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Lines in the landscape

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Ditches (linear constructions which store and/or move water where humans prefer it to go), via irrigation, drainage, and power, have helped drive the development of human societies. Now, ditches and other linear channels, typically carrying water, are numerous and found on every continent. Their form varies widely with use, which includes land drainage, irrigation, transportation, and boundary marking. Ditches support and shape biogeochemical cycles, biotic communities, and human societies, at multiple spatiotemporal scales. However, ditches are frequently overlooked by researchers in many disciplines. Here, we review the largely unrecognized role that ditches play in environmental processes and human societies. The effects of ditches can be both positive (e.g., biodiversity refuges, water for food production, nutrient retention) and negative (e.g., greenhouse gas emissions, dispersal of pollutants). We call for future management to consider and enhance the multifunctional role that ditches can deliver at the landscape-scale.

Human societies, globally, have enacted control of hydrological systems through drainage and irrigation, with evidence of linear waterways dating as far back as 8000 years[1]. Ditches enabled the expansion of agriculture and settlements, by both supplying and excluding water, and allowed early humans to produce a surplus of food, which allowed part of society to be freed from agricultural labor. Thus, ditches provided the opportunities for societies to focus time and resources on cultural and commercial endeavors[2]. Today, ~40% of global food production relies on irrigation and ~15% on drainage, and these dependencies are expected to increase[3]. Although ditches are widely distributed and found on every continent (even Antarctica[4]), their global extent is poorly quantified, with drained and irrigated cropland estimates varying between 130–200 Mha and 270–300 Mha[3,5]. In the Northern Hemisphere, forestry drainage occupies an additional 15 Mha[6] (Fig. 1C). The extent of ditch networks at the national scale can be extremely large (e.g., 300,000 km in the Netherlands[7]; 800,000 km in Sweden[8]) and a rough estimate of the global surface area of drainage ditches alone is 1.4–10.7 Mha[9].

As ditch and irrigation networks have grown globally, so have their effects on natural hydrological cycles; they have drained and degraded wetlands[10] and altered water flows through ecosystems at the landscape scale and beyond[11]. At the same time, the existence of non-human life has also become increasingly interconnected with these channels[12–14]. Ditches are palimpsests, echoes of past landscapes overwritten by human actions and naturalized again, embodying both creation and destruction. They challenge the human-nature dichotomy[15], both of, and not of, natural waters. Simultaneously, ditches constitute an integral part of the hydrological network supporting remnants of aquatic ecosystems[16] and exemplifying novel ecosystems[17]. Ditches often mimic natural waterways, whether by design or inadvertently, and yet sometimes surprise scientists by behaving differently[9]. In turn, they have the potential to serve as models for experimentation, which can provide insights into how natural ecosystems may respond to global change[18,19]. Ditch networks can vary widely in their characteristics across space and time, both among and within individual channels[20], which can switch between terrestrial and aquatic states. This range, coupled with a

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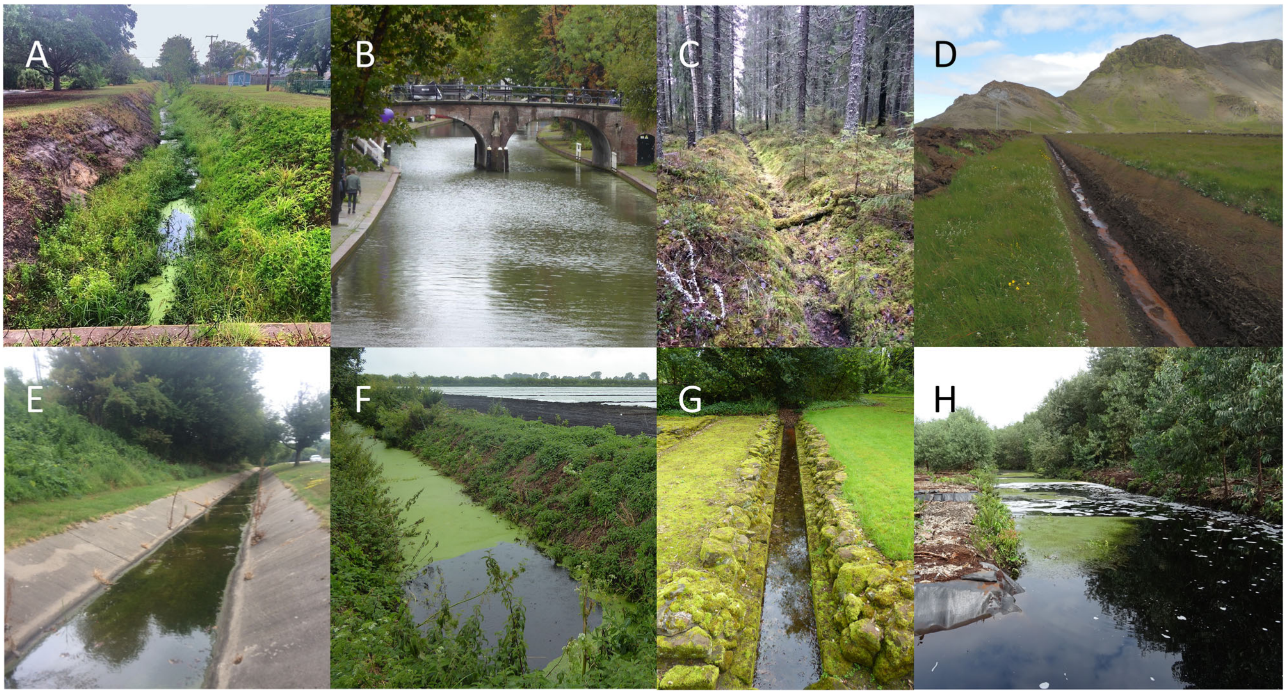

Fig. 1 | Ditches vary in form and function. **A** an urban drainage ditch in Venice, Florida, USA. **B** the Oudegracht ("old canal", dating from 1100 s) in urban Utrecht, the Netherlands, **C** an intermittent ditch in forestry, Sweden, **D** a ditch in a drained peatland converted to grassland, Iceland, **E** a roadside drainage in Ames, Iowa, USA, **F** a drainage ditch in intensively-managed arable peatland, UK, **G** monastic (latrine) drain at the medieval Norton Priory, UK, **H** water management canal in an Acacia plantation, Indonesia. Photo credits: Chelsea Clifford (**A**, **E**), Mike Peacock (**B**, **F**, **G**), Eliza Maher Hasselquist (**C**), Chris Evans (**D**, **H**).

high degree of human control, makes ditches ideal systems for adaptively responding to global environmental change and to shifting human needs and wants[18]. Yet the diverse ecosystem services from ditches often conflict when they sometimes could synergize to deliver multifunctionality (i.e., multiple ecosystem services simultaneously)[20,21]. Maximizing positive synergies requires collaboration between disciplines and stakeholders to optimize ditch potential and avoid pitfalls[18]. Unfortunately, despite their fundamental importance to society and potential to supplement ecosystem services, ditches remain understudied and undervalued[21,22].

