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Agricultural practices for cleaner water: a global synthesis of meta-evidence

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Abstract

Agricultural intensification has pushed nitrogen and phosphorus cycles beyond safe planetary limits, with agriculture now a primary driver of at least two Earth system boundaries being breached. Technological fixes alone are unlikely to resolve this: efficiency gains tend to lower production costs and drive further expansion (known as Jevon's Paradox), intensifying environmental pressure rather than relieving it. Reducing agricultural water pollution will therefore require a shift toward production systems that work with ecological processes rather than against them. Despite growing interest in agroecological and regenerative approaches, evidence on their effectiveness for improving water quality remains fragmented across practices, regions, and study designs. This review of reviews synthesizes global evidence from 67 multi-continental meta-analyses on how farm practices affect nutrient, pesticide, and sediment losses. Nonlegume cover crops cut nitrate leaching by about 50%–70% and sediment by 50%–60%. Residue retention and organic amendments reduced runoff nutrients by 25%–50% and sediment by up to 75%. Reduced tillage lowered sediment losses by about 60% but often increased nitrate leaching, highlighting the importance of complementary fertilizer management. Optimizing fertilizer rates, timing, and formulation, alongside precision irrigation, reduced nitrogen losses by 20%–70%. At the landscape scale, vegetated buffers, agroforestry, and wetlands typically removed 25%–90% of nutrients and 40%–95% of sediment. Improving soil cover, structure, and hydrological function can sharply reduce pollution without sacrificing yields, showing that poor water quality stems from management, not inevitability. However, important evidence gaps remain: pesticide transport lacks any global synthesis despite residues being among the most pervasive agricultural contaminants, quantitative evidence on adaptive grazing management remains limited, and most underlying studies are concentrated in temperate croplands of North America, Europe, and China, limiting confidence in applying these findings to tropical, arid, or smallholder systems.

Key words: water quality, farming, food production, regenerative agriculture, agroecological practices, nutrient loss

Introduction

Global food demand is expected to increase by 35%–56% by 2050 compared with 2010 levels, driven by population growth and changing dietary preferences (Shafi et al. 2019; van Dijk et al. 2021). Despite the enormous diversity of edible plants worldwide, with an estimated 50 000 species, only about 300 are commercially cultivated, and just 30 provide around 90% of humanity's caloric intake (Hammer et al. 2003; Massawe et al. 2016). To sustain this narrow crop base, large monocultures have been established far beyond their natural ecological ranges, reshaping landscapes through widespread clearing, drainage, irrigation, and heavy reliance on fertilizers and pesticides (Altieri 2009; Stoate et al. 2009; Ramankutty et al. 2018). In livestock systems, nutrients taken up by animals during grazing gets redeposited at high concentrations in urine and manure patches at rates far exceeding plant uptake capacity, particularly in monocultured pastures, resulting in low nutrient use efficiency and high losses via leaching and runoff losses (Burkitt 2014; Velthof et al. 2015; Vibart et al. 2016). These practices have profoundly altered hydrological and nutrient cycles, accelerating runoff, erosion, and the loss of nitrogen, phosphorus, and sediments to aquatic ecosystems (Gaugler et al. 2020; Sonderegger and Pfister 2021; Schulte-Uebbing et al. 2022).

Agriculture is a primary driver of nitrogen and phosphorus cycles being pushed beyond their safe operating limits and into the high-risk zone of the planetary boundaries framework (Richardson et al. 2023). Excess nutrients and sediments are transported into groundwater, rivers, lakes, and coastal waters, where they reduce water clarity, alter light availability and habitat structure, and stimulate excessive algal and microbial growth that depletes dissolved oxygen (Ferreira et al. 2015; Dodds and Smith 2016; Wurtsbaugh et al. 2019). The resulting eutrophication shifts aquatic systems toward algal- and detritus-dominated states (Ardón et al. 2021), destabilizing food webs, reducing biodiversity, and in severe cases creating hypoxic zones that lead to fish kills. Excessive sedimentation further smothers benthic habitats, clogging gills and reducing feeding efficiency for invertebrates and fish. The outcome is widespread degradation of inland and coastal water quality, undermining ecosystem services, fisheries, and human health.

While technological innovations such as precision irrigation, variable-rate fertilizer application, and sensor-based monitoring can improve the efficiency of water and agrochemical use (King 2017; Shafi et al. 2019), their benefits are far from straightforward. These systems are often energy- and resource-intensive, vulnerable to failure under extreme weather, and prohibitively costly for many farmers (Tzounis et al. 2017; Shafi et al. 2019). In energetic terms, modern high-tech agriculture has become increasingly unsustainable: long-term analyses show that industrial, fossil-fuel-dependent systems now yield lower energy returns on investment (EROI) than traditional agroecological solar-based farming, locking agriculture into an "energy trap" where external inputs exceed energetic gains (Galán et al. 2016; Tello et al. 2023). Moreover, gains in input efficiency rarely translate to reduced resource use at larger scales. In North America, for instance, decades of technological advances have failed to improve the edible energy efficiency of food production despite major investments in fertilizer and irrigation (Hamilton et al. 2013). This reflects Jevon's Paradox, where increased efficiency lowers costs and drives expansion, ultimately intensifying resource use and environmental pressure (Ceddia et al. 2013; Giampietro and Mayumi 2018). Engineering advances, by reducing the effort or risk of production, can thus entrench the very dynamics they seek to solve, fuelling further intensification and extending agriculture beyond ecological limits, with escalating impacts on water quality and ecosystem health (Woodhouse 2010; Sears et al. 2018; Hamant 2020).

Reducing the water quality impacts of agriculture will require a shift toward production systems that work with ecological processes rather than against them. Two complementary frameworks, agroecology and regenerative agriculture, offer pathways for doing so. Agroecology provides the scientific foundation for understanding and improving food systems by applying ecological principles to analyze how energy, nutrients, and organisms interact across farms and landscapes, thereby identifying management strategies that enhance resilience, equity, and sustainability (Gliessman 2016; Wezel et al. 2020; Bezner Kerr et al. 2021). Regenerative agriculture represents the practical application of this science and broadly aims to achieve resilient and profitable production through holistic farm management that improves the health of soils, ecosystems, and people while producing quality food and fibre (Newton et al. 2020; Jayasinghe et al. 2023; Sands et al. 2023). In practice, regenerative agriculture draws from agroecological principles through actions such as cover cropping, low or no tillage, integrating trees and perennial vegetation, restoring riparian buffers, managing grazing adaptively, and using organic amendments to rebuild soil structure and nutrient cycling (LaCanne and Lundgren 2018; Lal 2020; Rehberger et al. 2023). These practices aim to enhance productivity and resilience while reducing nutrient and sediment losses, improving water infiltration, and strengthening the capacity of landscapes to maintain clean and functioning waterways (LaCanne and Lundgren 2018; Lal 2020; Rehberger et al. 2023).

Despite growing interest in agroecological and regenerative approaches, evidence on their effectiveness for improving water quality remains fragmented across practices, regions, and study designs. Existing knowledge is often scattered among individual experiments or regional case studies, making it difficult to compare outcomes or identify generalizable patterns. To address this gap, this review synthesizes global and multi-continental meta-analyses that evaluate how different agricultural practices influence nutrient and sediment losses from farmland. It consolidates current evidence on strategies such as organic amendments, crop diversification, fertilizer conservation, vegetative buffers, and agroforestry, providing a foundation for understanding which interventions most consistently improve water quality across diverse agroecosystems.

Approach

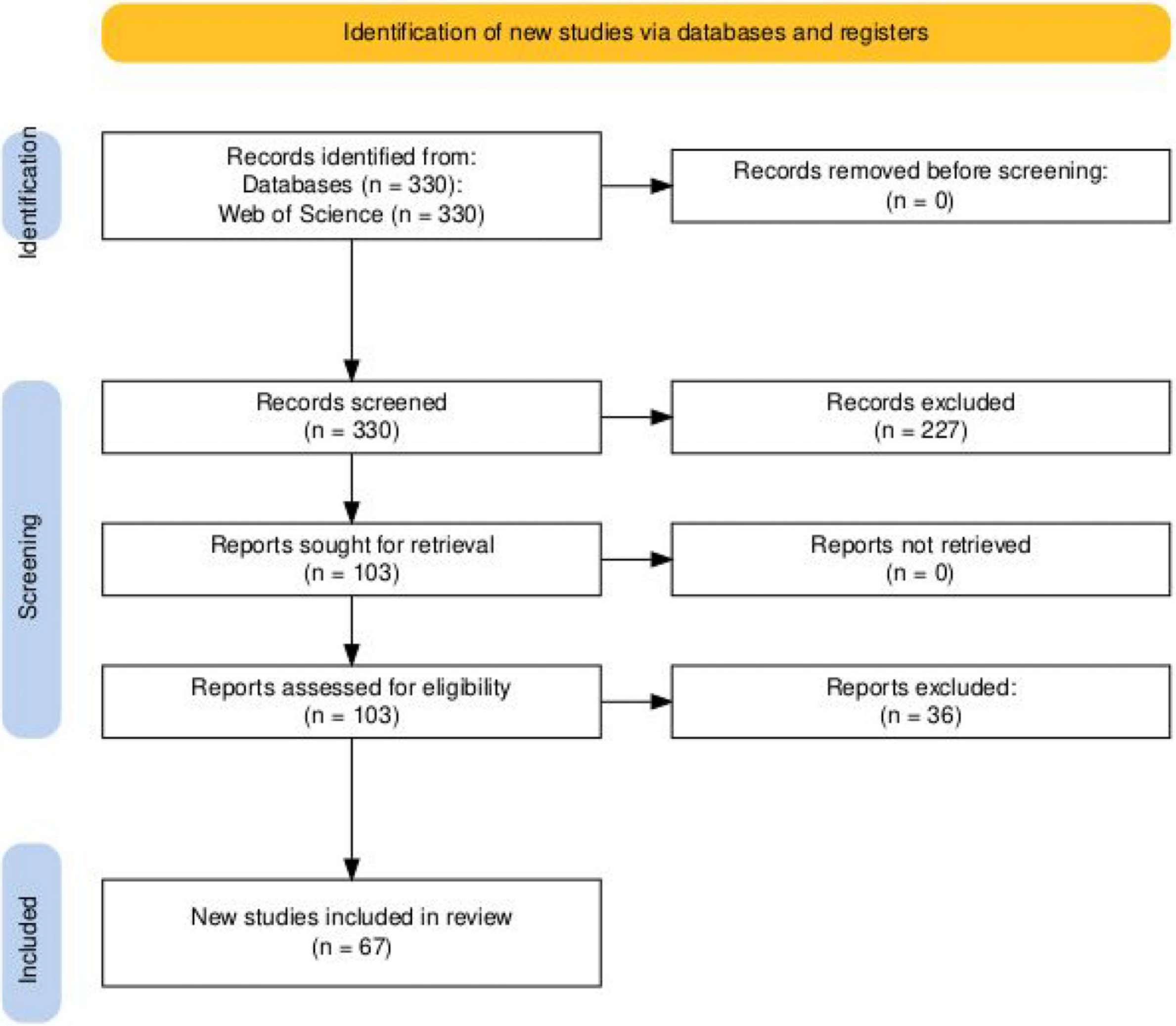
A systematic search was conducted using the Web of Science Core Collection on 20 August 2025 to identify global syntheses evaluating the effects of agricultural practices on water quality. The search included both meta-analyses and systematic literature reviews and was designed to capture studies that examined the influence of agricultural management practices and strategies (both in and off field) on nitrogen, phosphorus, sediment, or pesticide and herbicide losses through runoff, leaching, or erosion. The review process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework guidelines (Page et al. 2021). The search string used was:

