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Review

A Water–Energy–Food Nexus Perspective on the Challenge of Eutrophication

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Abstract: This paper attempts to understand and explore the problem of eutrophication in the context of agriculture with the help of a nexus perspective. Eutrophication is significantly linked to water and energy resources with theoretically well-defined trade-offs and threshold levels. While looking at the linkages between water and land resources comprehensively, our paper questions the present approach to designing and implementing watershed management, and analyses the effects of agricultural intensification, especially in dry regions. Eutrophication is the process by which excessive nutrient loads in water bodies lead to undesirable water-quality problems and the degradation of the overall aquatic ecosystem. Due to limited information and knowledge on water and soil quality in most countries, farmers continue to use fertilizers at an increasing rate and agricultural run-off has been carrying ever more nitrogen and phosphorus into water bodies. This is likely to become a vicious cycle of eutrophication affecting food and water security. Of late, soil- and water-conservation interventions, like watershed development, are further reducing run-off. It is argued that there is a need to rethink the assumptions under which watershed interventions are designed and implemented.

Keywords: water-energy-wood Nexus; eutrophication; trade-offs; typologies; resource scarcity; political economy

1. Background

Land degradation appears to be the most rapidly growing concern for sustaining agriculture productivity and food security in most developing countries. In the case of India, it is observed that in order to maintain a healthy growth of 3–4%, agriculture demands investments to the tune of 12% of Gross Domestic Product [1]. However, recent experience indicates that even higher investments (above 15%) are not able to sustain agricultural expansion due to the degradation of natural resources such as land and water [1]. One of the reasons is the continued focus on the use of chemicals [2,3]. Yields are either stable or growing marginally with higher input use and costs [4]. Policies continue to boost fertilizer use along with irrigation water. This has been resulting in intensive mono-crop practices that negatively affect the soils and make agriculture unsustainable in the long run. The quality of soils is further aggravated though the process of agricultural intensification using more water and chemical inputs. Watershed management is expected to attenuate such environmental impacts through soil- and water-conservation interventions in the dry regions. However, given exponential rates of agricultural intensification, especially in developing countries, some of the assumptions about the purported benefits of watershed management in promoting soil and water conservation urgently need to be revisited.

While water and wind erosion are part of a natural process, imbalanced water use, nutrient pollution and the related eutrophication are human-induced processes that need policy attention and intervention. Eutrophication is characterized by excess nutrient inputs in water bodies [5]. Nitrogen and phosphorus come from different sources, including agricultural fertilizers, wastewater, deforestation (e.g., for urban areas or livestock activities), and sediment delivery from impacted basins. Algal blooms and reduced water quality are the main symptoms of eutrophication. High phytoplankton biomass consumes dissolved oxygen while they decompose, causing anoxic conditions and biodiversity decrease. Fish communities are damaged due to little or no dissolved oxygen in the water, and many aquatic ecosystems lose value due to eutrophication [6,7]. It is estimated that 30–40% of the surface water bodies in the world are affected by eutrophication [8].

Agricultural intensification has been on the rise in most developing countries since the onset of green-revolution technologies. The ever increasing crop intensities coupled with the application of high and imbalanced chemical fertilizers and pesticides is hampering soil fertility. Soil degradation is compensated with increasing fertilizer application at the farm level. Different studies have shown that the costs of production (inputs) are growing at a faster rate than the output (value) growth, as yield rates are either stabilised or growing marginally [9]. While these are the first-generation problems of agricultural intensification, the second-generation problems are in the form of water-resource degradation in both qualitative and quantitative aspects. Much of this applied fertilizer is washed into the river and groundwater systems through run-off and seepage.

Eutrophication per se is not a new science, but the current knowledge of its impact on agriculture and crop production is very limited, especially in the developing countries of Asia, Eurasia and South America. The increased use of nitrogen in crop production in recent decades has increased the nitrate concentrations in water resources that are used for irrigation along with other compounds like phosphate, potassium and pesticides. In the absence of any information and knowledge on water or soil quality in most countries, farmers continue to use fertilizers at an increasing rate. This trend compounds the effects of eutrophication (Figure 1) on food and water security. Despite the seriousness of the situation, the issue has not warranted the attention of policy makers because the problem and its impacts have not been made explicit by scientific work on the subject.

