ENERGY CROPS AND ECOLOGICAL INTENSIFICATION: A MINI REVIEW

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https://doi.org/10.71066/FTTMK.2.10

Abstract

The deployment of energy crops is increasingly recognized not merely as a means of biomass production, but as a transformative approach to redesigning agricultural landscapes within sustainable energy systems. This review introduces a systems-level perspective that frames energy crops as multifunctional components of ecological intensification, contributing simultaneously to energy generation, carbon sequestration, and ecosystem restoration. Moving beyond conventional yield-centered evaluations, the study critically examines how spatial configuration, species selection, and land-use strategies influence the overall sustainability of energy crop systems. Particular attention is given to perennial lignocellulosic species and their integration into marginal and degraded lands. While energy crops present opportunities to reconcile energy production with ecological resilience, significant challenges remain, including trade-offs with biodiversity, water use, and socio-economic equity. The paper argues that future bioenergy strategies must shift toward landscape-scale optimization and multifunctionality rather than monoculture-based expansion.

Key words: Bioenergy, Biomass, Ecology, Energy, Land use, Sustainability

Introduction

Global energy demand, climate change mitigation targets, and concerns regarding fossil fuel dependency have intensified interest in renewable bioenergy systems. Among the various renewable energy alternatives, energy crops have emerged as a promising strategy for producing biomass while simultaneously contributing to carbon sequestration and rural development. Traditionally, the success of energy crops has been evaluated primarily through biomass productivity and energy yield. However, contemporary sustainability frameworks increasingly emphasize multifunctionality, ecosystem services, and landscape-scale environmental outcomes rather than biomass production alone (Brooker et al., 2023; Kremen, 2020; Makszim et al., 2025).

Ecological intensification represents a paradigm shift in agricultural and land management systems (Soós & Makszim, 2024). Rather than relying heavily on external inputs such as synthetic fertilizers, pesticides, and intensive mechanical interventions, ecological intensification seeks to enhance ecosystem functions that naturally support productivity and environmental sustainability (Kremen, 2020; Tittonell, 2018). Within this framework, energy crops can serve as multifunctional landscape elements that contribute not only to renewable energy generation but also to soil conservation, biodiversity enhancement, water regulation, and climate change mitigation (Makhsudov et al., 2025).

The integration of energy crops into ecological intensification strategies has become particularly important because conventional agricultural intensification has been associated with habitat fragmentation, biodiversity decline, soil degradation, and greenhouse gas emissions. Perennial bioenergy crops such as Miscanthus, switchgrass, willow, and poplar offer significant ecological advantages compared with annual cropping systems due to their extensive root systems, reduced soil disturbance, and long-term carbon storage potential (Blanco-Canqui, 2016; Smith et al., 2024).

This review examines the role of energy crops within ecological intensification frameworks, focusing on ecosystem services, carbon dynamics, biodiversity interactions, and sustainable land-use strategies. Particular attention is given to perennial biomass systems and their potential deployment on marginal and degraded lands.

Energy Crops as Components of Ecological Intensification

Ecological intensification is defined as the enhancement of ecosystem services that support agricultural productivity while reducing dependence on external inputs (Brooker et al., 2023). The concept recognizes biodiversity, ecological interactions, and ecosystem functioning as essential components of sustainable production systems.

Energy crops align closely with ecological intensification principles because they can simultaneously deliver biomass and ecosystem services. Perennial species maintain soil cover throughout the year, reducing erosion risks and improving soil structure (Makszim et al., 2024). Their extensive root systems increase belowground carbon inputs, improve water infiltration, and support microbial diversity. Unlike annual crops that require repeated tillage and replanting, perennial energy crops establish long-term vegetation cover, thereby minimizing disturbances to soil ecosystems (Blanco-Canqui, 2016).

Recent studies suggest that ecological intensification should not be evaluated solely at the field scale but rather at the landscape scale, where spatial heterogeneity and habitat connectivity influence ecosystem service delivery (Kremen, 2020). Within such landscapes, energy crops may function as ecological corridors, buffer zones, and semi-natural habitats that enhance connectivity among fragmented ecosystems (Makszim & Soós, 2025).

Perennial Energy Crops and Carbon Sequestration

Carbon sequestration is among the most significant environmental benefits associated with perennial energy crops. Deep-rooted species such as Miscanthus × giganteus and switchgrass allocate substantial proportions of biomass belowground, contributing to long-term soil organic carbon accumulation.

