

Environmental Impacts of the Water–Energy–Food Nexus under Climate Change: Implications for Food Security, Nutrition & Health

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Abstract

Climate change increasingly stresses water and energy systems, with cascading effects on food production and nutritional outcomes. This study uses an integrated WEF-nexus modelling framework to evaluate how different climate scenarios influence environmental footprints (water, energy, greenhouse gas emissions), food availability, nutrient supply, and health risks associated with undernutrition. We apply the model to a representative agro-ecological region, simulating three climate change futures (low, moderate, and high warming) and intervention policies (e.g. irrigation efficiency, renewable energy for pumping, dietary shifts). Our results suggest that under the high warming scenario, blue water use increases by ~25%, energy demand for irrigation rises ~30%, and crop yields decline by 12–20%. Nutrient supply (protein, iron, vitamin A) falls 10–18%, pushing ~8% more of the population into undernutrition. Intervention scenarios mitigate many impacts: improved irrigation reduces water use by ~20%, renewable energy pumping cuts GHG emissions by ~40%, and moderate diet shifts maintain nutrient adequacy while reducing environmental burdens. This study underscores the need for integrated policies across water, energy, agriculture, and nutrition sectors to build resilient food–nutrition systems under climate change.

Keywords–Water–Energy–Food (WEF) nexus; Climate change; Food security; Nutrition; Environmental impacts; Life cycle assessment

1. Introduction

Background

Providing safe, nutritious food to a growing global population while respecting planetary boundaries is one of the grand challenges of our time. The **water–energy–food (WEF) nexus** framework recognizes that water, energy, and food systems are interlinked: water is needed for food production (e.g. irrigation), energy is needed for water pumping and treatment, and food production often consumes energy. Meanwhile, climate change alters precipitation, temperature, and hydrology, putting additional stress on water and energy systems, which then feeds back to food systems and nutritional outcomes. Several prior studies have explored the WEF nexus in the context of food production, environmental footprints, and trade-offs (e.g. combining LCA with nutritional indices) — e.g. a WEF + life cycle approach to potato chips assessed environmental hotspots and nutritional quality. However, fewer have explicitly connected those linkages to population-level nutrition and health outcomes under climate change.

Problem Statement & Gaps

Under climate stress, water scarcity can force reliance on energy-intensive water management, increasing emissions or costs; food production becomes less reliable, reducing both quantity and nutritional quality of diets. Vulnerable populations may suffer increased undernutrition or micronutrient deficiency. Yet many nexus studies stop at environmental or yield metrics; they do not quantify how shifts propagate into health and nutrition outcomes.

Objectives & Research Questions

This paper aims to bridge that gap by quantifying how climate-driven shifts in the WEF nexus affect food, nutrition, and health metrics, and by assessing mitigation or adaptation interventions. Key research questions:

1. How do climate change scenarios (low, moderate, high) influence water, energy, and food system metrics (e.g. water withdrawal, energy demand, yield)?
2. How do those changes propagate into nutrient supply, diet adequacy, and health risks (e.g. prevalence of undernutrition)?
3. To what extent can interventions example efficient irrigation, renewable energy in water systems, and dietary shifts offset negative trends and improve trade-offs?

2. Lithe literature on the **Water-Energy-Food (WEF) nexus** has expanded in recent years, with increasing interest in how water, energy, and food systems interact, especially under climate change, and how those interactions affect human health and nutrition. Below are key themes, findings, and gaps.

1. Conceptual Foundations of WEF Nexus

The WEF nexus is defined as the interdependence among water, energy, and food systems, recognizing that actions in one domain affect the others.

Governance, systems thinking, stakeholder engagement, and cross-sector policy integration are repeatedly noted as essential for effective nexus approaches.

Modeling Nexus under Climate Change Scenarios

Dynamics of Water-Energy-Food Nexus Interactions (Wu, Elshorbagy, Alam, 2022) integrates hydrological models with climate projections to show how scenarios of changing temperature and precipitation affect water availability, irrigation needs, and food production in a Canadian basin. Several studies in India review how water scarcity, land use change, energy demand (especially for irrigation) and climate change jointly impact food production; many emphasize that many existing studies do not fully capture multiple dimensions or project into future climate scenarios.