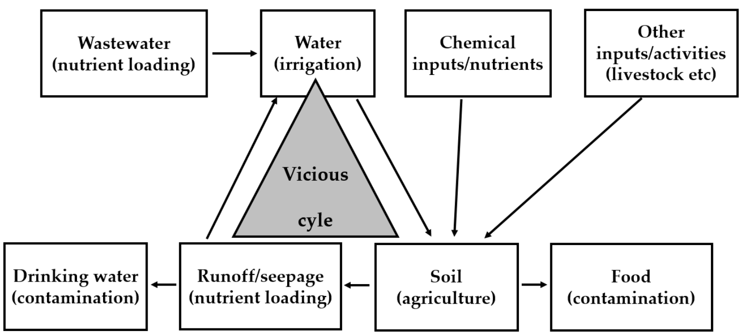

Figure 1. Vicious cycle of eutrophication and its relationships with human activities and environmental impacts.

In the regions with intensive agriculture, fertilizers and pesticides can contaminate surface-water bodies (rivers, lakes, etc.) or aquifers, where they can impact different water uses and affect ecosystem services. Cattle feed lots are also an important cause of non-point nutrient pollution [7], frequently at a more localized scale. Imbalanced and high chemical-input use is on the rise even in the regions with no surface irrigation due to increases in groundwater exploitation. In fact, chemical fertilizer use is being significantly promoted in these regions to enhance productivity (for instance, a second green revolution in the rain-fed regions in India). In Brazil, the widespread use of pesticides is associated with environmental and social impacts [10–12]. In these regions, eutrophication tends to grow at a greater pace due to groundwater irrigation i.e., the recycling of eutrophication or degradation of one resource (water) feeding into another (land), forming a vicious circle (Figure 1). The process is more rapid in the low rainfall regions with marginal or no run-off (absence of natural flushing of nitrates).

Soil- and water-conservation interventions like watershed management are further reducing the run-off. Watershed management and interventions are being promoted to stabilize rates of soil erosion and improve in situ moisture conservation across dry regions. Watershed interventions, it has been assumed, would result in increased moisture and availability of irrigation (groundwater) prompting the shift towards crop intensification (green-revolution technologies) with high chemical inputs. But in the absence of a proper understanding of the consequences of reduced run-off fostered with chemical intensification, no attention is being paid to water quality and its impact on soils and crops.

2. Objectives

This paper is an attempt to fill the knowledge gap with the help of a review of available evidence on the seriousness of the problem and its likely impacts on resource (water and soil) degradation and food security. This review paper also identifies some of the science gaps in terms of understanding the linkages between eutrophication and crop losses in different agro-ecological contexts. Broadly, the objective of the paper is to highlight the need for addressing the problem of eutrophication in the developing countries of Asia and South America. Specific objectives include:

(i) a review of evidence on the problem of eutrophication in general, and highlighting the need for understanding the linkages between eutrophication and soil quality crop yields (food security);
(ii) understanding eutrophication in the water, energy and food nexus perspective in order to address the problem in a comprehensive manner;
(iii) a review of evidence on the growing problem of eutrophication and its likely impact on soils and crops, especially groundwater-dependent regions; and
(iv) identifying important research questions for further research in this area.

The paper is organised in five sections. The following section discusses the issue of eutrophication in the context of the water, energy and food nexus. Evidence on the incidence and potential impact of eutrophication on soils and crops is discussed with the help of irrigation water-quality data. The evidence provided in this section, although limited, questions the assumptions that guide the promotion of watershed management in low rainfall and groundwater-dependent regions. The discussion highlights the need for new scientific approaches that improve the evidence base and provide guidance for decision makers who will increasingly be confronted with the challenge of eutrophication. Finally, the last section of the review paper identifies important questions that can be addressed by future research.