For the purposes of this paper, we define "ditch" as a narrow linear channel on Earth's surface constructed to store and/or convey water where humans prefer it to go. However, the vague boundaries of this definition are somewhat arbitrary; defining ditches is surprisingly non-trivial. Typically, they are narrow, but some can be wider than 25 m[23], and individual channels may run for just a few metres or for hundreds of kilometres in length. Although "ditch" is an English word, other languages classify what English-speakers might call *ditches* differently (see Table 1 for collated definitions). Therefore, even though ditches exist globally, the word "ditch" may not translate well across cultures. Even the English language might use different words for ditches depending on their dominant functions including: irrigation and drainage (e.g., rhyne, gripe, catchwater, gutter, dyke, conduit), water storage, power (e.g., leat), burial, bioreaction, transport (e.g., canal, waterway), defense (e.g., moat), livestock control, and boundary-marking, including as barriers (e.g., ha-ha) to encroachment. The purposes of ditches, the way they have been constructed and managed, and their resultant characteristics and classification vary over time and space (Fig. 1, Supplementary Table 1). Furthermore, the perception and value of ditches may influence how we classify them. The word "ditch" itself has a negative connotation within the English language both as the verb to 'ditch', meaning get rid of, and as exemplified by idioms like "ditching" something unwanted, and "dull as ditchwater." This perspective may lead humans to avoid defining features we value as ditches, reaching instead for more positively associated terms such as "canal," "stream," or "blue infrastructure." From an environmental perspective, ditches' inherent artificiality can devalue them[13,24]. That said, even artifice can be murkily non-dichotomous, as in the case of channelized streams. Naturalization away from constructed form often occurs over time, especially in the absence of repeated dredging[13], and ultimately ditches can become archaeological features[25]. Similarly, ditches and their subtypes fall somewhere within gradients in many of their physical characteristics, including size, network position, composition of bed material, connectivity to other waterbodies and floodplains, flow direction and speed, and even ability to hold water. The precise boundary around all ditch-like systems within these gradients and categories is, as we found, nearly impossible to agree upon, and ultimately arbitrary. That observation itself points towards ditches' actual status as indivisible component of socio-ecosystems (an ecosystem and its associated human actors). So, for the purposes of this article, we shall not endeavor to precisely corral "ditches" from "not ditches." We acknowledge that even our working definition will vary somewhat over the course of this article, in part as it crosses disciplinary lines and corresponding definitions.

In this paper, we present a multi-disciplinary perspective on how and why ditches are important. We review the state of knowledge pertaining to the different aspects of ditches including physical, biotic (excluding humans), chemical, and human dimensions. We also recommend future research and management considerations and outline knowledge gaps. Many of these future considerations presented will be opportunities, for ditches are rife with these; the potential for ditches to be adaptively managed for greater diversity of ecosystem services[13,18,21]. Given that people will continue to construct and maintain ditches, we as researchers have an opportunity to positively influence their design, use, and management[26]. At the same time, we can gain more broadly applicable knowledge from these distinctive, but common socio-ecosystems[19]. If we only let them, ditches can serve as a multi-tool for both humans and other species to survive and thrive under global environmental change[18], helping to achieve sustainable development goals[27], and addressing a myriad future challenges. We hereby invite researchers who have not yet done so to meet the multitudes of the ditch.

Human dimension

Our working definition of ditches necessitates human conception, execution, and embodiment. In other words, without people playing

Table 1 | Summary of ditch definitions collated from published work

Type	Definition	Reference
Agricultural	"Man-made channels created primarily for agricultural purposes, and which usually: (i) have a linear planform, (ii) follow linear field boundaries, often turning at right angles, and (iii) show little relationship with natural landscape contours."	Williams et al.[237]. Brown et al.[238]. Davies et al.[239]. Davies et al.[240]. Clarke[203]. Shaw et al.[241]. Hill et al.[187]. Biggs et al.[16]. Bubíkova and Hrivnak[242]. Nakano and Morii[243]. Williams et al.[244]
Agricultural	"Ditches are defined as artificial, linear channels < 3 m wide which follow anthropogenic boundaries (e.g., field margins). Drains are larger features (> 5 m wide) which display otherwise similar characteristics."	Gething and Little[245]
Agricultural	"Dutch ditches are linear water bodies typically several metres wide and up to 1 m deep."	Verdonschot al.[7]
Agricultural	"Drainage ditches are small, stagnant, line-shaped water bodies, dug to improve rainwater run off and regulate the groundwater level of surrounding agricultural areas."	Verdonschot et al.[246]
Agricultural	"Ditches are linear elements with a high edge ratio that are subjected to an intensive exchange of matter and organisms from the surrounding terrestrial matrix. Most of the ditches are likely to be relatively shallow with marked fluctuations in water levels and a higher probability of drying out during summer. Finally, ditches are regularly managed for efficient drainage."	Herzon and Helenius[21]
Agricultural	"Drainage ditches are limited to those structures created to drain production acreage."	Cooper et al.[247]
Agricultural	"Farm ditches are human-made linear elements that constitute the upstream parts of the permanent hydrographic networks in agricultural landscapes. Primarily implanted within farmed landscape to collect surface and subsurface water in order to drain excess water and/or to prevent soil erosion…"	Dollinger et al.[20]
Agricultural	"Agricultural drainage ditches are essentially headwater streams, which, like capillaries, act as direct links between agricultural fields and naturally occurring streams and rivers."	Fu et al.[248]
Agricultural	"Ditches were defined as open field drains which flow into streams and are generally unmapped."	Shore et al.[249]
Agricultural	""Ditch" is used to describe systems either created or maintained by human activities in order to increase water conveyance; whereas "drainage" refers to the practice water removal, or, when used in conjunction with "network" or "system," describes the entirety of streams and ditches modified for water conveyance."	Pierce et al.[250]
Agricultural	"Ditches… artificial linear water bodies whose depth and flow are regulated by sluice gates and pumping stations for the purposes of water-level management."	Watson & Ormerod[208]
Agricultural	"Artificial channels built for agriculture irrigation purposes, generally have a regular U-shape and are approximately 0.5–3 m wide and 0.5–1 m deep distributed around farmland in agricultural regions."	Sun et al.[195]
Forest	"Headwater streams were classified as ditches if they were perfectly straight, if they made unnaturally sharp turns (e.g., 90° turns), or if they were clearly part of ditch networks (i.e., numerous parallel watercourses, geometric drainage networks)."	Peacock et al.[165]
Roadside	"Grassed roadside drainage ditches are shallow, open vegetated channels that are designed to convey stormwater runoff to storm sewers or receiving water bodies."	Ahmed et al.[251]
General	"Drainage ditches are small, linear water bodies, usually <1.5 m deep and several metres wide, situated both in lowland and in highland zones."	Nsenga Kumwimba et al.[252]
General	"A long, narrow excavation artificially dug in the ground; especially an open and usually unpaved waterway, channel, or trench for conveying water for drainage or irrigation, and usually smaller than a canal. Some ditches may be natural watercourses."	European Protection Agency[253]
General	"Ditches, irrigation channels and water supply canals, are constructed linear waterways, although their physical characteristics and function may vary widely."	Peacock et al.[9]

