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Original Research Article

How Do Climate Policies of Agriculture and Forestry Contribute to Sustainable Development? A Case Study of North Macedonia

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ABSTRACT

Despite growing recognition of the role of agriculture and forestry in achieving climate and sustainability goals, empirical evidence remains limited, particularly in developing countries like North Macedonia. Using a participatory case study approach, this study examines the linkages (synergies and trade-offs) between climate mitigation Policies and Measures in the agriculture and forestry sector and the Sustainable Development Goals and quantifies them. Additionally, it uses Geographic Information System tools to visualise the most significant linkages across three case studies, making them concrete and serving as a communication tool to enhance policymaker engagement. Key findings reveal that agricultural policies within the Nationally Determined Contributions exclusively generate positive impacts with the Sustainable Development Goals, while forestry measures provide significant co-benefits with minimal trade-offs. Major synergies align with Goals 15 (Life on Land) and 6 (Clean Water and Sanitation), while the most notable trade-off occurs with Goal 2 (Zero Hunger). Further, the spatial analysis makes these linkages concrete, showing which regions would benefit most. Overall, the findings underscore the need for enhanced policy planning in the next revision of the Nationally Determined Contributions, alongside stronger judicial systems and streamlined administrative processes, to balance climate mitigation with sustainable development. The findings of this study empirically advance the literature on the effects of climate measures on sustainable development and show the added benefit of using spatial analysis to inform this literature's impact on policymaking. The assessment is qualitative and does not estimate the magnitude of greenhouse gas or carbon dioxide equivalent impacts.

KEYWORDS

Sustainable Development Goals, Climate change, Mitigation policy, Agriculture, Forestry, Geographic Information System.

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INTRODUCTION

The UN Sustainable Development Agenda and the 2015 Paris Agreement are two of the most important international policy frameworks of the twenty-first century [1], with the former being focused on sustainable development and the latter setting global targets for greenhouse gas emissions reduction to meet the target of 1.5 °C average global temperature by the end of this century. Unsurprisingly, scientific research has evolved in response to these frameworks. Initially, studies focused on mapping the interlinkages among the Sustainable Development Goals (SDGs) [2], treating the goals and their targets as a network to identify how thematic areas connect, where synergies exist, and where weaker links may hinder integrated policy implementation. Very valuable efforts were also undertaken to explore synergies and trade-offs among the SDGs, systematically assessing and rating relationships between targets to identify priorities for integrated policy action [3]. Over time, this has evolved into more detailed analyses that assess how individual SDGs relate to one another. A significant portion of this research has focused on energy [4], given its central role in both climate mitigation and sustainable development. However, there is now a growing body of research dedicated to sustainable agriculture and forestry practices [5], reflecting their critical importance in achieving multiple SDGs by assessing the interlinkages among forests, agriculture and climate change.

Despite this, recognising the interconnectedness between climate action and sustainable development in national policies (including the Nationally Determined Contributions (NDCs)) is the exception, rather than the business-as-usual case [6]. Moreover, a gap remains in implementing data-driven, spatially informed strategies that optimise both mitigation and sustainable development outcomes [7]. Additionally, previous studies published in the Journal of Sustainable Development of Energy, Water and Environment Systems (JSDEWES) have examined interactions between climate actions and energy [8], highlighting how distributed photovoltaic development can accelerate decarbonisation while supporting local economic development and energy access. Interactions between climate action and transport have also been analysed [9], demonstrating that alternative fuels can significantly reduce life-cycle greenhouse gas emissions compared with conventional fossil fuels. The role of buildings in the climate–sustainable development nexus has likewise been explored [10], showing that biomass-based district heating systems can be techno-economically viable while delivering social and environmental benefits. Research has further investigated waste and bio-based resource management in this context [11], indicating substantial untapped biomass and nutrient recovery potential that could contribute to circular economy objectives and emission reductions. Health co-benefits of climate change mitigation actions have also been a subject to research [12], confirming that mitigation measures can lead to measurable improvements in public health outcomes alongside emissions reductions. However, agriculture and forestry remain underexplored.

The latest Synthesis Report of the Intergovernmental Panel on Climate Change (IPCC) highlights that the window to raise ambition and implement existing commitments in order to limit warming to 1.5 °C above pre-industrial levels is rapidly narrowing, and that much more ambition in action and support is needed in implementing mitigation measures in every country in order to reduce greenhouse gas (GHG) emissions. The time sensitivity of mitigation actions is particularly pronounced in the Agriculture, Forestry and Other Land Use sector (AFOLU). Traditionally analysed for its adaptation potential, this sector is now recognised for its significant mitigation contributions [13]. According to recent assessments, it could deliver up to one-third of the emission reductions needed to avoid the most severe impacts of climate change [14]. Forests, as the main carbon sink, play a crucial role in achieving countries' net-zero targets. But without proper actions, there is a risk that natural carbon sinks will become sources, turning them from a solution into a problem [15].

As many as 118 of the 143 countries signatories to the Paris Agreement explicitly state that Agriculture- and Forestry-related emissions and their removal are included in the mitigation component of their updated NDCs (submitted within the 2020 cycle), compared to 108 in the previous NDCs (submitted within the 2015 cycle). Countries that set quantitative targets in their updated NDCs represent around 20% of the world's forest cover. However, most of the additional reductions in the AFOLU sector are not in the countries currently ranked in the top 10 globally in terms of forest area **[15]**.

North Macedonia has adopted quite ambitious climate targets for the short term (by 2030, enhanced NDC) and the long term (by 2050, Long-Term Strategy on Climate Action or LTS). North Macedonia's enhanced NDC (adopted in 2021) estimates an 82% reduction in net GHG emissions by 2030 compared to 1990 levels, achieved through the implementation of 63 mitigation Policies and Measures (PAMs). A total of seven PAMs related to agriculture and forestry have been introduced for the first time (elaborated in detail in the Results and Discussion chapter). These seven mitigation actions can result in a 29% decrease in greenhouse gas emissions from agriculture and a 95% increase in sinks (or GHG removals) by 2030. Moreover, North Macedonia is one of the few countries that has pioneered leveraging mitigation PAMs with the SDGs in its latest policy documents (the enhanced NDC and the Long-Term Strategy on Climate Action).

Besides these policy achievements, North Macedonia is already experiencing the negative impacts of climate change across key agricultural regions, highlighting the urgent need for adaptation and mitigation strategies to enhance agricultural resilience. Forest fires also pose a significant threat to the country. Over the past decade alone, more than 100 forest fires have occurred each year, jeopardising the progress of climate actions. By 2021, a staggering 18% of these forests had been ravaged by fires. In 2024, North Macedonia experienced a severe worsening of its forest fire situation **[16]**, exacerbated by extreme heat and prolonged drought. In July alone, 620 fires were recorded **[17]**, a significant spike attributed to high temperatures and dry conditions.

Digital technologies have been extensively employed in North Macedonia as smart tools across many fields of the environment, including climate change, and various Geographic Information System (GIS) platforms have been developed to visualise the impact. However, none of these GIS tools has been used to conduct a spatial assessment of synergies and trade-offs between climate change and sustainable development.

