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RESPONSE OF MAIZE YIELD UNDER DIFFERENT CLIMATIC AND PRODUCTION CONDITIONS IN VIETNAM

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ABSTRACT

Maize (Zea mays. L) is the second most valuable cereal crop in Vietnam as well as in the study area, a province in the North of Vietnam. It is grown at two different growing seasons, during winter (winter maize, grown from September till January) and spring (spring maize, grown from February till May). Maize is currently indeed more important than ever because of increasing food demand which is caused by increasing population in Vietnam. Nonetheless, the climate variability drives various challenges such as flooding and droughts in recent years, which are two principal abiotic stresses on maize production in Vietnam.

To identify the influence of climate variability on maize production, the study used DSSAT-CERES-maize model version 4.5 to simulate maize growth and yield. Additionally, the AGRICLIM model was applied to analyze changes in adverse weather conditions by indicators. To run the CERES-Maize model requires four main individual input data sets which are daily weather parameters, soil and crop characteristics, and agronomic management information. Additionally, field experiment data were used for calibration of crop parameters to ensure the simulation accuracy. The field experiments were conducted by Nguyen Huu Hong in 2008 (N.H.Hong, 2008) for two seasonal maize crops, during the spring and winter 2008 in Dong Hy district, Thai Nguyen province. To validate the model, annual observed maize yields (yield statistic reports) during a period of 15 years from 2000-2014 were used to compare with simulated maize yields. The performance of the simulated results afterwards were statistically assessed by the Normalized Root Mean Square Error (NRMSE). The NRMSE values proved that DSSAT-CERES-Maize reproduced crop growth parameters well, with the NRMSE values in a range between 19.4% and 10.3%, however, showing a better performance in spring maize simulation than in winter. Furthermore, the results also indicated the critical role of irrigation for good maize yields during the 15-year period and the influence of different soil types on maize yields. This evidence is expressed, for example, by a decline in simulated maize yields under rainfed conditions, where maize yields were reduced or crop failure occurred by lack of water for germination.

To simulate the maize production perspective till 2100, the study applied climate change scenarios, in specific the Representative Concentration Pathways RCP 4.5 and RCP 8.5, which are stabilized to limit radiative forcing at 4.5 and 8.5 W m^{-2}, respectively. The results show (under unchanged current crop management options such as used cultivars) that annual production of maize (incl. winter and spring maize) from 2035-2100 are slightly lower than in the past (reference period 2000-2014), caused by the balance of decreasing spring maize and increasing winter maize yields. However, taking into account the average of yearly maize yields over the whole period of

100 years, it was determined to be higher than the average of observed annual maize yields in the period (2000-2014) of about 1.1% under RCP 8.5 and 3.6% under RCP 4.5. Winter maize yields were calculated to increase up to 33.3% and 31.9% under RCP 4.5 and RCP 8.5, respectively, while spring maize yields, in opposition, decreased under both climatic scenario conditions, RCP 4.5 and RCP 8.5, by -30.3% and -33.9%, respectively. These results are mainly correlated with a higher number of dry days and less precipitation in spring compared with winter contribute to maize yield decline.

Additionally, due to climatic change conditions in the future, N leaching is projected to decrease considerably in spring season due to less precipitation, where it slightly increases in the winter season. Approximately 70% of total N leaching in spring seasons is less than 41 kg ha^{-1} while approximately 70% of N leaching in winter seasons is higher than 56 kg ha^{-1} under RCP 4.5. Likewise, N leaching in spring seasons is lower than in winter seasons under RCP 8.5. This is consistent with the higher number of dry days in spring seasons compared to winter season in the next decades up to 2100 under both climate change scenarios (RCP 4.5 and RCP 8.5), as calculated by AGRICLIM.

To adapt to the changed climate conditions in the future, it is necessary to foresee new approaches that would mitigate severe weather effects and improve crop productivity such as planting date changes, intercropping cultivations, mulch applications and additional irrigation.

Keywords: Climate variability, climate change, maize production, Vietnam, DSSAT-CERES, RCP 4.5, RCP 8.5.

