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Integrating Forest Conservation and Food Security: Managing Flood and Drought in Northern Thailand under CMIP5 Climate Projections

Muhammad Chrisna Satriagasa, Piyapong Tongdeenok*, Naruemol Kaewjampa

Watershed and Environmental Management Program, Faculty of Forestry, Kasetsart University, Bangkok, Thailand
* Corresponding Author. E-mail address: fforppt@ku.ac.th

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ABSTRACT

Increasing food demand and climate change-induced natural disasters pose significant challenges to food security. This study examines how forest conservation can mitigate disaster risks to agricultural land in Northern Thailand's watershed. The Soil and Water Assessment Tool (SWAT) and Hydrologic Engineering Center's-River Analysis System (HEC-RAS) models were used to assess flood impacts, while the standardized precipitation and evapotranspiration index (SPEI), vegetation health index (VHI), and standardized streamflow index (SSI) evaluated drought impacts, incorporating two Coupled Model Intercomparison Project Phase 5 (CMIP5) climate projections and five land-use scenarios. Historical data shows drought causing more yield loss than floods for rice and maize, a trend expected to continue. Under future Representative Concentration Pathways (RCP) 8.5, potential rice yield loss due to drought could reach 1,834 tons and maize yield loss 7,702 tons. Flood-induced losses are lower, with potential rice yield loss at 26.2 tons and maize at 16.9 tons. Reforestation can reduce these losses by up to 25% for drought and 20% for floods. Maintaining forests in mountainous and upstream watershed areas is essential to ensure food security. Policymakers should prioritize conserving these critical areas for effective water regulation and disaster risk reduction. Forests in these areas play a crucial role in regulating water flow, reducing runoff, and enhancing soil moisture retention, which is vital for mitigating the impacts of extreme weather events on agriculture.

1. Introduction

Agriculture in mainland Southeast Asia, especially in Northern Thailand, is a critical sector that underpins the livelihoods of millions and contributes significantly to the region's economy and food security (Blake et al. 2019). However, this sector is increasingly threatened by the dual impacts of floods and droughts, exacerbated by climate change (Bastola et al. 2023; Nara et al. 2014). Climate change and deforestation further increase the vulnerability of agriculture, leading to higher risks of soil degradation, water scarcity, and reduced biodiversity, which in turn affect agricultural productivity and sustainability, ultimately threatening regional food security (Ellis et al. 2021). These climatic extremes and deforestation pose significant risks to agricultural productivity, water availability, and the overall resilience of rural communities.

Forest conservation plays a crucial role in mitigating these risks by enhancing water yield for farmlands, maintaining biodiversity, and reducing the likelihood of water-related hazards, all of which support agricultural productivity and, by extension, food security in the region (Chakravarty et al. 2019; Chamberlain et al. 2020). This study also incorporates future climate scenarios, such as Representative Concentration Pathways (RCP4.5 and RCP8.5) and land-use change scenarios (SC0-SC5), to evaluate potential future impacts.

Given these challenges, this study aims to assess flood and drought impacts on agricultural production and food security in Northern Thailand watersheds. It seeks to address the following research questions: (1) What are the specific impacts of floods and droughts on agricultural productivity and food security? (2) How effective are the current mitigation and adaptation strategies in reducing the combined impacts of these hazards? (3) How can future climate projections inform the development of more resilient agricultural practices? By evaluating existing strategies and considering future climate scenarios, this study aims to provide actionable insights and recommendations for enhancing the resilience and sustainability of Northern Thailand's agricultural sector, offering valuable guidance for policymakers, stakeholders, and local communities.

Floods and droughts disrupt agricultural production through various mechanisms, such as crop damage from flooding (Chau et al. 2015) and water shortages caused by droughts, which reduce crop yields and increase the vulnerability of farming systems (Kang et al. 2021; Miyan 2015). In Northern Thailand, these hazards often occur within the same watershed, compounding their effects and challenging traditional water management practices (Foyhirun and Promping 2021; Igarashi et al. 2019). This situation is similar to global issues in other regions, i.e., Ethiopian, Iberian Peninsula, and Colombia, where watersheds experience similar climatic extremes, necessitating integrated water management strategies (Alemu 2016; Pulwarty and Maia 2014).

Several case studies have highlighted effective mitigation and adaptation strategies, such as adaptive management in Amazonian floodplain communities to cope with extreme floods and droughts (da Cunha Ávila et al. 2021) and indigenous household strategies in Baringo County, Kenya, to handle drought conditions (Pepela et al. 2019). These examples are relevant to Northern Thailand, as both regions experience similar climatic extremes that affect agricultural production and livelihoods. In the Amazonian floodplains, adaptive management strategies are crucial for dealing with both flooding and drought, much like the challenges faced in Northern Thailand's watersheds, where integrated water management is essential to mitigate the effects of both hazards. In Baringo County, local strategies for handling drought provide insights into how Northern Thailand can strengthen community resilience in the face of water scarcity.

These examples demonstrate diverse and effective approaches to managing the impacts of climatic extremes, offering valuable lessons for Northern Thailand's agricultural systems. Despite implementing various strategies, their effectiveness in managing the combined effects of floods and droughts remains unclear. Current strategy often focuses on single hazards, lacking an integrated approach addressing complex interactions between these events. Moreover, future climate change projections indicate increased frequency and intensity of floods and droughts (Muangthong et al. 2020; Satriagasa et al. 2023), necessitating reevaluating existing practices and developing more robust adaptation frameworks.

Furthermore, while forest conservation measures such as reforestation play a crucial role in environmental sustainability, they raise concerns about potential reductions in crop yields if agricultural land is reduced to make way for reforestation efforts (Danquah 2015; Klepacka et al. 2017; Stabile et al. 2020). However, several studies highlight the positive impacts of forests on crop yields, such as enhancing water yield for farmlands, increasing biodiversity that supports agricultural productivity, and reducing the probability of water-related hazards (Abiodun 2016; Edwards et al. 2014; Wang et al. 2019). This dual impact presents an additional challenge for the region's agricultural sustainability and food security.

In summary, this study addresses the urgent need to understand and manage the impacts of floods and droughts on agriculture in Northern Thailand. Through integrated assessment and forward-looking adaptation strategies, it aims to future-proof the region's agriculture against the backdrop of a changing climate.

2. Materials and Methods

2.1. Study Area

The Upper Nan Watershed (UNW) is located in the northernmost part of Thailand, bordered by Laos to the north and east (**Fig. 1**). This area, situated within Nan Province, spans from 18º27'55.72" N to 19º38'26.97" N and 100º21'39.14" E to 101º21'7.52" E, covering a total land area of approximately 4,588 km^2.