Note: this is not intended to be fully comprehensive. In the text, we mention the problems that arise when considering the English word "ditch" and other languages. For example, in Dutch, "ditch" best translates as "sloot". A sloot is defined as an artificial permanent linear water body, exhibiting a maximum width of 8 meters and usually not more than 1.5 m deep with negligible flow (<5 cm/s). Meanwhile, a greppel, is usually smaller than a sloot, with only artificial and intermittent or ephemeral flow, but would also translate to English as "ditch." We lump the two terms, sloot and greppel, along with several other independent Dutch words like (urban) wadi and goot, together as ditches in English.

a vital role at some point in their life history, a ditch is not a ditch. This fact may in great part be responsible for the lack of attention ditches have received in the natural sciences—they are not 'natural' when natural is understood as lacking human influence. In contrast, ditches have been a major topic of historical and archaeological inquiry (Fig. 1G), which traces ditches through time for at least the past 8000 years in different places around the globe precisely because they are clear signs of human activity. A range of social sciences have also addressed governance processes, how ditches affect human well-being, and a suite of ditch-related legal issues[28,29]. Ditches are thus prime examples of socio-ecosystems; complex and integrated systems that include both the ecological and sociological environments, and the interactions between them[30]. Given this, the human part of the equation is essential to understand the whole.

Within our broad definition of ditches, irrigation (i.e., applying water to land for agriculture) is well-established in archaeological and historical scholarship and has been implicated as a key driver of state formation (i.e., the creation of states) and economic/social stratification in early agricultural societies[31,32]. Evidence for ditch-based irrigation systems are found in Mesopotamia from as early as the 6th millennium BC[33–36]. Early and indigenous ditch-based irrigation systems have also been examined across Asia[37,38] and North[29,39,40], Central[41] and South America[42]. Irrigation ditches of the past few centuries are somewhat less prominently studied archaeologically than older ones (but see De Meulemeester[43]). However, they are the subject of more substantial documentary research[44]. It should be noted that ditches and other hydrological controls are not exclusive to agricultural societies; fisher-hunter-gather societies have also constructed ditches to facilitate fishing[45]. Ditches are often complex archaeological features due to burial and preservation processes related to long-use histories, especially in prehistoric contexts[46]. There are also strong scholarly traditions in the theoretical underpinning of archaeological and historical interpretation of irrigation ditches, sometimes borrowing ecological concepts, for example viewing ditches through the lens of niche construction theory[47] or coevolution[48]. Canals (Fig. 1B) and leats (ditches which specifically serve mills as either in- or outflows) have also been studied as part of power, transport, and urban histories[49]. Indeed, in Europe mill streams and their associated leats and sluices can be considered an example of coevolutionary socio-ecohydrological systems (*sensu* Sivapalan & Blöschl[48]), whereby over hundreds of years natural streams were modified to drive mills, which were later closed, leaving behind a hydrological legacy of remnant constructed channels[50].

Globally, 21% of wetlands have been anthropogenically drained[10], largely via drainage ditches (i.e., ditches that remove excess water from the land) (Fig. 1D, F, H), resulting in a massive loss of natural wetlands. Despite this, drainage ditches have been less often archaeologically or historically studied than irrigation ditches, although this is changing with the global rise in the importance and value placed on peatland landscapes for biodiversity and carbon sequestration[51]. While historical attention to drainage is common[52], research usually occurs at broader scales than examining or mapping the ditches themselves, with a view to understanding wider society, institutions, and worldviews. For example, the 17th century drainage of the Fens in eastern England has been the subject of extensive research, examining its economic impact[53], the politics of wetland drainage[54], and its public health implications[55]. Taking drainage ditches' relational and land parcel-formation into account also makes it possible to identify former hydrological conditions. For example, drainage ditches in now fully leveled reclaimed bog polder in the Netherlands sometimes still show a wedge-shaped structure, revealing their original orientation towards the top of the now missing domes of raised bogs[56] (Fig. 2). The drainage of wetlands, particularly over the last 1000 years for agriculture created both ditches and hedges which preserved relicts of past woodland cover and now form key havens of biodiversity in such environments[57,58].