Compared with conventional annual cropping systems, perennial bioenergy crops generally exhibit greater carbon sequestration potential due to lower soil disturbance and continuous carbon inputs through root turnover. Long-term field studies have demonstrated increases in soil organic carbon stocks following conversion of cropland to perennial bioenergy plantations, particularly under conservation-oriented management practices (Blanco-Canqui, 2016).

Recent climate modeling studies further indicate that Miscanthus and willow can maintain relatively high productivity under future climatic scenarios while continuing to provide carbon storage benefits (Smith et al., 2024). Such characteristics position perennial energy crops as valuable components of climate mitigation strategies within broader bioeconomy frameworks.

However, carbon benefits are strongly influenced by previous land use. Conversion of natural ecosystems with high existing carbon stocks into energy crop plantations may result in carbon debt and biodiversity losses that offset anticipated climate benefits. Consequently, site selection remains a critical determinant of sustainability outcomes.

Energy Crops, Biodiversity, and Ecosystem Services

The relationship between energy crops and biodiversity remains complex. While monoculture bioenergy plantations can reduce habitat heterogeneity and negatively affect species richness, appropriately designed perennial energy crop systems may enhance biodiversity relative to intensive annual agriculture (Tudge et al., 2021).

Perennial energy crops often provide nesting habitats, refuge areas, and foraging resources for birds, insects, and soil organisms. Increased vegetation complexity and reduced pesticide applications contribute to improved ecological conditions compared with conventional cropping systems. Furthermore, diversified bioenergy landscapes can support pollination services and natural pest regulation, both of which are central objectives of ecological intensification (Brooker et al., 2023).

Nevertheless, biodiversity outcomes depend heavily on crop species, management intensity, landscape configuration, and regional ecological contexts. Large-scale monoculture plantations may create ecological simplification similar to that observed in industrial agriculture. Therefore, the ecological benefits of energy crops are not inherent but depend on strategic deployment and landscape integration.

Marginal Lands as Opportunities for Sustainable Bioenergy

One of the most widely discussed strategies for minimizing competition between food and fuel production involves establishing energy crops on marginal lands. Such lands may include degraded agricultural fields, abandoned croplands, saline soils, contaminated sites, reclaimed mining areas, and erosion-prone landscapes (Blanco-Canqui, 2016).

The utilization of marginal lands offers several advantages. First, it reduces direct competition with food production. Second, perennial energy crops can contribute to land restoration through improved soil structure, increased organic matter accumulation, and enhanced ecosystem functioning. Third, marginal land cultivation may create new economic opportunities in rural regions.

However, the concept of marginal land remains controversial because definitions vary across studies and often neglect socioeconomic dimensions. Sustainability assessments increasingly emphasize that biophysical suitability alone is insufficient; economic feasibility, stakeholder acceptance, and long-term environmental impacts must also be considered (Jiang et al., 2018).

Challenges and Future Perspectives

Despite their considerable potential, energy crop systems face significant challenges. Water consumption remains a concern in arid and semi-arid regions. Large-scale expansion may alter hydrological cycles and affect local water availability. Furthermore, market uncertainties, policy instability, and fluctuating fossil fuel prices continue to influence the economic viability of bioenergy systems.

Another critical challenge involves balancing biomass production with biodiversity conservation. Future research should move beyond productivity-focused evaluations and adopt integrated assessments that simultaneously consider carbon sequestration, ecosystem services, biodiversity outcomes, and socioeconomic benefits.

Emerging ecological intensification frameworks emphasize multifunctional landscapes rather than maximizing output from individual fields. Under this approach, energy crops are viewed not simply as feedstocks but as strategic landscape components capable of delivering multiple environmental and societal benefits. Such perspectives may help reconcile renewable energy production with broader sustainability objectives.

Conclusion

Energy crops are increasingly recognized as multifunctional elements within ecological intensification strategies. Their capacity to provide renewable biomass while contributing to carbon sequestration, soil restoration, and ecosystem service enhancement makes them attractive components of sustainable land-use systems. Nevertheless, environmental benefits are highly context-dependent and influenced by species selection, management practices, and landscape design.

Future bioenergy development should prioritize perennial species, precision agriculture and climate-adaptive technologies and crop varieties, marginal land utilization, and landscape-scale planning approaches that maximize ecosystem multifunctionality (Shokirov et al., 2025; Szabó et al., 2025). Integrating ecological intensification principles into bioenergy policy and practice offers a promising pathway toward achieving climate mitigation, biodiversity conservation, and sustainable rural development simultaneously.

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