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Sustainable intensification of agricultural drainage

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Artificial drainage is among the most widespread land improvements for agriculture. Drainage benefits crop production, but also promotes nutrient losses to water resources. Here, we outline how a systems perspective for sustainable intensification of drainage can mitigate nutrient losses, increase fertilizer nitrogen-use efficiency and reduce greenhouse-gas emissions. There is an immediate opportunity to realize these benefits because agricultural intensification and climate change are increasing the extent and intensity of drainage systems. If a systems-based approach to drainage can consistently increase nitrogen-use efficiency, while maintaining or increasing crop production, farmers and the environment will benefit.

Sustainable intensification is defined as producing more food from the same amount of land with fewer environmental costs[1]. A key component of sustainable intensification is land improvement. Irrigation is the most widespread land improvement for agriculture[2] and the importance of proper irrigation design and management is well recognized. However, analyses of sustainable intensification have neglected another important land improvement: artificial drainage. As a fraction of total cropland, drained croplands produce a disproportionately large amount of grain, but also deliver a disproportionately large amount of eutrophying nutrients to aquatic ecosystems[3].

The importance of proper drainage-system design and management needs greater attention because drainage has enormous effects on ecosystem services, and the amount of drained croplands is rapidly growing[4,5]. Although more cropland benefits from irrigation than artificial drainage (300 versus 130–200 Mha), an additional 450 Mha of cropland may benefit from improved drainage[2,6]. Moreover, existing drainage systems are being expanded and intensified due to end of design life, changes in cropping systems and changes in climate[4,6–8]. This expansion and intensification of drainage systems will affect crop yields, soil organic carbon (SOC) stocks, greenhouse-gas (GHG) emissions, nutrient losses to water resources and cropping systems' resilience to climate change. Thus, a comprehensive systems-based strategy for drainage design that minimizes trade-offs between crop production and environmental performance is required. Nevertheless, research on the ecosystem services provided by drainage rarely goes beyond water quality and crop production.

Here, we develop and evaluate a conceptual model (visualized in Fig. 1) that describes the cascading effects of drainage on multiple ecosystem services. We focus on intensively managed, temperate humid cropping systems where modern subsurface drainage systems were pioneered and remain among the most intensive and widespread drainage systems in the world (Box 1). Next, by linking our conceptual model to alternative drainage-system designs that incorporate nutrient loss reduction practices, we demonstrate how future drainage systems can mitigate and adapt to climate change while minimizing trade-offs between crop productivity and environmental performance. Our analysis reveals an innovative systems approach to drainage design that can promote SOC storage and maximize crop yields while reducing N fertilizer inputs, nutrient losses to water resources and GHG emissions. Because this systems approach increases fertilizer N-use efficiency (NUE) while maintaining or increasing yield, there is a direct benefit to farmers that can aid policy and education initiatives to promote widespread adoption of improved drainage systems.

Crop growth and yield

Irrigated and rain-fed croplands across arid, temperate and tropical environments benefit from artificial drainage[2,4]. Drainage systems enable or improve crop growth in two key ways: they prevent soil salinization and remove excess water (Fig. 1). In arid and semi-arid systems, irrigation can lead to an accumulation of salts in the crop root zone due to evapotranspiration of irrigation water and upward capillary flow from a rising shallow water table. Drainage can flush salts from the root zone and maintain water-table depths that prevent capillary rise into the root zone. In many irrigated hot arid and semi-arid crop systems, drainage is required for both functions because precipitation can be intense and, at high temperatures, even brief periods of poor aeration in the root zone can damage crop growth[9].

In temperate humid regions, drains primarily function to remove excess water, leading to better field trafficability and crop growth. Before, during, and after crop growth, excess soil water reduces yield while increasing nutrient loss and economic risk. Before planting and during crop growth, wet soils limit field operations such as tillage, fertilization and pesticide application. This is a major challenge because the need for these practices is often greater in wet soils[10,11]. Poor field trafficability can also delay planting, which has a direct negative effect on yield potential due to a reduction in growing degree days[12]. During crop growth, diseases are more common in wet, poorly drained soils and plants may be more susceptible to diseases in these stressful growing conditions[9]. After crop growth, wet soils can delay harvest, which increases post-maturity yield loss and disease[9,13].