3. Nexus Context

Sustainable land and water management in the context of eutrophication could provide 'win-win' propositions under the water–energy–food (WEF) nexus. Eutrophication is very much linked to water and energy resources (Figure 2) and with theoretically well-defined trade-offs and threshold levels [13]. Water is used for irrigation (food security) and hydropower generation (energy security), as well as for industrial and domestic purposes. Energy is used in the development of water resources (water security), agricultural machinery, fertilizers, and pesticides for increasing crop production (food security). In turn, agriculture contributes to energy security through biofuels and supports water security through land-use practices, i.e., improved land cover can help aquifer recharge and base flows. All the three sectors have externalities that negatively impact the environment and natural resources. Water use results in waste/effluent generation in the domestic and industrial sectors. Water use for irrigation can affect water quality as well as deplete and degrade the resource itself, i.e., through excess use over and above sustainable limits and the recycling of nitrates and other nutrients. The energy-development process could lead to emissions increasing the carbon footprint. Excess use of chemicals and water in agriculture could result in eutrophication.

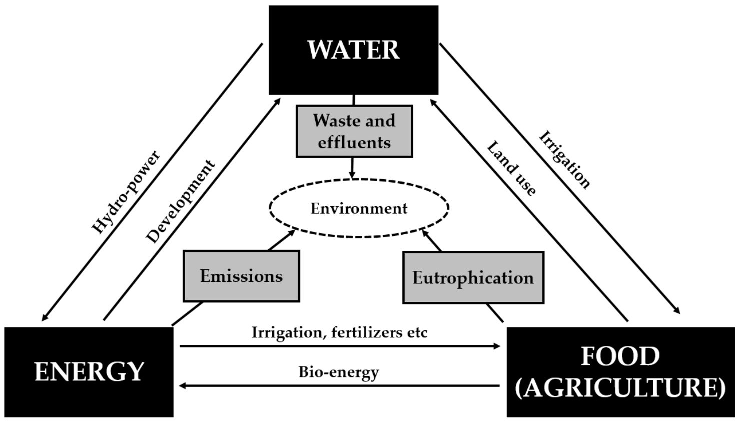

Figure 2. The broad framework of the water–energy–food nexus. Source: Adapted from Scott, et al. (2015) [14].

Eutrophication fits into the WEF nexus framework as the process of mitigating environmental degradation is linked to the '4 Rs' concept, i.e., recycle, reuse and recharge to achieve the objective of reduce (conserve). Irrigation water, which is loaded with nutrients, can replace direct fertilizer application. This results in a reduction of fertilizer use in crop production provided that water-quality information is available for the farmers. Given the low permissible levels for drinking water, treatment is required prior to use. Often, rural communities use the same source for drinking water and irrigation, especially during summer months when shallow wells go dry. The possibility of chemical contamination through groundwater seepage is high in the case of shallow wells (drinking water).

Even in the case of irrigation, water recycling with treatment is required in the event of nutrient loads exceeding the required level for given crops. In fact, technologies are available to produce fertilizers and energy from municipal wastewater (See https://www.treehugger.com). In some cases, water use can be reduced by changing either land use or the method of irrigation. Micro irrigation like sprinkler and drip systems significantly reduces irrigation water consumption at a smaller scale (plot or micro-watershed) and hence nutrient application. Less energy is thus required to meet the reduced demand for fertilizer and reduce pumping of water per unit of land (the total demand may remain constant as the reduction in water use per unit of land is compensated through area expansion.). Also, part of the irrigation water is reused through the recharge of aquifers in the river basin, which is a continuous process. This is more so in the case of flood irrigation. In the case of groundwater irrigation along with watershed interventions in low rainfall regions, the recharge would be localized, often on a limited micro-watershed or plot. Ultimately, energy and water resources are conserved as the demand goes down. The result: the same level of output (food) can be maintained at lower levels of water and energy inputs, or a higher level of output (food) at the same level of water and energy inputs. This ensures sustainability of resources through improved soil, water and food quality.

