# The effect of agricultural runoff on freshwater biodiversity and ecosystem functioning

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## Abstract

Nutrient runoff from agricultural operations threatens aquatic health and can have enduring and intricate consequences for the environment, ecological systems, and human populations. A comprehensive quantitative study of the literature was performed to identify various Nutrient Runoff Mitigation Systems (NR-MS) employed worldwide to avoid or repair environmental harm caused by excessive agricultural fertilization. Practical information on results from multiple NR-MS in the examined research was utilized to assess the methods based on ecological advantages, implementation costs, and feasibility. A comprehensive evaluation of the viability of NR-MS was conducted, along with a macro-level analysis of the obstacles hindering its widespread deployment. Recognized research deficiencies encompassed a scarcity of literature addressing nutrient runoff reduction, skepticism among farmers regarding voluntary policy adoption without significant incentives, and an overall absence of cost/benefit analyses, such as insights into the uncertainties related to NR-MS that could guide decision-makers in formulating successful and effective methods for various site conditions. The combination of review information enabled the creation of a complete decision-making structure to govern nutrient runoff, addressing current constraints and offering local NR-MS suggestions for regulators to adopt.

**Keywords:** Agriculture, Freshwater, Biodiversity, Ecosystem, NR-MS

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## Introduction

The increasing human population worldwide has established agriculture as a predominant and expanding method of managing land, utilizing around 42% of the Earth's land area (López-Carr, 2021). The encroachment of agriculture into indigenous forests is especially concerning in tropical regions, where trees are being rapidly supplanted by crops, resulting in detrimental effects on ecosystems and biological diversity (Spoorthi *et al.,* 2021). Stream ecological systems prove particularly concerning for two primary reasons: first, that they are significantly affected by farming due to the influx of nutrients, sediments, and pollutants, as well as the alteration or elimination of riparian plant life; they face the most pronounced declines in biodiversity, especially in tropical regions, and rank among the most threatened environments globally (Dudgeon and Strayer, 2025).

Agricultural operations adversely affect tropical stream ecosystems and invertebrate groups (Lima et al., 2022; Raja and Ravi Kumar Kennedy, 2019). Water quality diminishes, physical habitats are modified, and biological communities become simpler, characterized by substituting sensitive taxa with tolerant ones and declining biodiversity. There is scant evidence regarding the possible impacts of farming on the regular operation of tropical rivers, which is crucial for evaluating the status and health of these systems.

Ecosystems of freshwater face numerous pressures from humans. Pesticide contamination is a significant stressor impacting aquatic biodiversity (Ogidi and Akpan, 2022). Pesticides can infiltrate freshwater environments via spray drift, runoff, and leakage, potentially resulting in intricate combinations. A new meta-analysis indicates that few studies have examined the relationships among pesticide combinations and other freshwater stresses despite their considerable impact on freshwater preservation and biodiversity (Akyol *et al.,* 2023).

Chemicals such as pesticides entering aquatic environments are selective stresses, affecting various organisms according to their physical features and toxicological mechanisms (AbuQamar *et al.,* 2024). Thus, pesticide exposure results in non-random consequences on people and ecosystems (Pohn and Hommel, 2021). Enhancing the comprehension of the relationship between the toxicological characteristics of chemicals and their impact on community structure, the variety of species, and the environmental functionality is essential for forecasting the cumulative effects of pesticide combinations on aquatic environments, which is the primary objective of ecological risk evaluation (Weisner *et al.,* 2021).

Most research assessing the impacts of various stressors and their relationships has concentrated on analyzing effects simultaneously following disturbance (Jackson, Pawar and Woodward, 2021). The impact of several stressors can fluctuate over time. This implies that assessing stressor relationships immediately following a disruption (i.e., resistance) overlooks subsequent, non-additive impacts resulting from the exhaustion of particular energy stores or alterations in relationships between species. Therefore, to implement successful management strategies, it is crucial to comprehend how various stressors impact the vulnerability of people and their neighborhoods in the near term and their future responses, influencing their ability to adapt and recuperate.

Nutrient pollution, with chemicals, has been identified as a significant stressor impacting freshwater ecosystems (Tiwari and Pal, 2022). Nutrient enrichment accounts for approximately 32% of the variance in the biological state of European waters and often interacts with harmful compounds. Research indicates that nutrient enrichment diminishes the impact of pesticides and tiny particle inputs from agricultural practices (Alipour *et al.*, 2016). Enrichment of nutrients and the resulting eutrophication typically diminish biodiversity and unify populations at individual and community levels, favoring tolerant organisms (Lan *et al.*, 2024). Research elucidating this phenomenon is scarce and has predominantly been conducted in temperate or cold environments. Research on nutrient supplementation in warm climates, like the Mediterranean, reveals significant disparities in species predominance and ecological processes relative to temperate zones, potentially affecting ecosystem resistance to pesticide damage.