Excess soil water also has direct negative effects on crop growth and development regardless of the ability to maintain plant health through field operations. When soil moisture approaches saturation and O_2 availability becomes limited, root growth stops and root senescence accelerates[14]. A shallow root system limits water and nutrient uptake while increasing the risk of plant lodging, which is a major cause of yield loss. Aboveground, excess soil moisture reduces net photosynthesis due to reductions in stomatal conductance as

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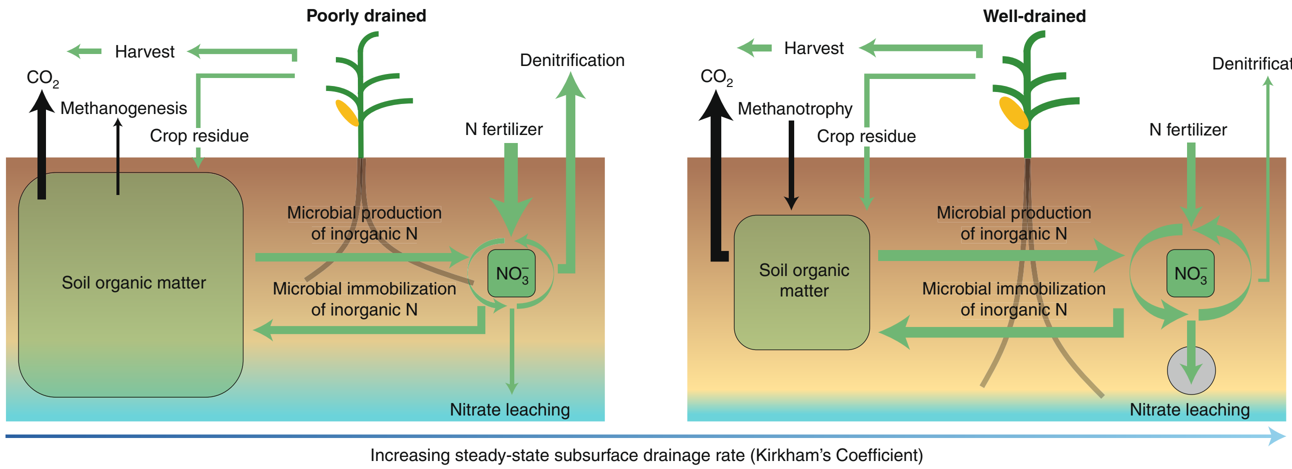


Fig. 1 | Changes in crop and soil processes with drainage. Drainage reduces denitrification and soil organic matter stocks while increasing root depth, nitrate (NO_3^-) leaching and microbial production of inorganic N (that is, soil N mineralization). We postulate that the increases in N mineralization and rooting depth reduce N fertilizer requirement, leading to greater fertilizer NUE and lower GWP of cereal crop production. See Box 1.

well as leaf protein and chlorophyll contents[15]. Resultant delays in plant growth can increase disease susceptibility[13]. Together, these factors can substantially decrease crop yields or cause complete crop failure.

Soil carbon and nitrogen

In many regions, drainage may be the primary cause of SOC loss following land conversion to agriculture (Fig. 1). Drainage increases soil aeration and temperature[16], which increase the output of SOC from heterotrophic respiration (that is, 'SOC mineralization') more than the input from net primary productivity (NPP)[17], resulting in smaller SOC pools (Fig. 1). The effect of drainage on SOC in organic peatland soils is well recognized; the Intergovernmental Panel on Climate Change (IPCC) and Kyoto Protocol provide C credits for rewetting of drained peatlands[18]. However, the effect of drainage on mineral SOC pools is generally underappreciated and not credited or discussed by the IPCC or Kyoto Protocol[19,20]. To our knowledge, no full factorial experiment has measured the effect of land conversion and drainage on SOC in mineral soils. Yet, observations, experiments and theory confirm that drainage reduces SOC. In a comparison of six, paired drained and undrained soils in Iowa, USA, SOC concentrations in drained subsoils were as little as 20% of those in paired undrained subsoils[21]. During the initial three years following drainage installation in a Minnesota maize–soybean system, SOC losses from 0–15 cm were 2,200 kg C ha^{-1} yr^{-1} (ref. [22]). In Belgium, widespread SOC losses of 400–900 kg C ha^{-1} yr^{-1} (0–100 cm) from 1960–2006 were attributed to drainage[23].

When SOC mineralization increases, so do soil N mineralization and nitrification (Fig. 1). Studies confirm that N mineralization and nitrification increase with drainage[24]. Net primary productivity responds positively to inorganic N whether it is derived from external fertilizer inputs or internal soil N mineralization[25]. In unmanaged perennial ecosystems, the positive response of NPP to soil inorganic N availability limits nitrate (NO_3^-) loss to waterways; however, in annual croplands, there is substantial soil N mineralization when plant N demand is low or zero[26]. This asynchrony between crop N demand and soil N mineralization leads to an accumulation of soil NO_3^-, which is easily lost to leaching or denitrification (see Fig. 1).

Experiments, process models and statistical models from plot to watershed scales agree that the amount of drainage (area drained per watershed or drainage intensity at the plot scale, see Box 1) is positively associated with NO_3^- leaching. Within the Mississippi River basin, the amount of artificial subsurface drainage explains a large proportion of intra-basin variation in the source of the total basin NO_3^- load[3]. At the plot scale, an increase in drainage intensity routinely increases NO_3^- leaching[27–29].