Drainage ditches are usually understood archaeologically as threatening wetland archaeology through desiccation and other changes to burial environments[59]. This threat has prompted numerous regional assessments of drainage ditch-driven wetland loss as a way to estimate where and what wetland archaeology remains well preserved in-situ[60]. The archaeological and palaeoecological value of wetlands and ditches (a cultural ecosystem service in its own right) often comes primarily through anoxic conditions allowing for the survival of materials that in drier contexts would decompose; e.g., wood or soft tissue as well as macro and microscopic ecofactual (i.e., organic without human workmanship, yet culturally relevant) material[61], and now even ancient molecules including DNA[62,63]. Thus, efficient drainage via ditches represents a direct threat to the survival of that material, including in some cases, the ditch itself. Similarly, palaeoecologists have usually understood drainage ditches to have generally negative impacts on the preservation of palaeoecological records although, if abandoned and silted-up, they can provide excellent ecological records spanning centuries to millennia[64–66].

Fig. 2 | Drainage ditches can give clues to lost landscapes. Ditches in the Netherlands (52.20°N 5.12°E) show a wedge-shaped structure, and point towards the top of the (now missing) dome of a destroyed raised bog. Maps data: Google Earth, Maxar Technologies.

Ditches have left an archaeological and historic legacy of past humans and their relationships to the wider environment, as well as a paper archive where ditches have been mapped and described. These records attest to the fact that many regions' wetland environments can be more a product of ditches (irrigation and drainage), and thus human agency, rather than of geology and climate. In drained contexts, the outcome has been described as a 'reclamation landscape'[67]. Key challenges moving forward will be to understand how these histories of reclamation or irrigation have impacted an array of different ecosystem services, and how this combined origin then frames and directly impacts drives for wetland restoration. There is a possibility that without a full understanding of the deeper history of ditches in any given location restoration activities (blocking ditches or reducing irrigation) might have perverse outcomes. For example, the draining of swamp and marshland has generally been associated with the historical reduction in mosquito-borne diseases (such as malaria and Dengue Fever). Here, a clear understanding of vector ecology, as well as educational efforts, may be required to balance the pros and cons of wetland restoration in the public imagination[68]. Given the overlapping, multi-directional, and complex network of ecosystem services that are underpinned by ditches, holistic inter- and transdisciplinary approaches will be required when making decisions relating to the tradeoffs involved regarding changes to ditch hydrological regimes. Recognition of the importance of ditches as socio-ecosystems is an important first step.

Generally, active ditches contribute to human wellbeing through ecosystem services across all categories: cultural, regulating, and provisioning (supporting ecosystem services are often left out of current frameworks[69,70]) (see Supplementary Table 1). Traditional ditch systems—generally gravity-fed, not lined or covered—often supply water to relatively small-scale agriculture, and as such are sometimes seen as low-value or somewhat primitive. Fernald et al.[71] examined hydrological ecosystem services in irrigation systems in New Mexico, USA, traditionally referred to as "acequias". Depending on soil type and gradient, these traditional irrigation systems can yield later-season return flows to mainstem rivers. This service is crucial in arid environments with flashy hydrographs. Raheem et al.[72] examined a comprehensive suite of ditch-related ecosystem services for traditional irrigating communities in northern New Mexico, USA. A significant contribution of that work is to use the traditional Spanish terminology from those communities to describe a range of landforms usually described in English in the ecological literature. This sort of translation, from conventional scientific or planning terminology to local usage, is crucial in ascertaining the extent of cultural ecosystem services[73]. Others have looked at ditches through an ecosystem services lens; for example, when considering sediment retention and bird habitat in northern Mexico[74], investigating the 'multifunctionality' of agricultural water use[75], and the "nature-based solutions" provided by subak irrigation systems in Bali[76].

Many ditches, and particularly irrigation channels, are designed to provide provisioning ecosystem services. Ditches carry water to farm fields, to orchards, to arbors, and to fish ponds to support food production systems for human use. Ditches are used to produce power, by driving mills of various sorts[77], which in turn help to produce food and goods. Sometimes fish, crustaceans[78,79], and other species that inhabit ditches provide nourishment for humans. Humans and animals drink water from ditches, although many ditches carry away waste and sewage[80]. This latter function, both historically and to the present day, can have negative impacts on people who live within ditched landscapes or urban spaces. Indeed, ditches can and do often deliver an array of ecosystem disservices many of which (e.g., pollutant dispersal, greenhouse gas emission, facilitation of the movement of invasive species) are discussed later. Furthermore, even when ditch construction creates certain beneficial ecosystem services, other ecosystem services can be lost due to the associated land drainage (e.g., loss of wetlands and their carbon sink capacity[10]) or degradation of natural stream channels (e.g., straightening of channels and removal of riparian zones which would otherwise reduce peak flows and lead to less flashy systems[11]).

There are also many examples of cultural ecosystem services arising from ditches, including traditional practices around the governance of irrigation systems around the world[77,81–83]. Festivals and other occasions may be timed around irrigation calendars, and annual ditch cleanings, blessings of irrigation waters, and harvest festivals often play a large role in many communities[72]. These services can also include traditions that arise in irrigation systems and communities that are not directly related to governance, such as the Matachines dances in northern New Mexico, USA, or stories about mythical beings (e.g., La Llorona in Mexico, a ghost that resides near waterbodies). These cultural ecosystem services often have a deep history and are related to many of the systems previously described with regard to archaeology.

Ditches can bring people together in some of the best and some of the worst ways. Beyond celebrations, the need for neighbourly cooperation in ditch maintenance has been common throughout history and was addressed in Swedish medieval provincial laws (*landskapslag*)[84], practiced among villagers in Tokugawa Japan[85] and continues today in many countries[86,87]. In the USA, such cooperation may take the form of authorities known as drainage districts or water management districts, whilst the UK has Internal Drainage Boards. Contrastingly, in contemporary legislation, ditches may be mostly ignored, e.g., in the USA Clean Water Act[88], and in New Zealand regulations where livestock do not have to be fenced out of agricultural ditches and streams <1 m wide and <30 cm deep[89]. When this lack of regulation is combined with their capacity to carry harmful pollutants and pathogens, whose load is typically elevated, often deliberately concentrated, in areas of high poverty[90], then artificial channels become hotspots for environmental injustice and exploitation[13,91,92]. Historically, drainage and irrigation have even served as tools of colonization, impinging upon the swampy refuges of indigenous and enslaved communities[93], and "reclaiming" arid environments for Western-style agriculture[94]. Ditches can exist not just as public/communal or private/individual infrastructure, but often at the nexus of the two, which can be pushed in either direction along the ditch continuum in exercises of power. In underserved communities today, if there is stormwater infrastructure at all, privately maintained ditches may take the place of public, more expensive subsurface infrastructure. Ditches' very existence can become a symbol of neglect and disempowerment[95–97]. Yet, local understanding of what standard public maintenance would achieve socially and environmentally (e.g., improved downstream water quality[98,99]) may fall short of the science. A better understanding, and regulatory acknowledgement, of ditches could empower others to help redesign ditches to best suit their priorities.

