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Environmental Costs and Future Transformation of Global Agriculture: A Perspective on the Two-Way Impacts of Intensive Agriculture and Climate

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Abstract. Focusing on the environmental challenges and transformation pressures facing global agriculture, this paper provides an in-depth analysis of intensive agriculture and the two-way coupling relationship between climate change. Through literature analysis and multidisciplinary approaches such as case comparison, it reveals the intensive agriculture on the climate system, the pressure pathways, and the feedback effects of climate change on agricultural production, while introducing the planetary boundary theory to quantify the safety threshold of agricultural activities. In addition, through the case comparison of oil palm cultivation in Southeast Asia and the green transformation of agriculture in Europe and the Netherlands, this paper discusses the innovative practices and policy tools for sustainable agricultural transformation and proposes the path of negative externality and the synergistic path of technology-policy-consumption, which provides a synergistic governance solution for the green transformation of global agriculture.

Keywords: Intensive agriculture, environmental externalities, climate impacts, planetary boundaries, sustainable agricultural transition

1. Introduction

Global agriculture is undergoing a profound transformation and escalating environmental and socio-economic pressures. On one hand, population growth continues to drive rising food demand. According to the Food and Agriculture Organization (FAO), global production of major crops reached 9.6 billion tonnes in 2022, a 56% increase from 2000. Key crops such as sugarcane, maize, wheat, and rice now account for nearly half of global output. However, hunger persists in many regions, highlighting the imbalance between increased productivity and food security. On the other hand, the environmental costs of intensive agriculture are mounting. Over the past two decades, pesticide use has risen by 70%, with the Americas consuming 50% of global pesticide use. Inorganic fertiliser use has reached 185 million tonnes (nutrient terms), with nitrogen comprising 58%. Meanwhile, greenhouse gas emissions from the agri-food system have risen by 10% [1]. Water scarcity, particularly in the Middle East and North Africa, further exacerbates agricultural vulnerabilities. Agriculture now stands at a critical nexus, as both a victim of and a source of emissions, posing a fundamental challenge to its long-term sustainablility.

This study aims to: (1) systematically analyse the environmental costs of intensive agriculture and its climate feedback mechanisms, (2) compare the ecological impacts of different agricultural systems through typical cases, and (3) assess innovative practices and policy tools for sustainable agricultural transformation. Employing multidisciplinary methods from agronomy, ecology, and earth system science, this research offers actionable insights for climate-resilient and ecologically sound agriculture reform.

2. Literature review

2.1. Environmental externalities of agriculture

Conventional intensive agriculture—often referred to as "petroleum agriculture"—has been a major driver of environmental degradation and greenhouse gas emissions. According to a study by the School of Resources and Environment at South China Agricultural University, the global warming potential (GWP) of major cereal production increased eightfold between 1961 and 2020. Over the same period, the System Sustainability Index (SI) decreased by a factor of three, mainly due to the sharp rise in fertiliser use, irrigation, and mechanisation. In South Asia, for instance, fertiliser usage, irrigation, and tillage have risen 83, 19 and 6 times respectively. This intensification has had significant ecological consequences, such as significant loss of biodiversity and pollution of water resources, and fragmentation of 80% of mammal habitats in the tropics [2].

2.2. Feedback effects of climate change on agriculture

Climate change also extertsa strong feedback effect on agriculture. Lin and others pointed out that rising global temperatures have led to an increased frequency and intensity of extreme weather events, such as droughts, floods, high temperatures, typhoons, which seriously disrupts crop cycles and reduce yields. These disruptions threaten food security and have a broader impact on rural economies. Moreover, climate warming is accelerating the spread of agricultural pests and diseases. As temperature and precipitation patterns shift, pests and pathogens are now able to survive in previously unsuitable regions. Their transmission routes are also evolving, making control more complex and costly.

Another major concern is soil degradation. Climate change-induced changes in precipitation and temperature increase soil erosion, nutrient leaching, and structural damage. Intense rainfall washes away topsoil rich in organic matterr, while droughts cause crusting and reduce water retention, impairing soil function and ecological balance. Crops in the tropical and subtropical regions are expected to be more negatively affected than those in temperate zones. Without effective adaptation, a local temperature rise of just 2°C could significantly reduce yields of staple crops like wheat, rice, maize [3]. Furthermore, higher soil temperatures accelerate the decomposition of organic carbon, releasing more CO2 into the atomosphere. This reduces the soil’s carbon storage capacity and weakens its role as a carbon sink, thus reinforcing the greenhouse effect and contributing to a harmful feedback loop between agriculture and climate.