While drainage increases N loss via leaching, it decreases N loss via denitrification primarily due to an increase in soil aeration[30] (Fig. 1). The increase in soil aeration can also reduce non-CO_2 GHG emissions from the soil surface. Artificial drainage can reduce nitrous oxide (N_2O) emissions[31,32], which account for most of the global warming potential from arable soils. In poorly drained arable soils, N_2O is predominately produced through denitrification and the rate of N_2O emissions is maximum at soil water contents near saturation because C limitation of heterotrophic denitrification (due to high NO_3^- to bioavailable C ratios) favours incomplete denitrification of NO_3^- to N_2O rather than N_2 (ref. [33]). Artificial drainage can also reduce methane (CH_4) emissions because soil aeration limits methanogenesis and promotes methanotrophy. Indeed, subsurface drainage of mineral and peatland soils can transform soils from CH_4 sources to sinks[34] (Fig. 1).

Fertilizer nitrogen-use efficiency

By taking together the above-described effects of drainage on plant and soil processes (Fig. 1), we hypothesize that an increase in drainage intensity (DI) increases fertilizer NUE by decreasing the agronomic optimum N fertilizer rate while increasing grain yield. This improvement in fertilizer NUE can be measured as an increase in grain production per unit N fertilizer input and the proportion of N fertilizer input recovered in crops during the growing season[25]. An increase in fertilizer NUE has the potential to mitigate climate change because N_2O emissions from N fertilizer application and GHG emissions associated with the synthesis of N fertilizer are the main contributors to total GHG emissions from cereal crop production[35]. However, to our knowledge, no work has investigated the effect of drainage system on the agronomic optimum N rate, NUE, or global warming potential.

How can drainage increase NO_3^- leaching and NUE? A full accounting of cropping system N dynamics elucidates this apparent contradiction. Although drainage increases dissolved NO_3^- outputs, it also decreases gaseous N outputs and increases soil N mineralization. In comparison to the total amount of soil inorganic N that is available to crops (NH_4^+ + NO_3^-), the increase in NO_3^- loss via leaching is small relative to the sum of decreased NO_3^- loss via denitrification plus increased NH_4^+ input via soil N mineralization[36].

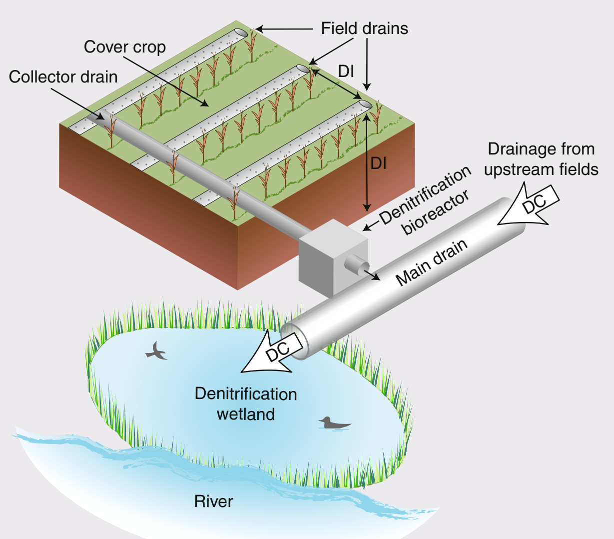
Box 1 | Subsurface agricultural drainage systems

Croplands have been artificially drained for millennia. However, it was not until the mid-nineteenth century when the invention of the clay pipe extruder led to mass production of clay 'tile' pipes and the widespread installation of drainage systems. In the early twentieth century, these systems spread from Europe to North America where they transformed non-arable wetlands into some of the most productive croplands in the world. Today, corrugated polyethylene pipes and self-propelled plows have replaced clay tile pipes and hand-dug trenches.

In extensively drained temperate humid regions, which account for approximately two-thirds of drained croplands[4], the piping systems form highly organized networks. Many field drains and collector drains contribute water to a main drain, which outlets to a surface waterway. Field and collector drains are the purview of individual farmers. Main drains are the purview of municipal organizations because they are shared by many farmers[2].

Three coefficients define the hydraulics of drainage systems (mm d^{-1}); they aid drainage-system design and allow cross-site comparisons of drainage rates[58]. The Kirkham Coefficient describes the steady-state drainage rate of a saturated soil profile and determines the duration of water ponding on the soil surface. Drainage intensity (DI) is the steady-state drainage rate from field drains when the water table is coincident with the soil surface at the midway point between two parallel drains. The DI is dependent upon, and used to determine, the spacing and depth of field drains. Narrower spacing and increased depth increase DI. The drainage coefficient (DC) is the rate at which the main drain can remove water from field drains. The size, slope and roughness of the main drain control the DC. The DI cannot exceed the DC regardless of the field drain spacing or depth.

Although drainage increases NO_3^- leaching from fields to waterways, it also creates unique opportunities to reduce NO_3^- leaching. Denitrification bioreactors can remove NO_3^- from field drains before reaching main drains. Denitrification wetlands can remove NO_3^- from main drains before reaching downstream surface waterways. These edge-of-field NO_3^- removal strategies, which are available only in drained croplands, can be coupled with in-field NO_3^- removal strategies that can be used in drained and undrained croplands. In-field strategies include increases in crop system diversity such as cover crops that create plant NO_3^- demand during times that are otherwise fallow. Moreover, drainage improves the effectiveness of in-field strategies[44,45].