Physical and hydrological

Ditches are found in diverse catchments, spanning natural (forests and wetlands)[100,101] to intensively managed (urban and agricultural) land uses[18,102,103] (Fig. 1). The morphology of ditches depends on the surrounding landscape and required function: drainage, irrigation, hydropower, transportation or boundary delineation (see Supplementary Table 1). Ditches often have relatively straight, narrow and deep channels (Fig. 1A, F). Floodplains may be disconnected, or absent entirely, and there is reduced lateral hydrological connectivity with the riparian zone. As such, ditches are recipients of terrestrial fluxes, often from intensively managed environments[104,105]. Because gullying processes rapidly degrade ditches with steep bed slopes, ditches are primarily a feature of low elevation gradient environments. Depending on their position in the hydrological network, ditches generally drain catchments to lower the groundwater table (e.g., to enable food and fiber production, including forestry and peat extraction), redirect water (e.g., in polder systems or fenland), serve as distributive irrigation systems, or serve as temporary water storage locations which can help mitigate impacts of peak flows and downstream flooding. Regardless of function, ditches alter the original water balance of a catchment and the downstream hydrological regime[11].

Similar to natural streams, ditch hydrological connectivity with surrounding terrestrial environments, and thus biogeochemical exchange, depends primarily on their local geography and geomorphology, i.e., position within the landscape, length, width, presence and density of subsurface drainage, and channel substrate which may be permeable (sand, loam, peat, Fig. 1C, D, F, H) or impermeable (clay, concrete)[106,107] (Fig. 1B, E, G). Regardless of channel substrate, many ditches are subject to gradual sediment and organic matter accumulation both in the form of alluvium from upstream reaches, fine sediments brought in by the tide in coastal areas, in-situ degradation of plants, and via bank erosion[108,109], necessitating occasional dredging to maintain original hydraulic function[110,111]. By providing alternative flow paths, ditches can help moderate erosion elsewhere in the landscape[72].

Depending on the hydraulic gradient between ditches and surrounding land, through riparian and hyporheic zones, ditches can either gain or lose water, with consequences for their water balances and flow[102,112]. Depending on the flow, ditches can include dry channels (Fig. 1C) that flow intermittently for irrigation or drainage, still or slow-moving waters, to fast-moving and flashy environments[108,113]. Their hydrology is determined by their topographical position[11,111]), being generally more dynamic in ditches positioned along existing flow pathways or running downslope, and more static in ditches positioned in lowlands between flow pathways or following contours. Ditches that follow existing flow pathways may be difficult to distinguish from straightened or modified streams, whereas ditches that do not follow existing flow pathways are artificially constructed waterways. Thus, the hydrological connectivity of ditches to the stream network and downstream aquatic ecosystems depends largely on their topographic setting and design, but can be modified by their specific purpose, management, and age (as abandoned ditches may become disconnected from the stream network). Whether a ditch is connected to a stream network has important implications for flow direction, the transport and magnitude of lateral chemical fluxes, and pollution risks for downstream ecosystems[109].

In addition to connecting to and often replacing portions of natural hydrological networks, ditches themselves are often installed in geometric networks that expand the hydrological network structurally and functionally (Fig. 3). Frequently these networks are associated with subsurface pipes, sluices, weirs, and pumps[114–116]. These structures are used to control the

Fig. 3 | Ditch networks can be extensive, vary in form/arrangement, and occur in different land covers. **A** Oil palm plantation on drained peatlands in Sarawak, Indonesia (2.66°N, 112.45°E), **B** agricultural land in The Netherlands (51.89°N 4.83°E), **C** drainage and irrigation canals in the Mesopotamian Marshes, Iraq (30.96°N, 46.94°E), **D** urban canals in Xochimilco, Mexico City (19.27°N 99.09°W). Maps data: Google Earth, Airbus, Maxar Technologies (**A**), Google Earth, Airbus (**B**, **D**), Google Earth, Airbus, Maxar Technologies, CNES / Airbus.

direction and volume of water flow, and can shunt flows between ditches and their inlets and outlets, thus bypassing buffering effects of soils, riparian habitats, and other natural ecosystem components. Ditches often receive water and pollutant fluxes from artificial drainage, such as urban stormwater or agricultural subsurface drains[18,104,117], or through direct water pumping into ditches[112]. With human pumping, with or without pipe networks, ditches can also convey water uphill. Thus, ditches are much more likely than non-tidal natural linear channels to flow in both directions at least occasionally, even if designed primarily for either irrigation or drainage. Due to the ability of ditches to defy natural watershed boundaries, the land areas with which ditches interact hydrologically can prove challenging to delineate, which can hinder the upscaling of aquatic fluxes of carbon and other solutes[118].

Another important aspect determining the hydrological regime of ditches and their connectivity to terrestrial and other aquatic ecosystems, is their management[20]. At the most basic level a distinction can be made between drainage ditches, which lower the adjacent terrestrial water table, and irrigation channels, which can contribute significantly to groundwater recharge via irrigation return flow[119]. Management can include channelization, dredging, vegetation removal, flow and water-level regulation[111,118,120], or riparian zone management (e.g., vegetation removal, establishing trees, widening floodplains, fencing out livestock[104,121]), all of which have the potential to affect in-situ hydrological processes as well as the eco-hydrology of the surrounding landscape. For example, the removal of vegetation and accumulated sediment from boreal forest ditches is periodically done to lower water tables to improve productivity, but it also results in increased concentrations of suspended sediment and nutrients[122]. Conversely, fencing out livestock from agricultural ditches has been shown to reduce bank erosion and thus decrease downstream nutrient and sediment loads[121]. Many types of management are deployed in combination, and integrated studies are needed to fully understand their cumulative impacts on ecohydrology.

