity and quality thresholds for species conservation within GDEs under interacting climate and land-use scenarios • GDEs as refugia and stepping stones in continental migratory networks
How can protected area and management strategies be designed to safeguard and restore GDEs?	• Integration of GDEs, groundwater catchments, and groundwater biodiversity into terrestrial and freshwater protected area accounting • Large-scale restoration and rewetting approaches for degraded GDEs
How do GDEs contribute to climate regulation?	• Potential role of GDEs in maintaining Holocene-like climate stability through groundwater-vegetation-atmosphere feedbacks • Quantifying GDE contributions to atmospheric moisture recycling and associated downwind precipitation and recharge
How do groundwater trends and GDE conditions affect global carbon cycling?	• Accounting of carbon stocks in global GDEs with a focus on groundwater-fed organic soil systems • Groundwater depletion as a carbon release mechanism in peatlands
How can GDEs be incorporated into global sustainability initiatives?	• GDE incorporation into SDG reporting and successor initiatives, with targets referenced to historical GDE extents • Incorporation of GDE response thresholds to inform groundwater inclusion in Earth resilience frameworks • GDEs as sentinel indicators of groundwater sustainability and Earth system change

GDE scholarship is not a new form of research but rather the collaboration of multiple research topics on groundwater system interactions that each have long histories of scholarship: groundwater-plant interactions, groundwater-surface water interactions, wetlands, groundwater-climate interactions, groundwater biology, groundwater ecology, and groundwater social-ecology. This collaboration around the concept of GDEs has been productive and impactful at the local scale and is only beginning to gain attention at the global scale. In an era of intersecting global challenges, tailoring global GDE science to interdisciplinary policy priorities can strategically position these efforts to advance the safeguarding of GDEs alongside the shared futures of the planet's biodiversity, climate, and society. Doing so may even make crucial advances regarding one of the most persistent challenges of groundwater science and management: making this "invisible" but global resource visible, protected, and prioritised.

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Data availability

All datasets used in this study are summarised in Supplementary Table 1. Derived data used to produce Figures 1-3 will be deposited in an open access repository following manuscript acceptance. No new data were collected for this study.

Code availability

Data processing scripts used to develop all figures are available at the GitHub repository https://github.com/xanderHuggins/global-gde-outlook and will be archived in an open access repository following manuscript acceptance.