It is crucial to emphasize the importance of soil N mineralization for crop N uptake. In cereal crops, N isotope tracer studies demonstrate that soil N mineralization—rather than N fertilizer—is the largest direct source of crop N uptake regardless of the amount of fertilizer input[36]. In the Midwest US, 39% of 491 trials measuring maize yield response to N fertilization across five states reported no yield response despite yields that met or exceeded regional averages[37]. These results indicate that soil N mineralization alone can maximize maize yield in particular environments and management scenarios.

An increase in soil N mineralization with drainage can explain a simultaneous increase in NO_3^- leaching and NUE if one portion of the increased soil N mineralization is lost as NO_3^- while another portion is taken up by the crop. Soil N derived from mineralization is a more efficient N source for crops than N fertilizer[26]. At the same time, a decrease in denitrification can neutralize the increase in leaching. Moreover, drainage increases the potential root volume of soil[38], which can have a positive effect on NUE[25]. Potential root volume is a key constraint on yield potential[39]. Together, these processes can increase fertilizer NUE because fertilizer N can be more completely used when excess water does not limit crop growth and drive soil N losses. However, we are unaware of direct tests for an effect of drainage intensity on maize response to N fertilizer.

In the absence of such data, we used the Agricultural Production Systems Simulator (APSIM) to illustrate a proof-of-concept for the impacts of drainage on multiple ecosystem services in maize-based cropping systems. The process-based model was previously well calibrated and tested for maize-based cropping systems that are typical of drained and undrained croplands in the Midwest US[14,38]. We ran the model for continuous maize and maize–soybean rotation cropping systems across 18 weather-years (2000–2018) to capture interannual variability. Subsequently, we identified the average annual agronomic optimum N fertilizer rate (AONR) for maize in drained and undrained systems, and evaluated how key cropping system processes respond to drainage across the 18 weather-years when the systems are managed at the average annual AONR for each system (Supplementary Figs. 1–3 and Supplementary Table 1).

In continuous maize, drainage reduced the AONR from 214 to 189 kg N ha^{-1} and had a slight positive effect on grain yield. Despite greater NO_3^- losses in the drained systems, the AONR was lower because inputs of plant-available N from soil N mineralization were greater and N losses to denitrification were lower (Fig. 2). Consistent with these patterns, grain yield at zero N, which is a robust indicator of mineralized soil N (ref. [25]), was 10% greater in the drained system. Moreover, agronomic efficiency (that is, kg grain kg^{-1} N fertilizer) at the AONR, a key metric of sustainable intensification, was 14% greater in the drained treatment (59 versus 52 kg grain kg^{-1} N fertilizer). The effect of drainage was proportionally similar in the maize–soybean rotation, but absolute effects were smaller because maize following soybean has a lower N fertilizer requirement than maize following maize, and soybean does not typically receive N fertilizer (Supplementary Figs. 4, 5).

Hence, we highlight that drained systems require less N fertilizer for optimum production. Although the effect of drainage on grain yield at the AONR was small, this result is consistent with previous research showing a more positive effect of drainage on grain yield because those works compared grain yield across different drainage intensities, but the same N fertilizer rate[27–29]. Thus, previous research assumed that N fertilizer requirement (that is, the AONR) did not differ with drainage intensity. Consistent with this research, the difference in grain yield between the drained and undrained systems was greater when the two systems were fertilized at the same rate (Supplementary Table 1).

Global warming potential

Our model outputs and literature review allowed us to sum the major sources of GHG emissions from the drained and undrained systems.