ZUSAMMENFASSUNG

Mais (Zea mays. L) ist die zweitwichtigste Körnerfrucht in Vietnam sowie im Untersuchungsgebiet, einer Provinz im Norden Vietnams. Er wird in zwei unterschiedlichen Jahreszeiten angebaut, im Winter (Wintermais, September-Jänner) und im Frühjahr (Frühjahrsmais, Februar-Mai). Mais ist aufgrund der wachsenden Bevölkerung und damit steigender Nachfrage nach Lebensmitteln in Vietnam wichtiger denn je. Die Klimavariabilität in Vietnam in den letzten Jahren führte jedoch zu zunehmenden abiotischen Stressfaktoren für Mais wie Überschwemmungen und Trockenheiten, die die Maisproduktion in Vietnam beeinträchtigten.

Um den Einfluss von Klimavariabilität auf die Maisproduktion zu erfassen, wird in der Studie Mais mit dem DSSAT-CERES Maismodell Version 4.5 simuliert. Zusätzlich wird das AGRICLIM Modell zur Analyse von Änderungen ungünstiger Witterungsbedingungen mittel Indikatoren eingesetzt. Die Datenanforderungen zur Durchführung der Simulation mit dem CERES-Maize Modell umfassen vier Arten von Eingabedaten, nämlich tägliche Witterungsparameter, Boden- und Pflanzeneigenschaften und produktionstechnische Informationen. Zusätzlich wurden Messdaten aus Feldversuchen für die Kalibrierung der Pflanzenparameter verwendet, um die Simulationsgenauigkeit sicherzustellen. Die Feldversuche wurden von Nguyen Huu Hong (2008) in den zwei saisonalen Wachstumsperioden, Frühjahr und Winter 2008, im Distrikt Dong Hy, in der Provinz Thai Nguyen, Vietnam, durchgeführt. Um das Modell zu validieren, wurden Durchschnittswerte jährlicher Maisertragsdaten aus Ertragsstatistiken von 15 Jahren (2000-2014) verwendet, um sie mit simulierten Maiserträgen zu vergleichen. Die Güte der simulierten Ergebnisse wurde anschließend mit dem normalisierten mittleren quadratischen Fehler (Normalized Root Square Error, NRMSE) statistisch bewertet. Die NRMSE-Werte zeigen, dass das DSSAT-CERES-Maismodell gute Ergebnisse liefert, wobei die NRMSE-Werte in einem Bereich zwischen 10,3% und 19,4% lagen und beim Frühjahrsmais bessere Ergebnisse erreicht wurden. Die Ergebnisse unterstreichen auch die wichtige Rolle der Bewässerung für gute Maiserträge in den 15 Jahren der Referenzperiode (2000-2014) und den Einfluss verschiedener Bodentypen auf den Maisertrag. Die Ergebnisse zeigen zum Beispiel einen Rückgang der simulierten Maiserträge ohne Zusatzbewässerung bzw. einen Totalausfall durch fallweise Verhinderung des Feldaufgangs durch Trockenheit.

Um die Perspektive der Maisproduktion im Jahr 2100 zu simulieren, verwendete die Studie Klimaszenarien, die sogenannten Repräsentativen Konzentrationspfade RCP 4.5 und RCP 8.5, die stabilisiert sind, um den Strahlungsantrieb bei 4.5 bzw. 8.5 W m^{-2} zu begrenzen. Diese

Ergebnisse zeigen, dass die Jahresproduktion von Winter- und Frühjahrsmais zusammen (bei gleichbleibender Produktionstechnik wie genutzte Sorten, usw.) in der fernen Zukunft (2035-2100) im geringfügig niedriger sein würde als in der Gegenwart (Bezugszeitraum 2000-2014), bedingt durch die Bilanz sinkender Erträge bei bei Frühjahrsmais und entsprechend zunehmender Erträge bei Wintermais. Berücksichtigt man jedoch den Durchschnitt der jährlichen Maiserträge über den gesamten Zeitraum von 100 Jahren (2000-2100 Klimaszenariendaten), zeigt sich, dass der simulierte Jahresertrag (gemittelter Winter- und Frühjahrsmaisertrag pro Jahr) beim RCP 8.5 Klimaszenario etwa +1,1% und beim RCP 4.5 Klimaszenario um 3,9% über dem Durchschnitt der beobachteten jährlichen Maiserträge (Referenzperiode 2000-2014) liegt. In beiden Fällen wird dabei ein deutlicher Anstieg der unbewässerten Wintermais-Erträge simuliert, nämlich eine Zunahme der Wintermais-Erträge um 31,9% unter dem Klimaszenario RCP 8.5 und um 33,3% unter dem Klimaszenario RCP 4.5. Die Erträge bei unbewässerten Frühjahrsmais hingegen zeigen einen starken Rückgang unter den beiden Klimaszenario-Bedingungen RCP 4.5 und RCP 8.5 um 30.3% bzw. 33.9%. Dieses Ergebnis ist durch eine deutliche Zunahme der Anzahl von Trockentagen und geringeren Nierschlägen in der Frühjahrsmaissaison im Vergleich zur Wintermaissaison bedingt.