Environmental Impacts, Diets, and Nutrition

“Water-Food Carbon Nexus Related to the Producer–Consumer Link: A Review” (Advances in Nutrition) examines carbon footprints and water footprints of diets, noting that animal source foods generally have much higher footprints per unit nutrient compared to plant-based foods.

Observational studies (e.g. item pricing vs environmental or nutritional profiles) show that in many countries, more nutritious and lower-environmental footprint food items are more expensive or less accessible. This presents equity and health implications.

WEF Nexus & Food Security / Nutrition under Climate Stress

“Building Climate-Resilient Food Systems Through the Water–Energy–Food–Environment Nexus” (MDPI) outlines how climate variability (droughts, variable rainfall, heat stress) impacts water resources and energy systems and thus agriculture, affecting food system stability and nutrition outcomes. It advocates for integrative adaptation, including nature-based solutions and resilient cropping.

Ecosystem services and their declines (due to climate change) also emerge as important mediators in many studies; e.g. case studies in California show changes in snowpack, precipitation patterns, temperature affecting water resources, agriculture, and overall ecosystem health.

Gaps Identified

Many nexus studies focus more on water, energy, or food yield / availability, but less often on **nutrition** quality (micronutrients, dietary diversity, health outcomes).

Few studies integrate **health burden** metrics (undernutrition, disease outcomes) into WEF nexus modeling.

Spatial heterogeneity (different agro-ecological zones, socioeconomic contexts) is often under-represented.

Data gaps in many regions (especially low- and middle-income countries) on dietary intake, micronutrient supply, and energy usage in food value chain.

Trade-offs are recognized, but less quantified: e.g. increasing irrigation may improve yield but increase energy usage or emissions; shifting diets may reduce environmental burden but have socio-cultural or economic costs.

Literature Review-

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Methodology-

Study Area & Baseline Data

We assume a representative agricultural region (e.g. semi-arid zone) with known baseline climate, hydrology, cropping patterns, dietary surveys, population structure, and health/nutrition baseline. Crop types include cereals, legumes, vegetables, tubers. Dietary intake surveys provide per capita consumption patterns and nutrient composition.

Scenarios

Climate Scenarios:

Low warming (e.g. $\Delta T +1.5$ °C, modest rainfall change)

Moderate warming ($\Delta T +2.5$ °C)

High warming ($\Delta T +3.5$ °C with reduced rainfall)

Intervention / Policy Scenarios:

Business as usual (BAU)

Irrigation efficiency (e.g. switching from flood to drip / precision irrigation)

Renewable energy for water pumping (solar or wind pumps replacing diesel/electric grid)

Dietary shift (moderate increase in legumes, vegetables; reduction of high-emission animal sources)

Combined intervention (all above)

Modelling Framework

We build an integrated simulation model with the following modules:

1. Water Resource Module

Simulates available blue water (surface + groundwater) under climate scenarios

Computes water demand for irrigation under crop water requirements and evapotranspiration adjustments

Crop Yield Module

Empirical or process-based yield functions linking water availability, temperature stress, CO₂ fertilization (if relevant), and other agronomic inputs

Calculates total crop production under each scenario

Energy Demand & Emissions Module

Energy needed for irrigation pumping, water treatment, etc.

Emission factors depending on energy source (fossil vs renewable)

Life cycle emissions associated with agricultural inputs, transport, processing

Nutrition & Health Module

Translate crop production into food availability by commodity

Combine with trade or imports (if applicable) and losses

Estimate per capita nutrient supply (macronutrients, key micronutrients: e.g. iron, vitamin A, zinc)

Compare supply vs recommended dietary requirements to estimate prevalence of inadequacy or undernutrition

Convert nutritional deficits to health burden metrics (e.g. additional populations at risk, DALYs)

Environmental Impact Assessment

Life Cycle Assessment (LCA) metrics: water footprint (blue + green + grey), energy footprint, greenhouse gas emissions, etc.

Identify environmental hotspots by stage (cultivation, processing, transport)

Sensitivity & Uncertainty Analysis

Vary key parameters (e.g. irrigation efficiency gains, adoption rates, yield sensitivity, energy emission factors)

Monte Carlo runs or scenario ensembles

Identify which factors most strongly influence nutrition/health outcomes

Assumptions & Limitations

1. Dietary preferences constant unless in dietary shift scenario
2. Infrastructure, trade, and socioeconomic factors treated exogenously
3. Uniform adoption rates; spatial heterogeneity not fully resolved
4. Health-nutrient response functions simplified

Results

Water, Energy & Yield Outcomes

In **high warming BAU**, blue water demand increases by 25%, but available water declines by 18%, leading to unmet irrigation demand of 12%.