As flow regimes in ditches change seasonally following either natural hydrological cycles or human activities[123], water retention time in ditches can vary dramatically, with consequences for biogeochemical function[11,109,124]. Due to their small size and volume, ditches are usually very sensitive to changes in flow, and can periodically be dry or overflowing. Thus, with more extreme hydrological events and changing global climate, many existing ditches may require adjustments in size, design, management, spatial density and/or expectations of function. The ultimate physical challenge of climate change will require careful consideration and balancing of multiple ecosystem services moving forward.

Biogeochemical

Ditches play a unique biogeochemical role due to their high connectivity with the surrounding landscape, processing inputs of nutrients, sediments, and pollutants from the wider environment[103]. Ditches, like other aquatic systems, are not passive pipes but active components of global biogeochemical cycles[125], and the biogeochemical fingerprint of water leaving a ditch system can be substantially altered relative to incoming flow. The degree of biogeochemical processing is controlled mainly by residence time (the amount of time water spends in the ditch before flowing elsewhere), as observed in other inland waters[126,127]. Residence time is itself determined by size, hydrological flow conditions, vegetation, landscape setting (e.g., upland versus lowland, effective catchment area), and management regime. Despite the global prevalence of ditches, they remain neglected in contemporary syntheses of the role of aquatic environments in biogeochemical cycles[128–130]. Omitting ditch processes from large-scale biogeochemical assessments, including global carbon models, could lead to significant errors. Here, we propose that ditches are best viewed as ubiquitous reactive surfaces; as lines that bind across and beyond catchments.

Ditches can act as nutrient sinks or sources within the landscape, and this dual functionality is dependent on multiple factors including nutrient load, flow direction, vegetation cover and type, and climate. Therefore, sink or source behaviour can vary significantly over space and time[117]. As in other aquatic ecosystems, high nutrient loading can cause a wide range of problems, including excess phytoplankton growth, declines of aquatic macrophytes, loss of biodiversity, and oxygen depletion[131]. These eutrophication effects are especially common in drainage ditches[132] because they often serve as headwaters that receive anthropogenic terrestrial nutrient loads first before transferring them to receiving waters, including, rivers, wetlands, lakes, seas[133], and groundwater[134]. Similarly, irrigation ditches can convey nutrients up gradient to land and municipal water systems[135].

Similar to other freshwater environments, vegetation and water residence time are important drivers of nutrient removal capacity[124,136,137]. Longer residence times (which may be facilitated by water control structures), contribute to the creation of anaerobic conditions, promote organic matter accumulation, and encourage microbial denitrification[104,138]. Reactive nitrogen (N) can also be removed by plant uptake[137,139,140]. Thus, ditches can mitigate N-loading from both agricultural activity[136] and urban runoff, often at rates comparable to or exceeding those of natural systems[141,142]. Vegetative uptake and sediment storage are also important pathways for phosphorus (P) removal in ditches and these processes, given time, can sometimes reverse even intense eutrophication[143]. Recovery timescales from nutrient and other forms of pollution are often difficult to predict because of legacy effects, whereby nutrients stored in sediments can be mobilized under certain physical and chemical conditions[144–146] or stored long-term, resulting in slow response times to changed nutrient loads[132,147]. For example, practices such as dredging can destabilize banks and reduce P sorption capacity, resulting in ditches becoming a P source rather than sink[148].

Besides nutrients, ditches also receive runoff and groundwater comprising a complex mixture of chemical compounds. These mixtures may include microplastics[149], pathogens[150], antimicrobial resistant genes[151], animal-borne hormones[152], pharmaceuticals[153], trace metals[154], pesticides[155], and salts[156], which may, alone or in combination, have unintended and as yet largely unknown effects on ditch ecosystems. Roadside (Fig. 1E) and urban ditches (Fig. 1A), in particular, may receive a toxic mix of runoff that includes heavy metals, PAHs (polycyclic aromatic hydrocarbons), tire materials, pesticides, exhaust emissions, nutrients, road salt, and Per- and PFAS (polyfluoroalkyl substances- so called "forever chemicals")[157–159]. Despite this, ditch networks can be managed to retain pollutants in runoff[160–162]. Indeed, because ditches often disproportionately contribute to catchment nutrient, sediment and pathogen loads[89] they could be prime candidates for pollutant removal and mitigation. Given the high degree of hydrological connectivity of ditches, water quality monitoring in these environments may yield important insights into emergent pollutant and contaminant pressures before they propagate to downstream environments.

The biogeochemistry of ditches extends beyond water quality, into landscape and global carbon and greenhouse gas (GHG) balances. The creation of ditches, especially in organic soils (Fig. 1D, F, H), causes adjacent terrestrial soils to dry out, which leads to extensive soil subsidence, oxidation, and carbon dioxide emissions[163]. This drainage also affects concentrations of organic carbon, in particulate (POC) and dissolved organic carbon (DOC) forms, often leading to increases in the overall aquatic carbon flux[164]. Increasing DOC concentrations may also pose additional problems, for example by imposing additional costs at drinking water treatment works[165].

An important fate of DOC and sediment organic matter in ditches is emission to the atmosphere in the form of GHGs. High loading of organic matter and nutrients, accumulation of organic sediment, fluctuating water table levels, connection to groundwater, slow water flow, low oxygen concentrations, and abundant vegetation (Fig. 1A) can render ditches as important sites for the production and release of the GHGs methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). The importance of ditches in drained organic soils (Fig. 1D, F, H) as landscape-scale hotspots of CH_4 emission has been known for decades[166]. This arises because drainage effectively stops CH_4 emissions from adjacent terrestrial soils, leaving ditches as hotspots of CH_4 emission in the landscape. Recent evidence has shown this hotspot effect can extend to regional and national scales, and applies to mineral soils too[22,167]. Ditches contribute significantly to global CH_4 emissions, contributing 3.5 Tg CH_4 yr^{-1}; equivalent to 1% of global anthropogenic CH_4 emissions[9]. In recognition of the potential for high area-specific emissions, the Intergovernmental Panel on Climate Change (IPCC) now has guidelines for reporting of ditch CH_4 emissions[168].