> (("meta-analysis" OR "systematic review") AND ("water quality" OR nitrogen OR phosphorus OR pesticide OR sediment) AND (loss OR runoff OR leachate) AND ("agricultural practice*" OR "land management" OR "regenerative agriculture" OR "conservation agriculture" OR "sustainable agriculture" OR "best management practice*" OR "soil management" OR "water management" OR "nutrient management" OR "erosion control" OR "grazing management" OR "adaptive grazing" OR "holistic grazing" OR "contour cropping" OR "swales" OR "natural sequence farming" OR "integrated pest management" OR "soil amendment*" OR "cover crop*" OR "organic amendment*" OR "tillage" OR "vegetative buffer*" OR "filter strip*" OR "wetland" OR "treatment pond" OR "treatment dam" OR "agroforestry" OR "perennial system*" OR "biochar" OR "biostimulant*" OR "fertilizer management"))

Studies were included if they met all the following criteria:

1. Were meta-analyses or systematic literature reviews.
2. Assessed at least one agricultural practice or management strategy related to soil, water, or nutrient management.
3. Quantified effects on at least one water quality variable, specifically nitrogen or phosphorus losses (via leaching or runoff), sediment losses, or pesticide/herbicide losses.
4. Synthesized data from at least two continents, ensuring that findings represented multi-regional or global patterns rather than local or single-region case studies.

Fig. 1. PRISMA flow diagram summarizing the literature search and screening process (Haddaway et al. 2022), including the number of records identified through the Web of Science search, the number screened and excluded at each stage, and the final number of meta-analyses and systematic reviews included in this review on the water quality impacts of agricultural practices.



Following the removal of duplicated articles, the titles and abstracts were screened to identify studies meeting the inclusion criteria. Full texts were then reviewed to confirm eligibility. As per the criteria above, only studies that explicitly quantified the effects of agricultural practices on water quality outcomes were retained. Studies limited to yield, soil health, or greenhouse gas emissions without water quality components were excluded.

Findings

Study selection and overview

The initial Web of Science search returned 330 nonduplicated records. Following title and abstract review, 75 full texts were assessed for eligibility, and 67 studies met all inclusion criteria. The selection process is summarized in Fig. 1 following PRISMA reporting guidelines (Page et al. 2021).

In-field practices and strategies

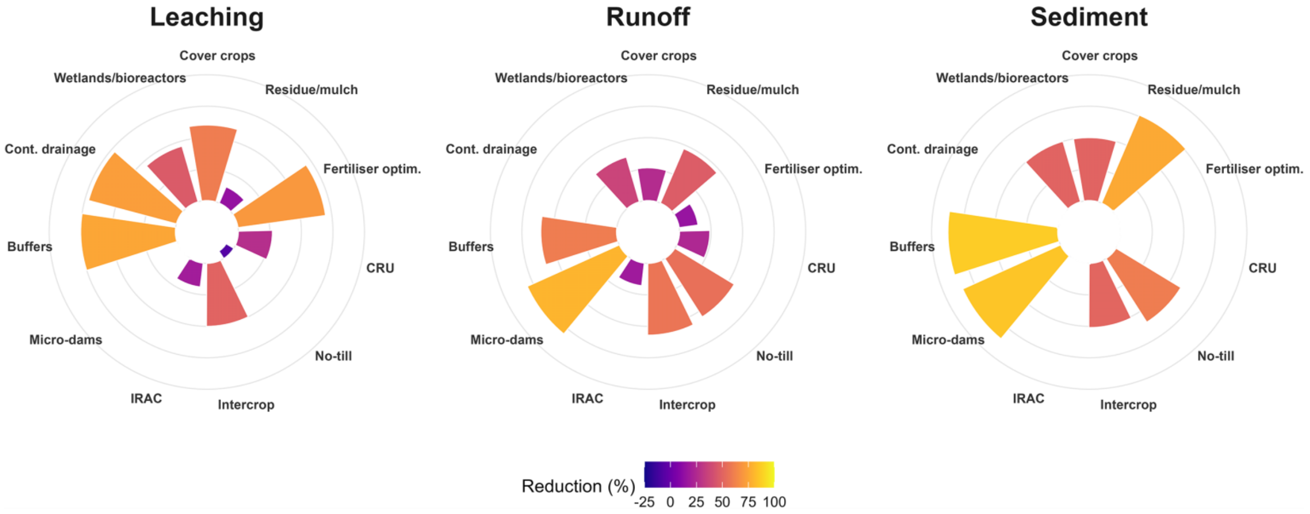
A substantial body of evidence demonstrates that practices such as cover cropping, agroforestry, reduced tillage, no-till, and residue return can markedly reduce nutrient and sediment losses from farmland (approximate reductions summarized in Table 1). Du et al. (2022) synthesized findings from 432 runoff and 459 erosion comparisons, showing that these practices reduced surface runoff by an average of 67% and erosion by 80% compared to conventional controls, with cover crops achieving the greatest reductions followed by agroforestry.Ren et al. (2023) found that these approaches increased yields by 12% overall, driven largely by a 41% gain in corn, with agroforestry and legume cover crops particularly effective due to improved soil nitrogen, moisture retention, and reduced erosion. Beillouin et al. (2021) examined crop diversification strategies collectively, including agroforestry, intercropping, cover crops, crop rotation, and variety mixtures, finding a median 51% improvement in water quality

Table 1. Summary of global meta-analysis evidence ($n = 67$ studies) on agricultural practices and their effects on nutrient, sediment, and pesticide losses to waterways via surface runoff and subsurface leaching.