Aufgrund der veränderten klimatischen Bedingungen wird die N-Auswaschung in der Frühjahrssaison aufgrund der geringeren Niederschläge voraussichtlich deutlich zurückgehen und in der Wintersaison leicht ansteigen. Etwa 70% der N-Auswaschung beim Frühjahrsmais beträgt weniger als 41 kg ha^{-1}, während 70% der N-Auswaschung in den Wintermonaten mehr als 56 kg ha^{-1} unter RCP 4.5 beträgt. Ebenso ist N-Auswaschung im Frühjahr niedriger als in den Wintersaisonen unter RCP 8.5. Dies steht im Einklang mit der höheren Anzahl trockener Tage in der Frühjahrssaison im Vergleich zur Wintersaison in den nächsten Jahrzehnten bis 2100 unter beiden Klimaszenarien (RCP 4.5 und RCP 8.5), die von AGRICLIM simuliert wurden.

Um sich zukünftig an die veränderten Klimabedingungen anpassen zu können, müssen neue Anpassungsmaßnahmen vorgesehen werden, welche die Auswirkungen extremer Witterungsbedingungen abschwächen und die Pflanzenproduktivität verbessern, wie z.B. Änderung der Anbauzeitpunkte, Mischkulturen, Mulchsysteme und zusätzliche Bewässerung.

Schlüsselwörter: Klimavariabilität, Klimaszenarien, Maisproduktion, Vietnam, DSSAT-CERES, RCP 4.5, RCP 8.5.

ORGANIZATION OF THE THESIS

The Ph.D. thesis is organized into 5 chapters.

Chapter 1: Introduction

General information about climate, soil conditions and maize production in Vietnam and general information about the study area is introduced in this first chapter.

Chapter 2: Literature review

Overview of study is arranged into several parts.

* Climate and climate change in global scale and regional scale

This section is about the global climate system, regional climate systems, besides, partly introduces climatic conditions and their influence in agriculture as well as in maize production.

* Prior studies about maize production worldwide and in Vietnam

Maize is grown worldwide. Therefore, numerous studies about maize have been carried out by various places from temperate regions to tropical and arid regions. This part takes an overview of the studies about maize productions and things about it.

* Crop modeling and its role in crop management in future

This section is about the approach to study maize production and crop modeling. This is based on the development of crop models worldwide. This trend develops in future is a novation as well as a vision further.

Chapter 3: Materials and Methods

Input data and methods for study are presented in detail in this chapter. Each step to carry out the study is described in this section.

Chapter 4: Results and discussion

To address the objectives and research questions, the results answer the questions about the signs of climate change in the study, the impact of climate conditions on maize production. Finally, the results show up the perspective of maize production in the future under climate change scenarios with various aspects from other studies around the same topic.

Chapter 5: Conclusions and recommendations

In this section, the results are concluded in a brief content with some suggestions and recommendations for further research as well as farming options.

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I. INTRODUCTION

1.1 Introduction

1.1.1 Vietnam and its weather system

Vietnam is located in the East of the Indochina Peninsula with an entire interior area about 329,241 km^2. In terms of administrative subdivisions, Vietnam is divided into 58 provinces and 5 municipalities (Kuntiyawichai et al., 2015).

Due to the elongated shape from 8ºN to 23ºN through 15 latitudes with the coastline about 3,260 km, Vietnam' climate is generally affected by the ocean climate system that combined with the influence of diverse terrains (Nguyen-Tien, Elliott, & Strobl, 2018).