Thus, the research gap lies in: (1) The lack of a structured assessment of NDC-SDGs synergies and trade-offs in agriculture and forestry sectors; (2) Absence of country or location-specific case studies to visualise and demonstrate the real-world policy implications of climate mitigation measures in these sectors using spatial (GIS) tools.

This paper aims to contribute to the Climate Action–SDGs Nexus debate by assessing the synergies and trade-offs between North Macedonia's NDC and the Sustainable Development Goals, with a particular focus on agriculture and forestry. In doing so, it is hypothesised that climate mitigation measures in agriculture and forestry generate predominantly positive synergies with the SDGs and that GIS-based spatial analysis enhances the policy relevance of these assessments. It complements previous research conducted in North Macedonia in the sectors of electricity and heat, buildings and transport. Gjorgievski *et al.* (2022) provide an analysis of these sectors, ensuring consistency and comparability with the present study **[18]**. Research on waste management policies in North Macedonia by Gusheva *et al.* (2022) further informs this assessment **[19]**. Additionally, it evaluates the practical value of applying GIS tools to enhance communication with policymakers, demonstrating how spatial analysis can support more informed decision-making and facilitate the translation of complex data into actionable insights. Results indicate that climate mitigation measures in agriculture and forestry generate predominantly positive synergies with the Sustainable Development Goals, with only limited trade-offs, and that the use of GIS-based spatial analysis significantly enhances the transparency and policy relevance of these interactions.

This study employs the SCAN/Q-SCAN framework as a structured expert-elicitation tool to surface and prioritise linkages between nationally defined mitigation PAMs and the SDGs.

The approach is diagnostic rather than predictive: scores represent expert-based appraisals of national relevance and likely direction of effects, conditional on current policy formulations. As such, results facilitate policy dialogue and spatial targeting but do not substitute for causal evaluation, ex-post impact analysis or quantitative systems modelling.

METHODS

This paper follows a three-step methodology to address the research gaps identified in the introduction, ensuring a structured and scientifically robust assessment of the NDC–SDGs synergies and trade-offs in North Macedonia's agriculture and forestry. All reported linkages are qualitative; the study does not quantify CO_2-eq reductions or magnitudes of SDG outcomes.

Policy Review: A comprehensive review of Macedonian climate and sectoral policies was conducted to assess the integration of climate mitigation actions in agriculture and forestry with sustainable development objectives. The selection included six key documents based on their relevance to climate policy and sectoral planning. These documents were selected because they explicitly outline climate mitigation actions relevant to agriculture and forestry:

- National climate strategies: Enhanced Nationally Determined Contributions (NDC), Long-Term Strategy on Climate Action (LTS), National Energy and Climate Plan (NECP);
- Sectoral strategies: National Strategy for Agriculture and Rural Development (NSARD) and the Strategy for Sustainable Development of Forestry (SSDF), including its 2023 amendment.

Each document was reviewed to identify:

- The presence and type of PAMs related to agriculture and forestry;
- Alignment of these PAMs with Sustainable Development Goals (SDGs);
- Investment estimates and implementation timelines;
- Cross-referencing of PAMs across documents to assess policy consistency.

Consistency was defined as the repetition and reinforcement of specific PAMs across multiple documents, indicating coordinated planning and policy coherence. **Table 1**. Summary of reviewed policies relevant to climate change summarises the selected documents, selection rationale, and aspects reviewed.

Table 1. Summary of reviewed policies relevant to climate change

Policy Document	Year Adopted	Sector Covered	Reason for Selection	Aspects Reviewed
Enhanced NDC	2021	National (All sectors)	Contains quantified mitigation targets and PAMs for agriculture and forestry	PAMs, SDG alignment, investment estimates
LTS	2021	National (Long-term)	Long-term climate vision and PAMs	PAMs, SDG alignment, consistency with NDC
NECP	2022	Energy, Climate, Agriculture	Integrates sectoral actions with national climate goals	PAMs, investment estimates, SDG links
NSARD 2021–2027	2021	Agriculture	Sectoral strategy with climate-relevant actions	Sectoral PAMs, SDG relevance
SSDF	2006	Forestry	Long-term forestry strategy with climate relevance	Forest-related PAMs, carbon sink potential
SSDF Amendment	2023	Forestry	Updates SSDF with climate adaptation and mitigation focus	Revised PAMs, integration of climate adaptation and mitigation measures, alignment with long-term forest management and carbon sink enhancement

Participatory Assessment of NDC-SDGs Synergies and Trade-Offs

This study is based on the SDG Climate Action Nexus (SCAN) tool [20], which identifies qualitative linkages between sector-specific climate actions and SDG targets. One step further, this study quantifies the strength of the linkages using a participative Q-SCAN method [19]. It builds on the scoring framework proposed by Nilsson *et al.* [3]. The aim was to have a mix of experts who both study the sectors and have hands-on experience with policymaking. Thus, experts from both academia and the public sector were invited to help quantify the importance of the SDG links for the national context. In total, 8 experts participated in the agriculture assessment and 7 in the forestry assessment. Most experts (10) work in academia, and the remaining (5) work in the public sector. The experts were first asked, in a written survey, to quantify the linkages on a scale from 0 to 3, whereby 0 indicates that the link is not nationally relevant and 3 indicates that the link is highly relevant for the national PAMs. Additionally, they were asked to provide written comments that justify their quantification. Next, during a follow-up workshop, the average score per link from the survey responses was presented to the experts, as in previous Q-SCAN implementations, and the sectors engaged in discussion until reaching consensus on links where the experts voiced disagreement with the average score.

Complemented by a participatory process, this method enabled identification, scoring and quantification of the strength and significance of NDC–SDGs synergies and trade-offs (**Figure 1**), providing a more comprehensive and evidence-based understanding of policy interactions. Stakeholder input was essential for validating and quantifying the SCAN and Q-SCAN results and for prioritising the most significant NDC–SDG interactions. This collaborative approach ensured the scientific credibility and policy relevance of the findings.

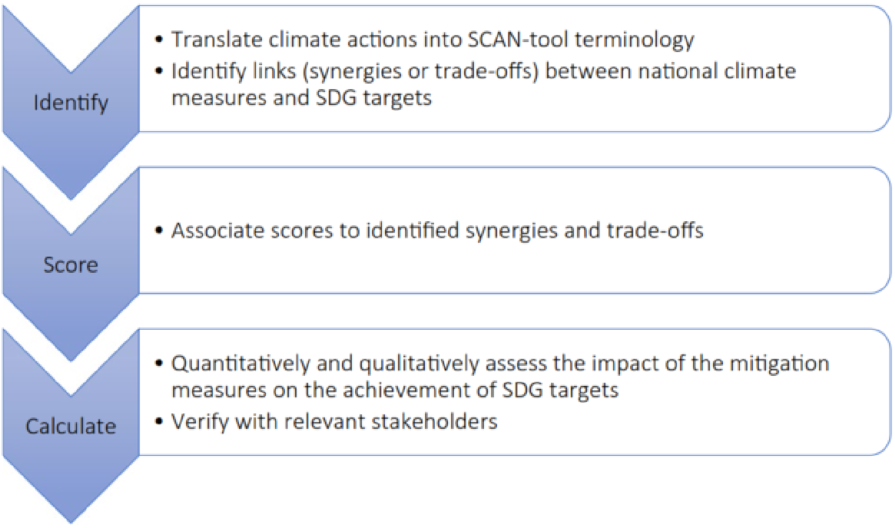

Figure 1. Q-SCAN illustration with steps presented on the left side and the required tasks for each step given on the right side