Practice/strategy	Primary mechanism	Runoff losses (surface)	Leaching losses (sub-surface)	Sediment	Pesticides	Key moderators/trade-offs
Cover crops (nonlegume)	Uptake of residual N, reduced erosion	↓ N, P ≈ 25%–30%	↓ NO_3^- ≈ 50%–70%	↓ 50%–60%	↓ variable	Strongest on coarse soils, dry years; biomass > 3 Mg ha^{-1}
Green manures (nonlegume)	Organic N retention, microbial immobilization	↓ N ≈ insignificant	↓ NO_3^- ≈ 20%–25%	↓ moderate	n/a	Short-term rise in N_2O; time decomposition with crop uptake
Legume/mixed covers	N fixation, residue inputs	↓ slight	– 0% to ↑ 20%	↓ moderate	n/a	Risk of excess N if mineralization precedes crop demand; can reduce leaching if replacing >110 kg N ha^{-1}
Reduced/no tillage	Lower erosion, residue cover	↓ particulate P ≈ 55%; ↑ dissolved P (variable, steep slopes)	↑ NO_3^- ≈ 7%–15%	↓ 55%–60%	↑ variable; increases for soluble compounds	Benefits rely on residue cover; requires fertilizer management for dissolved nutrients
Residue retention/mulching	Surface protection, infiltration	↓ N, P ≈ 25%–50%	↓ NO_3^- ≈ 10%–15%	↓ 50%–75%	↓ unknown	Most effective with >60% cover, moderate slopes; 0.3–0.8 kg m^{-2} or 2–7 t ha^{-1}
Organic amendments (manure, compost)	Improved aggregation, slower N release	↓ N, P ≈ 25%–30%	↓ NO_3^- ≈ 30%	↓ 20%–50%	n/a	Over-application increases leaching; strongest in Mollisols; replace 50%–75% of synthetic N
Biochar	Sorption, aggregation, N retention	↓ N, P ≈ 10%–20%	↓ NO_3^- ≈ 10%–15%	↓ 15%–25%	n/a	Stronger in sandy or degraded soils; high-temp. > 500 °C chars best; >10 Mg ha^{-1}; effects may diminish long-term
Fertilizer rate/timing optimization	Match supply to crop demand	↓ N, P ≈ 10%–20%	↓ NO_3^- ≈ 30%–70%	↓ minor	n/a	Losses increase sharply above optimal rate; higher soil organic C reduces N loss
Controlled-release fertilizer (CRU)	Gradual N release	↓ N ≈ 25%	↓ NO_3^- ≈ 25%–30%	n/a	n/a	Performance declines under heavy rain, high temperature; higher cost limits adoption
Precision irrigation/AWD	Reduce percolation and runoff	↓ N, P ≈ 30%–95%	↓ NO_3^- ≈ 20%–40%	↓ major	n/a	AWD may raise N_2O; drip/controlled systems best; soil texture and control accuracy critical
Intercropping/agroforestry	Continuous cover, deep rooting	↓ N, P ≈ 30%–70%	↓ NO_3^- ≈ 50%	↓ 50%–70%	n/a	Dense vegetation, moderate slopes (10°–15°), loam-clay soils improve effect; nonlegume perennials most effective
Integrated rice-animal co-culture (IRAC)	Animals aerate sediment and mobilise nutrients	↓ N, P ≈ 20%	↓ NO_3^- ≈ 20%	n/a	n/a	Rice-fish, duck, or crab cohabitants only; rice-crab systems most effective; stronger benefits in high-clay soils, lower N inputs, and higher-rainfall regions
Micro-dams/bunds	Trap runoff and sediment	↓ N, P ≈ 50%–70%	↓ minor	↓ 75%–85%	↓ 80%–90%	Fail under intense storms; best on moderate slopes and rainfall; interridge or interrow placement
Controlled drainage/subirrigation	Extend water residence time	↑ surface N, P ≈ 70%–80%	↓ NO_3^- ≈ 30%–75%	n/a	n/a	Strong subsurface reduction but raises surface runoff under saturation; best in cool, medium-textured soils, wet years
Wetlands/bioreactors	Denitrification, sedimentation, uptake	↓ N, P ≈ 25%–50%	↓ NO_3^- ≈ 25%–50%	↓ 40%–50%	↓ weak-moderate	Risk of P release under strong reduction; residence time > 3 days; performance depends on hydraulic loading; may increase N_2O or CH_4
Vegetated buffers/riparian strips	Filtration, infiltration, uptake	↓ N, P ≈ 60%–90%	↓ NO_3^- ≈ 60%–80%	↓ 75%–95%	↓ moderate; depends on sorption	Width > 10–15 m, low slope, dense vegetation maximize efficiency; hydraulic load more important than width alone

Note: Values represent approximate global ranges of percentage change relative to conventional or control systems, and they reflect median or mean values across studies rather than local extremes. Arrows denote direction of change (↓ = reduction; ↑ = increase). "n/a" indicates data not available or insufficient for quantitative synthesis at the global scale. Runoff refers to surface transport of nutrients, sediments, and agrochemicals to waterways; leaching refers to vertical or subsurface movement below the root zone.

Fig. 2. Effectiveness of agricultural practices in reducing nutrient and sediment losses to waterways. Circular bar plots show percentage reduction in leaching (subsurface), runoff (surface), and sediment losses relative to conventional management, based on global meta-analyses ($n = 67$ studies). Practices are ordered from in-field (left) to off-field (right) interventions. Negative values (inward bars) indicate increases in losses. Colour intensity corresponds to reduction magnitude. CRU, controlled-release urea; IRAC, integrated rice-animal co-culture; Cont. drainage, controlled drainage.



through reduced erosion and nutrient leaching, though outcomes were highly variable (3%–123%) with no clear differences between strategies. Basche and DeLonge (2019) showed that introducing perennials led to the largest increases in infiltration rates (59%), followed by cover crops (35%), while no-till effects were modest and climate-dependent. These broad patterns reflect specific mechanisms that vary among practices and contexts, which are examined in detail below.

Reduced tillage

Reduced tillage refers to farming systems that disturb the soil less than conventional ploughing, such as no-till or shallow noninversion tillage, often allowing crop residues to remain on the surface.

Compared with conventional tillage (CT), no tillage (NT) systems have consistently shown to reduce sediment and sediment-bound nutrient losses (Fig. 2). The minimal soil disturbance and greater cover from residue retention results in lower erosion and improved soil structure. Across 282 paired runoff plots from 41 studies, Mhazo et al. (2016) found that NT significantly reduced sediment concentration in runoff by 56% and soil losses by 60% compared to CT, with the greatest benefits observed on long plots, steep slopes, low-clay soils, and in temperate climates. Similar reductions were also observed by Rajbanshi et al. (2023). When NT is used in crops without residue retention, Xiao et al. (2021) observed smaller median sediment loss reductions of 26% compared with CT. Crops that used residue retention, regardless of tillage method, had a median sediment loss reduction of 55.5%. Combining no tillage with residue retention did not yield substantial improvements in sediment loss reductions than residue retention alone. As phosphorus is often bound to sediment, Daryanto et al. (2017*b*) observed similar reductions in particulate P loss, with a median reduction of 55% compared to CT. Reductions in particulate P loss were greatest in wetter areas, while no reductions were observed on steep slopes. Overall, NT can considerably reduce sediment and sediment-bound nutrient losses relative to CT, though this is largely driven by soil protection from residue retention, with benefits greatest in temperate regions given generally slower rates of residue decomposition and less intense periods of rainfall than the tropics.

In contrast to particulate nutrients, NT systems often had greater losses of dissolved nutrients compared with CT. In the study by Daryanto et al. (2017*b*), NT systems had considerably greater losses of dissolved phosphorus on steep slopes than CT, possibly due to limited vertical movement of phosphorus fertilizer and minimal mixing between soil, crop residues, and surface-applied fertilizer. Daryanto et al. (2017*a*) also found that nitrate loads in leachate were often higher, but runoff loads lower under no-till, despite similar nitrate concentrations, suggesting that changes in water movement by crop residues under no-till practices primarily drive the increased nitrate load. It may be that increased leaching compensates for the reduced runoff typically observed under NT relative to CT (Mhazo et al. 2016; Xiao et al. 2021). Likewise, Li et al. (2023) observed 7% greater nitrate leaching in no-till and noninversion tillage systems compared with inversion tillage. Concurring with Daryanto et al. (2017*a*), water throughputs were a primary predictor of nitrate leaching and where preferential flows dominate and reduce interaction between nitrate and the soil matrix. This is also observed in flooded rice systems, where Liang et al. (2016) also observed no-till systems to have greater N and P runoff, 15% and 40%, respectively, compared with conventional tillage. No tillage systems, therefore, require more attention on fertilizer conservation strategies to reduce the risk of nitrate leaching, with strategies potentially including smaller and more diffuse fertilizer applications, timing with crop uptake and avoiding periods of high irrigation or rainfall.

Comparable trade-offs are evident for pesticides. Elias et al. (2018) found that NT often increased pesticide concentrations and loads in runoff, particularly for highly soluble and weakly sorbing compounds. Among the pesticides examined, dicamba, metribuzin, atrazine, and cyanazine losses increased under NT, while alachlor and chlorpyrifos decreased. Pesticide loads tended to rise in fine-textured soils but decline in medium-textured soils, with the highest losses occurring in soils with moderate organic matter (around 2%–3%) and near-neutral pH, and the lowest in slightly acidic soils (pH $\approx$ 6.1–6.5) with higher organic matter ($>$2.3%). Weak acid herbicides such as 2,4-D and bromoxynil were more mobile under acidic conditions, whereas ionisable, highly soluble compounds like dicamba showed greater losses in neutral to alkaline soils. Overall, NT did not consistently reduce pesticide transport and in some cases exacerbated it, particularly in soils with low organic matter (<2.3%), neutral to alkaline pH, or where highly soluble pesticides were applied.

Cover cropping and green manure

Cover crops are plants grown between main cropping cycles to protect and improve soil health by reducing erosion, capturing residual nutrients, and enhancing soil structure. They can be sown as single-species covers, such as grasses or legumes selected for a specific function like nitrogen fixation or erosion control, or as multi-species mixtures, which combine complementary traits for multifunctional benefits, such as deep-rooted species to improve infiltration, legumes to supply nitrogen, and fast-growing grasses or brassicas to scavenge excess nutrients (Figs. 2 and 3). When cover crops are later incorporated into the soil to release nutrients and organic matter, they are referred to as green manures, which further enrich soil fertility.

Cover crops have also been shown to improve aggregate stability and reduce runoff and erosion, reducing sediment and sediment-bound nutrients from reaching waterways. Jian et al. (2020) found that cover cropping increased soil organic carbon by an average of 15.5%, and that these increases were strongly associated with reduced runoff (adjusted $R^2 = 0.86$) and erosion ($R^2 = 0.47$). Cover crops have generally been effective at reducing N leaching, though this reduction depends on the timing of N release from the cover crop residues and its uptake by the main crop and whether the cover crop was leguminous or nonleguminous (Yousefi et al. 2024). Wortman (2016) showed that nitrogen loss from bare fallow soil was 60% higher than from naturally vegetated (“weedy”) fallow, while managed cover crops reduced nitrogen loss by a further 26%.

Overall, nonleguminous cover crops are consistently effective at reducing nitrate leaching. Quemada et al. (2013) and Thapa et al. (2018) observed that replacing a bare fallow with a nonlegume cover crop reduced nitrate leaching by 50% and 56% (on average), respectively, while legume cover crops and legume–nonlegume mixed crops did not have any significant effect on reducing nitrate leaching. Thapa et al. (2018) also observed the percentage reduction in nitrate leaching was strongly related ($R^2 = 0.93$) to the shoot biomass ($\mathrm{Mg\,ha^{-1}}$) of nonleguminous cover crops, saturating at approximately 70% reduction with a shoot biomass of $3\,\mathrm{Mg\,ha^{-1}}$. These benefits appear to be more pronounced in drier years and in coarse-textured soils, which are more vulnerable to leaching losses.