Trade-Offs and Thresholds

Important features of the WEF nexus are the trade-offs and thresholds among the three resources [15]. While eutrophication reduces land productivity, improved management of water and land resources can not only reduce energy consumption in agriculture but also enhances production. The net energy consumption depends on the extent of nutrient concentration in water. Higher concentrations are associated with lower energy consumption (less energy required to produce fertilizers), characterizing the trade-off between energy and water. That is, if we use more water, less fertilizer is required, and vice-versa. In the case of eutrophication, the trade-off is in terms of allocating water to agriculture vis-à-vis drinking water (Figure 3). Eutrophication reduces the demand for drinking water from the source (due to contamination), which can be diverted to irrigation. The criteria for such trade-offs include the health impacts of contaminated water, the replacement costs of drinking water, and the net returns from diverting water for irrigation. Food security could be enhanced either through allocations to food crops (agriculture) or through net returns per unit of water by allocating water to other sectors and buying food in the international markets. However, increased irrigation does not necessarily result in food security if allocative efficiency favours commercial crops. In Brazil and other low-income countries, there is a growing debate concerning biofuel production (e.g., ethanol from sugar-cane crops) and food security [16,17]. There are also potential positive externalities in the form of fertilizer and energy as by-products from wastewater treatment. These possibilities further strengthen the 'win-win' possibilities of sustainable wastewater management.

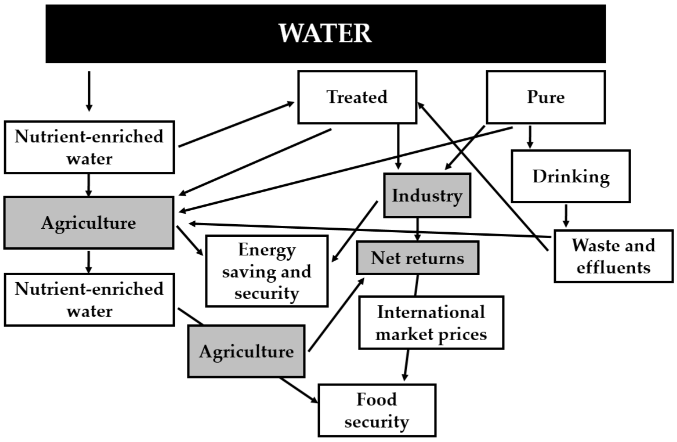

Figure 3. A simplified trade-off framework for eutrophication under the water–energy–food nexus.

The extent to which economic principles are applied in this context depends on the socioeconomic and political context of the country, as food and energy security could be viewed as key factors for protecting national sovereignty at the political level. Similarly, national or political priorities might go against economic rationality. For instance, in most developing countries environmental sustainability is not a high priority when compared to promoting food security or eliminating poverty. As a result, energy-saving technologies or clean-energy technologies are beyond their affordability. At present 'water rather than hygiene', 'energy rather than clean energy' and 'food rather than nutrition' are primary policy priorities.

This opens-up another dimension of trade-offs in governance and institutional aspects. Governance and institutions play an important role in resource management, but they are neither in place or sophisticated to handle the situation. In most developing countries, governance and institutional structures are very weak. Often, policies tend to serve political interests rather than resource sustainability. In some cases, policies are not backed by a legal framework for enforcing the policies. The trade-off is between political interests vis-à-vis resource interests. Several trade-offs can be observed in environmental governance in developing countries: (i) centralized vis-à-vis decentralized; (ii) short-term vis-à-vis long-term planning; (iii) efficiency vis-à-vis equity; (iv) public vis-à-vis private management, etc. [18]. Thus, there is a need for understanding resource as well as governance trade-offs for effective implementation of the nexus approach.

