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Research article

A GIS-driven suitability analysis of crop resilience to climate change in Son La province, Vietnam

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Abstract

Importance of the work: This research addresses the critical impacts of climate change on land suitability for key crops in Son La province, Vietnam.
Research gap: There is a lack of a comprehensive understanding of the effects of climate change on crop suitability in the mountainous regions of Vietnam.
Objectives: To assess climate change impacts on crop suitability under current (1970–2000) and future (2081–2100) climate change scenarios.
Materials and Methods: Using a weighted linear combination approach, environmental factors (annual temperature, accumulated precipitation, slope, soil type, humidity and depth) were modeled using the ESRI ArcMap software to generate suitability maps for fruit tree species (mango, longan and custard apple) and staple crops (maize and rice) under current conditions and under two future climate change scenarios—Shared Socioeconomic Pathways (SSPs) 1–2.6 (optimistic) and 3–7.0 (pessimistic).
Results: Under current conditions (1970–2000), most land was marginally suitable for fruit trees and staple crops. Future climate scenarios projected a 27–60% reduction in unsuitable land for mango and longan, with increases in marginally and moderately suitable areas. Mango land gains amounted to 14 km² of moderately suitable land under the SSP1-2.6 scenario and 185 km² under the SSP3-7.0 scenario. Custard apple sites decreased by 65% for moderately suitable land under SSP1-2.6; however, there was a very large 3,175% increase under SSP3-7.0. For maize, unsuitable land decreased by 10%, with moderately suitable areas expanding to 3,691 km², while for paddy rice, unsuitable land reduced by 37–47%, with 76 km² of moderately suitable areas.
Main finding: Future climate scenarios may improve land suitability for key crops, highlighting the need for national agricultural policies to incorporate adaptive strategies that leverage emerging opportunities for the mountainous regions.

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Introduction

Climate change poses considerable challenges to agriculture, threatening global food security and sustainable livelihoods (Lobell et al., 2008; Abbass et al., 2022). This susceptibility has drawn increased attention in the literature (Malhi et al., 2021; Lou et al., 2024). Rising temperatures and unpredictable rainfall are reducing crop yields, with predicted declines of up to 30% by 2050 in some regions (Toromade et al., 2024). Staple crops, such as rice and maize, are vital for food security but face threats from higher temperatures, shifting precipitation and extreme weather (Naik et al., 2024; Toromade et al., 2024). This impacts crop productivity and the livelihoods of millions of smallholder farmers (Emediegwu et al., 2022). Fruit trees are important for dietary diversity and income (Jansen et al., 2020); however, they also face risks, as climatic variability disrupts phenology (Apiratikorn et al., 2012), while droughts and heavy rainfall reduce harvest quality and quantity (Bacelar et al., 2024).

In Vietnam, fruiting trees and crop species are increasingly vulnerable to these changes (Dang et al., 2020) which have resulted in lower crop yields and trade imbalances that increase prices (Lobell et al., 2008), pest infestations (Skendžić et al., 2021), lower soil fertility (Mondal, 2021) and force changes to the timing of farm operations (Anwar et al., 2013). As a major exporter of rice and tropical fruit, Vietnam's agricultural sector is critically threatened by climate change, which could have severe implications for food security both domestically and globally (Anh et al., 2023).

In northern mountainous Vietnam, agriculture is the main livelihood, with Son La province known for its diverse agricultural production. Key crops include mango, longan, custard apple, paddy rice and maize—all vital for local economies and food security (Vu et al., 2023). Longan, custard apple and mango are exported globally (Thuy and Van Hieu, 2020), maize serves as food for humans and livestock, while paddy rice is a primary food source and an essential commodity (Thuy and Van Hieu, 2020). Over 38.6 km² is cultivated with fruit trees, with 50 km² dedicated to export crops. However, agriculture in these mountainous areas is highly vulnerable to climate change, threatening the livelihoods of local farmers (Ho et al., 2023).