Ditches can act as sources and sinks for CO_2. Carbon uptake by within-ditch vegetation, or the settling of suspended particulates, can lead to carbon accumulation in sediments[169,170], although this sediment is vulnerable to management interventions and storms[171]. There is a lack of knowledge about whether ditches also act as landscape-scale hotspots of CO_2 emission. Some evidence suggests that the CO_2 emissions from ditches may be small relative to those of the terrestrial ecosystem they drain[164,172] (but see Hendriks et al.[173]). Indeed, blocking ditches to restore water tables and thereby reduce CO_2 emissions is a key focus for land management in areas dominated by organic soils, which can lead to either the removal of ditches[174], or their modification to act as (effectively) irrigation rather than drainage systems. By altering overall water residence times, drainage networks potentially enhance rates of organic matter processing within freshwater ecosystems, and thereby reduce the organic carbon flux from land to ocean[175]. The resulting CO_2 emissions from ditch surfaces are rarely measured, and could represent a missing term in landscape or catchment-scale carbon budgets[176]. At the global scale, ditch CO_2 emissions are estimated at 30 Tg C yr^{-1} [177].

Nitrogen-enriched water discharging into ditches is well recognized as a source of indirect N_2O emissions in agricultural landscapes[178–180], and IPCC methodologies have been developed to facilitate reporting of these emissions[181]. Still, fewer studies have measured N_2O emissions from ditches directly. In a recent review, Webb et al.[182] detected significant spatial and temporal variation in emissions between different types of artificial waters including ditches. This variability is only partially explained by nitrate loading from surrounding catchments (e.g., N application to agricultural fields), as assumed in IPCC reporting, indicating additional drivers[183]. Although there is continued uncertainty in the magnitude and timing of ditch N_2O emissions, and their importance at landscape scales (i.e., when compared to terrestrial emissions), the global ditch emission is 0.03 Tg N yr^{-1} [177].

Floral and faunal

The ecology of ditches has been overlooked from both research and conservation perspectives. Many ditches are surrounded by agriculture (Fig. 1D, F, H) or urban landscapes (Fig. 1A, B, E, Supplementary Table 1) and heavily managed to facilitate a particular hydrological regime, roughness, or vegetation cover. Despite this, many ditches represent novel ecosystems with distinct biotic communities[21,184–186], and can support a high biodiversity of aquatic macroinvertebrates[106,187]), waterbirds[188,189], amphibians[190], macrophytes[191,192] and fish[193,194]. Ditches can also support floral and faunal assemblages similar to adjacent natural streams[123,195], lakes[7], and wetlands[170], and can be used by fish, amphibians, turtles, plants, and other taxa for reproduction[12,196,197]. At a landscape scale, the unique hydrological characteristics of ditches can provide important ecological niches for many species, thereby increasing regional biodiversity[186,195,198,199]. However, habitat quality and the biodiversity value of ditches is heavily dependent on management regimes[134,200]. Ditches with a variety of successional stages (environmental heterogeneity) and good water quality, that enables diverse aquatic plant communities to develop, tend to support the most diverse fauna[12,186,198]. Conversely, in ditches where riparian vegetation is periodically removed, steep bank angles maintained via dredging, or nutrient levels elevated, ditch freshwater biodiversity can be amongst the lowest in the wider landscape[201,202]. To maintain a ditch's original function regular management is necessary. However, where this can be undertaken with a consideration for biodiversity (e.g., marginal vegetation managed on one bank, macrophytes maintained in selected areas or habitat diversity increased[106,187,201]), ditches can display a very high conservation value[203].

In intensively farmed or urbanized landscapes (Fig. 1A, B, E, F, H, Supplementary Table 1), ditches often represent the only available refugia for aquatic and riparian wildlife and can reflect a range of natural habitat analogues that have been lost due to agricultural intensification, land drainage, and water abstraction[123,204]. As ditches can possess slow flow, still water, and highly variable water depths, ditch networks often support species that are typical of both lotic and lentic habitats[187,205]. However, the extent and importance of this "refugia" function depends on management regimes and the type of ditch system (e.g., concrete-lined systems will be less desirable for fish, boat traffic can lower plant biodiversity[12]), as well as wider catchment characteristics such as the presence of other waterbodies or set aside land[21]. Where ditches are located within and close to ancient wetland habitats, they may act as a 'memory' or palimpsest of lost aquatic habitats, and continue to support remnant flora and fauna present in lost natural lentic, river, fen and marshland habitats[206]. Evidence from the Fens of East Anglia (UK) show a high degree of correspondence between the freshwater flora of fenland farm ditches and that of Wicken Fen (the UK's oldest nature reserve)[207] and a lesser, but nevertheless strong, representation of the historic fen and marsh species. Ditches often support rare species (e.g., gastropods[208]) and one of the UK's rarest plant species, the fen ragwort (*Senecio paludosus*), survives in one Fenland ditch[209].

Ditches also provide connectivity between natural aquatic habitats through an often hostile terrestrial matrix (*sensu* Mazerolle[210]). Plants, amphibians, fish, crayfish, and turtles have been shown to use ditches to disperse across the landscape, highlighting how ditches can act as connectivity corridors and sometimes mitigate negative effects of habitat fragmentation[12,197,211]. Ditches in intensively managed landscapes may also provide habitat and passage for fully terrestrial species[212]. Inevitably this connectivity can also aid the dispersal of invasive and exotic species[114,213,214], which is an issue most ditch managers have yet to consider. Ditches not only provide hydrological connectivity but contribute important aquatic-terrestrial linkages. For example, ditch invertebrate communities transfer energy to the riparian zone and provide trophic resources for mammals and birds[215], and critical regulating ecosystem services including habitat for a reservoir of pollinators[216]. In this way ditches, comprising an aquatic habitat, bankside vegetation, and potentially with an uncultivated headland on one or both sides, offer the potential to establish 'blue-green corridors' of biodiversity reflecting both wetland and terrestrial biota and providing reservoirs of natural predators of crop pests that could provide multiple environmental services in arable landscapes. Such 'linear nature hotspots' with their close juxtaposition of different ecotones would require less land to be taken out of production than area-based conversion of fields for a similar gain in biodiversity.