Spatial Data Analysis Using GIS Tools

Given the highly specific focus of this research, particularly in the context of North Macedonia, several GIS tools have been identified as relevant for visualising and analysing the spatial dimensions of three prioritised NDC-SDG synergies and trade-offs. Two tools were applied: a) Climate-Smart Spatial Planning Tool (developed specifically for North Macedonia), which integrates climate projections, land use, and crop distribution data to assess how agriculture and forestry actions influence SDG outcomes; and b) European Forest Fire Information System (EFFIS), a global platform, used to evaluate how forest fires affect carbon sinks and to identify areas where prevention measures can mitigate negative impacts. Other GIS platforms were considered but ultimately not used due to temporary maintenance issues or restricted access requiring paid subscriptions for data retrieval, which limited their applicability within the scope and resources of this study.

The GIS analysis relied on technical descriptors from both platforms to ensure transparency and reproducibility. The Climate-Smart Spatial Planning Tool is publicly accessible via an online portal and provides multiple thematic raster and vector layers at spatial resolutions typically ranging from 10 to 30 metres, depending on the dataset. These layers include downscaled national climate projections, crop distributions, land-use classifications and anticipated changes in temperature and precipitation based on mid-century climate scenarios. All layers are derived from national data providers, satellite-based sources, and global climate models, with key assumptions relating to fixed baseline land use and projected climate conditions. EFFIS layers, produced within the Copernicus Emergency Management Service, offer burned-area data at 250 m to 1 km resolution generated from MODIS and Sentinel imagery, allowing the identification of fire intensity and extent for 2024. For all maps presented in the manuscript, figure captions and labels provide standard cartographic elements (including scale bars, north arrows and the relevant coordinate reference system) and full attribution for external spatial data (e.g., EFFIS and national protected area boundaries).

The availability and granularity of certain spatial inputs constrained the analysis. In particular, the current implementation of the Climate-Smart Spatial Planning Tool does not provide a full Digital Terrain Model for slope-specific quantifications, limiting detailed terrain-driven assessments for some agricultural measures. Furthermore, layer availability and update cycles may introduce minor differences over time between figures reproduced directly from the portal and static maps presented in this manuscript.

RESULTS AND DISCUSSION

This section presents the results of the NDC–SDGs synergies and trade-offs assessment for North Macedonia's agriculture and forestry sectors, followed by a discussion of their implications for policy and sustainable development. The findings are contextualised within the existing literature to highlight the growing research on integrated climate and sustainable development planning. Consistent with the study design, the findings summarise qualitative scores of linkage strength and direction; quantitative emissions accounting and outcome measurement are beyond the present scope.

Literature Review

A review of existing literature on NDC-SDG synergies and trade-offs shows that scientific research offers a well-established foundation for assessing these interactions, and that policymakers' demand for such studies is increasing **[21]**. Case studies from different regions **[22]** demonstrate how climate mitigation actions can support, or in some cases challenge, progress toward the Sustainable Development Goals. Many studies on SDG interlinkages focus on agriculture. Some (2024) explores how climate actions in Indian agriculture support the Sustainable Development Goals **[23]**. Other research highlights the role of forestry in the context of the SDGs. Timko *et al.* (2018) use a policy nexus approach to identify trade-offs and synergies in forest management **[24]**. Several studies apply nexus approaches more broadly to understand interconnections across sectors. Datta *et al.* (2024) examine the agriculture-forestry-livestock nexus in Bangladesh to evaluate synergies and trade-offs **[25]**. The water-energy-food nexus is a particularly important framework for analysing these interlinkages, as Leck *et al.* (2015) describe its theory and practical applications for tracing such connections **[26]**. Some studies **[27]** even show that targeted interventions can help reduce trade-offs among specific SDGs, particularly between SDG 13 (Climate Action) and SDG 2 (Zero Hunger).

Since SDG linkages vary across national and transnational contexts, it is important to recognise these differences. Coenen *et al.* (2022) highlight the variability of SDG interactions across countries and regions [6]. There is a clear need for granular, country-specific case studies. Gusheva *et al.* (2022) emphasise the value of such studies for understanding local contexts and informing policy [19]. This paper addresses this problem area by using GIS tools to visualise three prioritised NDC-SDGs interactions in North Macedonia, offering policymakers practical insights into how agriculture and forestry mitigation actions influence sustainable development outcomes at the local level.

Policy Analysis

The policy review shows that North Macedonia is among the few countries that have successfully aligned their national and climate policies. There is strong consistency across both national and sectoral levels. The LTS, enhanced NDC, and NECP highlight seven key mitigation actions for agriculture and forestry, backed by investment estimates. Sectoral strategies like the NSARD and SSDF further support climate action by adding measures that strengthen their impact. This coordinated approach reflects the country's clear commitment to sustainable development and effective climate mitigation. The identified policies are described in the subsections below.

<u>Agriculture mitigation measures.</u>

- Conversion of land use on slopes above 15% inclination: This measure suggests transforming field crop areas on steep slopes into more sustainable land uses, thus reducing soil erosion, increasing soil organic matter and effectively turning the soil into a carbon sink. By 2040, this measure can mitigate between 3.7 and 5.3 Gg CO_2-eq, depending on the scale of implementation. Investments range from €1.5 million to €2.3 million. It is part of the LTS, NDC, and NECP, aligning with SDG 13 (Climate Action).
- Contour cultivation on areas under field crops on inclined terrains (5−15%): Contour cultivation on sloped fields helps prevent topsoil erosion and maintains soil fertility, supporting climate mitigation by storing organic carbon. The measure is projected to reduce emissions by 28 to 39.7 Gg CO_2-eq by 2040, with investments between €1 million and €1.5 million. It is part of the LTS, NDC, and NECP, aligning with SDG 13.
- Perennial Grass in Orchards and Vineyards on inclined terrains (>5%): Introducing perennial grass cover in orchards and vineyards will reduce erosion and increase soil organic matter, improving soil health and carbon sequestration. This action is expected to mitigate 8.9 to 12.6 Gg CO_2-eq by 2040, requiring an investment of €1 million to €1.5 million. It is a key component of the LTS, NDC, and NECP, aligning with SDG 13.
- Use of biochar as a carbon sink on agricultural land: Applying biochar to agricultural soils enhances water retention, nutrient storage, and crop yields, while capturing three times its weight in CO_2. With a potential mitigation of 110 to 330 Gg CO_2-eq by 2040, this measure requires an investment of €30 million to €45 million. It is included in the LTS, NDC, and NECP, aligning with SDG 13.
- Photovoltaic Irrigation: This measure aims to replace petrol-fueled irrigation pumps with solar-powered alternatives, reducing emissions while enhancing water efficiency. The plan includes installing 1,000 photovoltaic irrigation systems annually, ultimately covering 20,000 ha of irrigated land. Emissions reductions are estimated at 93.3−186.6 Gg CO_2-eq by 2040, requiring €47 million in investment. This initiative is embedded in the LTS, NDC, and NECP, aligning with SDG 7 (Affordable and clean Energy), SDG 12 (Responsible consumption and production and SDG 13.