Understanding the spatial and temporal impacts of climate change is crucial for developing adaptive strategies to ensure food security. As climate change alters land suitability, it becomes essential to assess potential impacts and to develop mitigation strategies. Land suitability analysis (LSA) is vital for evaluating land for specific crops under future climate conditions. LSA promotes efficient land management and sustainable practices by considering factors including soil, climate and topography (Mugiyo et al., 2021). By incorporating climate change impacts, LSA aids in designing strategies for sustainable crop production and food security (Karapetsas et al., 2024). Typically, various methods for LSA use a geographic information systems (GIS). Common approaches include multi-criteria decision-making methods, such as fuzzy logic (Bikdeli, 2020), overlay (Parastatidou et al., 2024), analytical hierarchy process (Pilevar et al., 2020; AbdelRahman et al., 2022) and weighted linear combination (WLC; Bakhshi and Mohammadi Seyed Ahmadiyani, 2023), and machine learning techniques such as species distribution modeling (Kaky et al., 2020). Integrating future climate change projections with LSA helps in forecasting crop distribution and in addressing sustainable agriculture concerns (Mugiyo et al., 2021). The increasing availability of data, including satellite images and climate projections, enhances LSA reliability (Mugiyo et al., 2021).

Therefore, the current study applied the WLC method to prioritize land suitability for various crops in Son La province, Vietnam. Introduced by Malczewski (2000), WLC assigns weights to criteria based on importance and by integrating qualitative and quantitative data. It provides a continuous suitability scale, making it useful for multi-criteria decision analysis. WLC has been applied effectively in landfill site selection (Zarin et al., 2021), ecotourism (Aliani et al., 2017) and hazard mapping (Kouli et al., 2014), supporting its robustness for also assessing agricultural land suitability in a changing climate.

The results of research assessing the impact of climate change on cropland suitability have varied by region. For maize, studies in Belgium projected a 7% reduction in suitability by 2099 due to decreased precipitation (Karapetsas et al., 2024). In contrast, sub-Saharan Africa may see a 4% increase in suitable cropland (Egbebiyi et al., 2023). In Bihar, India, suitable rice areas could drop from 31% to 21%, while in Sri Lanka, increased precipitation may expand suitable areas from 22% to 39% and 48% by 2030 and 2050, respectively (Rotawewa & Muthuwatta, 2017). Furthermore, increased rainfall in China may enhance rice suitability (Pickson et al., 2022). Thus, while climate change poses risks to cropland suitability, it may also create opportunities for adaptation (Sumathi et al., 2015; Ye et al., 2015), highlighting the need for site-level analysis.

While some studies have assessed climate change impacts on cropland suitability in Vietnam, most have focused on the southern and central regions (Van et al., 2022; Dang et al., 2020; Herzberg et al., 2019). The current study addressed this gap by providing a comprehensive analysis of land suitability in the northern mountainous region, specifically Son La province, using a GIS and the WLC approach. By identifying suitable areas for key crops and fruit trees, the findings should offer valuable insights for local farmers and decision-makers, contributing to understanding the impacts of climate change on agricultural systems in mountainous areas and informing strategies to enhance resilience. The aims of the current study were: 1) to assess the suitability of selected crops and fruit trees under current (1970–2000) and future (2081–2100) climate scenarios using GIS; 2) to provide information on suitable production areas for local farmers and decision-makers in Son La province; and 3) to contribute to the literature on climate change's impacts on agricultural systems in mountainous regions.

Materials and Methods

Study area

Son La is a mountainous province located in northwest Vietnam (Fig. 1). With a total land area of approximately 14,000 km², it is the largest province in the region. It borders Hoa Binh and Phu Tho provinces to the east, Yen Bai, Lai Chau, and Dien Bien provinces to the north, Dien Bien province to the west and Thang Hoa and Houaphanh provinces in Laos to the south.