It is argued that trade-offs can be handled by balancing different societal objectives through negotiation between interest groups [19]. Some argue that environmental protection as well as long-term sustainability should be given priority over short-term socioeconomic gains [20,21]. This requires hard governance choices [22] that may go against political interests as well myopic socioeconomic requirements (food, employment, etc.). While guiding principles are required to negotiate outcomes, they need to be backed by science-based evidence. An evidence-based approach helps in formulating coherent policies across sectors and reaching agreements among stakeholders.

Such policy/political priorities set the threshold levels for the trade-offs between resource allocations. In the case of water, drinking-water needs are of high priority and thresholds are set at minimum requirement for survival in most countries. Regions with food shortages could favour setting higher threshold levels of water allocation to agriculture for achieving or maintaining food security. This would limit the allocation to industry and other uses irrespective of economic rationality (use efficiency and returns). Similarly, regions with energy shortages may prefer a greater threshold level of water allocation to hydro-power production. Thus, the trade-offs and thresholds vary according to regional interests and comparative advantages fostered by prevailing distribution of environmental resources and services and institutional risks. This is evident from the experience of the riparian river basin regions or countries. For instance, building hydropower-generation projects is economically more beneficial to the upper riparian countries (China and Bhutan) of the Brahmaputra river basin, which goes against the food security of the lower riparian countries (India and Bangladesh). In some cases, the policy priorities are set with political rather than economic motivations. In Brazil, a large country with continental size, cascading hydropower reservoirs on the same river can affect different states/municipalities located either upstream or downstream the project in different ways (see [23] for a comprehensive review of multi-purpose reservoirs in South America). Similarly, conflicts are observed in the context of the Mekong river basin in East Asia when differing interests have not been adequately reconciled [24].

In the case of eutrophication, threshold levels for resources (especially water) could be set by the availability of infrastructure for managing nutrient balance and treatment. In most developing countries, the cost of removing nutrients from the water can be high [25]. However, the negative externalities associated with eutrophication could offset these costs. For example, excess nitrates in food and drinking water increase morbidity rates in humans and impact aquatic life, as food contamination could have long-term and debilitating impacts on human and livestock health. Besides, higher levels of nitrates could turn soils acidic and barren. Effective water management could address the negative externalities arising from eutrophication and ensure sustainability of the process in the long run. Besides, effective management of wastewater could also generate positive externalities through by-products like fertilizer and energy.

Increasing dependence on groundwater coupled with agricultural intensification is likely to exacerbate the problem of soil degradation, in turn affecting agricultural production adversely. While water is critical for agriculture, the dependence on groundwater is growing in the less-endowed (low rainfall and no surface irrigation) regions. Improved access to irrigation is directly linked to energy (for pumping) and irrigated agriculture also demands more energy inputs (machinery, fertilizers, etc.). Further, irrigated agriculture enhances livestock and human activities in general. Together, this results in degradation of the water as well as soils affecting livelihoods and food security. These inter-linkages and trade-offs among resources could be assessed better in the water–energy–food security nexus framework (Figure 2). Eutrophication is one of the important loops that needs to be closed in the nexus framework [14]. The problem appears to be universal, especially in the developing countries, where soil- and water-testing is neither scientific nor systematic. Besides, input use regulations are not in place. There is a clear benefits that can emerge from addressing science and knowledge gaps in such institutional contexts.

4. Incidence and Impact of Eutrophication: Some Evidence

Nitrates in groundwater have been reported as a growing concern in different regions in Europe, United States and South and East Asia. In Europe, nitrate in drinking water exceeded in around one-third of the groundwater bodies for which information is currently available [26]. In India, nitrate pollution in groundwater surpassed national allowed limits (45 mg/L) and was reported in different Indian states [27]. In China, nitrate pollution of shallow groundwater is widespread, with almost 100% of water samples containing some level of nitrate, and with 30–60% of samples containing nitrates at levels above the national standard (20 mg/L) [28]. It is observed that approaches that did not address environmental challenges in a holistic manner produced rebound effects with implications for degradation of water and soil resources [29]. In Brazil, land use has been affecting raw surface-water quality for drinking supply [30], and there is eutrophication of local aquatic systems [31,32].