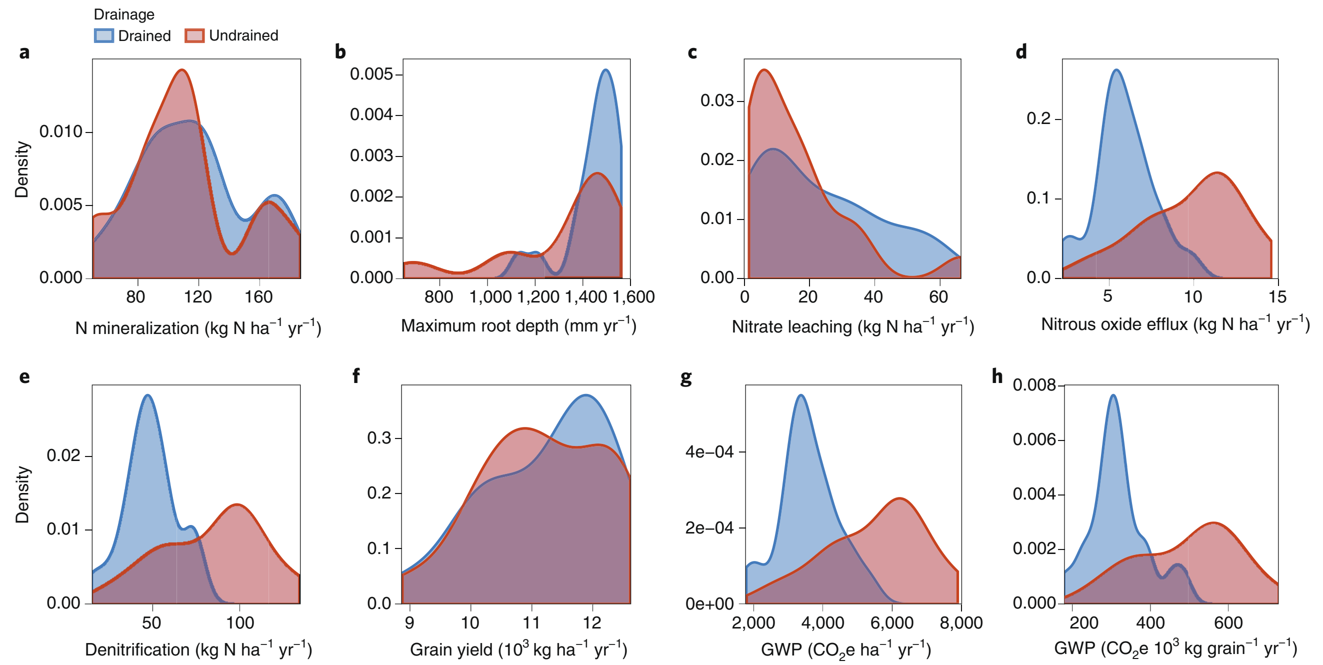


Fig. 2 | Probability density functions of key crop system processes. a, Soil N mineralization. **b**, Maximum root depth. **c**, Nitrate leaching. **d**, Nitrous oxide efflux. **e**, Denitrification. **f**, Grain yield. **g**, GWP (CO_2e ha^{-1} yr^{-1}). **h**, GWP (CO_2e 10^3 kg $grain^{-1}$ yr^{-1}). Data are shown for drained (blue) and undrained (red) continuous maize systems when fertilized at the AONR for each system (189 and 214 kg N ha^{-1} yr^{-1} for drained and undrained systems, respectively). Data are simulated from 18 weather-years across drained and undrained experimental fields in southeast Iowa, USA (Supplementary Information).

We set the boundaries of these calculations to include N_2O emissions from the soil surface, downstream N_2O emissions from NO_3^- leaching, and GHG emissions associated with the synthesis, delivery and application of N fertilizer (see Supplementary Information for details). These sources account for the vast majority of annual GHG emissions from crop production in temperate humid environments[35]. We then compared these annually recurring fluxes of GHGs to the total cumulative flux of CO_2 produced from SOC loss that is likely to occur from the installation or intensification of drainage. Losses of SOC to CO_2 cease within 10–20 years of changes in land use or management as the SOC pool re-equilibrates at a lower level[40]; hence emissions from SOC loss are not annually recurring. Moreover, drainage system design-lives far exceed 10–20 years.

Without considering SOC losses, drainage reduced mean annual global warming potential (GWP) in continuous maize by 56% due to the lower AONR (Fig. 3). The lower AONR reduced GWP by reducing N_2O emissions from the soil surface and GHG emissions associated with the synthesis, delivery and application of N fertilizer inputs. Although drainage increased downstream N_2O emissions due to increased NO_3^- leaching, this was a small source of GWP (Supplementary Table 2).

This potential reduction in mean annual GWP must be interpreted in the context of SOC losses that occur in the initial years following the installation or intensification of drainage systems (Figs. 1, 3). A comprehensive meta-analysis determined that total SOC loss upon initial land conversion to annual crop production is 27% (ref. [40]). In typical Midwest US mineral soils with artificial drainage, a 27% loss of SOC is ~100,000 kg CO_2e ha^{-1} (Supplementary Information). However, the intensification of drainage systems in previously drained and cultivated soils would cause a much smaller SOC loss. Moreover, the IPCC, United Nations Framework Convention on Climate Change and Kyoto Protocol track changes in GHG emissions relative to a base year of 1990. In situations where drainage was installed before 1990 and is intensified after 1990, SOC losses due to intensification might be as little as 10,000 kg CO_2e ha^{-1}.

Our analysis indicates that drainage of continuous maize systems, excluding the effect on SOC, reduces annual emissions of CO_2e by ~2,000 kg CO_2e ha^{-1} yr^{-1} due to lower N fertilizer inputs and N_2O emissions. Hence, owing to higher NUE, drainage could neutralize GWP from SOC losses within 5–50 years depending on the baseline SOC (Supplementary Table 4). Because most drainage systems have a project life expectancy of 100 years (ref. [41]), drainage could reduce total cropping system GWP in the long term.