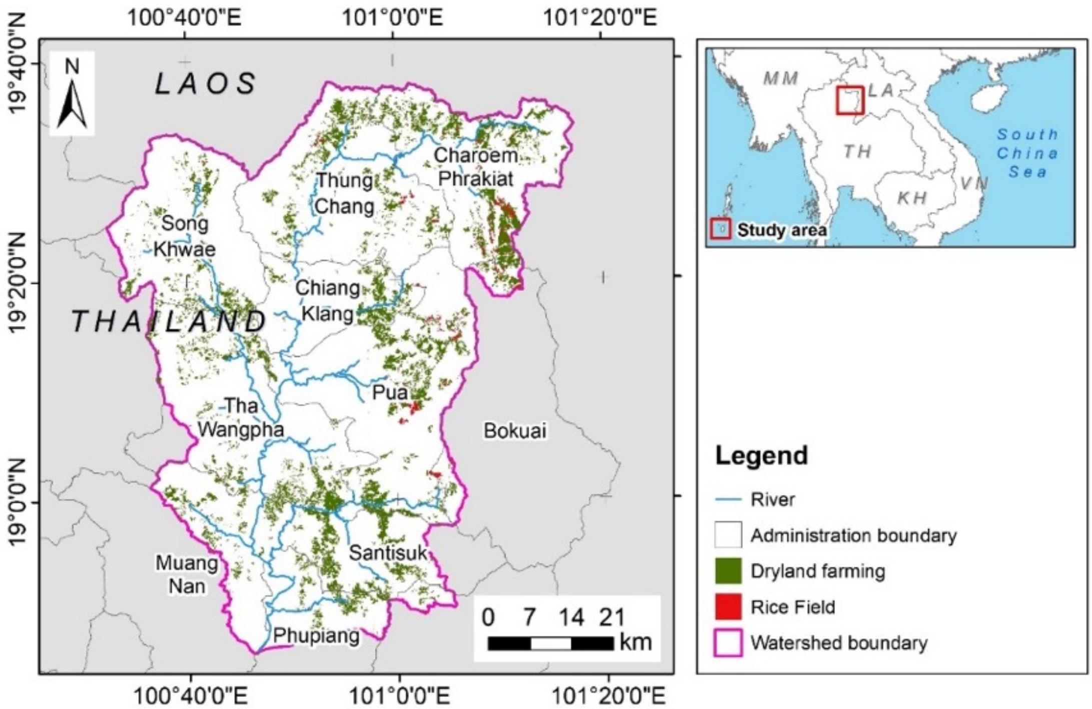


Fig. 1. Study area of the Upper Nan Watershed.

As of 2020, the watershed is home to around 475,000 people, most of whom rely on agriculture for their livelihood (National Statistical Office of Thailand 2022). Agricultural activities occupy a quarter of the UNW land area, with rice and maize being the predominant cash crops. The high demand for these crops has led farmers to expand cultivation areas, including encroachment on hillslopes and headwater regions, converting formerly forested areas into upland rice fields or dry farming land. This encroachment is illustrated in **Fig. 1**, showing the location of rice fields and dry farming in conservation-designated watershed class (WSC) 1 and 2 areas.

The UNW is inherently fragile due to its rugged topography and frequent exposure to northeast monsoon rainstorms from the South China Sea. Deforestation has exacerbated this fragility, and projected climate change is expected to increase the risk of water-related natural hazards further. These conditions pose significant threats to agricultural activities, which are the primary source of livelihood and food security for the local population.

2.2. Data Collection and Sources

Several types of data used in this study are detailed in **Table 1**. The data is sourced from various reputable organizations, ensuring a robust foundation for analysis. However, potential limitations include spatial and temporal resolution issues in the CHIRPS (Funk et al. 2015) and ERA5 (Copernicus Climate Change Service (C3S) 2017) imagery, and uncertainties inherent in the MPI-ESM-MR GCM CMIP5 climate projections (Center of Environmental Data Analysis (CEDA) 2017). The SWAT and HEC-RAS-modeled streamflow and flood maps are based on climate and land use scenarios (RCP4.5, RCP8.5, and SC0-SC5) and rely on specific assumptions. These extrapolated scenarios inherently introduce uncertainties in the predictions due to the assumptions made regarding future climate conditions, land use changes, and hydrological responses. As a result, the precision and accuracy of the modeled results may be impacted, particularly for long-term projections. Agricultural data from the Office of Agricultural Economics Thailand and the planting calendar from the Chiangmai Agricultural Extension Office of Thailand (Chiangmai Agricultural Extension Office 2023) may be influenced by reporting accuracy and local variations. These limitations should be considered when interpreting the results, and future research should aim for more granular and updated data to enhance reliability.

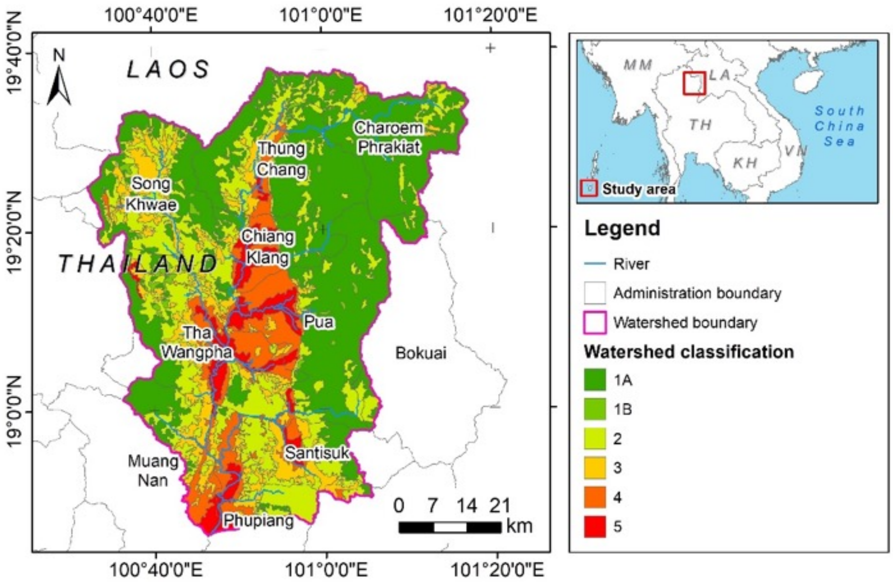
Table 1. Data used in this study, period, and data source

No	Data	Period	Source
1	Rainfall data from CHIRPS imagery	2000–2020	Funk et al. (2015)
2	Air temperature data from ERA5 imagery	2000–2020	Copernicus Climate Change Service (C3S) (2017)
3	MPI-ESM-MR GCM CMIP5	2021–2080	Center of Environmental Data Analysis (CEDA) (2017)
4	SWAT-modeled streamflow	2021–2080	Satriagasa et al. (2023)
5	SWAT & HEC-RAS modeled flood map	2021–2080	Satriagasa et al. (2023)
6	Rice and maize yield, harvest area, and productivity	2011–2020	Office of Agricultural Economics of Thailand (2023)
7	Planting calendar of Northern Thailand	2021	Chiangmai Agricultural Extension Office of Thailand (2023)

2.3. Climate Change and Land Use Scenario Analysis

This study used two climate change scenarios, Representative Concentration Pathways (RCP) 4.5 and 8.5, and five land-use scenarios (SC0 to SC5). RCP4.5 represents a moderate-emission scenario, while RCP8.5 represents a worst-case high-emission scenario. Climate change scenarios are based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) using the Max Planck Institute Earth System Model (MPI-ESM-MR). These climate projections were selected using a Taylor diagram, which compared several climate projections, selecting the best-performing model for representing future rainfall in the study area.