A recent study in the rain-fed Anantapur district (<600 mm rainfall) of Andhra Pradesh (south India) has reported disturbing water-quality indicators (Table 1). It has been observed that irrigation water in some of the groundwater-dependent regions has high levels of conductivity (EC), sodium (Na), magnesium (Mg), nitrates (NO_3) and fluorides (F) beyond maximum permissible limits. Nitrate loads have crossed 1000 mg/L in some cases (watershed II) that receives less rainfall in comparison to watershed I. Some of the villages in watershed II have experienced their soils turning sodic in recent years [33]. This is despite the fact that these areas are characterised by hard rock and basal aquifers. Water-quality impacts are dependent on aquifer geometry. Alluvial aquifers take less time to absorb pollutants when compared to hard rock and basal aquifers.

Table 1. Groundwater quality across watersheds in Andhra Pradesh, India.

Parameter	Watershed I		Watershed II	
	Pre-Monsoon (2014)	Post-Monsoon (2014)	Pre-Monsoon (2014)	Post-Monsoon (2014)
pH	7.74	9.3	8.16	8.2
EC (µS/cm)	3100	3100	5010	4960
TDS (mg/L)	1660	1984	2710	2660
Na (mg/L)	441.4	130.8	1075.5	934.7
K (mg/L)	12.5	37.9	89.6	125.3
Mg (mg/L)	154.2	37.7	207.8	227.4
Ca (mg/L)	73.7	17	463.1	456.3
Cl (mg/L)	644	556.3	831.6	950
SO_4 (mg/L)	125.9	299.7	323.3	353.5
HCO_3 (mg/L)	490	672.07	1140	1120
CO_3 (mg/L)	50	76.1	160	80
NO_3 (mg/L)	211.3	192.3	1113.6	1241.9
F (mg/L)	2	1.5	4.4	3.7

Note: ND = not detected; PH = potential hydrogen; EC = conductiviy; TDS = total dissolved solids; Na = sodium; K = potassium; Mg = magnesium; Ca = calcium; CI = chloride; SO_4 = sulphate; HCO_3 = bicarbonates; CO_3 = carbonates; NO_3 = nitrates; F = fluoride. Source: ACIAR (2015) [34].

The pre- and post-monsoon nitrate loads are not very different and in one case (watershed II) the concentration is higher during the post-monsoon period (Table 1). This defeats the objective of soil- and water-conservation interventions in the long run. It may be noted that soil conservation helps reduce eutrophication in the event that eutrophication is caused by topsoil sediment loads. In the present case, eutrophication is due to the seepage of nutrients to groundwater aquifers through irrigation. In India, for instance, watershed interventions are targeted to increase groundwater recharge/irrigation and enhance productivity through input-intensive agriculture. The emerging evidence clearly indicates that these practices are unlikely to sustain resource management in the long run.

It may be noted that along with nitrates, most of the other contaminants are also on the higher side. This may have more severe and complex impacts on soil quality when compared to nitrate contamination alone. Furthermore, contamination levels in groundwater irrigation water are more significant when compared to the contamination levels in wastewater irrigation water (direct wastewater use) (Table 2). This indicates the severity of the problem of water quality in the low rainfall groundwater-dependent regions. This calls for a better understanding of water-quality issues and their impacts on agriculture and food security.

Table 2. Wastewater characteristics across sample locations in Telangana (Karimnagar), India.

Parameters	Normal Range	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
pH	7.0–8.5	7.6	7.5	7.3	7.9	7.2	7.6	7.4	7.6	7.9	7.6	7.8	8.1	7.6
EC (µS/cm)	750	1469	1232	1468	1478	1225	1539	1369	1225	1125	772	813	379	1444
TDS (mg/L)	500	954	800	954	960	796	1000	889	796	731	501	528	246	938
Chloride (mg/L)	200	130	170	164	168	140	236	216	164	140	80	92	28	228
Fluoride (mg/L)	1	0.24	0.16	0.19	0.18	0.16	0.24	0.20	0.27	1.76	0.20	0.22	0.10	0.29
NO_3 (mg/L)	5–45	56	92	116	107	84	78	72	84	72	24	65	6	96
Total hardness (mg/L)	100	430	430	396	356	328	408	420	364	312	220	196	160	376
Alkalinity (mg/L)	75	560	384	484	480	368	460	392	352	368	268	256	140	388

Note: Same as in Table 1. Source: World Bank (2008) [35].