The topography of Son La consists of plateaus, streams and elevations ranging from 100 up to 2,879 m above sea level. This diverse elevation creates a variety of microclimates, many of which are highly conducive to agriculture. Hence, Son La plays a crucial role in regional agricultural production that contributes to Vietnam's food security. Indeed, Son La is well suited for the development of diverse cropping systems that include mango, longan, avocado, passion fruit, plum, papaya, orange, grapefruit, pear, lychee, banana, and apples (Vietnam Agriculture, 2024.

Growing conditions for selected tree species

The data used was obtained from the Vietnam Fruit and Vegetable Research Institute (FAVRI) for three perennial fruiting tree species (Supplementary Table S1), namely mango (*Mangifera indica*), longan (*Dimocarpus longan)* and custard apple (*Annona reticulata*), as well as for two annual crops (Supplementary Table S2): paddy rice (*Oryza sativa*) and maize (*Zea mays*). Overall, these five crops were selected for modeling as a reflection of their importance to Son La's agricultural sector and the need to understand and address the challenges posed by climate change to ensure the sustainability of regional production. The data in the tables were divided into four levels: highly suitable, moderately suitable, less suitable and not suitable. The highly suitable level indicates the optimal conditions for the tree and crop species to grow, whereas the unsuitable level suggests that the given conditions are unacceptable for these species. These growing conditions comprised the basis for each environmental parameter.

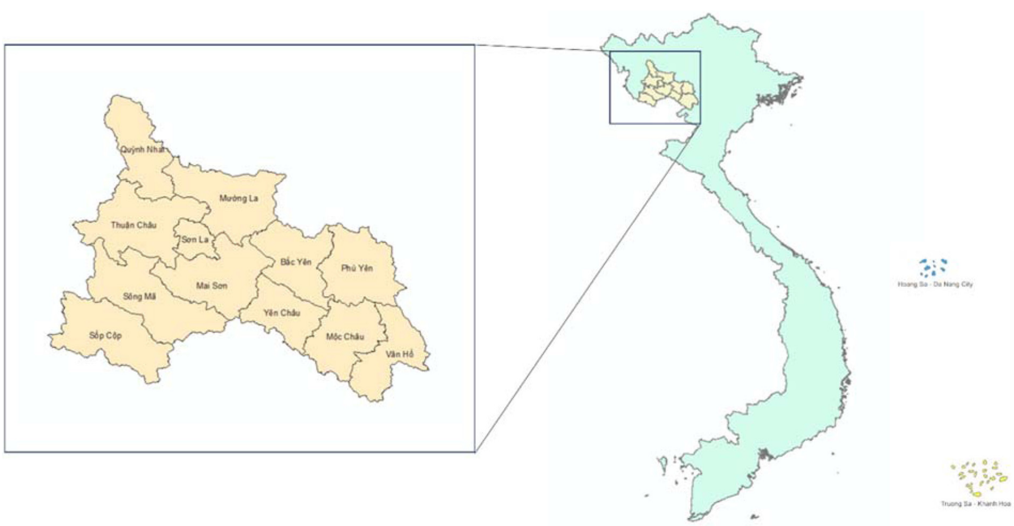

Fig. 1 Son La province and its administrative boundaries

Data preparation and inputs

Based on the growing conditions identified in Supplementary Tables S1 and S2, several raster layers were compiled as parameters for the suitability modeling of the tree species (Table 1). Overall, the parameters used were annual mean temperature (in degrees Celsius), annual precipitation accumulation (in millimeters), humidity (as a percentage), soil type (FAO soil classification), soil depth (in centimeters) and slope (in degrees), according to Tong et al. (2021). These parameters were as they comprise a crucial element in understanding the environmental conditions that influence the growth and suitability of tree and crop species.