We conducted a sensitivity analysis to determine the relative importance of N fertilizer inputs and SOC losses toward the mitigation of GWP (Supplementary Tables 2, 3). Our estimations of GWP are robust if, consistent with our concept model, large SOC losses are associated with large reductions in N fertilizer requirements whereas small SOC losses are associated with small reductions in N fertilizer requirements (that is, the amount of SOC loss is positively associated with the increase in N mineralization and decrease in denitrification; Fig. 1). This analysis has important implications for the amount of time required for new versus intensified drainage systems to offset the GWP generated from SOC loss with the GWP mitigated by lower annual N fertilizer inputs: new and intensified drainage systems should require a similar amount of time to offset SOC losses (Supplementary Table 3) because the new drainage systems produce large SOC losses but also large N fertilizer reductions, whereas the intensification of existing drainage systems produces relatively small SOC losses but also small N fertilizer reductions.

Water quality

The potential long-term benefits of drainage on GWP must not necessarily come at the expense of water quality. Although drainage increases downstream NO_3^- losses, drainage also creates unique opportunities to reduce downstream NO_3^- losses (see Box 1). In cropping systems without drainage, NO_3^- leaching is diffuse. As a result, strategies to reduce NO_3^- leaching from undrained croplands are limited. They rely on 'in-field' practices, including: (1) improved fertilizer management, which aims to synchronize inorganic N

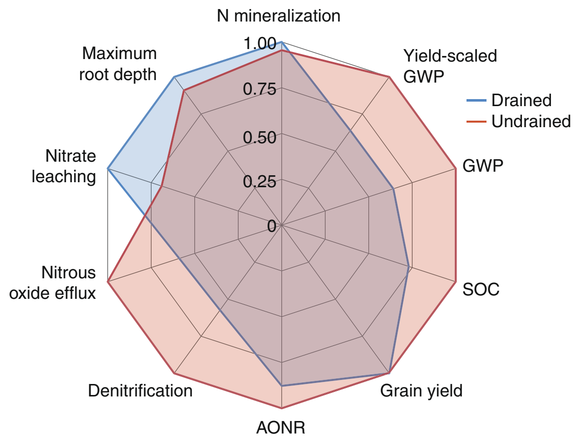


Fig. 3 | Relative differences in ecosystem properties and processes between drained and undrained continuous maize cropping systems in southeast Iowa, USA. All data other than SOC represent the mean annual simulated value across 18 weather-years. Relative differences in SOC represent the estimated difference in equilibrium SOC stock of 27,000 kg C ha^{-1} (Supplementary Information).

availability with crop N demand; and (2) the diversification of crop rotations with non-harvested cover crops, which aims to create N demand during times when fields are otherwise fallow. In contrast, strategies to reduce NO_3^- leaching from drained croplands can use these in-field practices as well as 'edge-of-field' practices because NO_3^- leaching from drained systems is concentrated through the drains[42,43]. Moreover, drainage can improve the effectiveness of in-field strategies because it allows timelier field operations[44], which are critical to the success of improved fertilizer management and cover cropping[45].

Edge-of-field technologies, installed at the end of drainage pipes, can reduce NO_3^- loss by promoting the complete denitrification of NO_3^- to N_2. All edge-of-field technologies promote denitrification by shunting NO_3^--rich drainage water through reduced-C substrates. Bioreactors, which are containers filled with reduced-C materials such as woodchips, can be fitted to the end of drain pipes; they reduce total NO_3^- loads by 12–100% (ref. [46]). Bioreactors are generally installed on field drains and do not require land retirement. A relatively new strategy to reduce NO_3^- losses is saturated riparian buffers, which are riparian buffer zones installed to intercept field drains that run from a field. As the drain pipes leave the field and enter the riparian buffer, they are intercepted with a perforated pipe that is buried in the riparian buffer perpendicular to the field drains and parallel to the waterway. As drainage water moves from the field it filters through the C-rich riparian buffer and denitrification can reduce NO_3^- loads by 27–96% (ref. [47]). In contrast to bioreactors and saturated riparian buffers that are installed by individual crop fields, wetlands are installed at the outlet of watersheds and treat many fields. They can reduce NO_3^- loads by 25–78% (ref. [48]). Wetlands require cropland retirement amounting to 1–6% of the total watershed[48]; however, they benefit biodiversity and pest management[49]. In addition, farmers can generate income from wetlands by leasing hunting rights.

All edge-of-field practices require proper engineering and this is an ongoing area of research. High-flow events, which account for most of the total annual NO_3^- loss, can bypass edge-of-field practices[48]; this is one reason for the large range in NO_3^- loss reductions reported above. To address this concern, government cost-share programs have minimum design standards. There is also concern about a potential trade-off between nutrient pollution of aquatic ecosystems and GHG emissions because denitrification by-products include N_2O. However, the fraction of NO_3^- that escapes these systems as N_2O (ref. [48]) is less than the IPCC indirect emission factor (EF_5) that accounts for N_2O emissions from leached NO_3^- (0.0075 kg N_2O–N kg^{-1} NO_3^-–N leached)[19]. Although edge-of-field practices have high up-front costs, they are relatively permanent and thus less expensive (cost kg^{-1} NO_3^- loss reduction) than in-field practices across their design life[42,43].

