

Evaluating the environmental and economic trade-offs of introducing perennial bioenergy crops in the low-productivity land of a Greek agricultural basin

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INTRODUCTION & AIM

In Mediterranean rural landscapes, agriculture has degraded water quality mainly through non-point source pollution. Since agricultural land is increasingly promoted worldwide as a valuable resource for sustainable energy production, integrating energy crops into farming systems could be an effective strategy to mitigate these impacts. However, to avoid competition with food and fiber crops, the highly productive agricultural land should remain prioritized for them and the installation of perennial bioenergy crops should be targeted in lower-productivity areas. When managed under low-input practices, such crops can enhance biodiversity, improve soil fertility, and reduce nitrate losses.

The Pinios River basin (PRB) in Thessaly, Greece, 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 with cotton and wheat being the main crops cultivated followed by smaller areas of corn. Switchgrass and cardoon, both described as low input crops, are selected, as they are proposed for sustainable biomass production in Thessaly’s action plan. However, determining their optimal spatial distribution within the basin’s lower-productivity land requires further analysis, as balancing biomass yield, water quality, and agricultural income is key to informed decisions. This study uses advanced tools to identify regional cropping patterns that meet both economic and environmental goals.

METHOD

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 observed flow rates and nitrate nitrogen (N-NO₃) concentrations with the simulation results confirmed the model’s accuracy.

Lower-productivity land was identified using criteria from the Joint Research Centre (Van Orshoven et al., 2012) and other studies. Key factors for defining productivity 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 lower-productivity land were identified and illustrated in **Figure 1**: lands with clay >50%, rooting depth <500mm, slopes between 5-15%, and slopes >15%.

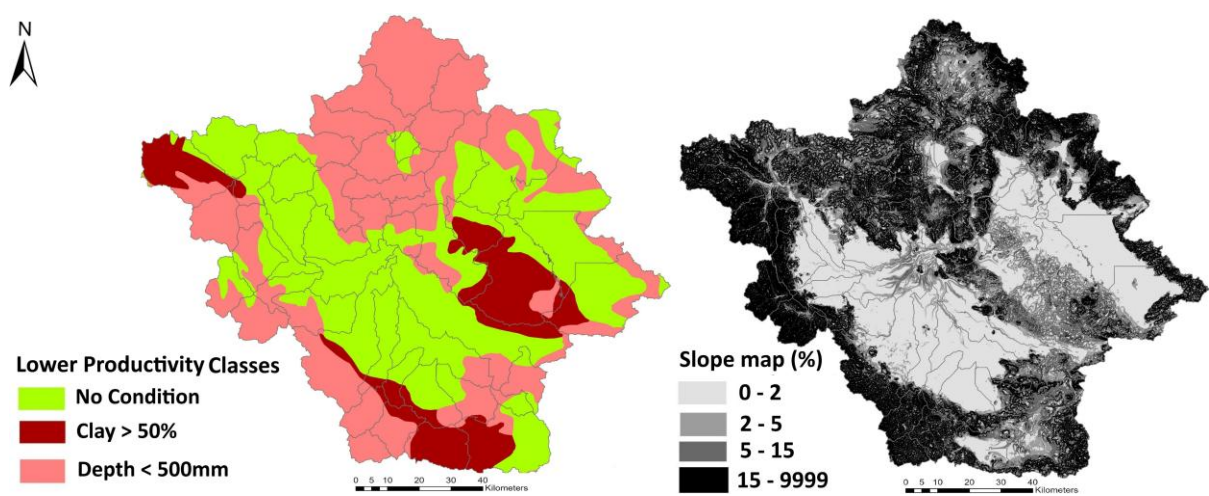


Figure 1. Lower productivity areas in Pinios River Basin based on the chosen criteria.