Studies of irrigation water quality in the Indian Punjab (known for high-input intensive agriculture) have also observed high concentrations of nutrients in groundwater [36–38]. Most of these regions are dependent on groundwater for 90% of their irrigation needs. Given the low rainfall and poor soils, a greater number of irrigations is required in this region when compared to other regions with good soils. Such an intensive use of groundwater can put farming at risk if policies are focused on quantity to the neglect of quality of water. Such an intensive recycling of soil pollutants could destroy the soils at any scale. Nutrient leaching is a far more important issue to farmers than farm-soil erosion. In rain-fed agricultural land, the leaching volume at 45 cm depth in the soil profile is significantly higher than surface runoff [39].

Eutrophication persists even as scale increases (watershed/basin). In small watersheds especially, upstream conservation and erosion control have a direct downstream impact (e.g., usually mitigating siltation and alleviating eutrophication in reservoirs and lakes). As watershed size increases, factors other than land use can also become important, such as natural features (e.g., intensity of extreme rainfall events) [39]. Similar findings can be deduced from trophic state indexes and nutrient criteria (e.g., reference/background concentrations) that have been developed in Brazil for eutrophication assessment [40–43].

Eutrophication at low nitrate levels in soils helps crop growth and production. Even in the case of normal or high nitrate levels in soils, the application of nutrient-loaded water (eutrophication) results in the over growth of plants and affects yield rates, as it extends the growth period and delays the maturity of grains. Moreover, excess levels would turn soils acidic and make the soils unfit for crop production. Sensitive or less tolerant crops start being affected at a level of 5 mg/L of nitrates, while more tolerant crops can take up to 30 mg/L, although this can go up to 50 mg/L [44,45]. However, there is not much evidence on the exact impact of eutrophication on crop yields, unlike in the case of saline water and salinity. Clearly more research is required to fill this critical knowledge gap.

5. Further Research

Hitherto, the problem of eutrophication and its impacts have been confined to surface-water bodies. Eutrophication impacts on soils and food security have not received policy attention because the problem is not alarming in terms of scale (spread) and intensity (impacts). Secondly, the linkages between eutrophication and agriculture are not well understood in the absence of systematic research on the yield impacts of eutrophication, as it is often linked to wastewater. Over the years, the phenomenon has spread to surface-water bodies, including rivers that are used for irrigation, as well as groundwater resources due to continuous and excessive use of chemical fertilizers over the past four decades. The problem of eutrophication and its impact on agriculture in surface irrigation-dependent regions does not build up continuously due to natural flushing (rainfall and flooding). In the case of groundwater-dependent regions, its impacts could build up faster in the absence of natural flushing. Given the fragile nature of these regions, it is a cause for policy concern. For example, the process could be very fast in these regions due to low rainfall.

Even the limited run-off is being checked through the watershed interventions of recent years. Watershed interventions emphasize the checking of runoff and the harvesting of rain where it falls. This aggravates the process of recycling of nutrients at a micro scale (plot level). Political economy considerations can, however, further complicate the process, because of the effects that decisions relating to financing and technology choices can have on the success of recycle/reuse initiatives at scale.

5.1. Research Questions

1. What is the relationship between the intensity of eutrophication and crop production? At present, there is limited evidence on the impact of nutrient loads in the water on crop yields. Knowledge on this would help in assessing the crop losses (food security) and economic losses due to eutrophication.