The land-use scenarios in this study are based on the watershed classification (WSC) concept, which is implemented for watershed and land-use management in Thailand, with further details provided in **Fig. 2** (Chankaew 1996). The land-use scenarios consist of three groups: baseline or business-as-usual (Scenario/SC0), reforestation/forest expansion (SC1 and SC2), and agricultural expansion/deforestation (SC3, SC4, and SC5). The forest expansion scenario in SC1 expands forests in WSC1, while SC2 expands forests in WSC1 and WSC2. The agricultural expansion scenario in SC3 involves the expansion of maize dry farming in WSC3; SC4 expands maize dry farming in WSC2 and WSC3, while SC5 expands rice fields in WSC5. The selection of maize for highland expansion and rice for lowland modeling reflects common conditions in real-world settings.



	WSC	Zone function	Criteria
	1A	Conservation only	High mountainous area with very steep slope (>50%)
	1B	Conservation only	
	2	Conservation and strictly controlled utilization	High mountain, rounded ridges, and steep slope (30-50%)
	3	Limited utilization	Mountain slope, foothills, terraced plains, and area near water course, moderate slope (25-35%)
	4	Higher utilization	Mountain foothills, low hills, and terraced plains, slightly sloping (6-25%)
	5	Intensive utilization	Lowland area with nearly flat slope (>5%)

Source: Chankaew, 1996

Fig. 2. Watershed classification in the Upper Nan Watershed.

2.4. Development of Flood and Drought Models

The flood map used in this study is based on Satriagasa et al. (2023), while the drought map is derived from a simulated drought risk model. The development of these flood and drought models is illustrated in **Fig. 3**. The flood model focused on downstream areas, while the drought model covered the entire watershed.

The flood map was created using streamflow data modeled by the Soil and Water Assessment Tool (SWAT) under five land use change (LUC) and two climate change (CC) scenarios. The LUC scenarios varied land use inputs in the hydrologic response unit (HRU), while the CC scenarios varied climate data inputs. The flood model simulation is limited to the downstream part of the watershed, which is the most impacted by flooding and encompasses an area of 82 km². ArcMap was used for spatial data processing and visualization, including generating flood extent maps and overlaying land use scenarios with flood-prone areas.

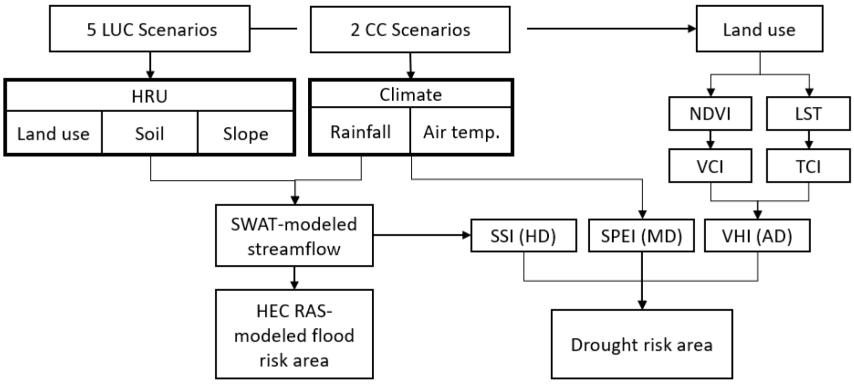


Fig. 3. Flood and drought model development.

The drought map encompasses three types of drought: meteorological drought (MD), agricultural drought (AD), and hydrological drought (HD). Meteorological drought was calculated using the standardized precipitation and evapotranspiration index (SPEI), which varies under CC scenarios. Agricultural drought was determined based on the vegetation health index (VHI), which is the sum of the vegetation condition index (VCI) and temperature condition index (TCI). The VCI was calculated using the normalized difference vegetation index (NDVI) and land surface temperature (LST) derived from Sentinel-2 imagery, with NDVI and LST calculations performed using Google Earth Engine (GEE). The processed results were further analyzed and visualized in ArcMap. Hydrological drought was assessed using the standardized streamflow index (SSI), based on SWAT-modeled streamflow by Satriagasa et al. (2023). Unlike floods, which primarily impact specific downstream areas, drought can affect the entire watershed. Therefore, drought modeling was conducted for the entire watershed, covering an area of 4,588.42 km².

2.5. Validation of Models

Both the flood and drought risk models were calibrated and validated for accuracy. The SWAT-modeled streamflow was validated using observed streamflow data from the N64/Ban Pakwang Station, managed by the Royal Thai Irrigation Department. The modeled streamflow performance received good ratings in the calibration and validation phases under the Nash-Sutcliffe Efficiency (NSE) metric and good ratings under the Root Mean Square Error (RSR) metric. However, it ranged from poor to intermediate under the Kling-Gupta Efficiency (KGE) metric. The flood risk map was validated against an actual flood map from 26 August 2018, mapped by Thailand's Geo-Informatics and Space Technology Development Agency (GISTDA), achieving 92.1% accuracy. Similarly, the drought risk map was validated using GISTDA's data, resulting in high accuracy for the critical success rate (CSI) and a very high detection rate for the probability of detection (POD).

2.6. Comparative Assessment of Flood and Drought Impact on Agricultural Yield under Climate Change, Reforestation, and Deforestation

Water-related hazards, particularly floods and droughts, can significantly affect the agricultural yield of rice and maize in the Upper Nan Watershed (UNW). While previous studies have highlighted the general impacts of these hazards on agriculture, this research provides a more detailed and spatially explicit analysis that integrates land use, crop productivity, and hazard data. This study employs spatial analysis to assess the specific impacts of floods and droughts on crop yields at the district level, which has not been comprehensively explored before in the context of the UNW. A land use map detailing agricultural land use, including rice fields and dry farming, was overlaid with flood and drought maps. This spatial analysis identifies the areas of rice fields and dry farming affected by simulated floods and droughts. Combining the hazard-affected areas with specific crop productivity data can estimate potential yield losses due to floods and droughts in tons. This approach aligns with methodologies used in similar studies, such as those by Prabnakorn et al. (2019) and Watanabe et al. (2018), who assessed the risks of floods and droughts in agricultural river basins. Other research, such as Bastola et al. (2023), explored the impacts of drought on maize cultivation in the Upper Nan River Basin, while Ngammuangtueng et al. (2019) analyzed the water, energy, and food nexus in rice production systems in Thailand. This approach allows for a more precise understanding of how these hazards impact specific crops and regions, providing insights that can inform more effective land and water management strategies. Based on the differences in estimates for each scenario, the impacts are calculated as follows:

a. The effect of climate change is determined by comparing the baseline scenario (SC0) under historical climate conditions with SC0 under future climate scenarios (RCP4.5 and RCP8.5). This comparison focuses on how projected changes in temperature, precipitation patterns, and evapotranspiration under the two climate scenarios will influence crop yield.
b. The effect of reforestation is assessed by comparing the baseline scenario (SC0) with forest expansion scenarios (SC1 and SC2). This evaluation quantifies the reduction in yield loss from floods and droughts due to increased forest cover, which enhances water retention and reduces runoff and erosion in the watershed.
c. The impact of deforestation/agricultural expansion is evaluated by comparing the baseline scenario (SC0) with deforestation/agricultural expansion scenarios (SC3, SC4, and SC5). Here, the analysis focuses on how replacing forested areas with agricultural land increases exposure to drought and reduces the ecosystem’s capacity to buffer floods.