First, the annual mean temperature and annual precipitation data for the current conditions (1970–2000) were used, along with the Shared Socioeconomic Pathways (SSP) 1–2.6 and 3–7.0 for the two future (2081–2100) climate change scenarios that were downloaded from the WorldClim database (https://www.worldclim.org/) with a 30 arc-seconds spatial resolution. The datasets for the current and future climate were chosen specifically based on their availability for Son La province. The WorldClim database is a widely used website from which global climatic data can be downloaded that is applicable for mapping and spatiotemporal modeling. For the two future scenarios (2081–2100), the annual mean temperature data were selected with a resolution of 30 arc-seconds for both SSP1–26 and SSP3–70. The Intergovernmental Panel on Climate Change developed these two SSP scenarios based on potential future socioeconomic and environmental conditions. The SSP1–2.6 scenario indicates a future characterized by low greenhouse gas (GHG) emissions and assumes sustainable development through strong international cooperation and effective climate change mitigation strategies. In contrast, the SSP3–7.0 scenario indicates a future with high GHG emissions and low collaborative efforts to address climate change, with a resultant high variability in temperature and precipitation patterns.

Next, high-resolution humidity data were downloaded from Karger et al. (2017) with a spatial resolution of 30 arc-seconds. Data for soil type and depth were derived from the Food and Agriculture (FAO) soil classification of harmonized world soil database ([version 1.2; Fischer et al., 2008]. Elevation data were downloaded from the Shuttle Radar Topography Mission (NASA JPL, 2013)) with a resolution of 30 are-seconds. The elevation data were used to derive the slope in degrees for the Son La study area. Finally, the land use/land cover (LULC) map was downloaded from ESRI with 1/3 arc-second resolution. The LULC map supported refining the outputs by removing unsuitable areas classified as built-up areas, water bodies and barren land. All data were clipped to be within the Son La province boundary, uniformly projected and added as inputs into ArcMap [version 10.7; ESRI, 2019 for the WLC method.

The WLC approach was applied to develop the suitability maps for different tree and crop species (Fig. 2), following the growing conditions table in ArcMap [version 10.7; ESRI, 2019]. Using the downloaded environmental data, weights were assigned to annual mean temperature, annual precipitation accumulation, humidity, soil type, soil depth and slope based on their relevance to the optimal growing conditions. All parameters were assigned a weight of 0.20 and a value of 0.16, derived from the total number of environmental variables used divided by the total number of environmental variables which were assumed to be of equal importance (Aduana-Alcantara et al., 2023).

Table 1 Data sources specifications

Criterion	Data source	Resolution	Format
Annual mean temperature (°C)	WorldClim	30 arc-seconds	GeoTIFF
Annual precipitation (mm)	WorldClim	30 arc-seconds	GeoTIFF
Humidity (%)	CHELSEA	30 arc-seconds	GeoTIFF
Soil type	FAO	NA	Shapefile
Soil depth	HWSD	NA	Shapefile
Slope (°)	SRTM (elevation)	30 arc-seconds	GeoTIFF
Land use/land cover	ESRI	1/3 arc-second	GeoTIFF

NA = not applicable; CHELSEA = Climatologies at high resolution for the earth's land surface areas; FAO = Food and Agriculture Organization; HWSD = harmonized world soil database; SRTM = Shuttle Radar Topography Mission.

Suitability analysis using weighted linear combination

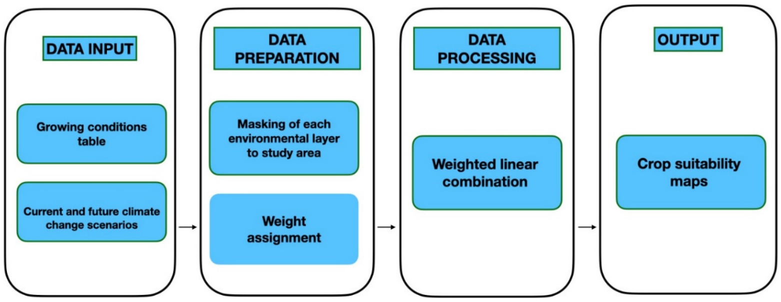

Fig. 2 Flow chart of methodology

Next, the weighted environmental parameters were reclassified into four distinct suitability classes, according to the growth condition table for each species: highly suitable, moderately suitable, less suitable and unsuitable. These classes were assigned values of 4, 3, 2 and 1, respectively, using the Reclassify tool in ArcMap. Then, the reclassified parameters were combined using the Raster Calculator spatial analyst tool. The output from the Raster Calculator tool included maps displaying values ranging from 1 to 4, with the higher the combined value, the greater its suitability in that area. The final output was integrated with the reclassified LULC map to refine the analysis by confining all suitable areas within their respective land cover classifications. For example, water bodies and built-up areas in Son La province were given a value of 0 indicating their unsuitability, while suitable areas, such as agricultural or cropping areas, were given a value of 1.