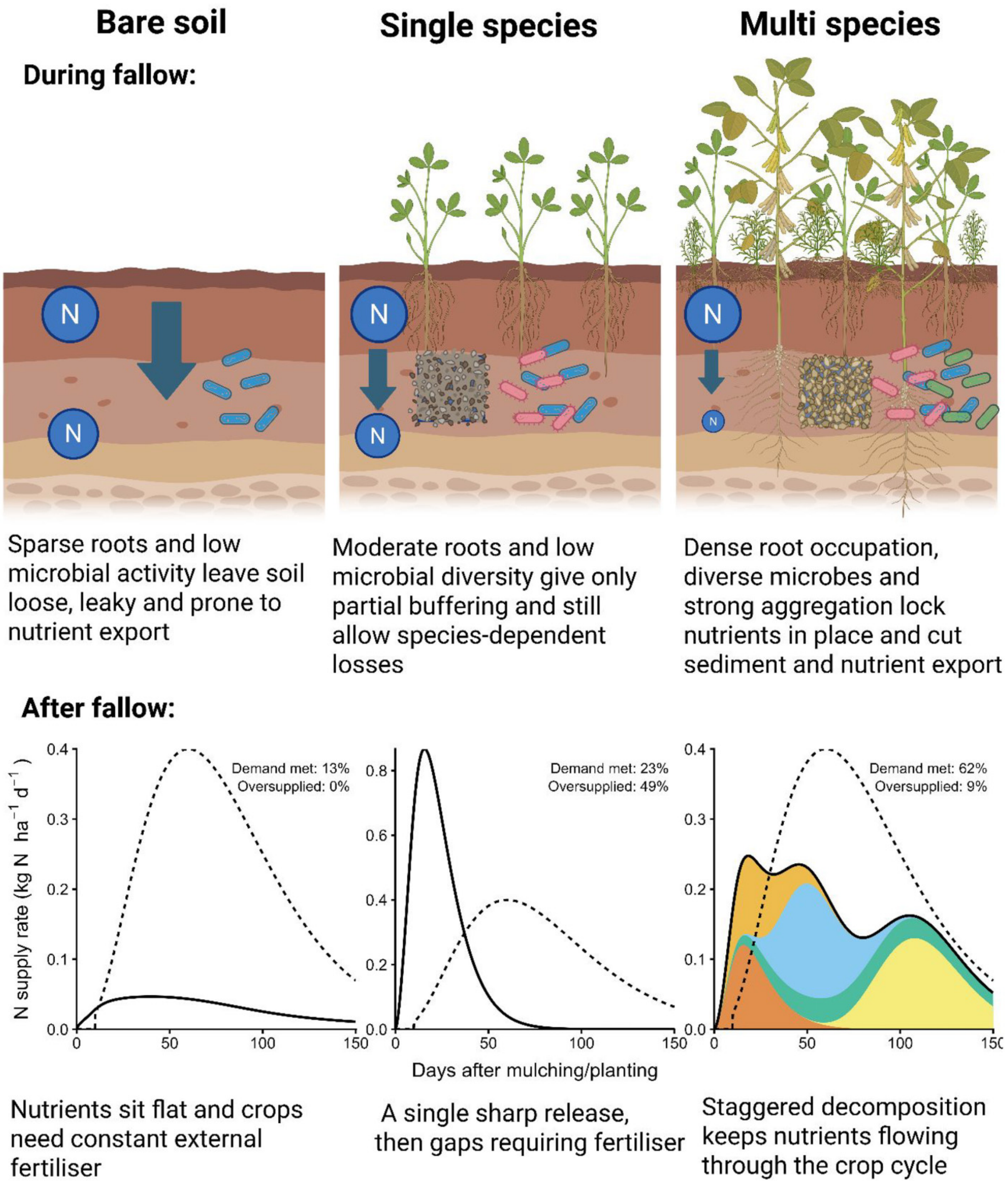
The global meta-analysis by Nouri et al. (2022) reinforces these findings, showing that cover crops reduce nitrate leaching by an average of 69% relative to bare fallow, with Brassicaceae and Poaceae families achieving reductions of 75% and 52%, respectively. Genera such as *Avena* and *Brassica* were particularly effective, with reductions reaching up to 81%. The effectiveness of cover crops was highest in Ultisols, Histosols, and Inceptisols, and was more pronounced in vegetable systems and under conventional tillage compared to no-till or reduced tillage systems. Interestingly, Nouri et al. (2022) found no overall effect of cover crops on water drainage, suggesting that nitrate leaching reductions are primarily due to increased nitrogen uptake by cover crops or altered soil microbial activity rather than reduced percolation.

In contrast, leguminous cover crops often provide less benefit for water quality due to their ability to fix atmospheric nitrogen, which can lead to higher soil N levels and increased leaching risk if the release of nitrogen from residues does not align with the main crop’s uptake needs. Thapa et al. (2018) and Yousefi et al. (2024) found that legume and mixed legume–nonlegume cover crops did not significantly reduce nitrate leaching compared to bare fallow. However, Tonitto et al. (2006) reported that legume cover crops could reduce nitrate leaching by approximately 40% if they supplied more than $110\,\mathrm{kg\,N\,ha^{-1}}$ as green manure and replaced conventional fertilization, with yields also matching those of fertilized bare fallow systems under such conditions. In their review, few studies had experiments lasting longer than 2–3 years, necessitating further work on long-lived perennial systems and using multispecies mixtures to manage decomposition over time. Furthermore, Xu et al. (2024*a*) found that incorporating cover crops as green manure reduced nitrogen leaching by approximately 22% and yield-scaled ammonia volatilization by about 21%, while only temporarily increasing nitrous oxide emissions in short-term (<5 year) studies. Nonlegume green manures were particularly effective at reducing NH_3 losses without elevating N_2O, and substituting part of the mineral N fertilizer with green-manure-derived N helped avoid additional gaseous losses. Although effects on N runoff were insignificant, these findings indicate that green manuring can substantially lower nitrogen leaching and volatilization, especially when managed over longer timeframes and with careful species and fertilizer selection. Overall, longer-term research is needed on perennial and multispecies systems to better synchronize residue decomposition with crop N demand and refine fertilizer recommendations following leguminous cover crops, which may allow fertilizer inputs to be reduced or avoided entirely.

Water and fertilizer conservation

A range of fertilizer and irrigation management strategies have been shown to substantially reduce nutrient and sediment losses to waterways while maintaining or improving crop yields. Improved nutrient management practices, including optimizing fertilizer rates, timing, and placement,

Fig. 3. Conceptual diagram of soil processes under bare, single-species, and multispecies fallows. During fallow periods, multispecies cover crops have more dense and diverse root structures than single-species crops or bare fallows. Consequently, the structure and root exudates are hypothesized to support a wider diversity of soil microbes, improve soil aggregation, and immobilize nutrients and sediment. After the fallow period, if cover crop residues are retained as green manure, then if selected correctly, multispecies cover crop mixes can be designed to ensure species decompose and mineralize nutrients at different rates and collectively provide nutrients in better synchrony to the main crop demands than single-species cover crops or bare fallows can, reducing the need for external fertilizer.



Sparse roots and low microbial activity leave soil loose, leaky and prone to nutrient export

Moderate roots and low microbial diversity give only partial buffering and still allow species-dependent losses

Dense root occupation, diverse microbes and strong aggregation lock nutrients in place and cut sediment and nutrient export

Nutrients sit flat and crops need constant external fertiliser

A single sharp release, then gaps requiring fertiliser

Staggered decomposition keeps nutrients flowing through the crop cycle

help match nutrient supply to crop uptake, lowering the risk of nitrate leaching and gaseous emissions that degrade water quality. Controlled-release fertilizers gradually release nitrogen in synchrony with crop demand, reducing excess nitrate available for leaching (Fig. 2). Precision irrigation systems such as drip or soil moisture-controlled irrigation deliver water directly to plant roots, minimizing runoff and nutrient transport.

Optimizing fertilizer application rates and timing is critical because nutrient losses increase sharply once crop nitrogen demand is exceeded, leading to diminishing returns for yield. Wen et al. (2023) showed that while moderate fertilization boosted apple yields, higher rates caused large increases in nitrogen losses, with N_2O and NH_3 emissions rising by over 200% and nitrate leaching by around 70%. In cereal and paddy systems, Hina (2025) and Meng et al. (2023) also found that N losses more than doubled at high nitrogen inputs across major cereal systems. Though, at least in paddy systems, combining organic and inorganic fertilizers, deep placement, and enhanced-efficiency formulations can reduce N leaching and runoff by approximately 7%–10% and 9%–20%, respectively (Liu et al. 2025*b*). Xu et al. (2024*b*) further showed that soils with greater organic carbon lose less nitrogen at any given rate, with modelling showing that applying optimal N rates alongside increasing SOC could reduce fertilizer N losses by 34.8%–59.6% without yield penalties. Reduced phosphorus inputs (10%–90% reduction from conventional P rates) have also been shown by Jin et al. (2023) to reduce phosphorus leaching by 16.0% in vegetable fields and 31.5% in cereal fields, while reductions did not affect vegetable yield, cereal yield was reduced by approximately 4.6%.