The correlation between diversity and its functioning has become a fundamental and enduring discourse among scientists for years. Despite an agreement about the beneficial impacts of biodiversity on the health of ecosystems, there is inadequate knowledge on how various stressors influence this relationship (Ahmed *et al.*, 2022). Although data indicate that the positive connection between persists under ecologically stressful situations, these results have been drawn from random perturbations of relatively basic species groupings, frequently comprising only one trophic layer. The manipulations of biodiversity are crucial to elucidate the underlying mechanisms that govern the biodiversity-ecosystem functioning link. Yet, these methodologies exhibit bias in other respects. Initially, under natural settings, alterations in biodiversity are irregular and contingent upon the nature of anthropogenic influences (e.g., species introductions, temperature change, chemical pollution). The repercussions of alterations in biodiversity extend beyond a singular trophic level, throughout the entire food web. The effects of stresses on the environment and biodiversity performance are variable across time, resulting in different reactions and restoration trajectories influenced by the interactions of stresses. Examining the impacts of various agricultural chemicals on species makeup and ecosystem functionality aids in establishing thresholds for managing ecosystems and enhances our comprehension of the biodiversity-ecosystem functioning link under ecologically pertinent sources and stress concentrations.

## Background

A Systematic Quantitative Literature Review (SQ-LR) was performed to identify the prevailing global approaches to mitigate nutrient runoff from farming areas. The SQ-LR was performed to build a dependable and reproducible method for identifying these criteria, adhering to recognized literature. Thus, the SQ-LR facilitates identifying relevant research related to a specific topic according to any included or excluded criteria applied during the initial search process. The SQ-LR commences with the recognition of resources and the establishment of search criteria. A sequence of screen phases is established to refine the research, typically from hundreds of articles to a few hundred, aligned with the particular objective of the article's theme. This established criteria enhances the search parameters and facilitates a more profound study of the final publishing list, allowing significant discoveries to be summarized in various formats as SQ-LR results. Not all articles chosen are presented through outcomes; instead, some are more advantageous within the debate to offer enhanced insight into prevailing trends and subsequent prospective actions.

This paper indicates that the SQ-LR employs the search parameters; despite the substantial volume of Nutrient Runoff Mitigation Systems (NR-MS) research, this summary is intended to furnish foundational understanding of NR-MS. This study provides a foundation for policymakers and decision-makers to facilitate NR-MS adoption. This research thoroughly identifies and quantifies the overall performance of NR-MS; site-specific evaluations are consistently advised to guarantee a more precise understanding of optimal management procedures.

*Search Parameters*

The articles featured in this SQ-LR were up-to-date as of the end of 2020 and were sourced from three databases: Scopus, Web of Science, and ProQuest. 2022 was excluded due to its substantial and non-representative deviation from the pattern. This is mainly due to the extensive COVID-19 restrictions enacted globally, which diminished chances for study and the dissemination of significant findings relative to the period before the pandemic. Additionally, China's rigorous COVID-19 prevention protocols likely diminished the volume of articles from the second-largest research contributor in our review.

To ensure reliability and uniformity, the identical query was employed across all databases; however, it was tailored to the individual coding. The subsequent criteria were used to acquire the articles from each of the three databases:

The inquiry employs a four-tiered search framework to acquire publications pertinent to mitigation solutions for nitrogen runoff. The initial tier delineates the objective and enumerates three standard terms in the literature concerning runoff decreases.

The second layer delineates a set of terms that underscore the topic of this SQ-LR and its many manifestations in literature.

The secondary search level underscores the activity, emphasizing publications that describe procedures rather than those that analyze implications or effects of chemical runoff. Tier four omits prevalent papers on micronutrients that are not pertinent to the present research. To demonstrate that research on nutrient reduction techniques is a relatively underexplored area in the context of fundamental water quality issues, broad searches were conducted, revealing the quantity of studies related to runoff of nutrients (this research), soil subsidence, microbiology dangers, metal leakage, and general aspects of water quality.

The comparative ratio of NR-MS-related measures to those in previous studies was observed. Thus, this offered a chance to discern the diverse applications of mitigation strategies and the variability present in the general research regarding each. The objective of this SQ-LR was to acquire an exhaustive compilation of literature regarding Nitrogen Runoff Mitigation (NRM). To ensure time and establish a clear border, only materials from 1990 onwards were utilized. No limitations were placed on the kind of paper. Exclusively reviewed materials were used, and care was taken to limit the number of non-article forms, resulting in only seven articles out of the total 295 not being in the form of an article for a journal or reviews. The objective was to acquire a comprehensive overview of the NR-MS research and discern patterns and evolutionary traits of these methodologies across time. As a result, government papers were omitted, primarily due to the challenges in obtaining a comprehensive list of states, stemming from secrecy restricting public access to substantial numbers of these documents. The search findings were confined to English language articles that were freely available through the authors' institution's repository.