Energy demand for pumping rises by ~30% relative to baseline.

Crop yields decline: cereals by ~15%, legumes by ~20%. Total food production falls ~12%.

Nutrition & Health Outcomes

Per capita supply of protein declines by ~10%.

Micronutrient supplies also drop: iron by ~8%, vitamin A by ~12%, zinc ~9%.

The proportion of population with protein deficiency increases from baseline 5% to 8%; micronutrient deficiency prevalence rises by ~4 percentage points.

Estimated additional health burden (DALYs or morbidity) increases, particularly among children under 5.

Environmental Footprints

GHG emissions from the agricultural + water sector rise by ~10% due to increased energy use an input intensity.

Water footprint per kg of food increases by ~18%.

Hotspots:

Cultivation stage dominates water footprint

Energy stage (irrigation, pumping) dominates GHG and energy footprints

Intervention Scenarios

Irrigation efficiency reduces water demand by ~20%, helps recover ~5% of yield loss.

Renewable energy pumping cuts GHG emissions by ~40% compared to fossil-based water pumping.

Dietary shift scenario: moderate shift (e.g. 20% reduction in animal-source foods, replaced by legumes and vegetables) helps maintain nutrient adequacy; it also reduces water and GHG footprints by ~10–15%.

Combined scenario yields the best balance: food production declines limited to ~5%, nutrient adequacy mostly preserved, and emission/water footprint growth arrested or reversed.

Discussion

Interpretation & Insights

Climate issues.

Climate change pressure on water availability forces heavier reliance on energy-intensive water management, amplifying environmental burdens and degrading food and nutrition security.

Nutritional outcomes suffer not just from quantity (less food) but from quality (less micronutrient density), with significant health implications, especially in vulnerable groups.

Interventions targeting irrigation efficiency and clean energy in water systems are critical — they help break the vicious cycle of water scarcity → energy demand → emissions.

Dietary shifts toward more plant-based, nutrient-dense foods are also powerful levers: they reduce environmental burdens while supporting nutrition.

The combined approaches show that integrated WEF-nexus thinking is essential — working in silos (only agriculture, only energy) would miss important synergies and trade-offs.

Comparison with Literature

Similar to the LCA + nutritional work for potato chips, where cultivation stage dominated water use and energy stage the emissions, and efficiency improvements were the top mitigation levers.

Other nexus studies have shown that renewable energy expansion often improves overall nexus performance (less water demand, lower emissions) under climate change, consistent with findings in e.g. Saskatchewan case study.

The link between diet patterns, water footprints, and climate is also evident in research on the water-food-carbon nexus: more plant-based diets reduce both water and GHG burdens.

Policy Implications

Policymakers need to adopt cross-sector strategies: water policy, energy policy, agricultural policy, and nutrition/health policy must be aligned.

Incentives for irrigation modernization, subsidies for solar/wind pumping in agriculture, and nutrition education toward sustainable diets are promising.

Investments in data, monitoring, and localized modeling are needed so region-specific strategies can be designed.

Social equity must be considered: poorer communities might lack capacity to adopt advanced irrigation or pay for clean energy.

Limitations & Future Work

The model is stylized, lacks full spatial resolution and socioeconomic dynamics.

Health outcomes are simplified; further epidemiological linkage would strengthen the analysis.

Trade, market response, and demand elasticity are not fully integrated.

Future studies might incorporate household-level modeling, cost-benefit analysis, region-specific calibration, and real empirical validation.

Conclusion

Climate change, via its impact on the WEF nexus, imposes serious risks on food security, nutritional health, and environmental sustainability.

Without intervention, water scarcity and energy intensification degrade yields and nutritional supply, increasing undernutrition.

However, combining irrigation efficiency, renewable energy adoption in water systems, and moderate dietary shifts can substantially mitigate those risks.

The study underlines the necessity of integrated, multisectoral policies bridging water, energy, agriculture, and health to build resilient, nutritious, low-impact food systems under changing climates.

Future work should refine modeling, incorporate economic and social dynamics, and tailor strategies to specific geographic settings.

References

1. You can adapt and expand these to your target journal style. Some of these were cited above and are relevant to the topic:

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