Results

Land suitability of species under current climate (1970–2000)

The suitability analysis was conducted using a weighted average overlay approach that generated 15 suitability maps for various fruit trees and crops in Son La province (Fig. 3). These maps were based on key environmental factors: annual average temperature, annual accumulated precipitation, slope, soil type, soil depth and humidity. In the current climate scenario, the annual average temperature was in the range 11.4–23.8°C, based on the data from the WorldClim database. The annual accumulated precipitation in the region was in the range 1,300–2,039 mm, while the slope values were in the range 0.01–27.5°. The resulting maps were based on the specific growing conditions for each species (Tables S1 and S2) to determine the suitability and unsuitability of areas across the region.

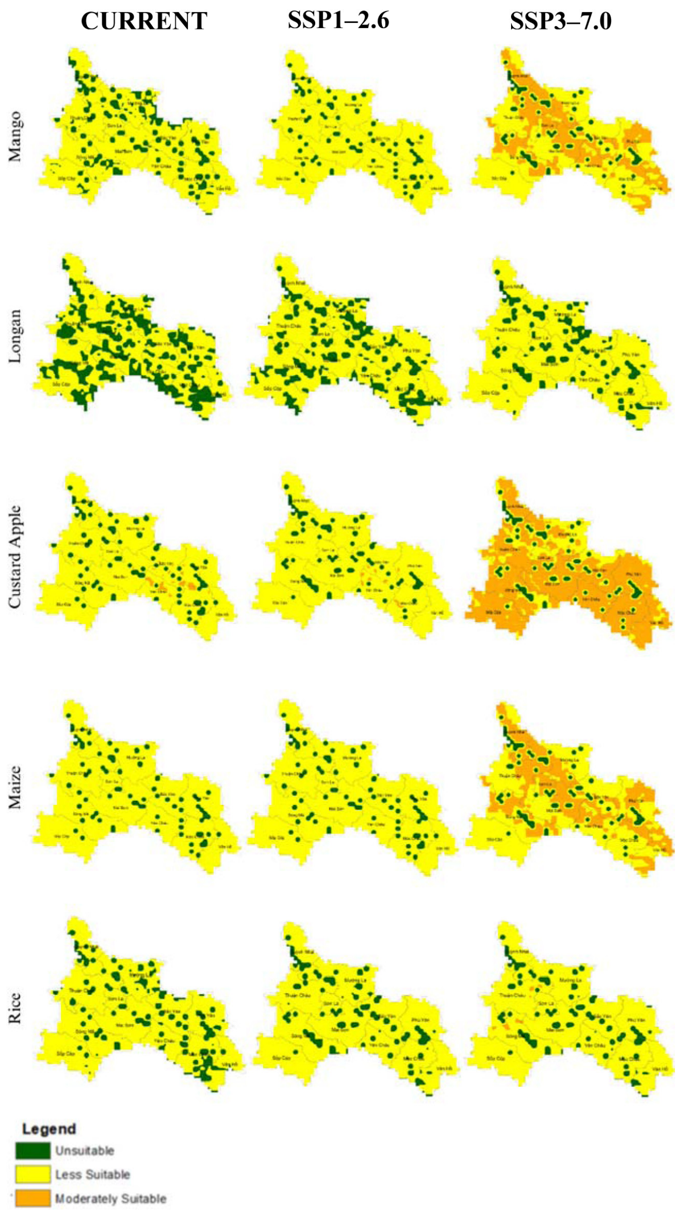

Fig. 3 Suitability maps of selected fruit trees and crops under current (1970–2000) and future climate change scenarios (2081–2100), with the future scenarios characterized by either low greenhouse gas (GHG) emissions (SSP1–2.6) or high GHG emissions (the SSP3–7.0)