In addition to the difference of horizonal climate zone, Vietnam' climate can be deivided by Hai Van Pass at 16ºN and listed by 7 sub-regions, which based on the various patterns of topography. Their symbols are R1 to R7 (Nguyen & Nguyen 2004), as shown in Fig. 1. From Hai Van Pass towards the north (R1, R2, R3, and R4), weather is distinct to four seasons in a year, including spring (February to April), summer (April to September), autumn (September to October) and winter (November to February).

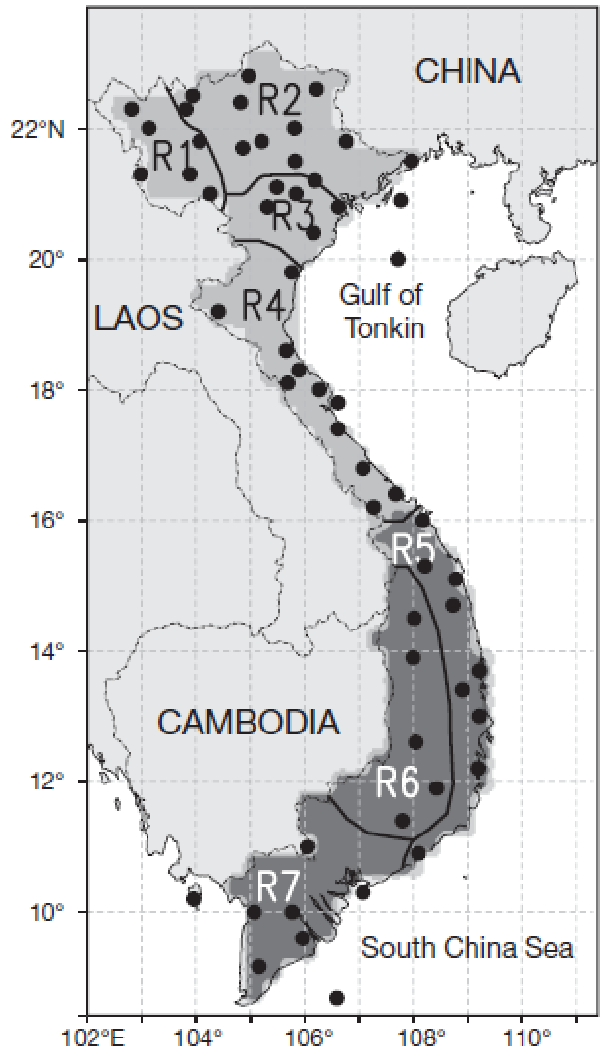


Fig. 1. Climatic Sub-regions in Vietnam (Nguyen & Nguyen 2004)

Differently, from Hai Van Pass towards the south (R5, R6, and R7), there are only two main seasons, which are the dry season (November to April) and the rainy season (May to October) (Thi-Minh-Ha et al., 2011).

To forecast the weather, Vietnam has a total number of 138 weather stations for 329,241km^2 with the average density approximately 2385.8 km^2 station^{-1}. However, there is a huge disparity of the weather station density between highland areas and the other areas, which was reported by the Vietnamese National Weather Service Center in 2014. The averaged density in the highland area is approximately 2815.8 km^2 station^{-1}, and be lower than 430 km^2 compared with the national average density. In comparison with the density which the World Meteorological Organization (WMO) claimed for a mountainous area, 250-575 km^2 per station, the averaged density in the highland area in Vietnam remains much lower than recommended density (Ecole & Sup, 2014).

1.1.2 The study area

Thai Nguyen province, the study area, is a mountainous province and locates in the north of Vietnam (Fig. 2). The province covers an area of 3536.4 km^2 with around 1.227 million people, therein, approximately 65% of habitants living in rural areas (reported by General Statistic Office of Vietnam, 2016). In terms of administration, Thai Nguyen is divided into 9 sub-divisions which include 1 capital of the province (namely Thai Nguyen city), 6 districts (namely Dai Tu, Dinh Hoa, Dong Hy, Phu Binh, Phu Luong, Vo Nhai), 1 town (namely Pho Yen), and 1 provincial city (namely Song Cong).