Although a large number of studies on the environmental impacts of agriculture and climate feedbacks, notable gaps remain. Firstly, existing research often isolates single impact factors, lacking a systematic analysis of the bidirectional feedback mechanisms between agriculture and climate. Second, while many studies focus on negative impacts, there is a lack of comparative research on successful transition cases. Third, policy tools for agricultural green transformation are fragmented and fail to provide integrated solutions.

To address these gaps, this study constructs an analytical model of "two-way impacts of agriculture and climate" and introduces the planetary boundary theory to quantify the critical points of agricultural activities, so as to integrate scattered environmental externalities into systematic risk assessment. The author analyses the complex interaction between agriculture and climate and explores the path of sustainable transformation of agriculture through the synergy of technology-policy-consumption.

3. Two-way influence mechanism between agriculture and climate

3.1. Pressure path of agriculture on the climate system

Livestock production processes constitute a non-negligible environmental pressure on the climate system. In particular, ruminants (e.g., cattle and sheep) emit large amounts of methane (CH_4) through enteric fermentation, which has a significantly higher unit warming potential than carbon dioxide (CO_2) in the short term but with a shorter half-life. The livestock sector as a whole contributes about 15% of global anthropogenic GHG emissions and is the largest anthropogenic source of methane [4]. Meanwhile, fodder crop cultivation leads to land use changes, such as deforestation and reclamation, releasing soil carbon pools and contributing to long-term CO_2 accumulation, while fertiliser application and manure management release nitrous oxide (N_2O), which has a 100-year-scale warming potential of 265 times that of CO_2. In addition, intensive farming, while reducing emissions intensity per unit of output, increases nitrogen and phosphorus pollution and water stress. Grassland management has the potential to sequester carbon, but it is difficult at the global scale to offset the net increase in emissions from livestock systems, and carbon stocks are vulnerable to reversal by drought or mismanagement.

Agricultural activities exacerbate climate stress through multiple pathways, which not only change the climate system directly but also threaten the stability of agricultural production and resource sustainability through feedback mechanisms such as warming, changes in precipitation patterns, and the frequency of extreme weather events, etc. A deeper understanding of climate change feedbacks on agriculture is needed in order to address the global agricultural transition.

3.2. Feedback effects of climate change on agriculture

Climate change feedback on agricultural production through both direct physiological effects and resource restructuring. Although higher atmospheric CO_2 concentration promotes photosynthesis and reduces transpiration in C3 crops, ozone pollution and aerosol weakening of solar radiation form an offsetting effect. At the same time, climate warming has significantly altered the pattern of agricultural resources: the northward shift of the heat belt has driven changes in cropping systems, such as the northward expansion of winter wheat cultivation in the Yellow and Huaihai Seas. However, increased precipitation variability and extreme events are undermining resource gains, and heat waves and droughts are already leading to an increased risk of water deficits for cool-loving crops in the arid northwest of the country. Such asynchronous changes in light-heat-water resources are forcing agricultural production systems into an adaptive reconfiguration challenge [5].

Intensive agriculture has a response mechanism to climate change under specific production conditions and unique sensitivity. Firstly, temperature increase and precipitation changes affect the production conditions of intensive agriculture; different crops have different response mechanisms to the increase of CO_2 concentration, and warm and humid environments are more likely to breed weeds and pests, which indirectly affects the physiological process of crops and yield stability.

Secondly, higher temperatures increase the evaporation rate and uneven distribution of precipitation, leading to a greater scarcity of water resources in arid areas, and the high water demand of intensive agriculture will make the problem of water resource shortages more prominent and lead to water resource management problems; some excessive cultivation and irrational irrigation in intensive agriculture will also further aggravate the degradation of the soil, reduce soil fertility and productivity , and thus cause impacts on agricultural resources and the environment. In addition, in order to cope with climate change, intensive agriculture needs to invest more money in the construction of irrigation facilities, the cultivation of resilient varieties, and the control of pests and diseases, thus increasing the cost of agricultural production [6]. Decreased crop yields and quality due to climate change may lead to a food crisis, affecting the stability of food prices and market supply, which in turn will have a negative impact on socio-economic and political stability.

3.3. Tipping points and systemic risk assessment

Planetary boundaries are set by critical thresholds on a global scale and contain nine interrelated boundaries for climate change, biodiversity loss, biogeochemical flows (nitrogen and phosphorus cycles), stratospheric ozone depletion, ocean acidification, global freshwater use, land system change, atmospheric aerosol loading and chemical pollution. The Planetary Boundary Framework (PBF) quantifies the safe space for human-induced environmental change and helps to prevent the unaffordable consequences of human activities on the Earth's environment [7].