Future drainage-system design

Ageing drainage infrastructure, changing cropping systems and changing climate are increasing the extent and intensity of drainage (see Box 2). Thus, there is an immediate opportunity to adopt new drainage-system designs. A systems approach that integrates drainage, crop–soil processes, and nutrient loss reduction practices can be used to design artificially drained cropping systems that mitigate and adapt to climate change. Science, engineering and adaptation can minimize trade-offs between drained and undrained systems. If this outcome is achieved together with farmers, through reducing N fertilizer inputs while maintaining or increasing yield, environmental benefits would be rapidly attained.

Over the past 30 years, there has been enormous progress in drainage-system design for crop production and water-quality goals. Designs have shifted focus from the removal of all water, as fast as possible, to the control of water within individual fields. From this work, two major designs have emerged: (1) controlled drainage; and (2) altered drain depth and spacing. Both strategies modify the soil water-table depth and duration. Demand for these modifications was originally due to NO_3^- loss mitigation, but more recently includes soil-water conservation for climate-change adaptation[50,51]. Nevertheless, adoption of these systems is extremely limited.

Controlled drainage refers to the temporary installation and removal of gates at the end of field drains so that drains operate only when necessary. Gates are often removed in the spring to ensure field trafficability and installed in the summer to conserve soil water. This strategy has been widely researched in Europe and North America. Due to less water discharge, controlled drainage can reduce NO_3^- loss by 18–75% with positive or no effects on crop yield[29]. Although recent work suggests NO_3^- loss reductions may be overestimated if controlled drainage creates lateral flow of water to adjacent fields, the variability in NO_3^- loss reduction and crop yield is poorly understood due to limited understanding of the system[50]. Moreover, major limitations to the use of controlled drainage include field suitability and active management. Fields generally require a slope <0.5% but must be large enough to justify the cost of installation and farmers must manage the gates.

Alteration of drain spacing and depth is another strategy to control drainage intensity and depth to water table. This method does not require active management and does not have the field-suitability limitations associated with controlled drainage. Historically, subsurface drains in temperate systems have been placed at approximately 1–1.3-m depth due to a trade-off between drain depth and spacing[2]. For a desired drainage intensity, deeper placement reduces spacing requirements which reduces material and installation labour costs. However, shallow, narrow drain spacing results in less NO_3^- leaching than deep, wide drain spacing despite the same drainage intensity[28]. Similar to controlled drainage, NO_3^- leaching from shallow drainage systems is lower than from conventional systems due to less water discharge. Early indications suggest that this practice has variable, but small effects on yield. Overall, it is likely that this system works well in regions such as northwest Europe and the Midwest US where drainage is required to remove excess water in the spring, but crop water use exceeds growing-season precipitation. Limitations to the adoption of altered drain depth and spacing include lack of farmer familiarity and lack of research to identify potential long-term cost savings, such as greater fertilizer NUE, that offset greater installation costs.

Box 2 | Drainage in the US corn belt

Artificial subsurface drainage transformed the Midwest US into one of the most productive agricultural systems in the world. However, this productivity comes with environmental costs. Locally, NO_3^- loss from maize and soybean croplands impairs drinking waters and aquatic ecosystems. Regionally, maize and soybean croplands are the primary source of NO_3^- loading to the Gulf of Mexico.

There is an immediate opportunity to redesign Midwest drainage systems for multiple ecosystem services. In this region, drainage systems are undergoing a rapid transformation that began approximately 30 years ago and will continue over the coming decades[41]. The extent and intensity of these systems are increasing due to end-of-design-life, changing land-use and changing climate[5,7].

Contemporary Midwest US drainage systems are insufficient. Modern drainage design standards in Iowa recommend a drainage coefficient (DC; Box 1) of 1.27–2.54 cm d^{-1}; yet a review of Iowa drainage main infrastructure estimated that 95% of drainage basins have a DC of less than 0.95 cm d^{-1} (25–63% of modern design standards)[59]. Moreover, many systems rely on the original clay pipes installed >100 years ago, and those pipes are crumbling. Land-use change and climate change have combined to generate greater water flow to drains[51,52]. When contemporary drainage systems were installed, a much larger fraction of Midwest cropland was alfalfa, small-grain cereals, and pasture (Supplementary Fig. 4). During the 1970s, those crops were replaced by soybean, which transpires less water in the spring. In addition, the Midwest is becoming warmer and wetter. Over the past century, precipitation and humidity have increased[51,52]. As a result, the number of workable field days has decreased and drainage mains receive more water than they were designed to handle. These factors demand greater drainage intensity and DC for both crop growth and field trafficability.