<u>Forestry mitigation measures.</u>

- Establishing integrated forest fire management: To combat the increasing threat of forest fires, North Macedonia is implementing an integrated management approach to reduce the average annual burned area by 3,000 ha. This measure is expected to cut emissions by 345 Gg CO_2-eq by 2040 and is included in the LTS, NDC and NECP. Investments range from €1.45 million to €1.5 million, with full implementation targeted by 2040. Additionally, the SSDF enhances this action by including assessments of the forest carbon sink and adapted forest management techniques. This measure is linked with SDG 15 (Life on land) and SDG 13.

- Afforestation: Afforestation efforts focus on converting 5,000 ha of barren land into oak tree forests (*Quercus* spp.), which will sequester 312.5 Gg CO_2-eq by 2040. The measure, part of the LTS, NDC, and NECP, requires an investment of €7.8 million to €11.7 million and is linked with SD15 and SDG13. The SSDF further strengthens afforestation by integrating climate adaptation strategies and by evaluating forest carbon sequestration potential.

Synergies and Trade-Offs in Agriculture and Forestry Among Nationally Determined Contributions and Sustainable Development Goals

Agriculture sector. Application of the SCAN tool in North Macedonia identified 26 positive synergies between the NDC's PAMs for agriculture and the SDGs, all of which were quantified in a participatory approach using QSCAN. The findings confirm that climate actions in agriculture contribute exclusively positively to SDG implementation (**Figure 2**), with most synergies classified as medium or high importance.

The strongest synergies are with: SDG 15 (Life on Land) due to enhanced water efficiency in irrigation and protection against land erosion; SDG 12 (Responsible Consumption and Production) because of addressing food waste and promoting sustainable production; SDG 6 (Clean Water and Sanitation) because of lower water consumption through efficient irrigation techniques; SDG 8 (Decent Work and Economic Growth) due to increased productivity and economic benefits from improved irrigation and fertilizer use; and SDG 2 (Zero Hunger) – reduced crop loss through better agricultural practices. The SDG 12 linkage is particularly significant, as the PAMs directly address food waste, offering a pathway to more sustainable agricultural practices. However, some globally recognised mitigation actions, such as agroforestry, were not included in North Macedonia's NDC, making them ineligible for the Q-SCAN analysis despite their potential relevance **[28]**. This situation highlights an opportunity to develop future policies that explore additional climate-smart agricultural strategies.

Although the assessment for the agriculture sector produced exclusively positive synergies, as reflected in the expert scoring and illustrated in **Figure 2**, this outcome should be interpreted with important boundary conditions. The absence of identified trade-offs in the Q-SCAN results reflects the way national agricultural mitigation PAMs are defined in the enhanced NDC, as well as the collective judgment of the participating stakeholders, rather than an inherent absence of potential negative interactions. In real-world implementation, additional trade-offs may emerge that are not captured within the current scoring framework. These include the possibility of rebound effects from improved irrigation efficiency, risks of unintended intensification, unequal access to the required investments among farmers, and land-use conversion outcomes that may affect soil, water or biodiversity. Acknowledging these context-dependent factors clarifies that the positive synergies observed in the analysis represent expected outcomes under the specific PAM formulations, while broader implementation dynamics may produce more complex interactions.

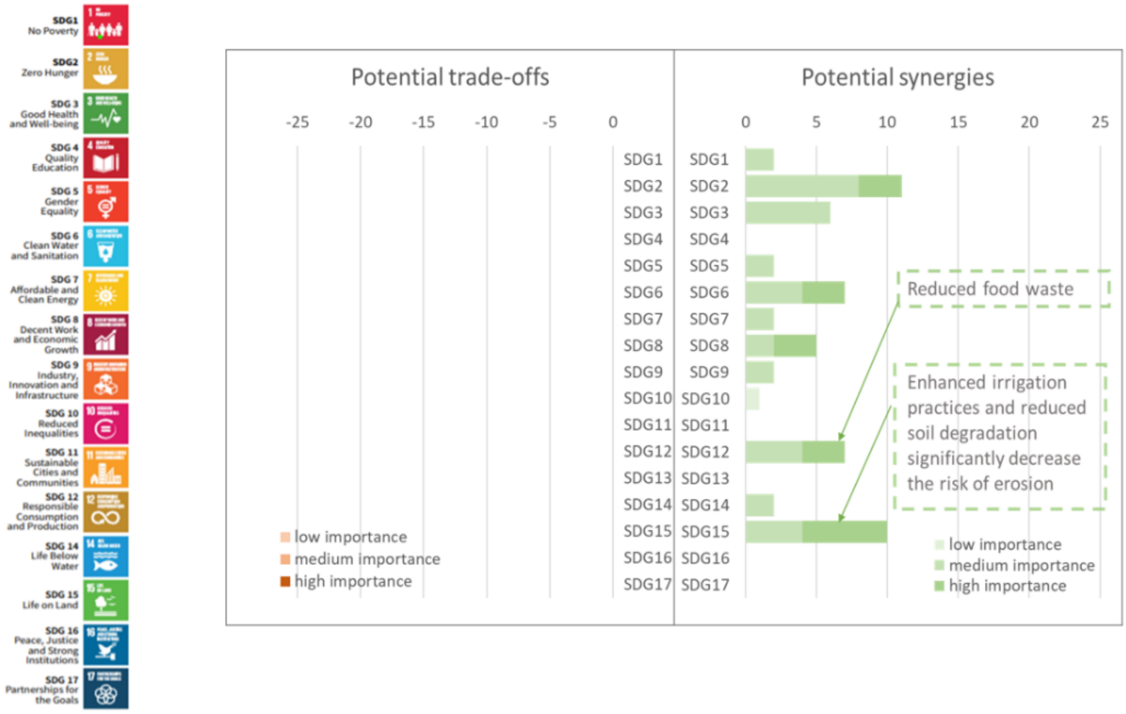

Figure 2. Q-SCAN tool results for the Agriculture sector, NDC-SDGs synergies and trade-offs

Forestry sector. Using the SCAN tool, 32 positive synergies and 5 trade-offs were identified between North Macedonia's forestry-related climate actions (PAMs) and the SDGs. These were further assessed and quantified through the Q-SCAN method, which included a participatory process involving key stakeholders from academia, government, and international organisations. Overall, forestry climate actions contribute more positively than negatively to SDG progress (**Figure 3**). However, most synergies have medium or low importance, except for a strong synergy with SDG 6 (Clean Water and Sanitation), driven by conservation, restoration, and sustainable management of natural areas. Prioritising native species and protecting drinking water sources can ensure sustainable forest management in these areas, as confirmed in other research **[29]**.

The highest number of synergies was identified with SDG 15 (Life on Land), where forestry PAMs support biodiversity, reduce soil erosion, and promote sustainable wood harvesting, ultimately protecting natural habitats. However, trade-offs were noted with SDG 2 (Zero Hunger) and SDG 10 (Reduced Inequalities), mainly due to legal restrictions under the Forest Law. These rules help prevent deforestation but can limit local communities' and small farmers' access to forest resources.