Calculating agricultural yield loss is time-specific, as yield loss refers to crops in the field at the time of the hazard event—planted, matured, and ready for harvest. We account for the specific growth stages of rice and maize and the timing of hazards during the wet season to avoid overestimating losses. This study focuses on wet-season rice and maize because dry-season crops are planted in much smaller areas. Wet-season flood and drought data are synchronized with these crops’ planting and growing periods to provide a more accurate estimate of potential yield loss.

2.7. Integrating Flood and Drought Loss

Due to the distinct areas affected by simulated floods and droughts, the total yield losses from these water-related hazards differ significantly. Flood-prone areas are typically identified using elevation data, hydrological models (e.g., SWAT), and historical flood events to simulate which low-lying regions are most at risk. Floods typically impact these low-lying areas, resulting in immediate but localized yield losses. Drought-prone areas, on the other hand, are identified through climate data (e.g., precipitation, temperature, and evapotranspiration) and soil moisture levels, allowing for a more widespread and prolonged assessment. Droughts affect larger regions over extended periods, causing more gradual yet extensive yield reductions.

An equivalent yield metric is employed to compare these impacts accurately. This metric involves two key variables: (1) kilogram yield loss, calculated by multiplying crop productivity by the affected area, and (2) the area affected by the hazards derived from flood and drought maps. The yield loss from both flood and drought is then divided by the affected area, resulting in a standardized measure of yield loss per hectare (kg/ha). This standardized metric accounts for the differing spatial extents of the two hazards and allows for a comprehensive comparison of their severity and extent across the study area. Using this approach, the analysis can reveal which hazard poses the greater threat to crop yields under each land use and climate scenario.

3. Results and Discussion

3.1. Results

3.1.1. Trend of rice and maize production

Rice and maize are the most important agricultural commodities in the Upper Nan Watershed (UNW). Based on data from the Office of Agricultural Economics of Thailand, between 2011 and 2020, rice yield showed a positive trend, with 168,000 tons produced in 2020. This yield increase was supported by an increase in the harvest area during the same period, reaching 20,000 ha in 2020. This finding is consistent with Amnuaylojaroen et al. (2021), who projected increasing rice production in Northern Thailand under similar conditions but noted potential decreases due to climate change effects, such as rising temperatures and changing rainfall patterns. However, despite the increasing yield and harvest area, rice productivity slightly decreased during this period, with 81 kg/ha in 2020. This decline in productivity could be attributed to factors such as lower soil fertility, inefficient water use, or suboptimal farming practices in certain areas, which may have led to a decline in per hectare output despite the overall increase in yield. Similar declines in productivity have been observed by Ramsden et al. (2017), who found that declining soil fertility and inefficient farming practices contributed to lower rice productivity despite increased overall yields.

In contrast, maize yield and harvest area followed a downward trend between 2011 and 2020, with maize production at 394,000 tons and a harvest area of 37,000 ha in 2020. Despite the decrease in yield and harvest area, maize productivity increased, reaching 105 kg/ha in 2020. This increase in productivity could be due to improvements in crop management, such as the adoption of more efficient farming techniques or better inputs (e.g., fertilizers and pest control), which allowed farmers to maintain or even increase the per hectare output of maize, despite a reduction in the total area under cultivation and a lower overall yield. Supasri et al. (2020) noted similar trends in Northern Thailand, where maize productivity increased due to improved management practices, even though production declined due to reduced land area. Phuphisith et al. (2022) also highlighted the role of sustainable practices in increasing maize productivity despite environmental constraints.

Both rice and maize productivity is not the same in every district within the UNW (**Fig. 4**). The highest productivity of rice is found in the middle and downstream areas of the watershed, where rice fields are primarily located in the plain lowlands with abundant water supply. These districts include Chiang Klang, Pua, Tha Wang Pha, Muang Nan, and Phupiang. Similar findings were reported by Charoenratana et al. (2021), who observed that rice productivity was highest in lowland areas with adequate water availability, confirming the importance of water supply for rice cultivation. In contrast, maize is better suited to the upland and mountainous areas, which are the predominant physical characteristics of the UNW. Therefore, maize is grown widely throughout the watershed, particularly in areas with suitable elevation and terrain, and demonstrates high productivity. Amnuaylojaroen et al. (2021) and Supasri et al. (2020) emphasized maize's adaptability to upland areas in Northern Thailand, which continues to perform well despite challenging environmental conditions.

The suitability of these crops was determined based not only on productivity but also on specific criteria such as land elevation, water availability, and terrain characteristics. Rice thrives in lowland areas with flat terrain and sufficient water. At the same time, maize is well adapted to upland and mountainous regions with less water availability but suitable soil conditions for dry farming. This pattern aligns with findings from Punyalue et al. (2018), who demonstrated the success of maize in upland regions due to its adaptability to less fertile soils and lower water availability, particularly when intercropped with legumes, to improve soil health.

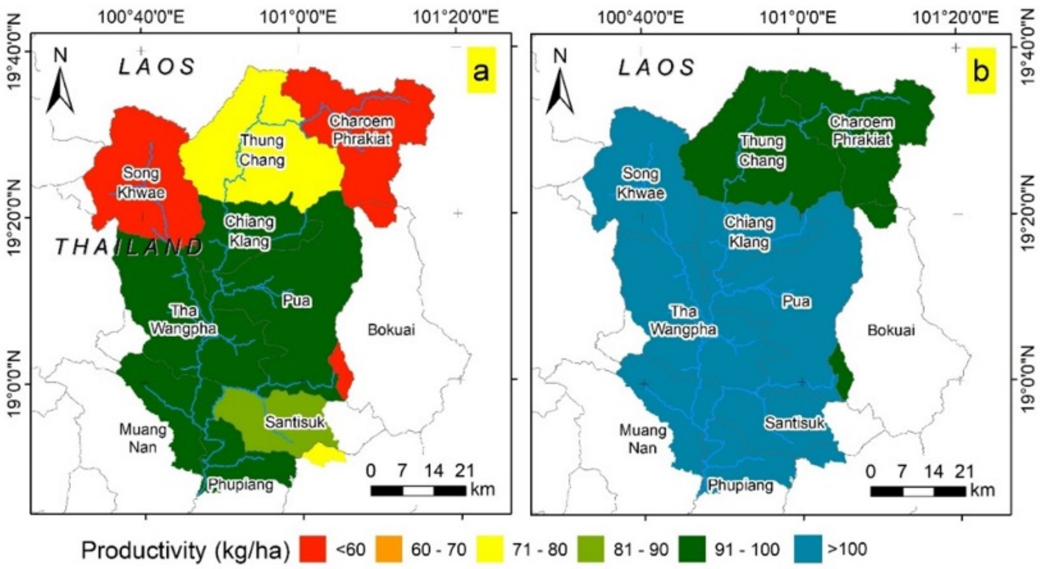


Fig. 1. Crop productivity of rice (a) and maize (b).

Planting and harvest timing are crucial when relating agricultural production to water-related hazards such as floods and droughts. Although floods and droughts can occur at any time of the year, the most severe situations are typically experienced during specific seasons: floods during the wet season and droughts during the dry season. This study focuses on wet-season floods and droughts, which present significant agricultural crop hazards. Therefore, examining the planting calendar in a particular area, as shown in **Table 2**, is highly important. This table shows that planting mainly occurs from the beginning to the end of the wet season, while harvesting is scheduled from the end of the wet season to the dry season. Amnuaylojaroen et al. (2021) and Bastola et al. (2023) emphasized the importance of aligning planting and harvest schedules with climate projections and water availability to mitigate the impacts of climate change on rice and maize productivity in Northern Thailand.