Controlled-release urea (CRU) is one of the most widely studied technologies for improving nitrogen use efficiency (NUE). Yang et al. (2021) showed that CRU can improve NUE and increase crop yields by around 7.7%, while reducing reactive nitrogen losses by 24%–46%, including a 24% reduction in nitrate leaching. Zhang et al. (2019) found that CRU increased maize yield by 5.3% and NUE by 24%, while reducing nitrate leaching by 27.1%. Zhang et al. (2024) reported nitrogen loss reductions of 33%–49%, with greater reductions observed in cooler, drier regions with low soil organic carbon and neutral pH, while higher temperatures, heavy rainfall, and slower or poorly matched release rates and coating materials reduced performance. Comparable results have been reported in vegetable systems, where enhanced-efficiency fertilizers such as polymer-coated urea reduced nitrate leaching by 29%–46% without yield penalties (Pan et al. 2024). While broadly effective, its higher cost has slowed large-scale adoption, and the environmental footprint of CRU coating materials remains poorly quantified (Zhang et al. 2019). A recent lifecycle assessment from a 4-year maize trial in China found that slow-release fertilizer reduced total greenhouse gas emissions by 90–593 kg CO_2-eq ha^{-1} relative to conventional urea across varying nitrogen application rates (Han et al. 2026), suggesting net environmental benefits beyond water quality alone. However, such assessments remain rare, and incorporating LCA into CRU product design and evaluation has been identified as a priority for the field (Jumakir et al. 2026).

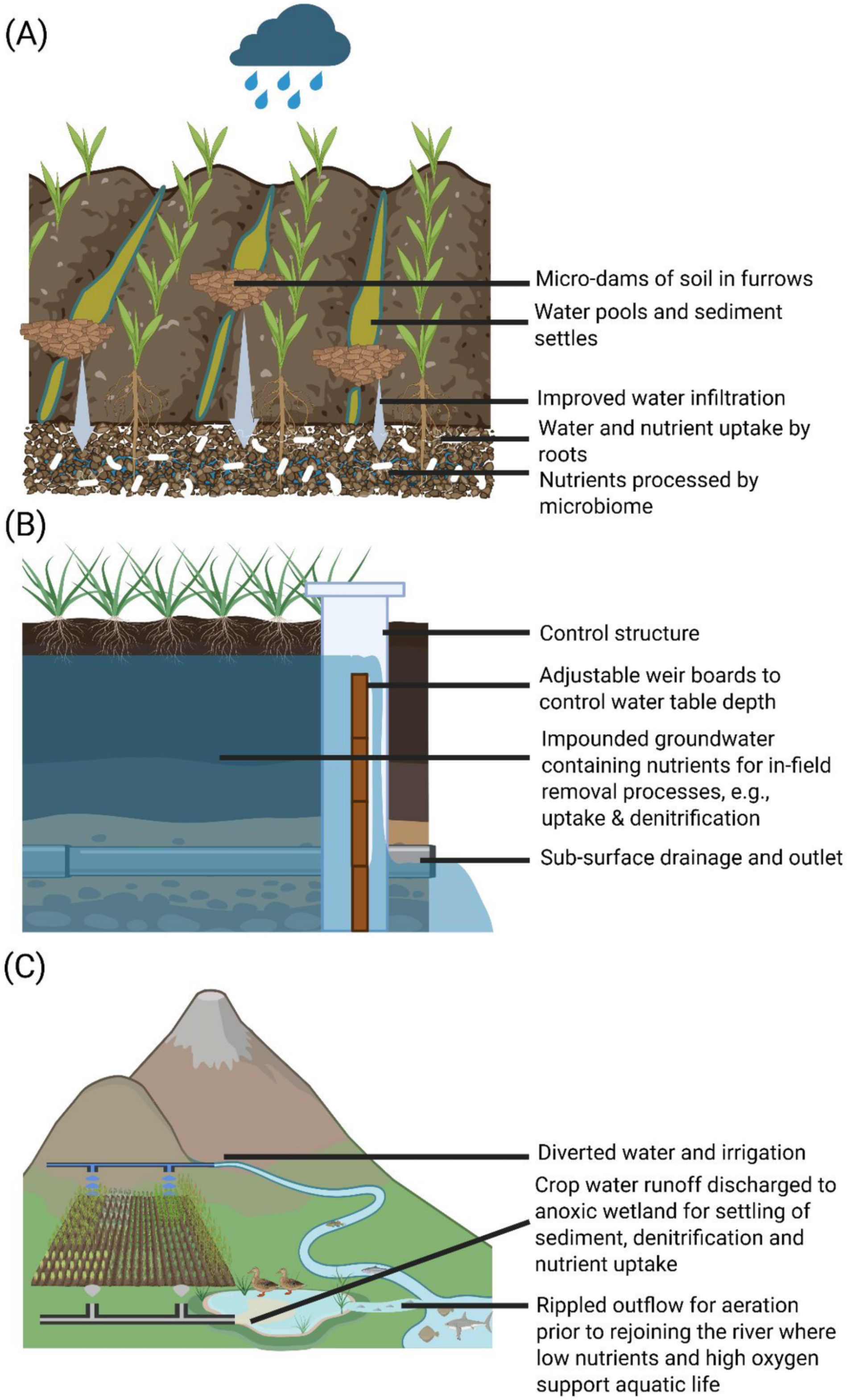
Irrigation practices and drainage management strongly influence the movement and retention of nutrients and sediment (Figs. 2 and 4). Wang et al. (2023) showed that efficient irrigation systems, such as evapotranspiration-controlled, soil-water-controlled, or drip irrigation, reduced soil phosphorus loss by 94% compared with flood irrigation. In rice systems, Qiu et al. (2022) found that alternate wetting and drying (AWD) and controlled irrigation both enhanced yield and NUE while cutting nitrogen leaching relative to continuous flooding, though AWD slightly increased N_2O emissions. Zhu et al. (2023) found that fertigation improved yields and nitrogen use efficiency but could increase nitrate and ammonium leaching, especially under sprinkler or surface irrigation and in humid climates; losses were minimized by combining organic and synthetic fertilizers and maintaining moderate nitrogen rates. Fertilizer placement relative to surface drainage features also influences nutrient losses. In ridge-and-furrow systems, fertilizer is applied on raised ridges and covered with mulch, which diverts percolating water laterally away from crop rows and reduces nitrate leaching. As a result, tile-drain losses typically fall from about 10%–16% of applied nitrogen under flat planting to 8%–11% under ridge-furrow cultivation, with deep-profile leaching around 44% lower (Han et al. 2025). However, misplacement in furrows or high rainfall can reverse this benefit.

Broader water control can also be achieved through drainage regulation. Controlled drainage (CD) manages water table height by adjusting the elevation of drainage outlets using structures such as flashboard risers, thereby retaining water in drains, reducing drainage rates and volumes, and extending the residence time of water in contact with soil and sediment where nutrient transformation can occur. Subirrigation extends this concept further by actively pumping water back through subsurface drainage pipes to maintain the water table near the root zone via capillary rise. In paddy systems, controlled irrigation and drainage (CID) combines water table management with alternate wetting and drying to regulate both inflow and outflow. Wang et al. (2020) synthesized 61 studies across 1050 data pairs spanning these approaches and found that CD reduced total drainage outflow volume by 19%, nitrate concentration in drainage water by 19%, nitrate loss in drainage outflow by 36%, total nitrogen loss by 32%, and total phosphorus loss by 19% on average relative to free drainage. These figures reflect combined losses across surface and subsurface drainage pathways, as the underlying studies varied in measurement approach and drainage type. Subgroup analyses showed stronger nitrate reductions in subsurface-drained dryland crop systems and in arid and cold climates, where longer water retention times promoted denitrification and reduced leaching. In contrast, CD showed little benefit or slightly increased losses under surface drainage, and paddy rice yield declined slightly under CD, possibly because maximum water levels in some studies were set too high. However, the raised water table under CD can create anaerobic conditions that limit nitrification, leading to elevated ammonium concentrations in outflow, highlighting the importance of carefully managing water table depth to balance nitrogen transformation pathways.

Intercropping and agroforestry

Intercropping, where two or more crop species are grown together, can improve water regulation by maintaining continuous soil cover and increasing root diversity, which enhances infiltration and reduces erosion. Liu et al. (2025*a*) found that intercropping reduced surface runoff by 29.2% and

Fig. 4. Conceptual diagram of drainage intervention strategies. In panel (A), micro-dams are small mounds created in furrows between ridges that pool drainage water, slowing runoff and improving infiltration. Panel (B) shows how controlled drainage can be used to raise the height of the sub-surface water table and regulate drainage. Slowing drainage increases the time available and conditions for nutrient uptake by plants or denitrification. Panel (C) shows an off-channel wetland being used to treat agricultural runoff before it enters the natural waterway. The wetland may also provide co-benefits, such as waterfowl habitat, while outflow aeration is required as the hypoxic conditions needed for denitrification are incompatible for downstream aquatic life.



soil evaporation by 10.3%, while increasing water use efficiency by 29.5% compared with monocultures (Fig. 2). These reductions in runoff were positively associated with soil nitrogen and negatively with pH and clay content, suggesting greater infiltration and reduced overland flow under intercropped systems. Nutrient losses were also lower, with Wang et al. (2023) reporting that intercropped systems reduced soil phosphorus loss by 61% on average, and Liu et al. (2021) showing that ground cover crops intercropped within tree systems reduced runoff by 70% and soil loss by nearly 50% relative to bare ground. Total nitrogen, nitrate, and ammonium concentrations declined by around 50%, while total and dissolved phosphorus decreased by almost 60%. Nonleguminous perennial grasses were more effective than legumes in reducing runoff and soil loss, primarily because legume cover crops in these studies were predominantly annual species with lower and more seasonal vegetation coverage, shorter growth periods, and lower C/N ratios that favour faster decomposition and nitrogen mineralization, reducing their capacity to retain nutrients relative to the perennial nonlegume grasses (Liu et al. 2021).