It is important to note that several well-established forestry mitigation approaches (such as proforestation, enhanced natural regeneration and other forms of conservation-oriented management) are not included in the current Macedonian NDC or sectoral strategies. Consequently, these measures fall outside the scope of this assessment. The forestry PAMs evaluated here reflect only those actions formally adopted at the national level, namely afforestation and integrated forest-fire management.

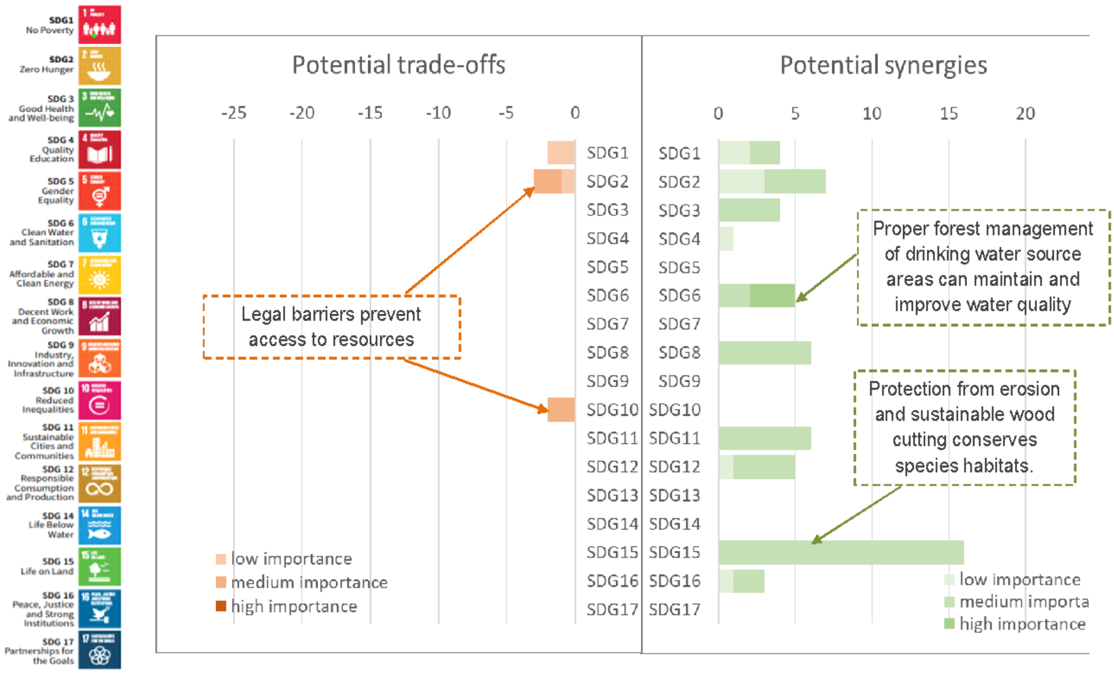

Figure 3. Q-SCAN tool results for Forestry sector, NDC-SDGs synergies and trade-offs

Spatial Analysis of Synergies and Trade-Offs

The subsections below illustrate the practical impact of agriculture and forestry PAMs through three case studies, one in the forestry sector (Case Study 1) and two in agriculture: perennial grass in orchards and vineyards (Case Study 2), and photovoltaic irrigation (Case Study 3). Using GIS tools (as described in the Methods section), these case studies are visualised to show how mitigation actions affect SDG outcomes on the ground. They also serve as effective communication tools, helping policymakers to understand key climate and development linkages. These case studies provide empirical evidence of how mitigation actions can be spatially targeted to maximise SDG synergies, contributing to the literature on climate-smart agriculture. Raihan (2024) emphasises the value of GIS in agriculture for evidence-based decision-making and sustainability [30]. Aguayo Lopes da Silva *et al.* (2023) review how the forest sector's contribution to the Sustainable Development Goals is addressed, highlighting methodological approaches for assessing synergies and trade-offs [31].

A key limitation of this research is the absence of a full Digital Terrain Model (DTM) layer in the Climate-Smart Spatial Planning Tool for North Macedonia. Currently, the tool provides only a basic terrain image, lacking the detailed 3D representation that a DTM would offer. Without this detailed elevation information, the research is restricted in its ability to assess critical spatial dynamics, particularly related to terrain and slope. As a result of this limitation, only two of the five proposed climate measures in the agricultural sector were elaborated as case studies.

Case study 1. Forest fires undermine climate goals and their synergies with SDGs. Forest fires pose a significant threat to the targets stipulated in North Macedonia's NDC, particularly affecting the synergy between forestry PAMs and SDG 15 (Life on Land), and impacting SDG 6 (Clean Water and Sanitation). Fires degrade ecosystems, increase erosion and flooding, and, when they occur near drinking water sources, they reduce aquifer replenishment and spring yields, undermining climate resilience and sustainability efforts.

This case study combines data from EFFIS and the Climate-Smart Spatial Planning Tool to analyse forest fire patterns in North Macedonia. EFFIS provides real-time and historical data on fire frequency and intensity. At the same time, the Climate-Smart Spatial Planning Tool links these patterns to environmental factors, including expected temperature and precipitation due to climate change in North Macedonia, water systems and soil health. Overlaying both tools shows a clear connection between rising temperatures, reduced precipitation, and increased fire severity, especially in western regions projected to warm by 4.5–5.5 °C [32] (Figure 4a). Even in the eastern regions, where maximum temperatures are expected to be 1 °C lower, severe fires persisted in 2024. In 2024 alone, fire damage exceeded national expectations by 32 times, threatening biodiversity (SDG 15) and water security (SDG 6).

Further analysis reveals that most fires in 2024 occurred outside protected areas (Figure 4b), often in unmanaged lands such as abandoned fields and ungrazed pastures. This situation highlights the need for integrated landscape fire management, which coordinates fire prevention across land types to reduce risks and improve forest resilience, as confirmed by various scientific studies [33].

a)

b)