At the same time, the extent of drainage is growing northward. From 2000–2011, maize and soybean production in North Dakota and South Dakota increased by 1.6 Mha (30%). This increase was coincident with the drainage of approximately 6,200 ha yr^{-1} of wetlands[5]. Unique to states within the intensively drained Midwest US, North and South Dakota require permits for large subsurface drainage projects. In North Dakota, <10 permits were issued from 1975–2002, whereas >1,200 permits were issued from 2003–2014. In South Dakota, <400 permits were issued from 1986–2002, whereas >4,000 permits were issued from 2003–2012 (Supplementary Information).

Controlled and shallow drainage could become important adaptations to climate change. The frequency of intense rainfall and drought are increasing[52]. In major portions of drained temperate humid croplands, crop water use exceeds average precipitation during crop growth[53,54]. Field trafficability and early-season crop growth are limited by excess soil water, but late-season crop growth is limited by insufficient water. There is a great advantage to avoid draining too much water, because this water can support late-season crop growth[51].

Controlled and shallow drainage systems could also mitigate climate change. In both systems, drainage intensity for the surface soil is increased while conserving subsoil moisture. Despite the increase in drainage intensity, shallow drain depth consistently reduces NO_3^- leaching because the amount— rather than rate—of water removal is the main control on NO_3^- leaching[28]. Shallow and controlled drainage could also reduce N_2O emissions: in cereal cropping systems, N fertilizer is the primary source of N_2O and most N_2O emitted to the atmosphere is produced from denitrification at or near the soil surface[55]. Similarly, most mineralized soil N that crops access is derived from 0–30 cm (ref. [56]). Thus, potential benefits of drainage on NUE (Figs. 1–3) should be maintained. Additionally, controlled and shallow drainage systems could benefit SOC storage. In drained systems with a water deficit during crop growth, roots can input C below the drains in the summer[38] while the return of shallow water tables to the drain depth from autumn to spring would limit mineralization of the root C inputs.

The implementation of improved drainage systems and management that achieve these goals will require substantial education and policies that reduce current barriers to adoption. Uncertainty and capital are two major barriers[57]. Uncertainty is one reason why adoption of improved N fertilizer management has lagged behind other conservation practices (that is, N mineralization is highly variable from year-to-year and sometimes less in drained than undrained systems, see Fig. 2). Coupled research and education could reduce this uncertainty. In contrast, capital-intensive technologies, such as shallow, narrow drainage, are adopted more slowly regardless of certainty and will require incentives[57].

Upgrades to drainage systems and edge-of-field NO_3^- loss reduction strategies could be incentivized if they are coupled. Incentives could come from cost-share programs or other policies. For example, US farmers are hesitant to upgrade drainage systems because regulations do not permit an increase in drainage intensity or coefficient (Box 1) without the mitigation or retirement of 'farmed wetlands', which are areas that have been continuously cropped since at least 1985 but exhibit wetland characteristics[7]. If farmed wetlands could be mitigated with the installation of a denitrification wetland, drainage could be improved while wetlands are protected. This would benefit farmers and the environment because NO_3^- loss would be reduced at the drainage main outlet, while an increase in upstream crop production from the improved drainage could offset the lost crop production from the wetland installation. The installation of denitrification wetlands could be further incentivized by permitting water recycling. Water recycling uses water collected in the wetlands during times of excess moisture in the early spring to irrigate during times of water deficit in the summer[51]. At present, farmers are not allowed to recycle water from denitrification wetlands. However, water recycling would probably have a limited effect on the denitrification capacity of the wetland because most denitrification occurs in the spring when excess water is removed from the croplands, while irrigation would occur in the summer when NO_3^- loss is low due to high crop N demand and low water flow.

Thus, the impacts of drainage systems on crop production and environmental performance need to be, and can be, better managed for the long-term sustainability of agriculture. In developing nations, agricultural intensification demands the installation of new, innovative drainage systems that are sustainable. In developed nations, ageing infrastructure, land-use change and climate change demand an increase in the area and intensity of drainage systems. Our concepts should apply broadly to croplands that require drainage for excess water and represent the majority of drained croplands[4]. It may also be possible to transfer some of our concepts to croplands that require drainage for irrigation water management. Nevertheless, in all these regions, a systems approach that designs drainage for multiple ecosystem services (for example, water conservation, increased fertilizer NUE and reduced GWP) can minimize trade-offs between environmental quality and crop productivity.

Agriculture has reached a decisive moment for the design of future cropping systems. Will the majority of drainage installations aspire to a single goal: maximum economic return to drainage? If so, we expect that the impacts of increasing drainage on SOC mineralization, soil N mineralization, and NO_3^- leaching will prevent targeted improvements to water quality. Alternatively, if drainage systems are designed with a systems perspective to minimize trade-offs between crop productivity and environmental performance, there is great potential for widespread benefits around the globe.

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Author contributions
M.J.C. led the concept development and writing; all authors contributed to the concept development, data interpretation and writing. S.V.A. conducted the modelling. H.J.P. led data analyses and figure development; M.J.C. contributed to data analyses and figure development.

Competing interests
The authors declare no competing interests.

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