Under the current climate conditions (1970–2000), a large proportion of the land was classified as marginally suitable, with limited areas deemed moderately or highly suitable for cultivation (Supplementary Table S3). Among the species, the largest areas of marginal suitability was recorded for custard apple (13,555 km²) and mango (12,188 km²). The moderately suitable land was limited to 291 km², found in Yen Chau, Phu Yen, and Bac Yen districts and considered suitable for custard apple.

In addition, the staple crops (maize and paddy rice) were allocated to a substantial proportion of marginally suitable land (12,207 km² and 13,915 km², respectively), accounting for large portions (84.3% and 95.7%, respectively) of the total land in Son La province.

Land suitability of fruit tree species under future climate change scenarios

The two future SSP scenarios represented projected climatic conditions based on different potential climatic changes, for modeling agricultural suitability in a changing climate. For these scenarios, the annual average temperature values were projected to be in the range 13.5–25.8°C, with the annual accumulated precipitation values were projected to be in the range 1,328–2,113 mm.

Under the future climate scenarios, major reductions in unsuitable land are projected for mango and longan. These species had expected reductions in unsuitable land by 27-35% under the SSP1-2.6 scenario, and around 60% under the SSP3-7.0 scenario (Supplementary Table S3). However, the marginally suitable land for longan was projected to increase substantially, with a 17.79% rise under SSP1-2.6 and a 40.66% rise under the SSP3-7.0 scenario. For mango, there was a slight increase in marginally suitable land of 6.03% under the SSP1-2.6 and 8.80% under the SSP3-7.0 scenarios. Notably, both climate change scenarios led to the emergence of moderately suitable areas for mango, which transitioned from having no moderately suitable land to gaining 14 km² under the SSP1-2.6 and 185 km² under the SSP3-7.0 scenarios. In contrast, custard apple was projected to experience more adverse impacts, with the marginally suitable area for this species expected to increase slightly (1.27%) under the SSP1-2.6 scenario but to decline considerably (by 68%) under the SSP3-7.0 scenario. Furthermore, there were contrasting trends in the projections for moderately suitable land for custard apple across scenarios, with a 64.60% reduction in moderately suitable land under the SSP1-2.6 scenario compared to a large increase in moderately suitable land under the SSP3-7.0 scenario, with a rise of 3,174.57%, mostly in the districts of Mai Son, Yen Chau, Bac Yen, Phu Yen and Moc Chau, with a total area of 9,529 km². These divergent outcomes highlighted the varying impacts that different climate change scenarios can have on the suitability of land for custard apple cultivation.

Land suitability of staple crops under future climate change scenarios

There were also large changes in land suitability for the annual crops under the future climate scenarios. Unsuitable land for maize decreased by 10.22% under both the SSP1-2.6 and SSP3-7.0 scenarios, while marginally suitable land decreased slightly by 1.33% under the SSP1-2.6 scenario, with a larger decrease of 27.7% under the SSP3-7.0 scenario. However, moderately suitable land for maize was projected to expand considerably, with a total of 3,691 km² under the SSP3-7.0 scenario, throughout most of the Son La districts, except for the Sop Cop district.

Similarly, there was a projected large reduction in unsuitable land for paddy rice, with a 37.17% decrease under the SSP1-2.6 and a 47.33% decrease under the SSP3-7.0 scenarios. However, the marginally suitable area for paddy rice increased by 4.82% under the SSP1-2.6 and by 8.80% under the SSP3-7.0 scenario. In total, there were 76 km² of moderately suitable in the districts of Song Ma and Thuan Chau under the SSP3-7.0 scenario.