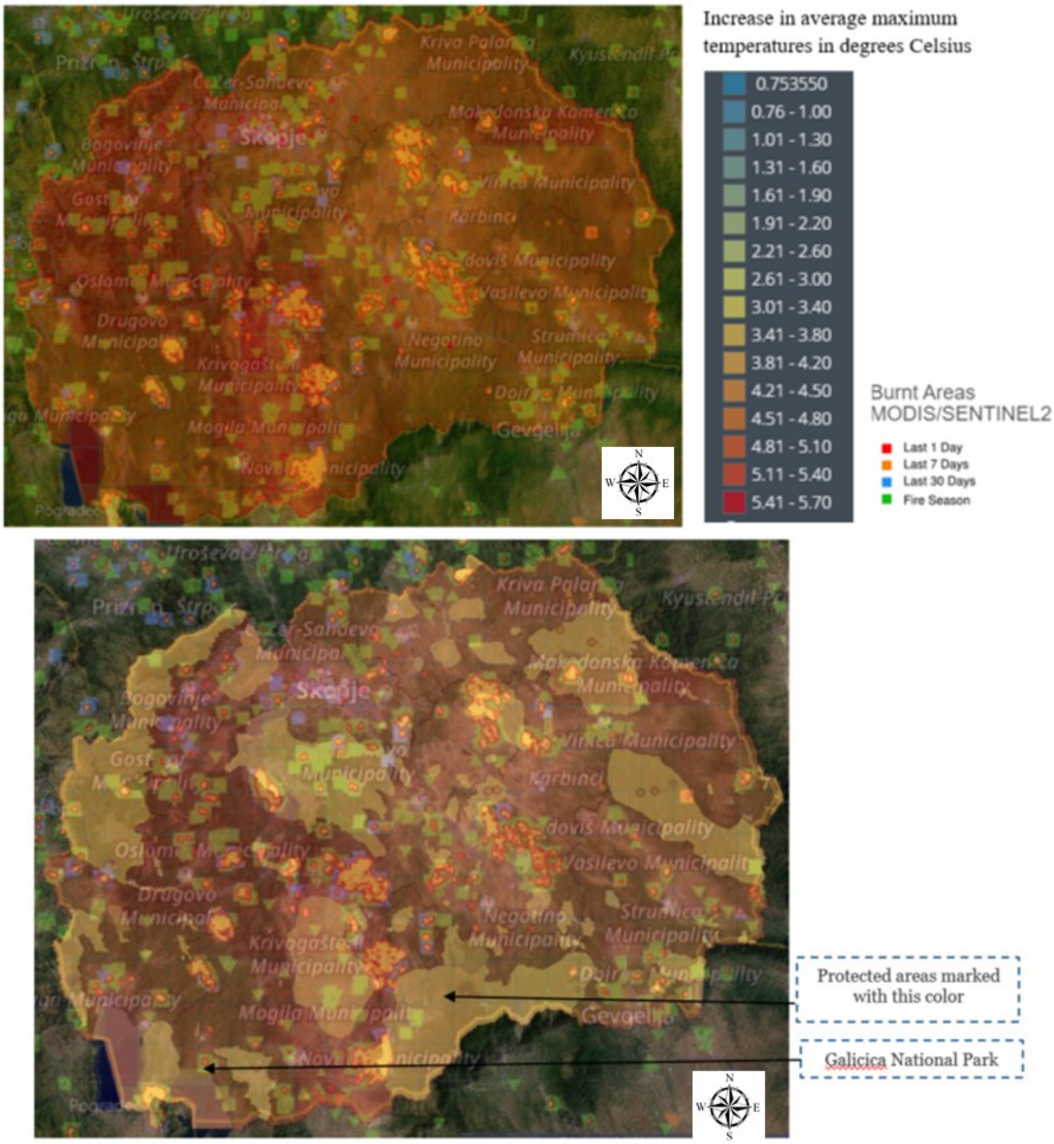

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Figure 4. Burned-area extent and protected areas for 2024 overlaid with pessimistic scenario of projected increases in average maximum daily temperature without (a) and with (b) the Protected Areas layer; prepared by the research team based on Burned-area polygons, EFFIS, Copernicus Emergency Management Service (2024), and Protected areas and Projected temperature change, Climate-Smart Spatial Planning Tool, Ministry of Environment and Physical Planning (accessed August 2025)

In summer 2024, severe fires in Galicica National Park – home to endemic species like the Balkan chamois and rare birds – destroyed critical habitats, threatening long-term biodiversity (SDG 15). These fires disrupted ecosystems and conservation efforts, putting species at risk of extinction.

The Jasen Nature Reserve, near Skopje, also experienced repeated fires in 2024 and 2025, reducing its carbon sink capacity and undermining North Macedonia's NDC targets for emission reductions. Fires near the Skopje Aquifer, a key drinking water source, increased sediment runoff into rivers and streams, contaminating supplies and raising concerns over long-term water availability (SDG 6). Reduced aquifer replenishment following recent fires has raised concerns about long-term water scarcity.

<u>Case study 2. Cover cropping in Kavadarci vineyards, a sustainable solution for resilient wine.</u> Kavadarci, a major wine-producing region in North Macedonia's Vardar area, faces growing climate risks. By 2050, temperatures are expected to rise by up to 4.5 °C, while precipitation may drop by 19–22% [32], increasing drought stress and threatening grape yields and quality. Extended heat stress could shorten the grape-growing season, jeopardising the economic sustainability of vineyards.

Cover cropping offers a nature-based solution to improve vineyard resilience. It enhances soil organic carbon (SOC), boosts water retention, and strengthens soil health, key to maintaining productivity under extreme weather. If applied across 11,000 ha of vineyards, cover cropping could increase SOC by 0.43 g/kg annually (16,500 tons) [34], supporting biodiversity (SDG 15), reducing reliance on synthetic inputs, and promoting sustainable production (SDG 12). Improved soil moisture also reduces irrigation needs, contributing to water efficiency and SDG 6 (Clean Water and Sanitation).

The Climate-Smart Spatial Planning Tool was used to identify suitable areas for implementation by combining data on temperature rise, precipitation decline, and crop distribution. Kavadarci emerged as the most suitable region for this PAM (Figure 5 and Figure 6), highlighting its potential to mitigate climate change. Given the region's economic dependence on viticulture, stabilising yields and improving grape quality through cover cropping also supports SDG 8 (Decent Work and Economic Growth), helping secure livelihoods in the face of climate stress.

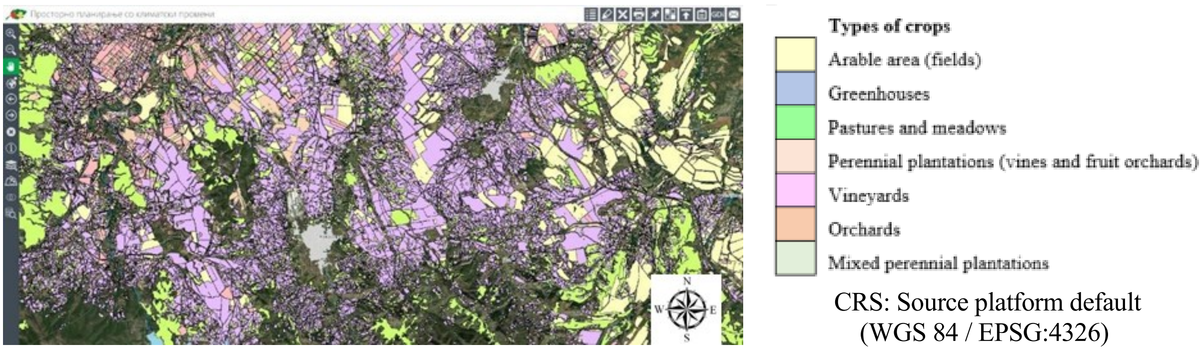

Figure 5. Vineyard areas in the Kavadarci region based on the "Types of crops" layer of the Climate-Smart Spatial Planning Tool

The findings highlight the potential of cover cropping to enhance soil moisture retention, reduce irrigation needs, and mitigate the effects of rising temperatures, making it a crucial climate adaptation strategy for vineyard sustainability. This result is consistent with broader scientific evidence showing that cover crops improve soil structure and water-holding capacity, especially under drought and heat stress. According to Kaye and Quemada [35], cover cropping increases resilience by reducing vulnerability to extreme weather events, improving soil water management during droughts, and supporting long-term soil health, all of which are essential for adapting to climate change in agricultural systems.