Agroforestry extends these same principles into more vertically and functionally diverse systems where trees, crops, and sometimes livestock coexist. The inclusion of trees improves infiltration, stabilizes soil through deeper and more permanent root systems, and reduces overland flow and erosion. Muchane et al. (2020) found that agroforestry reduced soil erosion by an average of 50%, independent of soil texture, while runoff was 57% lower and infiltration 75% higher than in monocultures. Soils under agroforestry also had greater macroaggregate stability and 46% higher inorganic nitrogen availability, particularly in clay soils, reflecting enhanced nutrient cycling and organic matter turnover. While increased infiltration can raise the potential for nitrate leaching, the deep roots of trees help recapture nutrients from subsoil layers, thereby reducing losses to groundwater. Phosphorus availability was generally unchanged or only marginally improved, except in loam soils where organic inputs and mycorrhizal associations facilitated P mineralization and mobilization.

Tree cover within cropping systems can also vary widely in structure and function. Mokondoko et al. (2022) showed that erosion in coffee agroforestry systems declined by 51% under low shade (30%–50%) and by 93% under traditional high-shade systems (>50% shade, >200 trees ha^{-1}) compared with monocultures. The protective canopy reduces raindrop impact and runoff, while litterfall and root turnover build soil organic matter and aggregate stability. In grazed systems, trees similarly improve ground cover and water regulation. England et al. (2020) found strong evidence that plantations, remnant native vegetation, and riparian plantings reduce erosion and improve water quality in dairy landscapes, though results for silvopastoral systems were limited by insufficient data. The specific role of trees within riparian zones, including nitrogen-fixing and nitrate-reducing species, in facilitating denitrification and nutrient interception is discussed further in the landscape and buffer revegetation section below.

Soil amendments

Physical and organic amendments

Organic amendments, including mulches, manures, crop residues, composts, biochar, and microbial inoculants, influence how soils retain and release water and nutrients, thereby shaping the effects of farming systems on water quality (Breza and Grandy 2025). By improving soil structure, infiltration, and organic matter content, these materials can reduce runoff, erosion, and leaching, although their effectiveness depends on composition, application rate, and management. Surface mulches and crop residues primarily protect the soil physically, while composts, manures, and biochar enhance soil aggregation and nutrient retention through organic and chemical mechanisms.

Surface mulching reduces runoff and erosion by shielding the soil from raindrop impact, preventing crusting, and slowing overland flow. They can increase infiltration and aggregate stability, allowing more water to enter and remain in the soil while trapping sediment and limiting soil particle detachment. Fan et al. (2023) reported average reductions of 47% in runoff and 76% in soil loss in mulched systems compared to without mulch. Straw and wood-based mulches performed better than mineral materials, especially when covering more than 60% of the soil surface, though the benefits declined on steeper or wetter sites. Rajbanshi et al. (2023) and Abdalla et al. (2020) also observed comparable overall effects across land uses. Furthermore, Girona-García et al. (2021) found straw and wood mulches to be roughly three times more effective than hydro-mulch in controlling post-fire erosion. Maintaining moderate mulch loads of approximately 0.3–0.8 kg m^{-2} is generally sufficient to stabilize soil, limit surface sealing, and enhance infiltration (Fan et al. 2023).

Returning crop straw or retaining residues can also improve water quality via the same mechanisms as in mulching. Xia et al. (2018) found that straw return reduced nitrogen leaching by about 9% and runoff by 26%, with greater benefits when straw was left on the surface rather than incorporated. Shi et al. (2025) observed similar reductions, with straw return decreasing nitrogen runoff by an average of 18%, with paddy systems showing smaller reductions (1.6%) than upland systems (24.5%). The decline was driven primarily by lower runoff volume in upland soils and reduced N concentration in paddy soils, with stronger reductions under cooler and wetter conditions, higher soil total nitrogen, and greater straw application rates (Xia et al. 2018; Shi et al. 2025). In terms of nitrate leaching, Li et al. (2021) found that incorporating crop residues reduced leaching by 14% on average, particularly in loam and silty soils, although it increased nitrous oxide (N_2O) emissions by 30%. Wang et al. (2023) reported that systems returning straw had roughly 88% lower phosphorus loss than those removing it, possibly due to greater microbial immobilization and reduced erosion. Ranaivoson et al. (2017) showed that surface residues doubled infiltration and reduced runoff and erosion by half to four-fifths once residue cover exceeded about 2–3 t ha^{-1}. Crop residues between 4–7 t DM ha^{-1} also reduced weed emergence and biomass, which may allow for herbicide reductions to also occur though herbicide use was not reported.

Composts and manures can reduce nutrient and sediment losses through two main pathways: by improving infiltration and water retention and by enhancing vegetation growth that slows surface runoff and stabilizes soil (Gravuer et al. 2019). Their high organic carbon content and moderate carbon-to-nitrogen (C:N) ratios foster microbial immobilization of nitrogen and phosphorus, moderating nutrient release and reducing leaching and runoff. When used to partially replace synthetic fertilizers, these amendments supply nutrients more gradually and in organic forms less susceptible to loss, while increasing soil cohesion and trapping nutrient-rich particles within stable aggregates. However, the extent of these benefits varies among amendment types, even at equivalent nitrogen application rates, due to differences in physical structure, nutrient composition, C/N ratio, cation exchange capacity, pH, and water-holding capacity.

Livestock manures generally reduce nutrient losses, with improvements in nutrient retention most pronounced in organic-rich soils such as Mollisols, but losses can be exacerbated in coarse-textured or low-organic soils such as Entisols (Xia et al. 2017; O'Brien and Hatfield 2019; Liu et al. 2020*a*). Across 141 experiments, Xia et al. (2017) found that replacing 50%–75% of synthetic nitrogen with livestock manure reduced nitrogen leaching by 29% and runoff by 26% on average. These reductions were linked to enhanced soil aggregation and microbial nitrogen immobilization driven by the higher C/N ratio of manure relative to synthetic fertilizer, which slowed nutrient transport and sediment detachment.

Composting further stabilizes nutrients by converting soluble nitrogen and phosphorus into more complex organic forms with higher C/N ratios, reducing their mobility and susceptibility to leaching or runoff. The degree of stabilization varies with feedstock composition: Zhao et al. (2020) reported that roughly one-third of nitrogen in conventionally produced compost can be lost through leaching and volatilization, but losses can be halved by using feedstocks with C/N ratios of 25–30 and 60%–65% moisture content. In practice this typically requires blending carbon-rich materials such as straw (C/N ~75:1), cornstalks (~60:1), or dried leaves (~55:1) with nitrogen-rich inputs such as cow manure, pig manure, or grass clippings (all ~15:1), or using materials that naturally fall within the optimal range, such as horse manure or coffee grounds (both ~25:1; Idowu et al. 2023).

Biochar can also mitigate nutrient and sediment losses by improving soil structure, sorption capacity, and nitrogen retention, though its effectiveness depends strongly on feedstock type, pyrolysis temperature, soil texture, and management context. Across 88 studies, Borchard et al. (2019) found that biochar reduced nitrous oxide (N_2O) emissions by 38% and nitrate leaching by 13%, with greater reductions in longer experiments and in sandy or paddy soils prone to leaching. Zhang et al. (2021) found more moderate reductions in nitrate leaching of about 10%–15%, with long-term applications sometimes led to higher abundances of nitrifier and denitrifier genes (e.g., AOB-amoA and nirK), correlating with renewed N_2O emissions and leaching over time. Biochars produced from lignocellulosic materials at high pyrolysis temperatures (>500 °C) and applied at rates above 10 $\mathrm{t\,ha^{-1}}$ under moderate fertilizer inputs (<150 $\mathrm{kg\,N\,ha^{-1}}$) were most effective (Borchard et al. 2019), suggesting that both feedstock chemistry and thermal stability govern their capacity to immobilize nitrogen and retain water. Complementing these findings, Gholamahmadi et al. (2023) reported that biochar reduced runoff by 25% and erosion by 16% on average, with effects strongest in tropical soils and with high-temperature biochar, which improve aggregation and infiltration while reducing particle detachment. Overall, biochar can meaningfully reduce nutrient and sediment losses in the short to medium term, particularly in coarse-textured or degraded soils, but sustained water-quality benefits depend on maintaining appropriate application rates, feedstock quality, and integration with broader nutrient management practices.

Biological and biochemical amendments

While physical and organic amendments mainly influence nutrient losses through improved soil structure and infiltration, other amendments act biochemically by altering nitrogen cycling. Microbial inoculants, nitrification and urease inhibitors, and biochar affect microbial activity and enzyme function, modifying nitrogen transformations that control gaseous and leaching losses.

Lv et al. (2024) found that microbial inoculants containing bacteria, fungi, and mixed consortia had variable effects on nitrate leaching but consistently reduced gaseous nitrogen losses. Their effectiveness depended on inoculant composition, soil pH, organic carbon, total nitrogen, climate, and fertilizer management. Where inoculants increased denitrification gene abundance (nirK, nirS, and nosZ), nitrous oxide emissions and ammonia volatilization declined, reflecting enhanced microbial conversion of N_2O to inert N_2 gas and potentially less nitrate available for leaching. Fungal inoculants, particularly arbuscular mycorrhizal fungi, were most effective in high-nitrogen systems, while bacterial inoculants performed better in neutral to alkaline soils where ammonia volatilization is prominent. However, these effects were often transient, with high soil organic carbon or pre-existing microbial activity reducing inoculant persistence.

Chemical inhibitors have also been used to slow nitrogen transformations. Cai and Akiyama (2017) showed that nitrification inhibitors such as dicyandiamide (DCD) and combined urease-nitrification inhibitors such as N-(n-butyl) thiophosphoric triamide plus DCD (NBPT + DCD) reduced nitrous oxide emissions and nitrate leaching from livestock urine patches by around 50%, while increasing plant nitrogen uptake by 10%–15%. Liquid formulations outperformed coated forms, and effectiveness was greatest under cool, moist conditions that slow nitrification. Di and Cameron (2016) similarly reported that DCD reduced nitrate leaching by 30%–50% and nitrous oxide emissions by an average of 57% across a wide range of soils and climatic conditions, with greatest efficacy in autumn and winter when nitrification activity is highest. However, most studies were from temperate regions, particularly New Zealand, limiting relevance to tropical systems, and data for other inhibitors such as 3,4-dimethylpyrazole phosphate (DMPP) and nitrapyrin remain scarce.