Economic data for conventional crops, switchgrass and cardoon were collected to estimate the average annual net income per crop. A Genetic Algorithm (GA) integrated with the SWAT model was used to identify optimal crop distribution schemes. The elitist multi-criteria GA, based on NSGA-II in MATLAB’s Global Optimization Toolbox, simultaneously optimized multiple objectives and generated a three-dimensional Pareto front (Panagopoulos et al., 2012). This front represents the minimization of annual N-NO₃ load and the maximization of biomass production and farmers’ net income. The GA explored potential crop distributions in lower-productivity areas, assessing the feasibility and biomass potential of bioenergy crops in land less suitable for conventional cultivation.

RESULTS & DISCUSSION

The results indicated that the target of 10⁶ tons of biomass, set in Thessaly’s action plan, can easily be achieved without any major conflict with food and fiber production. Up to a 20% reduction in N-NO₃ loads and biomass yields reaching 2×10⁶ tons are achievable, though with a maximum 10% decrease in farmers’ net income. The trade-off analysis (Figure 2) highlights promising compromise solutions, demonstrating potential basin-scale environmental benefits alongside substantial biomass production.

The produced 100 optimal Pareto solutions provide a basis for generating an equal number of maps depicting them within the PRB. Even though irrigation levels were not included in the optimization targets they were taken into consideration in the manual selection of the compromise solutions to protect the area’s water bodies. For the needs of this study, two solutions are chosen to be presented (Figure 2).