Table 2. Planting calendar in Northern Thailand

Commodities	P/H	Year n												Year n+1											
		J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Rice wet season	P					X	X	X	X	X								X	X	X	X	X			
	H									X	X	X	X	X								X	X	X	X
Maize wet season	P					X	X	X	X									X	X	X	X				
	H									X	X	X	X									X	X	X	X

Notes: P (planting), H (harvesting), J F M A M J J A S O N D (January–December). Source: Chiang Mai Agricultural Extension Office.

3.1.2. Impact of water-related hazard scenarios on agricultural yield

3.1.2.1. Impact of flood scenarios on agricultural yield

Based on the overlay operation using ArcMap GIS software, it was found that sizeable agricultural land areas, including rice fields (RF) and maize dry farming (DF), are impacted by modeled floods. The extent of agricultural land affected by floods varies across scenarios, resulting in potential yield losses. This finding is consistent with studies like Venkatappa et al. (2021), who also found that croplands in Southeast Asia, particularly rainfed fields, are highly vulnerable to floods, leading to significant losses in crop production. Detailed potential yield loss due to flood events is presented in **Table 3**. The data show that climate change significantly impacts the total yield potentially affected. Dessens et al. (2022) noted similar impacts on land suitability in Cambodia, Laos, and Myanmar, where extreme climate scenarios, such as RCP8.5, showed more severe effects on agricultural production.

Table 3. Flood-impacted agricultural production in UNW (tons)

	DR	SC0	SC1	SC2	SC3	SC4	SC5
RF	Historical	25.4	25.3	25.2	25.4	25.5	25.5
	Future RCP4.5	25.2	25.1	25.1	25.4	26.2	25.2
	Future RCP8.5	26.1	26.1	26.0	26.1	26.2	26.0
DF	Historical	16.2	16.1	16.0	16.2	16.3	16.3
	Future RCP4.5	16.1	16.0	16.0	16.2	18.9	16.1
	Future RCP8.5	16.9	16.8	16.7	16.9	17.1	16.8

Notes: value indicating the lowest (return period/RP 1 year), middle (RP 5 years), and the highest estimation maize (RP 100 years); dry farming (DF), rice field (RF), baseline scenario (SC0), WSC-1 maize dry farming expansion (SC3), WSC1 and two maize dry farming expansion (SC4), and WSC5 rice field expansion (SC5).

Fig. 5 illustrates the modeled flood risk map, representing flood events under RCP4.5 (return period one year) to RCP8.5 (return period 100 years) across Scenarios SC0 to SC5. The map indicates the areas of agricultural land use, including rice fields and maize dry farming, projected to be impacted by flooding under these scenarios. The flood map helps visualize the spatial distribution of flood risks across different land-use scenarios. It highlights the potential extent of agricultural land affected by floods under varying climate change conditions.

For rice fields, the yield loss under the future climate scenario RCP4.5 is lower than during the historical period, whereas the yield loss under the future climate scenario RCP8.5 is predicted to increase. Specifically, during the historical period, the potential yield loss for rice fields was 25.4 tons, while in future RCP4.5 and RCP8.5 scenarios, it ranged from 25.1 to 26.2 tons. Amnuaylojaroen et al. (2024) found similar patterns in their analysis of rice yields under different climate scenarios, noting that higher emissions scenarios like RCP8.5 tend to exacerbate yield losses, especially due to increased flooding.

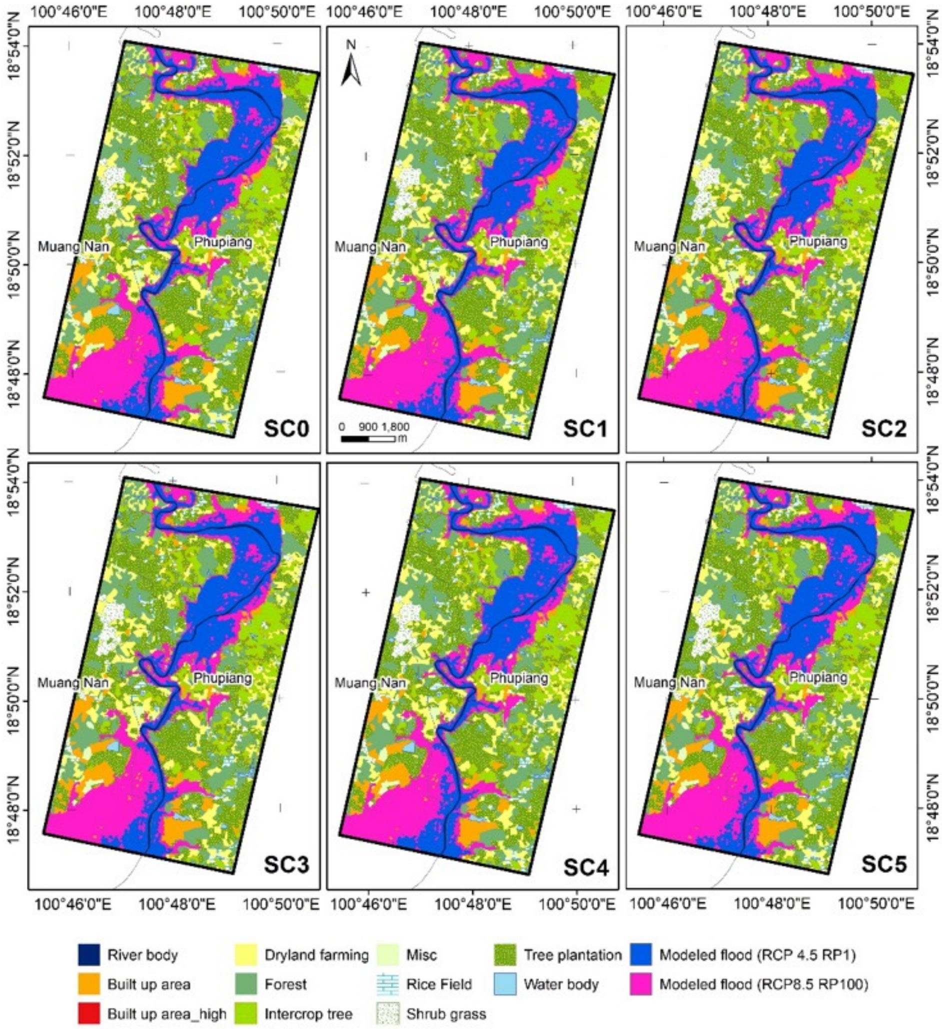


Fig. 5. Flood risk map of the Upper Nan Watershed, showing projected flood risks under land use scenarios SC0 to SC5, modeled with climate change projections RCP4.5 and RCP8.5, and return periods from 1 to 100 years.

For maize dry farming, the yield loss under the future climate scenario RCP4.5 is also predicted to be lower than during the historical period, but it increases significantly under the RCP8.5 scenario. The data shows that the potential yield loss for maize dry farming under the historical period is 16.2 tons, while under future RCP4.5 and RCP8.5 scenarios, it ranges from 16.0 to 18.9 tons. This finding aligns with Venkatappa et al. (2021), who observed that maize is particularly sensitive to precipitation patterns, with yield losses increasing under more extreme climate conditions.