The Stockholm Resilience Centre's 2023 update shows that global nitrogen cycle fluxes in 2025 are projected to still exceed the planetary boundary threshold of 62 Tg N year-^{1}, and that six indicators, namely, climate change, biosphere integrity, land system change, freshwater use, and emerging pollutants have already exceeded the planetary thresholds [8]. Nitrogen cycling and biodiversity loss are closely related to the use of agricultural fertilisers and the expansion of cultivation areas. Nitrogen fertiliser abuse in the Midwest "Corn Belt" of the United States has led to the expansion of the "Dead Zone" in the Gulf of Mexico; the expansion of oil palm cultivation in Southeast Asia has caused the loss of habitat and degradation of the carbon storage function of the Sumatran tiger.

4. Comparative case studies

4.1. Case study 1: tropical rainforest damage from oil palm cultivation in Southeast Asia

This chapter compares typical negative and positive agricultural system cases to reveal the actual performance of the two-way mechanism of the agricultural system and climate change and analyse the long-term and short-term impacts of different governance pathways on the ecosystem.

The expansion of oil palm cultivation is a typical example of agriculture-driven climate change. In Southeast Asia, expanding cultivation accelerates tropical forest destruction and triggers deep carbon release. In Indonesia and Malaysia, which produce 87% of the world's palm oil, more than 10% of deforestation between 1990 and 2010 was attributed to oil palm plantations, with peat swamp forests being the most severely converted. In typical cases, such as Sumatra and Kalimantan, the conversion of primary peat forests to oil palm plantations has resulted in a double carbon loss: the biomass carbon pool collapses -427.2 ± 90.7 tonnes of carbon per hectare are lost, equivalent to direct emissions from deforestation. On the other hand, continuous carbon release from peat oxidation-drainage plantations causes the decomposition of the subsurface peat layer at a rate of 17.1 ± 3.6 tonnes of carbon per hectare/year, accounting for 63% of the total process carbon loss.

Measured data show that CO_2 emissions from such converted oil palm plantations (12-95 tonnes C/ha/year) are 1-2 orders of magnitude higher than those of other crops, with a peak of 95 tonnes C/ha/year recorded in Riau Province, Indonesia. Despite the carbon sequestration capacity of mature oil palm (64 tonnes CO_2/ha/year net uptake), pre-existing carbon losses in peatlands take 59-220 years to offset [9].

The climate feedback mechanism of this case is a vicious cycle of declinelocal climate drought and yield. As a typical rain-favouring oil palm crop, growth and yield are highly dependent on stable precipitation, while climate anomalies caused by the El Niño phenomenon prolonged droughts can significantly suppress oil palm productivity.

On one hand, drought directly inhibits oil palm physiological processes: water stress leads to a decrease in the proportion of female flowers and reduced bunch formation, and water supply lagging directly threatens oil palm yield. On the other hand, secondary hazards exacerbate production difficulties: drought increases the proportion of forest fires and damages the ecology of the plantation, while insufficient soil moisture hinders nutrient uptake, and cost pressures to reduce fertiliser application lead to tree decline, creating a negative cycle of low yield and reduced investment.

Expected production cuts have pushed up international palm oil prices (in El Niño years often by 10-15%), fuelling plantation expansion, but the ecological vulnerability of newly cleared forest lands, such as the remote forests of Kalimantan, can exacerbate regional droughts, creating a vicious cycle of “deforestation-warming-deforestation” highlighting the vulnerability of tropical peat forests as a carbon reservoir and the long-term climate costs of deforestation. This highlights the vulnerability of tropical peat forests as carbon reservoirs and the long-term climate costs of deforestation. Palm oil producers are now shifting to a sustainable form of oil palm cultivation, choosing to plant on existing farmland, but with little success, and the previous destruction of Sumatran wildlife habitat has yet to be fully restored, with Sumatran orangutans and tigers still relying on captive rescue. The two-way interaction highlights the necessity of adaptive transformation and the need to enhance the oil palm plantation system.

4.2. Case study 2: European agricultural green transformation practices: example of transforum programme in the Netherlands

In recent years, the European Union (EU) has promoted green transition through the Common Agricultural Policy (CAP), which provides direct subsidies to stimulate organic farming and ecological farming. For example, in Austria and Sweden, the proportion of organic arable land is more than 10%, reducing nitrogen pollution by reducing fertiliser use and enhancing soil carbon sinks. At the technical level, precision agriculture is implemented to optimise resource use and reduce environmental externalities. In terms of policy, the European Union has set up the Climate-Smart Agriculture Programme, which links carbon emission reduction to subsidies for farmers [10].