Synthesis and conclusions

We have demonstrated that ditches are important socio-ecosystems[30] whereby human society and nature are interconnected and co-evolving. Ditches exert a range of effects upon adjacent environments across scales, and have done so for at least the past 8000 years. These effects can be both positive (e.g., support for global crop production and thus the whole of human society, refuges for biodiversity, processing pollutants, sites of important cultural ecosystem services) and negative (e.g., GHG emissions, dispersal of pollutants downstream, degradation of biodiversity, damaging palaeoecological records, habitats for invasive species). An emerging challenge is to manage these waterways in a multifunctional manner; that is, maximizing positive synergies whilst minimizing trade-offs, in order to deliver multiple ecosystem services at the same time. This is difficult, with no "one size fits all" solution, because of the many different social and ecological purposes that ditches are managed for (Fig. 1, Supplementary Table 1). Some opportunities for multifunctionality have been demonstrated; e.g., raising ditch water levels in temperate agricultural peatlands during the winter season has been shown to decrease carbon dioxide emissions without any negative effects on crop yield[217]; carefully designed riparian integrated buffer zones can reduce ditch nutrient loads, increase biodiversity, and allow the production of biomass[218]. Nevertheless, in many cases the primary function of a human-created channel may be incompatible with secondary co-benefits[13], e.g., irrigation and urban channels built to transport water may be dredged of sediment and vegetation to increase water flows, which therefore vastly reduces biodiversity and aesthetic value. Further difficulties in managing for multifunctionality arise because ditches frequently cross land boundaries and catchments, with different owners/managers being responsible for consecutive sections of channel. Collaborative thinking is required between individuals or organizations if a management strategy is to be coherent, effective[219], and environmentally just. Finally, global and climatic change will increasingly stress the functioning of ditches, and in many ways human reliance on them for water security will increase as climate patterns and flow regimes become more unpredictable. Therefore, ditches will require ongoing adaptive management[26]. Considering these disparate and diverse issues, ditch management can clearly be perceived as a "wicked problem"[220].

Despite this complexity, there are opportunities in ditch management, because ditches are extensive, important, undervalued, and understudied. Additionally, because ditched landscapes are often intensively managed makes them excellent candidates for testing novel environmental management strategies[18]. Many channels are overbuilt for their intended purpose[221] (e.g., roadside ditches may only rarely carry water during storms) and therefore slight changes to design or management could provide bonus ecosystem services. Even lack of regulation can present an opportunity to innovate. However, questions arise when considering ditches through the framework of ecological concepts such as conservation and restoration: how do we apply these concepts to highly managed and artificial ditch ecosystems? The EU's Water Framework Directive (WFD) can perhaps give some answers. Although ditches are generally overlooked in the WFD[16], the WFD does provide guidance for heavily modified and artificial waterbodies. Specifically, the WFD acknowledges that these waterbodies may have important functions (e.g., navigation, land drainage, water regulation, etc) which may prevent them from achieving "good ecological status". Instead, the aim is for these modified waterbodies to reach the lower threshold of "good ecological potential"[222].

Perhaps a creative rethinking of traditional paradigms in environmental management is necessary to answer such questions of conservation and restoration. Because of the aforementioned conflicts in management at the ditch-scale, it may be that the opportunity for multifunctional management only arises when ditches, in conjunction with their associated connections to groundwater, wetlands, streams and lakes, are considered as habitat networks[223] or meta-ecosystems (*sensu* Loreau et al.[224]) at the landscape scale; when entire ditch networks are adaptively managed for multiple social and environmental gains (as suggested for constructed wetland management[225]). Indeed, the necessity of landscape-scale thinking is now reflected in terms such as hydroscapes[226], pondscapes[227], riverscapes[228], wetlandscapes[225], and wetscapes[229], and "ditchscapes" should also be integrated into thinking about, and managing for, the wider environment. Another consideration is the temporal scales, which can dramatically alter how traditional biological conservation view ditches and the resulting'scapes' they create[230]. The role of archaeology, history and allied disciplines is vital to understanding the deeper historical ditchscape trajectories for both hydrological and biodiversity management, but also cultural heritage, tangible and intangible.

The success of managing novel ditchscapes for multifunctionality depends on a variety of factors, but we believe that one of the most significant limitations is mapping. Simply put, we do not know where ditches are. Detailed channel maps, across a range of spatial scales, would help to solve an array of management questions (e.g., where do we prioritize ditch management?) and research gaps (e.g., how do we accurately upscale biogeochemical processes?). Mapping methods are constantly being refined and it is now possible to map ditches at local and regional scales using remote sensing and novel machine learning methods[231–235]. However, location alone is only part of the puzzle because most purposes would also require information on ditch size (width and depth) and flow (perennial, intermittent, or ephemeral; see Fritz et al.[236]), at minimum. Channel width is essential to calculate ditch surface area, and is key for some global upscalings of processes and cycles as well as for IPCC reporting[168], yet it is frequently unknown[9]. We are optimistic that these issues will be resolved in the near future by the use of remote sensing based mapping aided by artificial intelligence methods[8], provided that mapping efforts use these tools to include, rather than exclude, ditches[170].

A final challenge is the need to widely reframe how individuals, and society at large, perceive ditches. Assuming that artificial aquatic ecosystems lack ecological value promotes neglect[13]. Environmental decision-makers assume ditches are low-quality ecosystems, and manage accordingly; subsequently, their assumption becomes a self-fulfilling prophecy. Considering the prevalence of English-language ditch idioms with negative connotations, it is clear that changing perceptions will be no easy task.

If the challenges are addressed, and opportunities seized, then multifunctional management of ditchscapes could be an effective way to boost ecosystem services and provide nature-based solutions at scale, and across a gradient of land cover intensities, from urban, through agricultural, to forest, and wetlands. Such successful ditchscapes would link to multiple Sustainable Development Goals including "clean water and sanitation", "climate action", and "life on land"[27]. Ditches have the potential to serve as resilient waterways on a changing planet; lines in the landscape recording the past, providing for the present, and directing us onwards to a more sustainable future.

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