Overall, most fruit trees and crop species in the region were projected to experience an expansion of marginally suitable areas under the future climate scenarios. For example, custard apple was expected to have the largest moderately suitable area under the high GHG emission SSP3-7.0 scenario, covering most districts in Son La province. Additionally, this high GHG emission scenario was likely to increase the moderately suitable land for maize and paddy rice, involving areas that are not currently identified as suitable for moderate cultivation using the baseline climate conditions. Across all current and future climate scenarios, there were no highly suitable areas for any of these species in Son La province.

Discussion

Based on the study results, a projected increase in annual temperature (~2°C) from 11–23°C to 13.5–25.8°C and in annual precipitation from 1,300–2,039 mm to 1,328–2,113 mm, suitable areas for fruit trees and staple crops were expected to expand under both the SSP1-2.6 and SSP3-7.0 scenarios.

This aligned with Zabel et al. (2014), who predicted that climate change may increase suitable cropland in northern high latitudes, including in the north of Vietnam.

Three fruit tree species—mango, longan and custard apple—were projected to expand into new suitable areas under the future pessimistic climate scenarios, since warmer temperatures during growth favor high-quality fruit production. For example, mangoes thrive in sub-tropical and tropical climates, requiring cool, dry conditions before flowering and temperatures of 30–33°C for optimal yields (Laxman et al., 2016). Longan may experience phenological changes due to rising temperatures (Lai, 2022). Although longan can be grown year-round, productivity may vary, with optimal temperatures of -2 to 18°C during vegetative growth and of 15–35°C during fruit development (Manochai et al., 2005; Rajan et al., 2020). Milder winters reduce the risk of seedling death and improve fruit quality, making regions with warmer winters more suitable for longan, especially for overwintering crops (Yang et al., 2010). This aligned with the pessimistic climate scenario in Son La, where longan could thrive in warm, humid subtropical and tropical climates. Li et al. (2020) also reported increased longan suitability in southern China, a region sharing similar climatic conditions with northern Vietnam (Cui et al., 2021).

For custard apples, moderately suitable areas were projected to increase substantially under the future pessimistic scenarios, from 313.8 km² to 10,161.9 km², covering most of Son La province. Temperature is crucial for optimal custard apple development, with lower temperatures around 13°C leading to fruit splitting and discoloration, so that ideal production occurs in the range 25–29°C (Deuter, 2011)—conditions that some areas in Son La currently meet.

Land suitability of staple crops under climate change scenarios

While rice land suitability is predicted to shrink in the Mekong Delta region due to climate change (Dang et al., 2020), the northern mountainous region of Vietnam has the potential to expand its agricultural production. Paddy rice, which grows best in the range 22–28°C, may experience reduced yields with increasing temperatures, though growth may not be greatly hindered (Krishnan et al., 2011). Studies have reported that increased temperature and precipitation could expand highly suitable areas for paddy cultivation in some regions of China (Pickson et al., 2022; Zhang et al., 2021), Malaysia (Alam et al., 2014) and in mountainous areas of Korea (Ko et al., 2014).

There were notable increases in the area under maize, an important crop in the region, particularly in central Son La province. This was consistent with other studies suggesting that maize yields and suitability may increase due to higher temperatures and elevated CO_2 levels (Egbebiyi et al., 2023; Zhang et al., 2021), which enhance photosynthesis, particularly in cooler regions (Farooq et al., 2023).

Application of weighted linear combination and limitations of the study

The WLC approach offers several advantages and limitations in suitability analysis. The integration of GIS can aid decision-makers in policymaking. In addition, the output of the WLC approach is relatively easy to interpret, making it suitable for the utilization of both quantitative and qualitative datasets such as environmental factors with expert-set importance for each criterion (Shenavr & Hosseini, 2014). This also explains why it is the most-used approach in LSA (Malczewski, 2000).