2. What is the relationship between land use (crop systems)/livestock intensity and eutrophication and its impacts? Understanding the influence of land use (nature of crops, forests, etc.) and livestock density and composition on water-quality aspects could help in mitigating eutrophication through appropriate policies.
3. What is the influence of bio-physical (including hydrogeology) characteristics on eutrophication? Natural factors (beyond human control) such as rainfall, soils, hydrogeology, etc., influence water quality to a large extent. Understanding these linkages would help in designing program interventions.
4. How far do the impacts differ between groundwater-irrigated (rain-fed) and surface-irrigated situations? Establishing and understanding these linkages would help in prioritizing and targeting the areas of interventions for mitigation or for assessing eutrophication.
5. How can nexus analysis of the trade-offs illuminate the role of political economy considerations in influencing the management of environmental resources, public services and institutional risks with the potential to impact upon the adoption of measures to combat the challenge of eutrophication?

Answers to these questions would help to define the trade-offs and thresholds in a more scientific and systematic manner. They would help in understanding the limitations of watershed management and resetting the watershed-management priorities across agro-ecological contexts. Similarly, input policies need to take the inter-linkages and their externalities into consideration.

5.2. Approach

These research questions would require an effort to understand the problem in different agro-ecological and institutional contexts. The water-stressed regions of Asia, Eurasia and South America, especially India, China and Brazil, can provide a number of agro-ecological scenarios for research and policy uptake. Other water-stressed regions which are at the early stages of agricultural intensification, can provide different bio-physical contexts in terms of soils, land cover, hydrology, climate, rainfall, etc. Given the complex resource linkages collaborative research involving specialists from several disciplines, such as water science, soil science, hydrogeology, crop science, livestock, climatology, energy, socioeconomics would be important (Figure 4).

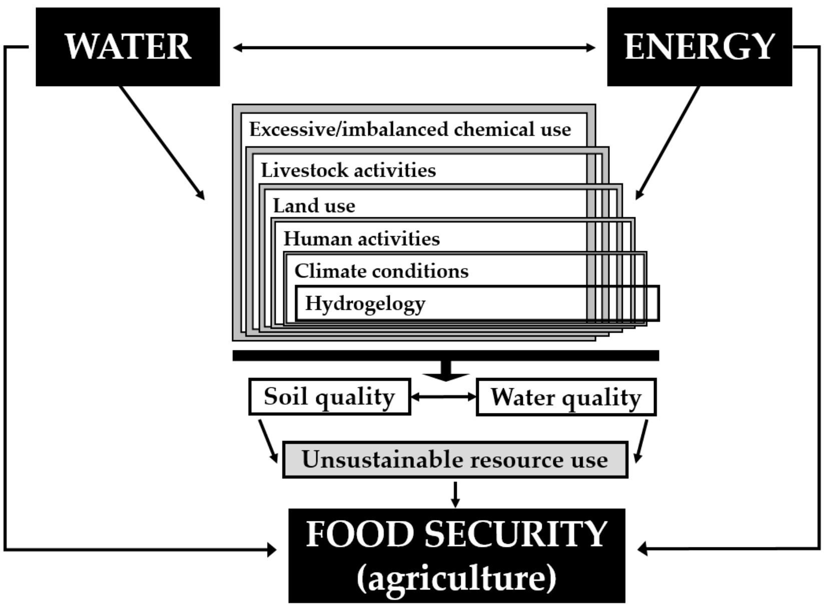

Figure 4. Understanding the nexus: a trans-disciplinary approach.

There would be a clear need for understanding and interpreting science with regards to water quality and its impact on soil degradation. Water and soil are interconnected and, hence, a holistic approach is necessary. At the same time, location-specific attributes like hydrogeology, climatic conditions, land-use practices and livestock activities determine sustainable resource-use practices. Policy uptake would be advanced if all aspects of agricultural intensification are considered in a comprehensive manner. Often, policies are formulated on a sectoral basis without looking at the inter-linkages, and prove to be ineffective in most countries. Adopting a water, energy and food nexus approach to addressing resource-management problems is more likely to result in the design of comprehensive and effective policies that advance the cause of sustainable development (Figure 4).

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Conflicts of Interest: The authors declare no conflict of interest.

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