The reforestation effects shown by scenarios SC1 and SC2 indicate that reforestation can reduce the yield loss of rice and maize due to flooding. In most cases, SC2, which has more forest cover, performs better in reducing yield loss than SC1. Conversely, agricultural expansion leading to deforestation results in higher yield losses due to flooding events, with SC4 experiencing the most significant effects due to a larger area being converted to maize dry farming. Taniushkina et al. (2024) highlighted the importance of reforestation in mitigating flood risks and its positive effects on crop yield stability, similar to the patterns observed in SC1 and SC2 in this study. Dessens et al. (2022) also emphasized the role of land use changes, such as deforestation, in increasing agricultural vulnerability to floods.

However, it is important to note that the values presented in **Table 3** are relatively close, making it difficult to evaluate increasing or decreasing trends without statistical validation conclusively. Due to this study's limited number of data points, a comprehensive statistical test, such as ANOVA or t-test, could not be conducted. This limitation represents a gap in the current research, and future studies should aim to collect more extensive datasets that would allow for more robust statistical analysis to substantiate the observed trends.

3.1.2.2. Impact of drought scenarios on agricultural yield

Like the flood model, the drought model map was also overlaid with the Upper Nan Watershed (UNW) land use map, revealing the agricultural lands of rice fields (RF) and maize dry farming (DF) affected by drought hazards. The extent of drought hazards varied under different climate change (CC) and land use change (LUC) scenarios. **Fig. 6** demonstrates the drought risk under the RCP4.5 scenario, showing a range of drought risk classifications from Very Low Risk (VLR) to Very High Risk (VHR) across land-use scenarios SC0 to SC5. Meanwhile, **Fig. 7** illustrates the drought risk under the RCP8.5 scenario, where the projected impacts show more severe risks, with larger areas falling under higher drought risk categories, such as high risk (HR) and very high risk (VHR), particularly in agricultural areas. The agricultural land impacted by drought was converted to yield loss estimates using productivity data from the Office of Agricultural Economics of Thailand. The potential yield loss of rice and maize in the UNW due to drought events is detailed in **Table 4**.

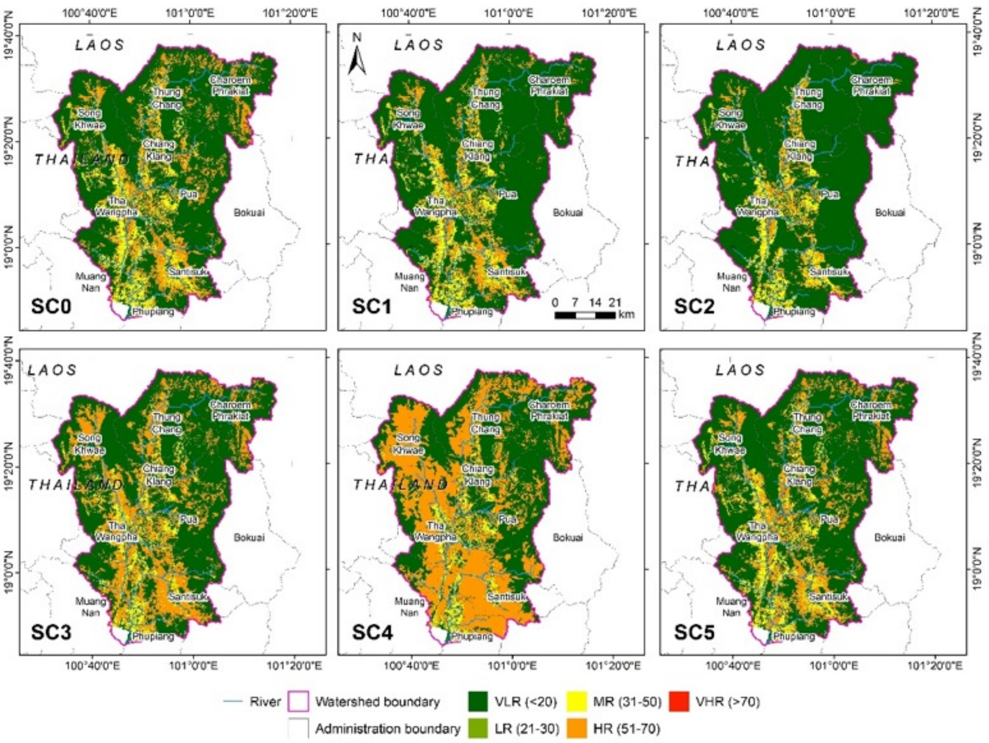


Fig. 6. Drought risk map of the Upper Nan Watershed under the RCP4.5 climate change scenario, showing land use scenarios SC0 to SC5 and drought risk classifications: VLR (Very Low Risk), LR (Low Risk), MR (Medium Risk), HR (High Risk), and VHR (Very High Risk).

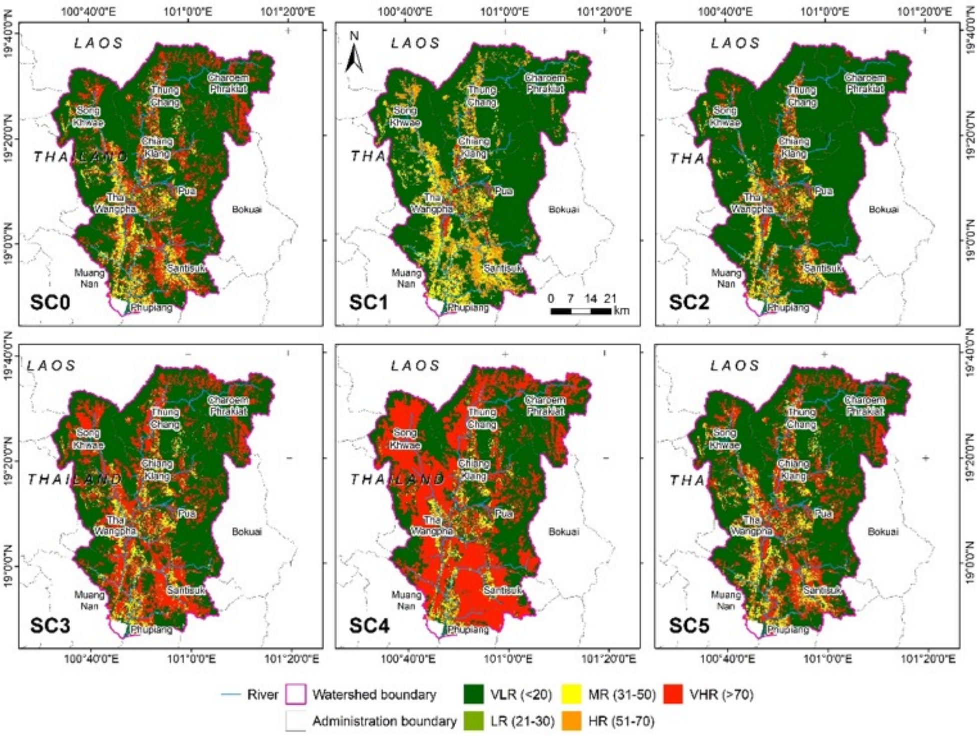


Fig. 7. Drought risk map of the Upper Nan Watershed under the RCP8.5 climate change scenario, showing land use scenarios SC0 to SC5 and drought risk classifications: VLR (Very Low Risk), LR (Low Risk), MR (Medium Risk), HR (High Risk), and VHR (Very High Risk).