While the current study presents a positive outlook for agricultural development in Son La amidst changing temperature and rainfall patterns, it is important to acknowledge the limitations of the current analysis. Factors, such as the frequency and vulnerability of extreme weather events, habitat loss and the indigenous knowledge of local farmers, were not considered. These omissions may have introduced bias in calculating the weights assigned, as many of these aspects play a crucial role in shaping agricultural practices and resilience to climate change (Ebi et al., 2021). Additionally, variables, such as sunlight and flooding occurrences, were omitted due to data unavailability, yet they are important contributors to agricultural productivity and risk management. The resolution of the spatial data could be improved in the future, as it would improve the accuracy of the maps generated. Despite these limitations, the WLC approach applied in the current study provided sets of maps that could serve as baseline information for future GIS-related land suitability analysis in Son La, Vietnam.

Recommendation for climate-change-responsive actions

Climatic factors, such as temperature and rainfall, are crucial for crop production (Cetin, 2020), highlighting opportunities for agricultural development in Son La province and similar mountainous areas due to climate change. The finding that land suitability for some crops may improve even under pessimistic climate scenarios has important implications for Vietnam's climate policies. Based on the current results, a nuanced policy shift is needed. Current strategies, such as the National Climate Change Adaptation Plan (The Prime Minister, 2020) and the Sustainable Agriculture Development Strategy (The Prime

Minister, 2022, should not only focus on adaptation but also leverage potential agricultural opportunities by identifying key agricultural areas and suitable crops.

Specifically, the current results could aid Son La province in developing a land use master plan and climate adaptation strategies, targeting highly suitable areas in southeastern districts, such as Van Ho, Moc Chau, Bac Yen and Mai Son, where the hot, dry climate favors fruit tree cultivation. This study identified areas suitable for various fruit trees and crops based on climate and precipitation change, which can be used to inform policymakers. Future research should also explore factors including pests, diseases and natural disasters driven by climate change that may influence crop yields. This underscores the need for a comprehensive strategy to manage climate change effects through high-tech applications and best practices. Adaptive agricultural strategies, such as promoting climate-resilient crops and sustainable farming practices, are essential in regions projected to become more suitable for agriculture. This aligns with climate-smart agriculture goals, enhancing food security while adapting to climate shifts.

Promoting agroforestry models in Vietnam's mountainous regions, such as integrating fruit trees with annual crops (for example, longan-maize-forage grass) has proven economically beneficial and effective in increasing farmers' resilience by diversifying income sources and mitigating climate impacts (Do et al., 2019). Capacity building for farmers and government support for adaptive practices, such as enhancing irrigation systems, can help minimize extreme weather impacts. Future research should incorporate factors such as resource accessibility, market demand and infrastructure, to improve land suitability assessments in Son La and similar regions (Wu et al., 2019).

This study has contributed to global datasets and has advanced understanding of agricultural species distribution under climate change. Governments should explore potential opportunities from changing climatic conditions rather than focusing solely on the negative impacts. The expansion of suitable areas, mostly in sparsely populated regions, may face labor shortages and high investment costs, requiring careful planning. Effective land management must consider trade-offs between land use and ecosystem services (Zabel et al., 2019).

Conclusion

Based on the area estimates per climate scenario, the suitability of selected species varied in Son La province, northern Vietnam. Most of the species mapped had higher suitability areas in the future pessimistic climate scenario than in the current and optimistic scenarios, likely due to the shifting of climatic conditions, such as temperature and precipitation patterns, favoring certain crops and tree species. This increase reflects the resilience of both perennial and annual species, highlighting their adaptability to climate change. Identifying suitable areas could serve as a foundation for site selection with stakeholders in the province, resulting in the targeting of specific locations for development. This approach would allow for investment in resilient infrastructure and practices to protect yields from pests and diseases linked to climate change. Increased engagement with local farmers, policymakers and researchers should offer valuable insights for successful agricultural planning and adaptation strategies. This study has served as a baseline for future research on climate impacts in agriculture using geospatial technologies, providing insights into responses under two future climate scenarios for key crops and fruit trees. Such studies are essential in marginal, climatically impacted mountainous regions to enhance sustainable agricultural practices, food security, and rural livelihoods.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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