The TransForum programme in the Netherlands breaks the vicious circle between agriculture and climate and involves a variety of fields, including agricultural technology innovation, regional development, and international cooperation. The common features of these projects are a learning process based on real-world problems, encouraging multi-stakeholder participation, breaking the traditional linear model of R&D, and fostering interdisciplinary collaboration. Specifically, the goal of the practical projects is to address the ecological and social barriers of current agricultural systems and promote sustainable development, while the approach is to identify and implement needed innovations through experimentation, collaboration, and learning. Evidence suggests that synergistic "policy-technology-market" interventions can break the agro-climatecycle.

5. Transformative pathways to sustainable development

5.1. Exploring pathways to address negative externalities

To offset the environmental externalities of agricultural production, the emerging movement of "Alternative Proteins" (APs),can help to mitigate the environmental costs of traditional animal agriculture. APs include plant-based proteins, edible insects, and cell-based agricultural products that emphasise clean and non-polluting production processes and aim to provide a healthier, greener, and more humane source of protein [11]. Based on a combination of ethical, cultural and economic factors, APs has not yet been legally defined, but they can still be seen as a useful exploration of the sustainable transformation of agriculture, especially animal husbandry.

5.2. Exploring the synergistic path of technology-policy-consumption

The Dutch TransForum programme includes three innovative strategies in its practice:

Vital Clusters, which drive a low-carbon cycle technology integration, reducing direct agricultural carbon emissions from activities. Emphasis on cross-industry integration: for example, the "New Hybrid Farm" project integrates cultivation, farming, and energy, breaking through land regulations to allow for an intensive, circular development of the model and the realisation of internal material and energy cycles. Emission reduction, carbon sequestration, and efficiency enhancement. This will enhance resource efficiency and promote carbon sequestration.

Regional Development, which reconciles ecological and community needs through adaptive policy instruments and multi-actor collaborative mechanisms: for example, the North Frisian Woodlands project has enabled farmers to take ownership of their environmental management through a "regional contract." This will incentivise and empower climate-friendly agricultural practices at the local level and enhance ecosystem resilience.

International agri-food network, replacing trade in primary agricultural products transfer through knowledge and technology: For example, the Shanghai Greenport project exports Dutch facility-based agricultural technology and restructures global value chains. This will reduce the overall carbon footprint of the global food system, avoid carbon leakage, and empower the global low-carbon transition.

The project aims to achieve this through technological innovation: cross-sectoral integration of biotechnology, logistics optimisation and energy recycling; policy synergy: establishment of the KOMBI Multi-Body Network and promotion of regulatory deregulation and subsidy linkage through the Regional Compact system; and consumption guidance: development of a visual platform for tracking the sustainability of products and reinforcement of civic responsibility in consumption to achieve the transition. The core of the project is the systematic integration and optimisation of the synergistic paths of technological innovation to drive the low-carbon transformation of agriculture, policy optimisation to build institutional safeguards, and consumption transformation to guide market orientation.

6. Conclusion

This paper systematically analyses the environmental costs of intensive agriculture and its climate feedback mechanism, clarifies the two-way influence mechanism between agriculture and climate, and provides a new perspective for the transformation of sustainable agricultural development. Agricultural activities constitute multi-path pressures on the climate system, such as greenhouse gas emissions from animal husbandry, nitrogen and phosphorus pollution from intensive farming, etc., while climate change also feeds back to agricultural production through direct physiological effects and resource restructuring pathways, affecting crop growth cycles, yield stability, etc. By quantifying the tipping points of agricultural activities through the planetary boundary theory, the analytical model of "two-way impacts of agriculture and climate" is constructed, which helps to systematically assess the risk of agricultural activities. Comparative analyses show that the expansion of oil palm cultivation in Southeast Asia has accelerated the destruction of tropical forests and triggered the release of deep-seated carbon, forming a vicious closed loop of "deforestation-warming-deforestation," while the European Union promotes the green transition through the Common Agricultural Policy, and the Dutch TransForum project practice breaks the link between agriculture and climate. While the European Union promotes green transformation through the Common Agricultural Policy and the Netherlands' TransForum programme breaks the vicious circle between agriculture and climate, showing that synergistic interventions of policy, technology, and market can achieve sustainable transformation of agriculture. Based on this, a negative externality coping path and a "technology-policy-consumption" synergistic path are proposed, emphasising the systematic integration and optimisation of technological innovation to drive the low-carbon transformation of agriculture, policy optimisation to build institutional safeguards, and consumption transformation to guide the market orientation in order to cope with the problem of the global agricultural transformation and realise the sustainable development of agriculture.

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