Like all ecological communities, soil microbial communities and their trophic interactions are heavily governed by their environment (Erktan et al. 2020; Thies and Grossman 2023); long-lasting changes are more likely to be achieved through practices that alter soil structure and the profile of available nutrients.

Grazing management

Grazing management strongly influences water quality through its effects on soil cover, compaction, and nutrient cycling. Overstocking or continuous grazing reduces vegetation cover and increases bare ground and soil compaction, leading to greater runoff, erosion, and sediment and nutrient delivery to waterways (Lai and Kumar 2020; Teague and Kreuter 2020; Centeri 2022). Livestock urine patches are also major point sources of nitrogen, often exceeding plant uptake capacity and resulting in nitrate leaching and nitrous oxide emissions (Di and Cameron 2016; López-Aizpún et al. 2020; Rivera and Chará 2021). Unrestricted access to waterways can allow trampling and grazing along streambanks, which destabilizes banks, increases erosion, and delivers fine sediment directly to channels (O'Callaghan et al. 2019). Defecation and urination in or near waterways further contribute nutrients, pathogens, and organic matter, elevating risks of eutrophication and microbial contamination (Hooda et al. 2000; Foote et al. 2015).

Low overall stocking rates coupled with grazing strategies (Stout et al. 2000; Smith et al. 2013), such as rotational and adaptive grazing (Park et al. 2017; Teague and Kreuter 2020; Hulvey et al. 2021), that aim to maintain adequate ground cover, sustain intact root systems, and distribute manure and urine more evenly, exclude livestock from waterways, and use off-stream watering points can reduce these risks (Muirhead 2019; Grudzinski et al. 2020). Reviews of riparian exclosure fencing consistently support its role in reducing faecal indicator bacteria and sediment, with reported microbial water quality improvements ranging from zero to 96% and a median of around 62% (Muirhead 2019). Fencing appears most beneficial for faecal bacteria and sediment carried in runoff, which showed the largest responses to exclosure fencing, while nutrients, particularly nitrogen which can travel subsurface, responded least consistently, improving in only around one third of analyses, and establishing buffer widths greater than 5–10 m appears to increase the likelihood of water quality improvements (Grudzinski et al. 2020).

In addition to fencing, managing cattle attraction to waterways through behavioural modification is an important complementary strategy. Cattle are strongly drawn to riparian areas as sources of water, forage, and shade, with riparian zone use increasing as daily temperatures rise and shade-seeking identified as a key driver of stream-side congregation (Rawluk et al. 2014). Malan et al. (2018) reviewed 37 studies and found that off-stream watering points (OSWPs) can reduce the time cattle spend in riparian zones and lower direct faecal and sediment inputs to waterways, though their effectiveness was highly variable (63.7%) and depended on site design, placement, and animal behaviour. Many studies measured water quality inconsistently, using indicators such as *Escherichia coli*, turbidity, or nutrient concentrations, and few provided clear guidance on OSWP design for tropical systems where heat, shade, and trough water quality influence livestock use. Providing alternative nonriparian shade has been shown in a case study to reduce the time cattle spend within riparian zones by around 30% on average (Clary et al. 2016), though benefits appear highly context-dependent and were small or inconsistent in smaller paddocks where cattle routinely encounter riparian zones during normal foraging (Kaucner et al. 2013). Riparian vegetation, including hedgerows increasingly incentivized through agri-environment schemes (Canning et al. 2021), may similarly reduce cattle congregation at waterways, complementing the benefits of fencing and off-stream watering points. However, planted riparian buffers without complementary off-stream shade provision elsewhere in the paddock could paradoxically increase cattle pressure on waterways, and the water quality implications of riparian hedge planting therefore warrant further investigation.

Beyond structural management, dietary manipulation offers a complementary pathway. Alternative forages such as plantain and chicory can reduce urinary nitrogen concentration and increase urination frequency through a diuresis effect, diluting urine patch nitrogen loads; however, Bryant et al. (2020) found that forage species alone are unlikely to reduce nitrate leaching by more than 20%, and meaningful reductions of 31%–59% required combining forage choice with extended grazing rotations and reduced fertilizer inputs, albeit at some cost to pasture productivity.

In contrast to conventional grazing systems that rely on cattle or sheep, integrated rice-animal co-culture (IRAC) systems, where rice is cultivated together with aquatic or semi-aquatic species such as fish, ducks, or crabs, show how livestock can also play constructive roles in nutrient management. These species coexist within flooded paddies without compacting soils or damaging crops, and their lower body weight and energy demands produce far less concentrated waste than larger-bodied grazers. Their activity aerates sediment, improves oxygen exchange, and stimulates microbial nutrient cycling, while their dispersed excreta supply organic nitrogen in synchrony with rice uptake. Chen et al. (2024) found that integrating livestock into rice systems increased rice yield (+3.5%) and nitrogen use efficiency (+4.3%) while reducing N_2O emissions (−17%), ammonia volatilization (−11%), nitrogen runoff (−18%), and leaching (−19%). Effects varied among IRAC types, with rice-crab systems showing the strongest improvements. Benefits were generally greater in soils with high clay content, under lower N application rates and frequencies, and in regions with higher rainfall.

Off-field practices and strategies

Landscape and buffer revegetation

Re-establishing perennial vegetation across landscapes, riparian zones, and field margins is one of the most effective strategies for reducing runoff, sediment, and nutrient transport from agricultural land. Vegetation improves soil stability and infiltration by increasing root density, surface roughness, and organic matter inputs that promote aggregate formation. In semi-arid regions, Wu et al. (2020) and Liu et al. (2020*b*) found that restoring grassland, scrubland, or forest vegetation reduced runoff and sediment yield by 50%–70% on average, with grasslands and scrublands providing the best balance between erosion control and water yield. Grasslands were most efficient at reducing sediment through their dense fibrous roots, while forests and scrublands were more effective at reducing runoff on coarser soils and steeper slopes. Both studies observed vegetation effects to plateau beyond about 60% cover, with optimal efficacy arising on slopes between 10° and 30°, and rainfall intensity strongly moderating performance (Wu et al. 2020; Liu et al. 2020*b*). At larger scales, Bartley et al. (2020) found that gully rehabilitation, including check dams and revegetation, reduced sediment yields by 12%–94%, with the most durable outcomes when contributing catchments maintained at least 60%–70% vegetation cover and when about 20% of gully floors received structural treatment. While engineering structures such as check dams can help stabilize channels initially, revegetation of gullies and adjacent slopes was required for long-term success, as structural measures alone tend to fail over time.

At the field and field-margin scale, vegetation strips act as filters that trap sediment, nutrients, and agrochemicals from surface runoff before it enters riparian zones or drainage networks. These include in-field contour grass strips, vegetated barriers or hedgerows planted along slopes, edge-of-field grass or shrub buffers downslope of cropped areas, vegetated waterways and drains that stabilize flow paths, and swales or filter cells around roads, drains, or irrigation storages. Riparian buffers, which are vegetation strips adjacent to waterways, provide an additional layer of protection by stabilizing streambanks, supplying leaf litter and habitat for aquatic organisms, and moderating water temperature and algal growth through shading.

Across studies, such vegetative buffers substantially reduce pollutant transfer from fields to waterways. Rajbanshi et al. (2023) and Wang et al. (2023) found that hedgerows and grass buffer strips reduced runoff by about 60% and phosphorus loss by up to 87%, while Zheng et al. (2020) observed higher nitrogen and phosphorus concentrations in hedgerow soils, indicating effective interception and storage of nutrients that would otherwise be lost downstream. Ferrarini et al. (2017) demonstrated that herbaceous strips of perennial biomass crops such as switchgrass can cut sediment-bound nitrogen and phosphorus losses by around 80% and total sediment loads by up to 95%. These systems can also produce harvestable biomass that returns nutrients to fields when used as mulch. Beyond nutrients, Chen et al. (2016) found that infiltration exerted the strongest positive influence on pesticide retention by vegetated filters, followed by sedimentation, but that this effect weakened for strongly adsorbed pesticides, as there was an interaction where infiltration mattered most for more mobile and weakly adsorbed compounds.

Buffer design strongly influences performance. Liu et al. (2008), Lind et al. (2019), Tsai et al. (2022), and Ramesh et al. (2021) showed that width, slope, soil texture, and vegetation structure together determine sediment and nutrient retention, with even narrow (3–10 m) buffers substantially reducing sediment loads, and buffers wider than 10–15 m typically removing more than 75% of nitrogen and phosphorus. While width remains an important design factor, Klein et al. (2023) demonstrated that filter strip effectiveness is more strongly governed by hydraulic load and infiltration capacity, and recommended using mechanistic tools such as the Vegetative Filter Strip Modeling System (VFSMOD) to more accurately represent these processes. That said, Chen et al. (2016) showed that their meta-regression of pesticide removal outperformed the pesticide module of VFSMOD ($R^2 = 0.83$; $Q^2 = 0.81$ vs. 0.72), showing that strip efficacy depends not only on hydraulic load but also on the sorption behaviour of the chemical and on sediment characteristics such as clay content. Overall, coarse-textured or steeper sites benefit most from wider or multi-tiered buffers that combine grasses and woody vegetation.

