Optimizing the allocation of bioenergy crops within a typical Greek cropping system to balance sustainable biomass production and nitrates water pollution mitigation.

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Abstract Pinios river basin, located in Thessaly, Greece constitutes the country's greatest agricultural producer, contributing to the quality degradation of surface and groundwater bodies. To mitigate these effects, integrating bioenergy crops into existing cropping systems presents a promising and effective strategy, offering the dual benefit of environmental protection and renewable energy production. Their environmental and economic effectiveness, however, is highly dependent on the specific characteristics of the land in which they are to be installed. Therefore, it is essential to assess bioenergy crops' economic and environmental footprints for informed regional planning. This study employs the Soil and Water Assessment Tool (SWAT) to develop a representative model of Pinios river basin and evaluate its current state with respect to nitrate pollution. A multi-objective, elitist Genetic Algorithm (GA) embedded in MATLAB is then applied to identify optimum spatial allocations of crops, with respect to the net farmers' income, biomass production and quality in rivers and groundwater. The analysis of the resulting two-dimensional trade-off curves revealed highly promising outcomes, demonstrating the potential for enhanced environmental benefits at the river basin scale while generating substantial biomass.

Keywords: Bioenergy crops, hydrologic modeling, land use change, optimization, water quality

1. Introduction

In Mediterranean rural landscapes, agriculture has contributed to the decline of water quality due to non-point source pollutants, such as fertilizers (Claro et al., 2024). Since agricultural land is increasingly promoted worldwide as a valuable resource for sustainable energy production (Nikkhah et al., 2020), integrating energy crops into farming systems could be an effective strategy to mitigate these impacts.

Biomass production must consider social, ecological, and health factors. For instance, to minimize competition for land use, priority should be given to favorable agricultural lands for food production. Consequently, marginal lands, defined as subject to soil degradation or erosive, drought-prone, or nutrient-poor, are being promoted for bioenergy crops. Cultivating perennial bioenergy crops on marginal agricultural land necessitates sustainable fertilization strategies that support high biomass productivity, while minimizing nutrient losses (Von Cossel et al., 2019). Bioenergy crops cultivated under low-input agricultural practices can have many beneficial environmental effects, such as enhancing agrobiodiversity, improving soil fertility, reducing nitrate losses, etc.

The Pinios River basin (PRB) in Thessaly, a vulnerable area for nitrate pollution, was selected, serving as an example of agriculture's impact on water quality. The basin covers 11,000 km² and features a Mediterranean climate and fertile soils. Switchgrass and cardoon, both described as low input crops (Giannoulis et al., 2020), are selected, as they are proposed for sustainable biomass production in Thessaly's action plan. However, decisions on their optimal spatial distribution within the basin's marginal land require further analysis, since balancing biomass yield, water quality, and agricultural income is essential for informed decision-making.

2. Materials and methods

This study employs the widely utilized Soil and Water Assessment Tool (SWAT) model to simulate the PRB and assess its nitrate pollution levels. SWAT is a semi-distributed, GIS-based model used to simulate hydrology, nutrients, crop growth, etc. (Aloui et al., 2023). A baseline scenario for the period 2018-2023 was created for the basin. The comparison of measured flow rates and nitrate nitrogen ($N\text{-}NO_3$) concentrations with the simulation results confirmed the model's accuracy. Specifically in the baseline scenario, the average $N\text{-}NO_3$ concentration at the outlet was 1.42 mg/l.

Marginal land was identified using criteria from the Joint Research Centre (Van Orshoven et al., 2012) and other studies. Key factors for defining marginality included unfavorable soil texture, shallow rooting depth, and slope class. Only agricultural lands were taken into consideration for bioenergy crop installation.

Thus, four types of marginal land were identified: lands with clay >50%, rooting depth <500mm, slopes between 5-15%, and slopes >15%.

Economic data for existing crops, switchgrass, and cardoon were collected to estimate the average annual net income per crop. A Genetic Algorithm (GA) combined with the SWAT model was applied to identify optimal crop distribution solutions. The elitist multi-criteria GA, based on NSGA-II in the MATLAB Global Optimization Toolbox, optimizes multiple objectives simultaneously, producing a multi-dimensional Pareto front. The front dimensions correspond to the criteria being optimized (Panagopoulos et al., 2012), in this case the minimization of annual $N\text{-}NO_3$ load and the maximization of biomass production and farmers' net income. The GA generates a three-dimensional Pareto front, exploring potential crop distributions in marginal lands and evaluating the feasibility of bioenergy crops, their biomass potential, and their impact on water resources, when installed in agricultural areas dimmed less favorable for conventional crops.

3. Results and discussion

It is important to note that planting switchgrass and cardoon on small areas of already marginal land can lead to a significant reduction in $N\text{-}NO_3$, especially when compared to the limited area of deployment. The results indicated that the target of 10^6 tons of biomass, set in Thessaly's action plan, can easily be achieved without any conflict with food production. The analysis of two-dimensional trade-off curves revealed promising results, emphasizing the potential for environmental benefits at the basin scale, while also producing significant biomass. Figure 1 displays the spatial distribution map of all crops in the basin for the selected optimal compromise solution, aligning with the plan's biomass target. A 7% reduction in the entire basin's $N\text{-}NO_3$ was achieved with bioenergy crops in just 6% of its total area.

As observed, the areas of installation for both energy crops are mainly in the northern, eastern and southern parts of the basin. This occurs because those areas were mostly lands where more than one marginality criteria applied and conventional crops in the baseline scenario showed lower yields. Switchgrass is installed in triple the area than cardoon most likely due to the crop's advanced ability to enhance water quality. The overall results demonstrate the potential of low-input perennial bioenergy crops in developing even in areas considered less suitable for conventional crops.

Switchgrass proved to be more effective in reducing $N\text{-}NO_3$ losses even in smaller slopes, which resulted in favoring this specific crop in the chosen compromise solution. On the other hand, cardoon achieved higher yields in specific areas, which resulted in a better total net income than switchgrass. Both the crops are regarded as very effective in reducing $N\text{-}NO_3$ loads, as in a lot of cases their implementation achieved, in a local scale, significant improvements. The water balance of the basin was not severely inflicted by implementing these crops in non-irrigated lands (1% increase), since cardoon, which had very low water needs, was mostly placed in these areas. The results indicate that bioenergy crops can be a viable solution for producing biomass and achieving environmental goals, if holistic approaches are adopted.

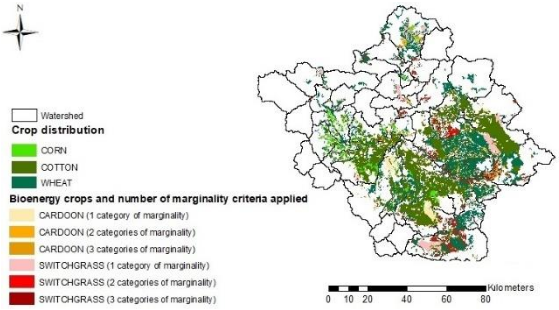

Figure 1. Spatial distribution of crops in the chosen compromise solution

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