Table 4. Drought-impacted agricultural production in UNW (tons)

	DR	SC0	SC1	SC2	SC3	SC4	SC5
RF	Historical Dry S.	1,646	1,278	1,370	1,539	2,229	2,229
	Historical Wet S.	1,832	1,409	1,533	1,708	1,437	1,437
	Future RCP4.5	1,832	1,409	1,533	1,708	1,437	2,442
	Future RCP8.5	1,834	1,409	1,533	1,708	1,437	2,440
DF	Historical Dry S	7,524	5,666	3,095	11,219	7,294	6,938
	Historical Wet S.	7,687	5,444	2,848	11,424	19,823	19,400
	Future RCP4.5	7,702	5,448	2,849	11,439	19,891	7,504
	Future RCP8.5	7,702	5,448	2,849	11,439	19,891	7,504

Notes: rice field (RF), dry farming (DF), baseline scenario (SC0), WSC1 forest expansion (SC1), WSC1 and 2 forest expansion (SC2), WSC1 maize dry farming expansion (SC3), WSC1 & 2 maize dry farming expansion (SC4), and WSC5 rice field expansion (SC5).

Table 4 shows that climate change, under both RCP4.5 and RCP8.5 scenarios, significantly affects drought hazards in the UNW, potentially increasing yield losses in the future. For instance, under the historical dry season, the potential yield loss for rice fields is 1,646 tons, while it ranges from 1,409 to 2,440 tons under future scenarios. For maize dry farming, the yield loss under the historical dry season is 7,524 tons, ranging from 2,849 to 19,891 tons under future scenarios. This result is consistent with Amnuaylojaroen et al. (2024), who found that drought conditions in Southeast Asia, especially under RCP8.5, are likely to impact rice and maize yields significantly. Their analysis emphasized the importance of adaptive measures to mitigate these effects, similar to the need for such measures identified in this study.

Reforestation measures, as simulated in SC1 and SC2, can sharply reduce the yield loss of both rice and maize. Specifically, for rice fields, the potential yield loss under SC1 and SC2 in future RCP4.5 and RCP8.5 scenarios is significantly lower than in scenarios with agricultural expansion. Conversely, agricultural expansion is predicted to lead to higher potential yield losses due to drought events, with SC4 experiencing the most significant effects due to a larger area being converted to maize dry farming. This aligns with the findings of Srinivasan et al. (2024), who reported that land use changes, such as deforestation for agricultural expansion, exacerbate the vulnerability of agricultural systems to climate extremes, particularly droughts. Similarly, Dessens et al. (2022) observed that reforestation can enhance land suitability and reduce the negative impacts of droughts on crop yields.

3.1.2.3. Comparative assessment of flood and drought impacts

Standardized yield loss per square kilometer was analyzed to determine which water-related hazard harms crop yield in the Upper Nan Watershed (UNW). As shown in **Table 5**, historical data reveals drought has caused more yield loss than floods for rice and maize. This trend is expected to continue. Furthermore, climate change is projected to increase yield loss from both hazards for rice and maize.

Table 5. Standardized yield loss per square kilometer by flood and drought in UNW (tons)

		DR	SC0	SC1	SC2	SC3	SC4	SC5
Flood	RF	Historical	0.31	0.31	0.31	0.31	0.31	0.31
		Future RCP4.5	0.31	0.31	0.31	0.31	0.32	0.31
		Future RCP8.5	0.32	0.32	0.32	0.32	0.32	0.32
	DF	Historical	0.20	0.20	0.20	0.20	0.20	0.20
		Future RCP4.5	0.20	0.20	0.20	0.20	0.23	0.20
		Future RCP8.5	0.21	0.21	0.20	0.21	0.21	0.21
Drought	RF	Hist. Dry	0.36	0.28	0.30	0.34	0.49	0.49
		Hist. Wet	0.40	0.31	0.33	0.37	0.31	0.31
	RF	RCP4.5	0.40	0.31	0.33	0.37	0.31	0.53
	RF	RCP8.5	0.40	0.31	0.33	0.37	0.31	0.53
	DF	Hist. Dry	1.64	1.23	0.67	2.45	1.59	1.51
		Hist. Wet	1.68	1.19	0.62	2.49	4.32	4.23
	DF	RCP4.5	1.68	1.19	0.62	2.49	4.34	1.64
	DF	RCP8.5	1.68	1.19	0.62	2.49	4.34	1.64

Notes: rice field (RF), dry farming (DF), baseline scenario (SC0), WSC1 forest expansion (SC1), WSC1 and 2 forest expansion (SC2), WSC1 maize dry farming expansion (SC3), WSC1 & 2 maize dry farming expansion (SC4), and WSC5 rice field expansion (SC5).

The presence of forests in scenarios SC1 and SC2 has been determined as effective in reducing yield loss from floods and droughts based on the extent of yield loss reduction observed in the simulations. Effectiveness was measured by comparing the yield loss in forested scenarios (SC1 and SC2) to non-forested or deforested scenarios, such as SC3, SC4, and SC5. The simulation results indicate that forests mitigate yield loss through enhanced water flow regulation, increased soil infiltration, and reduced surface runoff. Although the reduction varies, forests in SC1 and SC2 significantly impact yield loss reduction, particularly for drought-induced losses. The simulation indicates that forests have a more significant impact on reducing yield loss due to drought than floods. Various studies highlight that forests provide essential water flow regulation, including canopy protection, enhanced soil structure, increased infiltration rates, greater water-holding capacity, and reduced surface runoff (Ding et al. 2023; Jourgholami et al. 2019; Li et al. 2019; Majeed and Lee 2017; Slamet et al. 2021). These factors collectively decrease the probability and severity of water-related hazards for surrounding land uses and downstream areas, including agricultural areas. Scenario SC2 demonstrates the high effectiveness of reforestation in the headwater and sloped areas of WSC1 and WSC2, which is predicted to combat drought-induced yield loss due to climate change.

Similarly, in agricultural expansion scenarios SC3, SC4, and SC5, yield loss from floods shows little to no difference compared to the baseline. However, yield loss from drought significantly increases, indicating that deforestation driven by agricultural expansion will considerably decrease agricultural commodity yields.

3.2. Discussion

3.2.1. Effect of climate change and land use change on water-related hazard and food security

The analysis of yield losses due to water-related hazards in the Upper Nan Watershed (UNW) underscores the significant impact of climate change and land use change on agricultural production. Historical data reveal that drought has consistently caused more yield loss than floods for rice and maize, a trend projected to persist in future scenarios. This result aligns with previous studies, such as those by Chen et al. (2018) and Liu et al. (2019) in China, which found that drought is more likely to cause greater yield loss than floods. Moreover, climate change exacerbates this issue, with scenarios RCP4.5 and RCP8.5 indicating increased crop yield losses due to intensified drought and flood events. Similar findings are reported in studies around the globe, including those by Adunya and Benti (2020), Arora (2019), and Berhane (2018).