Drainage control systems

Drainage strongly governs nutrient export from farmland. For example, Li et al. (2024) showed that subsurface drainage accounted for most of the global variation in nitrate leaching losses. The extent and timing of drainage determine how long percolating water interacts with soil microbes and minerals that transform or retain nutrients. In contrast, surface runoff primarily mobilizes sediment and phosphorus. Managing both pathways through drainage interventions can therefore curb losses before water leaves the farm. Structural measures such as check dams and micro-dams slow runoff, trap sediment, and promote nutrient transformation, improving water quality between the field and downstream ecosystems.

Micro-dams, which are small earth bunds or shallow depressions formed along crop rows or between ridges to slow and capture runoff (Fig. 4). Klein et al. (2023) showed they are an effective way to reduce erosion and nutrient loss. In ridge crops such as potatoes, interridge bunds or holes created with a Dyker interrupt overland flow, while in row crops such as maize, small depressions between rows serve the same purpose. Across studies, micro dams typically reduced runoff volumes by about 70%–90% and lowered sediment and pesticide losses by roughly 80%–90%, showing consistent effectiveness in reducing erosion and chemical export under moderate rainfall events.

At the drainage-network scale, controlled drainage systems regulate subsurface outflow by adjusting tile levels to retain water and enhance nutrient transformation. Both CD and controlled drainage with subirrigation (CDSI) reduce subsurface nutrient losses compared with free drainage (Kalibatienė et al. 2025), with CDSI achieving mean reductions of 72.5% in subsurface nitrate and 55.9% in total nitrogen, while conventional controlled drainage achieved total phosphorus mean reductions of 56.8% (Wu et al. 2025). CD performed best in wet years and on medium-textured soils, where higher water tables and slower flow increased residence time and denitrification. Coarse soils showed weaker effects because rapid percolation limited anaerobic zones. Under CDSI, higher nitrogen inputs and small-grain or overwinter crops improved efficacy by sustaining evapotranspiration and reducing subsurface drainage. However, Wu et al. (2025) found that while subsurface nitrate losses declined considerably, surface runoff and associated nitrate export increased by approximately 70%–80%, as elevated water tables and lateral flow mobilized dissolved nitrogen to surface pathways. These trade-offs highlight that while water table management can substantially reduce nitrate leaching, its success depends on alignment with local hydrology and crop dynamics. System design must account for rainfall patterns that control drainage frequency, soil permeability that governs water retention and denitrification potential, and crop growth stages that influence evapotranspiration and nutrient uptake.

Wetland and bioreactor systems

Wetlands and engineered treatment structures can intercept off-field and transform nutrients in runoff before they transit further downstream (Fig. 4). Global estimates suggest that wetlands collectively remove roughly 17%–21% of anthropogenic reactive nitrogen inputs (Jordan et al. 2011). Beyond nutrient retention, wetlands provide multiple co-benefits worthy of protection and restoration, including biodiversity support, flood moderation, carbon sequestration, and local climate regulation (Canning et al. 2021).

Wetlands, denitrifying bioreactors, and saturated or integrated buffer zones typically remove 25%–50% of nitrate and 30%–50% of total phosphorus (Carstensen et al. 2020), though anoxic or strongly reducing conditions can occasionally trigger phosphorus release. Their performance depends strongly on hydraulic and nutrient loading, hydraulic residence time, wetland depth, temperature, and redox conditions, which together control rates of sedimentation, plant uptake, and microbial transformation (Land et al. 2016).

Comparable behaviour has been observed in ecological ditches (vegetated agricultural drainage channels designed to slow flow and settle sediment and facilitate nutrient transformation), where pollutant removal efficiencies averaged 65% for ammonium, 46% for total nitrogen, and 50% for total phosphorus, with performance improving under moderate influent concentrations, longer residence times, and warmer conditions, but declining during winter or when vegetation senesced (Shen et al. 2024).

Within wetlands, plant community composition can also influence treatment efficiency by modifying nitrogen cycling and organic matter decomposition. Experimental systems show that species mixtures can improve total nitrogen removal and chemical oxygen demand relative to monocultures, though gains for phosphorus or suspended solids are limited and often driven by particularly effective species rather than strong complementarity (Brisson et al. 2020). Land et al. (2016) showed that total nitrogen and phosphorus removal efficacy by wetlands is highly dependent on nutrient loading rate, hydraulic loading rate, and climate, with median removal efficiencies of 37% for TN and 46% for TP. Removal increased with longer residence times and controlled hydrology but declined in precipitation-driven or pulsed systems where short residence times limited contact between water and sediments. Similar findings were observed by Ury et al. (2023), whereby phosphorus retention was particularly variable, and while wetlands act as nutrient sinks in most cases (84% for total P and 75% for phosphate), they can also switch to sources under high hydraulic loading, low influent phosphorus concentrations, or where legacy sediment P is mobilized. Median TP retention within sink wetlands was about 2.0 $\mathrm{g\,m^{-2}\,year^{-1}}$, with releases of $-0.5\ \mathrm{g\,m^{-2}\,year^{-1}}$ from source systems.

A critical, often overlooked factor is monitoring resolution. Anderson et al. (2024) showed that much of the apparent inconsistency in reported phosphorus retention stems from inadequate sampling frequency and duration rather than true functional differences among wetlands. Across 243 studies, average phosphorus retention varied widely ($51 \pm 164\ \mathrm{g\,m^{-2}\,year^{-1}}$), with about 70% of datasets relying on weekly or less frequent sampling and more than two-thirds monitored for fewer than 3 years. Such sparse temporal coverage failed to capture the short-lived, storm-driven pulses that dominate annual phosphorus fluxes, and the omission of these events frequently led to wetlands being misclassified as nutrient sources rather than sinks (Anderson et al. 2024).

Effective nutrient removal in treatment wetlands depends on maintaining stable, mildly anoxic conditions and carefully managing inflow rates. Under unstable anoxic conditions, denitrification may be incomplete, producing nitrous oxide (N_2O) rather than inert dinitrogen gas (N_2), while prolonged or strongly reducing conditions can trigger microbial reduction of ferric iron (Fe^{3+}) minerals, dissolving iron-phosphate complexes and releasing soluble phosphate back into the water column (Wu et al. 2019; Martínez-Espinosa et al. 2021; Pinto et al. 2021). These biogeochemical dynamics mean that the conditions optimal for nutrient removal can simultaneously create undesirable outcomes, such as a restructuring of vegetation and microbial communities (Lamers et al. 2012). More broadly, using wetlands to improve water quality involves potential trade-offs that need to be carefully managed. The same conditions that enhance nutrient removal can also lower dissolved oxygen to levels harmful for fish and invertebrates, produce unpleasant odours, and shift greenhouse gas balances through increased emissions of methane or nitrous oxide (Canning et al. 2021; Åhlén et al. 2023).

Knowledge gaps and research priorities

Despite major progress in understanding how agricultural practices affect water quality, the global evidence base remains uneven. Most meta-analyses focus on nitrogen and, to a lesser extent, phosphorus, with far fewer on sediment and almost none on pesticides. The lack of global syntheses on pesticide transport is notable given that residues are now among the most common agricultural contaminants in rivers, wetlands, and estuaries. This imbalance has directed research and policy attention toward nutrients, leaving gaps in understanding broader contaminant dynamics and ecosystem impacts.

Entire categories of practice remain largely unevaluated at the global scale. Few reviews assess measures such as multipurpose farm dams (including detention dams designed to slow runoff and trap sediment, retention dams that store water for irrigation while incidentally settling suspended material, and farm storage dams used for water collection), contour cropping, or the use of rock lines, vegetative barriers, and bunds to stabilize gullies and trap sediment. These approaches are widely used in erosion-prone regions but are represented only in local studies. Practices such as push–pull cropping, which modifies pest and nutrient cycling, and adaptive grazing systems that improve ground cover and infiltration, also lack quantitative synthesis. As a result, most global evidence centres on a narrow set of well-studied practices, including no-till, cover crops, organic amendments, and vegetative buffers, while many effective regional strategies remain overlooked. Furthermore, interactions among practices and landscape effects are also poorly understood. Most syntheses examine single interventions, yet combined measures can generate cumulative benefits or trade-offs, though it is unclear if benefits are additive or multiplicative.

Geographic bias further limits current knowledge. Most studies have been conducted in temperate croplands of North America, Europe, and China, with little representation of tropical, arid, or smallholder systems. These underrepresented regions encompass much of the world's agricultural expansion and land-use change, where soils, hydrology, and management differ markedly. Livestock, mixed cropping, and peri-urban systems are particularly under-studied despite their high diffuse pollution potential.

Conclusion

Global syntheses show that agricultural practices that restore soil cover, structure, and hydrological function can markedly reduce pollutant losses from farmland. Across continents, cover crops and nonleguminous green manures consistently reduced nitrate leaching by 50%–70%, while residue retention, mulching, and organic amendments lowered runoff and sediment losses by 25%–75%. Reduced or no-tillage systems decreased sediment and particulate phosphorus losses by roughly half compared with conventional tillage, though trade-offs were evident where dissolved nutrient and pesticide losses increased. Fertilizer and irrigation optimization, including controlled-release formulations and precision water control, reduced nitrogen and phosphorus losses by 20%–50% without yield penalties. At landscape scales, vegetated buffers, revegetation, and agroforestry reduced runoff and sediment by more than half, and drainage regulation, wetlands, and bioreactors removed 25%–50% of nitrate and phosphorus from inflows.

Agricultural pollution and degraded aquatic ecosystems are not inevitable; they arise from choices in how land and water are managed. Cleaner water is achievable through practices already proven to work, but their benefits will only be realized if adoption becomes widespread. This will require coordinated effort across policy, extension, farm planning, and finance to embed these strategies as standard practice. With sustained commitment, healthy rivers, wetlands, and coasts can become a defining measure of successful agriculture rather than its casualty.

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The author declares there are no competing interests.

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