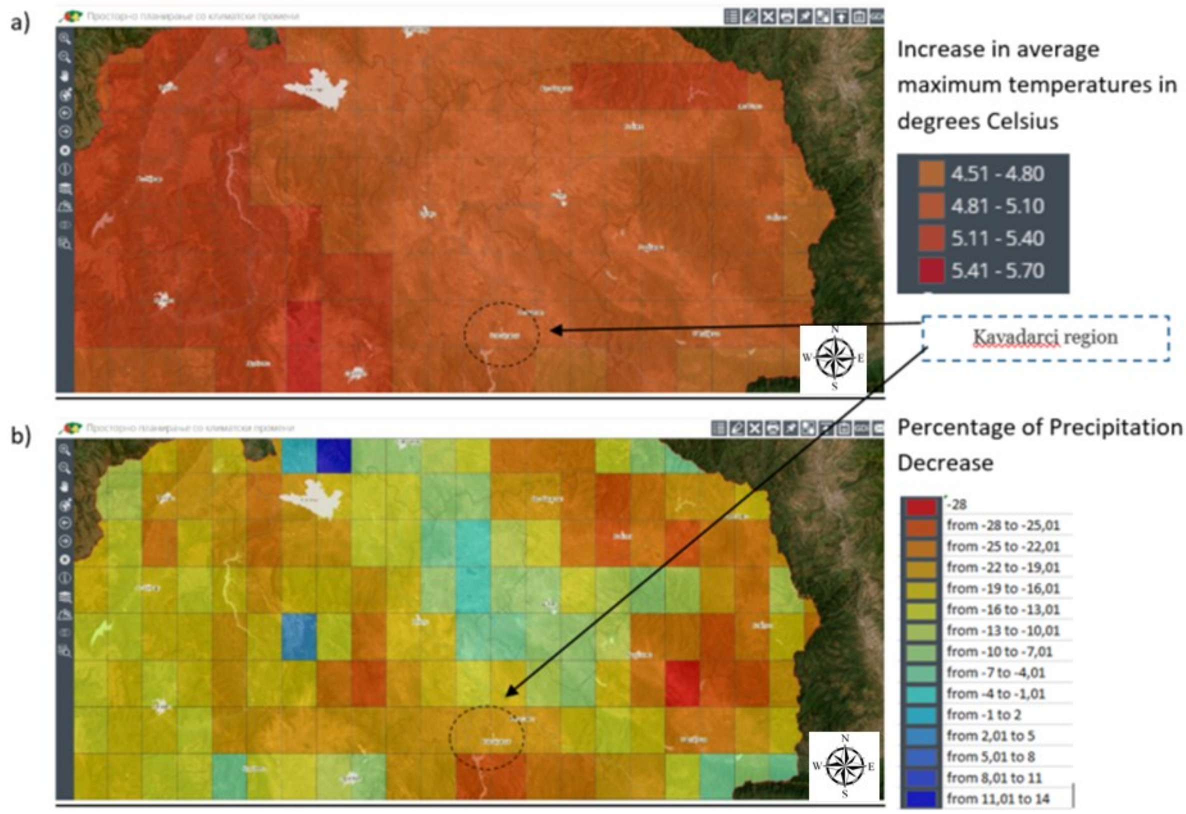

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Figure 6. Vineyard distribution in Kavadarci with projected changes in average maximum daily temperature (a) and precipitation under a pessimistic scenario (b); sourced from Crop distribution and climate projections, Climate-Smart Spatial Planning Tool, Ministry of Environment and Physical Planning (accessed August 2025)

Case study 3. Photovoltaic irrigation in the Prespa Region. This region, a major apple-producing area near Prespa Lake, is projected to face a temperature rise of up to 4.2 °C and a precipitation decline of 7–10% by 2050 (**Figure 7** and **Figure 8**) **[32]**. These climate pressures make it a priority area for implementing photovoltaic (PV) irrigation, which improves water efficiency while supporting broader climate adaptation goals.

Using the Climate-Smart Spatial Planning Tool, the region's suitability was assessed by integrating three key data layers: projected increases in temperature, precipitation decline, and crop distribution. Prespa is the most suitable location due to its vulnerability to water scarcity, the concentration of high-value orchards, and access to a reliable water source, the Prespa Lake.

PV irrigation systems offer multiple benefits: they reduce soil erosion, improve water use efficiency, and support ecosystem preservation (SDG 15). By replacing fossil-fuel-powered pumps with solar-powered systems, they also lower greenhouse gas emissions (SDG 12). Additionally, PV irrigation helps prevent runoff and water contamination, contributing to SDG 6 (Clean Water and Sanitation). The technology supports local employment in installation and maintenance, boosting agricultural productivity and aligning with SDG 8 (Decent Work and Economic Growth).

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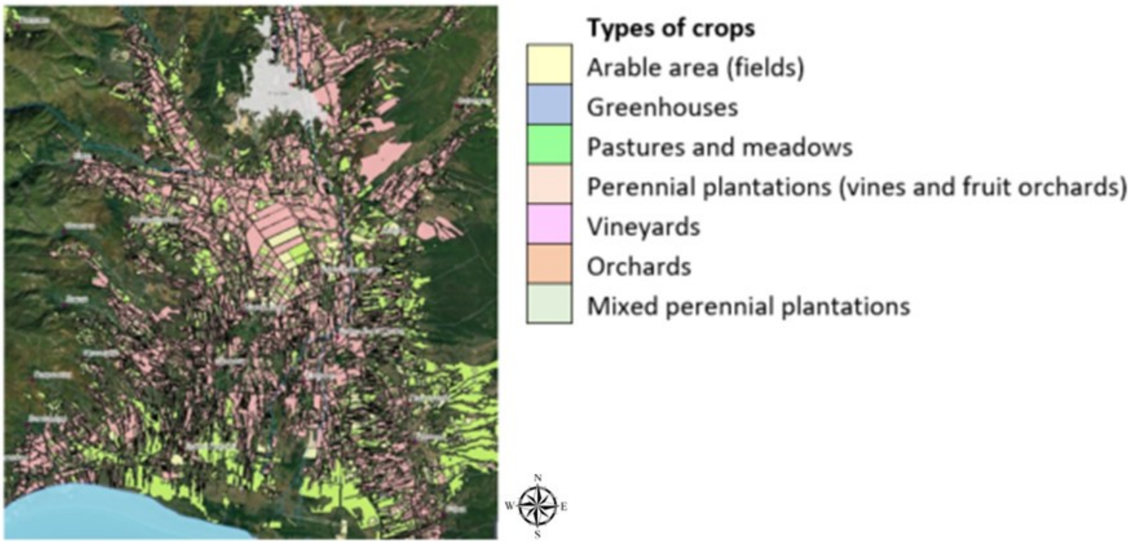

Figure 7. Orchard areas in the Prespa region based on the "Types of crops" layer of the Climate-Smart Spatial Planning Tool