*Article Evaluation and Eligibility Evaluation*

Following the amalgamation of articles based on the criteria, a total of 1800 articles were discovered, of which 610 were eliminated due to redundancy throughout the three repositories. From the 950 left, an additional screening process that involved evaluating titles and abstracts was conducted, eliminating 1230 articles.

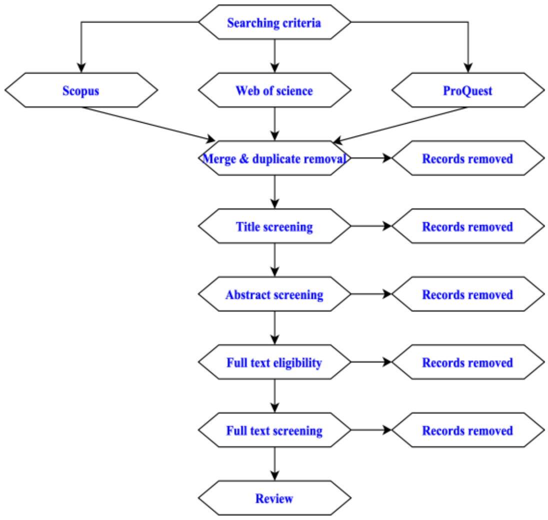


**Figure 1: Systematic analysis of the research.**

During secondary assessment, papers were predominantly excluded owing to content about sediments or ground runoff (Figure 1). Ultimately, tertiary filtering involved a comprehensive qualification assessment, during which documents containing data extraneous to the study's topic were excluded. As a result, the culmination of the three-tiered filtering approach yielded 280 papers for inclusion in this evaluation's text analysis and information synthesizing components. Certain NR-MS, such as bio- and organic fertilizers, were excluded due to a paucity of articles regarding their NRM utilization, coupled with a predominant emphasis on crop yield enhancements.

*Content analysis*

In the content evaluation, the final 280 papers discovered through filtering were categorized to provide an extensive summary of the data addressed in each publication. This was accomplished using Microsoft Excel, without each row containing the writer, publishing year, title, and publisher as fundamental data.

This was supplemented with other data to discern patterns and associations about NR-MS. Thus, the investigation encompassed the country of research, climate, and Gross Domestic Product (GDP), in addition to the paper's topic (i.e., general farming, tracking, or a summary), the place of research (field versus laboratory), the types of nutrients and crops examined, and the land/watershed region. The database determines whether models were created and emphasizes any potential restrictions that could lead to mistakes, such as those arising from global parameterization. Additionally, the database records whether field information was gathered. It enumerates the kinds of mitigation techniques referenced in each paper, emphasizing their cost, simplicity, and ecological advantages on a low-to-high scale, as well as any suggested remedies that might have been superior or potentially offered more significant benefits.

Essential data about the magnitude of research and ways of transportation were integrated into the SQ-LR. This information offers a comprehensive overview of the crucial primary regions related to nutrient runoff, highlighting significant study domains correlated with the volume of articles. A considerable percentage of articles are classified under the "Other" section. This group was established to emphasize materials that either did not conform to the established variables, such as studies on agricultural plots conducted in controlled laboratories, or those that concentrated more on general farming methods, including aspects related to policy on agriculture. Aside from this, most investigations were performed in tiny streams with an extent of less than 6 $km^2$. These constituted 25% of all papers and emphasized a concentration on farm-scale NR-MS to mitigate nutrient runoff entering streams.

The result underscores a predominant emphasis on surface runoff as a transportation method from agricultural regions to water bodies. As attention increasingly shifts to the impact of runoff on ecologically sensitive areas, the analysis of direct nutrient routes is becoming a prominent trend in agricultural research, leading to a greater emphasis on runoff over leaching in research. In practice, seeing and tracking the consequences of runoff from the surface is more straightforward than discerning the impact of subsurface leaking on the surroundings; hence, this could contribute to the preponderance of studies centered on surface runoff.

*Synthesis of Information*

This study's data synthesizing procedure entailed aggregating and evaluating many factors influencing the strategies implemented to reduce nutrient runoff from agricultural regions. Therefore, the information was synthesized to ascertain how research recognized the significance of a mitigation approach and the analytical methodologies employed by journals to substantiate or emphasize priority regarding nutrient mitigation approaches. Thus, this procedure was used to identify and address inquiries concerning:

- The standard objectives and emphasis of articles about nutrition reduction methods (cost versus practicality (ease of application) against benefit).