RCP4.5 represents a moderate climate change scenario where greenhouse gas emissions stabilize by mid-century, leading to a relatively lower increase in temperature and less severe water-related hazards than RCP8.5. On the other hand, RCP8.5 represents a high-emission scenario with continued increases in greenhouse gas emissions, resulting in more extreme temperature rises and significantly more severe drought and flood events. Consequently, agricultural yield losses under RCP8.5 are projected to be substantially higher than under RCP4.5, as more intense and frequent water-related hazards directly affect crop productivity.

Floods and droughts can affect agricultural yield in several ways. Yield loss due to flooding can be caused by oxygen deficiency (Pedersen et al. 2017), pathogen proliferation (Elad and Pertot 2014; Martínez-Arias et al. 2022), nutrient leaching (Mo'allim et al. 2018; Salazar et al. 2014), grow delays (Xiong et al. 2019), and combined flood-drought stress (Gao et al. 2019; Qian et al. 2020). Drought-induced yield loss can result from reduced water availability (Žalud et al. 2017), photosynthesis impairment (Zargar et al. 2017), oxidative stress (Hussain et al. 2019), growth and developmental changes (Danilevskaya et al. 2019), and heat stress (Chukwudi et al. 2021). These causes of yield loss induced by flood and drought are predicted to continue and intensify if no measures are implemented to combat climate change.

Forests have been proven to mitigate yield loss, as demonstrated in scenarios SC1 and SC2, which highlight the protective effect of reforestation. Forest ecosystems provide vital water regulation services, protecting the forested areas and downstream regions utilized for agriculture, settlements, and other land uses from water-related hazards. However, agricultural expansion, as seen in scenarios SC3, SC4, and SC5, leads to significant deforestation, increasing vulnerability to drought and threatening food security. This underscores the critical balance between land use for agricultural expansion and the maintenance of forest cover to safeguard crop yields against climate-induced hazards. Additionally, it highlights the potential of reforestation as a viable solution to enhance resilience and ensure sustainable food security.

3.2.2. Role of reforestation reducing water-related hazards and improve food security

Even though climate change is likely to lead to a more variable climate and an increased probability of extreme water-related hazards, which will increase agricultural yield losses, many studies have shown that several measures can help cope with this inevitable situation. One of the suggested climate change adaptation measures is reforestation (Hobbs et al. 2016; Ivetić and Devetaković 2016; Locatelli et al. 2015).

Reforestation emerges as a pivotal strategy in mitigating the adverse effects of climate change on agriculture. Scenarios SC1 and SC2 demonstrate that reforesting headwater and sloped areas can substantially reduce yield losses from floods and droughts. The high effectiveness of reforestation in these areas suggests that strategically placing forests is essential for maximizing their protective benefits. This finding emphasizes that forests are crucial in reducing flood and drought impacts and improving food security. By enhancing soil structure and increasing its water-holding capacity (Ding et al. 2023; Jourgholami et al. 2019), forests reduce surface runoff (Slamet et al. 2021), minimizing flood risks. Tree roots stabilize the soil and increase infiltration rates (Archer et al. 2016), reducing the likelihood of flash floods. Furthermore, forests act as natural sponges, absorbing excess rainfall and slowly releasing it, thereby maintaining stream flow during dry periods and mitigating drought impacts.

Specifically, scenario SC2, which involves extensive reforestation efforts, shows a pronounced reduction in yield loss due to drought compared to flood scenarios. This indicates that forests play a more crucial role in combating drought-induced yield loss, likely due to their ability to improve soil moisture retention and reduce surface runoff.

Furthermore, the contrast between reforested scenarios (SC1 and SC2) and agricultural expansion scenarios (SC3, SC4, and SC5) underscores the detrimental impact of deforestation. The significant increase in yield loss due to drought in deforested areas highlights the importance of maintaining forest cover to ensure food security. This evidence strongly supports policies and practices that promote reforestation and sustainable land use to enhance resilience against water-related hazards.

In addition to reforestation, Arunrat et al. (2022) highlight the need to adapt crop patterns in Northern Thailand to address future climate challenges. They note that rice is susceptible to climate change, while maize, soybeans, mung beans, and cassava are less affected. Therefore, changing crop patterns is suggested to better cope with the expected climate impacts. Furthermore, selecting climate-resilient commodities and modifying specific climate stress tolerance (Rivero et al. 2022) have also been recommended by several studies to enhance survival in an unpredictable future.

In conclusion, reforestation, as depicted in scenarios SC1 and SC2, does not reduce crop yield by decreasing the agricultural area; instead, it can increase crop yield by reducing the probability of yield loss due to water-related hazards. In contrast, deforestation, as depicted in scenarios SC3, SC4, and SC5, tends to decrease crop yield by increasing yield loss from water-related hazards. Climate change exacerbates this situation by increasing the frequency and severity of water-related hazards such as floods and droughts, further impacting yield loss. For clarity, the relationship between reforestation, deforestation, climate change, and yield loss are summarized in **Table 6**.

While this study provides valuable insights into the impacts of climate change and the benefits of reforestation, it has several limitations. Firstly, the study relies on historical data and model projections, which may not account for all variables or future uncertainties. Secondly, the scenarios (SC1 to SC5) are simplified representations and may not capture the full complexity of real-world land use changes and climate dynamics. Additionally, the study focuses on specific crops and geographic regions, which may limit the generalizability of the findings to other contexts and crop types.

Table 6. Relationship of reforestation, deforestation, climate change, and yield loss

Scenario	Impact on crop yield
Reforestation (SC1 and SC2)	Crop yield loss reduced
Deforestation (SC3, SC4, and SC5)	Crop yield loss increase
Climate change	Variable impact

Future research should address these limitations by incorporating more comprehensive models that consider various variables and uncertainties. Long-term empirical studies are needed to validate the projected impacts of reforestation and other adaptation measures across different regions and crop types. Moreover, future studies should explore the socio-economic aspects of implementing large-scale reforestation, including the costs, benefits, and potential barriers to adoption by local communities. Finally, interdisciplinary research that integrates ecological, agricultural, and socio-economic perspectives will be crucial in developing holistic strategies to enhance resilience to climate change.

4. Conclusions

This study underscores the critical impact of climate change and land use on agricultural productivity in the Upper Nan Watershed (UNW). Data show drought, exacerbated by climate change, threatens crop yields more than floods, especially for rice and maize. Reforestation, as seen in scenarios SC1 and SC2, significantly reduces yield losses from floods and droughts by 20–30% for rice and 40–50% for maize, compared to deforestation scenarios that increase yield losses by 35–45% for rice and up to 60–70% for maize. Reforestation enhances soil moisture retention and reduces runoff, while deforestation does the opposite. These findings highlight the need to balance agricultural land use with forest conservation for long-term food security. The impacts in the UNW are relevant to similar regions like Laos, Vietnam, and Cambodia, where reforestation and sustainable land use can mitigate agricultural vulnerability to climate change. Policymakers in mainland Southeast Asia must prioritize these practices to enhance resilience against water-related hazards and ensure agricultural stability. Collaborative efforts can share best practices and resources to implement these strategies effectively. Reforestation and sustainable land use not only mitigate hazards in the UNW but also offer a broader regional strategy for a more resilient and secure agricultural future.

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