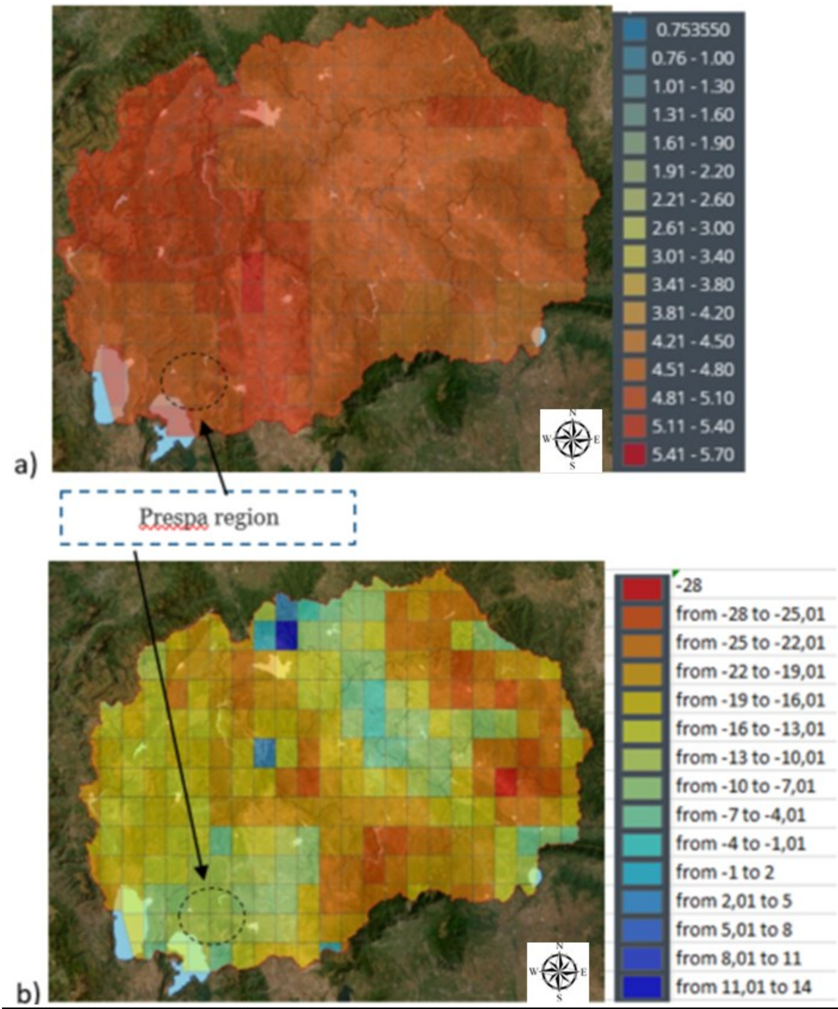

Figure 8. Orchard areas in the Prespa region with projected average maximum daily temperature increase (a) and precipitation decline (b), highlighting suitability considerations for photovoltaic irrigation; sourced from Crop distribution and climate projections, Climate-Smart Spatial Planning Tool, Ministry of Environment and Physical Planning (accessed August 2025)

While PV irrigation requires an upfront investment, its long-term benefits make it a financially attractive and environmentally sound solution [36]. According to FAO's Practice Brief on Solar-Powered Irrigation Systems [37], these systems significantly reduce greenhouse gas emissions, improve access to water during dry spells, and enhance food security and income generation. The brief also highlights that, despite high initial costs, innovative financing models and group-based systems can improve affordability and adoption, especially for small-scale farmers. In the context of Prespa, where water scarcity and climate change threaten agricultural productivity, PV irrigation offers a practical and scalable adaptation strategy that aligns with both environmental and economic goals.

Stakeholders' Perspectives on Policy Implementation and Alignment with The Sustainable Development Goals

The case study insights were validated by 15 stakeholders from various institutions, including the Macedonian Academy of Sciences and Arts, Ss. Cyril and Methodius University in Skopje (across multiple faculties), Delft University of Technology, UNDP, Adaptation fund and GDi GROUP LLC. These stakeholders, specialising in agriculture, forestry, climate change and GIS technologies, provided valuable input for the analysis.

Based on the synergies and trade-offs between climate change mitigation actions in agriculture and forestry and their impact on the SDGs, three critical areas for action were prioritised:

- Strengthening synergies with SDG 15 through afforestation, sustainable forest management and climate-smart agricultural practices;
- Enhancing water resilience (SDG 6) via efficient irrigation and forest conservation;
- Addressing trade-offs with SDG 2 by streamlining administrative processes for forest resource access, rather than altering protective legislation.

These priorities reflect a balanced approach to climate and development, aligning with recommendations from the IPCC and other global frameworks.

CONCLUSIONS

This study provides empirical evidence to advance understanding of how climate mitigation policies can influence the achievement of the Sustainable Development Goals. By applying the SCAN and Q-SCAN tools, supported by GIS-based spatial analysis and stakeholder validation, the research offers a data-driven, context-specific assessment of NDC-SDGs synergies and trade-offs. These findings advance scientific research on integrated climate and development planning and offer a replicable methodology for other countries seeking to align their climate commitments with sustainable development priorities.

The analysis confirms that mitigation actions in the agriculture and forestry sectors generate more synergies than trade-offs with the SDGs, particularly with SDG 15 (Life on Land), SDG 6 (Clean Water and Sanitation), SDG 12 (Responsible Consumption and Production), and SDG 8 (Decent Work and Economic Growth). These findings reinforce the importance of the agriculture, forestry, and land-use sector in achieving North Macedonia's climate targets and broader development goals.

This research shows how GIS tools can enhance policy decision-making by visualising spatial dimensions of climate risks and opportunities. While GIS applications in climate policy are not new, their use for quantifying and communicating NDC-SDG interactions at the local level offers policymakers valuable insights. The three case studies, forest fire management, cover cropping in vineyards, and photovoltaic irrigation, illustrate how spatial analysis can inform targeted interventions and improve climate resilience in vulnerable regions.

The interpretation of the results, however, should remain within the methodological limits of the SCAN/Q-SCAN approach. The scoring reflects expert judgement based on the formulation of national mitigation measures and does not quantify causal impacts, CO_2-equivalent reductions, or measurable outcome magnitudes. As a qualitative diagnostic tool, the approach identifies potential synergies and trade-offs but cannot substitute for ex-post impact evaluation or biophysical-economic modelling. These limitations may be addressed in future studies through the integration of quantitative assessments, expanded datasets and regular monitoring of policy outcomes.

North Macedonia's approach, which integrates seven mitigation actions (PAMs) across agriculture and forestry, reflects a strong alignment between national climate commitments and sustainable development priorities. However, trade-offs, particularly in relation to SDG 2 (Zero Hunger), highlight the need for improved governance mechanisms. Rather than reforming protective legislation, the study recommends streamlining administrative processes and strengthening judicial systems to ensure equitable access to forest resources while maintaining environmental safeguards.

Because the national NDC and forestry strategy do not currently include measures such as proforestation, natural regeneration, or extended-rotation management, the forestry mitigation portfolio remains relatively narrow. Including such measures in future policy cycles could strengthen the country's long-term carbon-sink capacity and enable more comprehensive future SCAN/Q-SCAN evaluations.

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