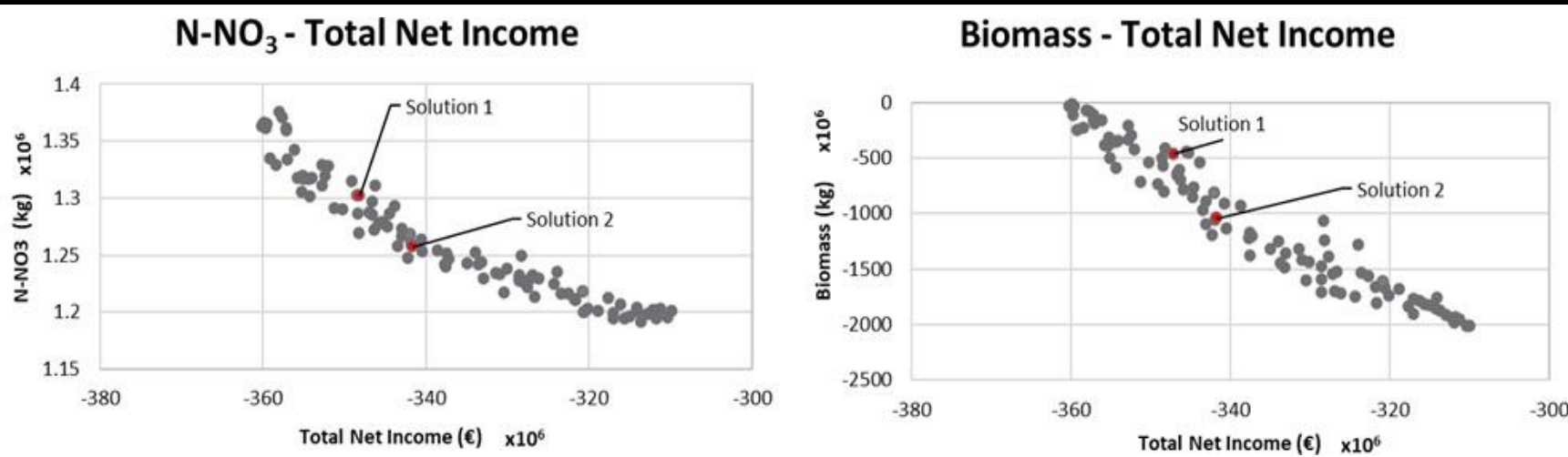


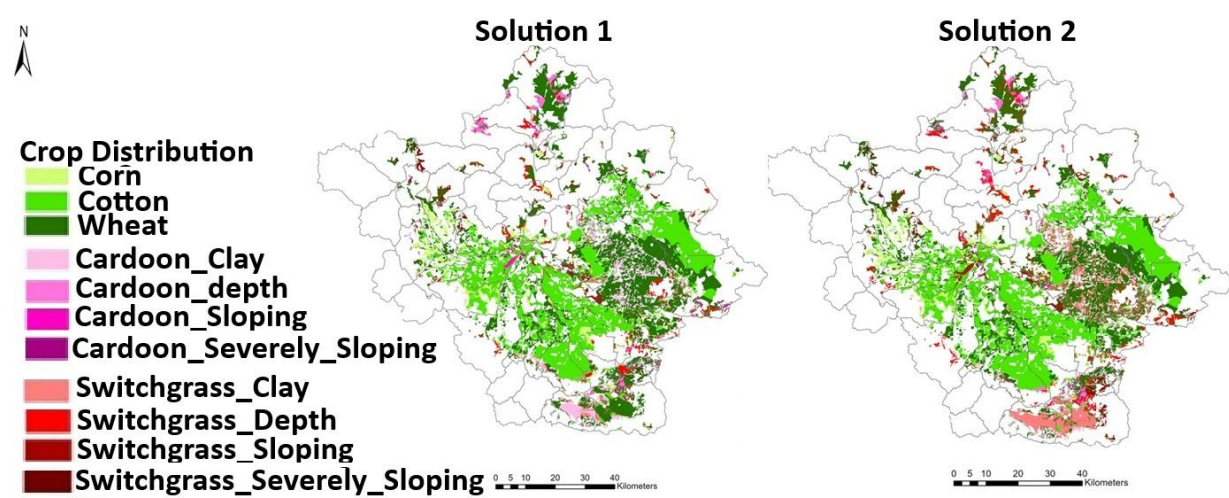
Figure 2. Compromise solutions presented in the optimal trade-off curves between annual N-NO₃ loads (minimized) from land to waters and Total Net Income (maximized) and between mean annual biomass production (maximized) and Total Net Income (maximized) from the 3-criterion optimization.

Solution 1 was chosen as it represents a more conservative strategy and therefore a more realistic and sustainable plan for PRB, whereas Solution 2 fully achieves the biomass production target of 10⁶ tons. **Table 1** summarizes the results produced by these two solutions and the baseline scenario.

Table 1. Mean annual (2018-2023) results produced by the 3-criterion optimization in the 2 selected solutions and the baseline scenario.

Scenarios	Bioenergy crops as % of cropland	N-NO ₃ (kg)	Irrigation (m ³)	Biomass production (tons)	Total Net Income (€)
Baseline	-	1.49x10 ⁶	720x10 ⁶	-	345x10 ⁶
Solution No.1	15.6%	1.29x10 ⁶ (-13%)	722x10 ⁶ (+0.3%)	0.47x10 ⁶	347x10 ⁶ (+0.6%)
Solution No.2	20.5%	1.25x10 ⁶ (-16%)	773x10 ⁶ (+7%)	1.05x10 ⁶	342x10 ⁶ (-1%)

The primary distinction between the two solutions lies in bioenergy crop proportions, Solution 1 shows near equal areas of switchgrass and cardoon, whereas Solution 2 allocates about four times more to switchgrass. Switchgrass proved more productive and effective in reducing N-NO₃ losses, particularly on steeper slopes, which favored its selection in Solution 2. Both crops were highly effective in reducing N-NO₃ loads, and in many cases their implementation locally achieved the good ecological status required by the EU. The basin’s water balance was only slightly affected by introducing these crops on non-irrigated lands (a 1% increase). Figure 3 shows the spatial allocation maps of the proposed solutions.



Spatial allocations map of Solution 1 (left) and Solution 2 (right).

As observed, the areas of installation for both energy crops are mainly in the northern, eastern and southern parts of the basin. The maps show that switchgrass was mostly chosen in areas where steeper slopes are found whereas cardoon was favored in soils with higher clay content.

CONCLUSION

The optimization analysis highlighted that solution outcomes vary according to whether water, income or biomass is prioritized. Importantly, even modest allocations of energy crops on low-productivity land can deliver meaningful environmental benefits, relative to their limited area of deployment. Further research should include refining the lower-productivity criteria as an integrated approach would form a sustainable action plan to enhance and balance the environmental issues of the PRB.

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