- The temporal popularity of specific nutrient reduction strategies and the overall prevalence of various ways.
- Priorities for riches and mitigation measures among countries.
- The effects of geolocation on strategic preferences.
- Preferences concerning innovative techniques rather than established ones.
- The prevalence of models compared to in situ research for analyzing NR-MS effectiveness.
- The advantages of employing "layering" are that there are many ways to mitigate runoff of nutrients, as contrasted to singular approaches.
- How to build an extensive mitigation framework for participants across many circumstances.
- Proposals that offer participants a customizable strategy for execution that accommodates diverse consumer requirements, grounded in prevalent environmental and economic risk factors.

Reduced flow conditions exert indirect impacts. Elevated temperatures can modify the pattern of aquatic insect development, adversely affecting the breeding cycles of birds and bats due to temporal discrepancies in food supply. Prolonged lack of flow leads to a decline in oxygen levels, jeopardizing fish habitats. Bacterial and chemical concentrations in agricultural ditches vary according to water volumes and flow rate. Small travels can intensify the effects of chemical and bacterial loadings due to decreased dilution ability; some studies indicate that although low flows typically prolong pesticide place of residence duration, they lead to heightened local deterioration, thereby mitigating the downstream effects.

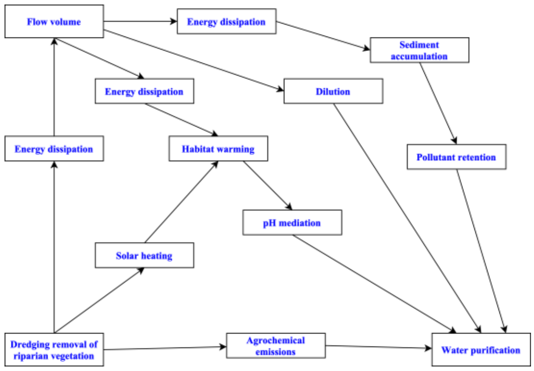


**Figure 2: Water purification process.**

Flow significantly influences sediment motions (Figure 2). As stream strength diminishes, the ability for sediment movement is similarly reduced, resulting in an accumulation of finer deposited material. Sediments can adversely impact habitat availability by obstructing interstitial gaps and decreasing oxygen levels in hyporheic regions. Research indicated that reduced habitat accessibility, due to the loss of coarse ground and spaces, was a significant filter for pollution-sensitive invertebrate species. Precipitated fines can impede the growth of the algae, diminishing their initial productivity and decreasing the food supply for grazing animals, which then affects greater trophic levels. Scour arises from limited flow restrictions, such as those caused by culverts, weirs, and arches; as sand accumulates behind these barriers, its transportation capacity upstream is enhanced.

## Conclusion

The present study identifies pertinent studies on the efficacy of various solutions concerning nutrient runoff to establish a comprehensive grasp of the benefits and drawbacks of these methods. The collected data, encompassing nutrient loading reduction proportions, cost enhancements, modeling and monitoring uses, and targeted vitamins and minerals, was utilized to identify optimal tactics; quantitatively demonstrating the efficacy of NR-MS proved challenging, primarily due to insufficient numerical data regarding three critical feasibility elements: ecological benefit, cost, and affordability. Notwithstanding this, the information at hand was analyzed and synthesized, leading to the proposal of a system for making decisions designed to offer a uniform approach for politicians. This structure aims to ensure that runoff leadership is tailored to particular sites and considers variations among different rivers and lakes, while upholding a standard of uniformity to mitigate problems stemming from disparate practices.

The escalation of agricultural practices has resulted in a notable reduction in the value of ecological services offered by adjacent environments. The population surge emphasizes addressing the intensification of agriculture, frequently necessitating multiple measures. Effective interaction and instruction are essential for enabling farmers to comprehend the significance of ways of managing and the associated benefits for both the environment and the economy. A crucial component is government backing for owners to guarantee the implementation of a unified and efficient management approach to tackle the problem of nutrient runoff. Decision-makers must formulate a flexible amalgamation of policies that optimize crop yield, enhance waterway quality, and, crucially, underscore the importance of collaboration among participants.

Research is polarized over a cohesive approach reconciling the social, economic, and environmental advantages and repercussions of various NR-MS. This article points out several critical issues within the literature, starting with an insufficient number of studies focused on nutrient runoff reduction, followed by gaps that hinder the identification of suitable NR-MS, and concluding with systemic obstacles that impede the implementation of standard uniform addresses to controlling and reducing runoff cost-effectively and cooperatively. Although research highlights the economic impacts of nutrient runoff, there is a scarcity of cost evaluations regarding NR-MS, which constitutes a limitation in executing the nutrient strategy. Although a structure was suggested to establish a uniform methodology for managing water quality, subsequent research will necessitate more comprehensive and analytical information to assess the efficacy of NR-MS, allowing for a deeper consideration of site-specific components and enhancing structures to optimize preventive and remedial procedures.

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