Thai Nguyen is considered a capital education for people who are living in the mountainous areas in the north of Vietnam. The province is also known as an industrial zone because of many factories and mineral mines. In recent years, Thai Nguyen is famous for its biggest mine, Nui Phao mining which is known as the world’s largest tungsten (Wolfram, W) mine. The reserve of the mine was estimated approximately 66 million tons as the report of Masan Resources group in 2012. Besides, Thai Nguyen province is famous for some agricicultural products such as tea, rice and maize (see Fig. 4a). Thai Nguyen’ green tea products are considered the best tea products in Vietnam.

Due to the location and stratified by climate conditions, Thai Nguyen province belongs to the region R2 (see Fig. 1) which has a typical characteristics of the sub-tropical climate. This means Thai Nguyen' weather is affected by Southwest monsoon compared with the influence of a complex topographies (Thi-Minh-Ha et al., 2011). The topography is characterized by high hills and moderate mountains in the northern part and the southwest part of the province. In the center and the southeast regions, the topography is generally considered as the midland region of the province which is not as high as in the northern regions, where almost all local residents are settled (Thai Nguyen, 2015).

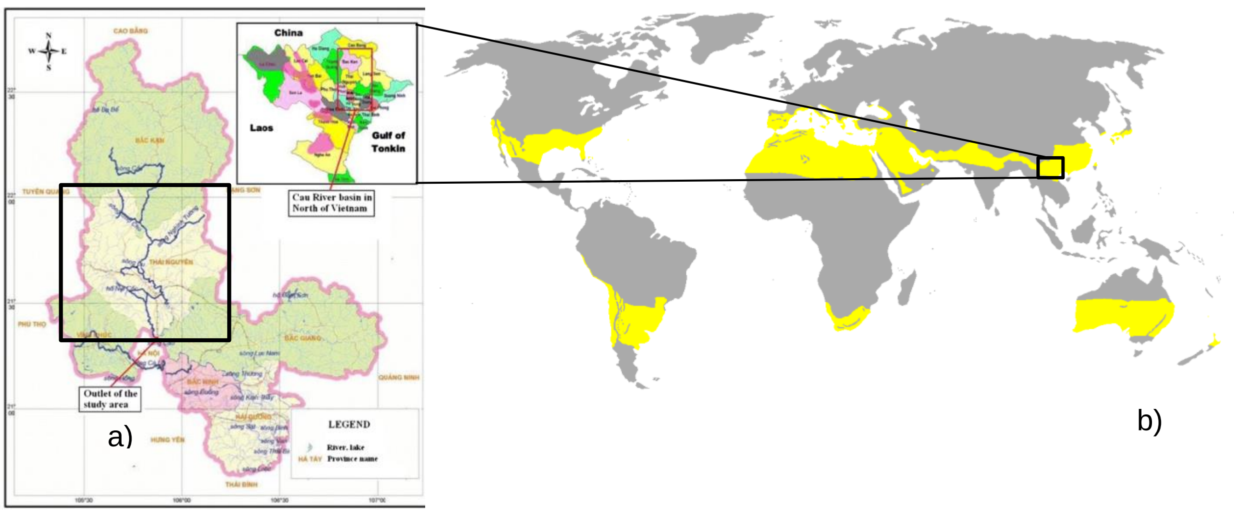


Fig. 2. Thai Nguyen location and Cau river (Ha Ngoc et al., 2015)

In terms of the hydrological system, Thai Nguyen occupies a part of a river flowing through the province, namely the Cau river. The river supplies a large amount of irrigation for agriculture by delivering water into numerous streams and channels for irrigation. However, the huge rainfall amount in summer still causes flooding and damages to the local agriculture and local infrastructure, especially in areas which are near the Cau River Basin (Ha Ngoc et al., 2015).

1.1.3 Maize physiology and production

Maize (Zea mays L.), a C4 plant also well-known as corn, is cultivated around the world under a wide range of climates. Mexico is known as one of the maize origin centers (Mickleburgh & Pagán-Jiménez, 2012).

Maize can grow in the temperate climate and have suitable rates of dry weight and leaf area accumulation within a range of temperatures between 16 and 28 °C (Hardacre & Turnbull, 1986). In tropical regions, the optimum leaf appearance temperature and leaf photosynthesis are in the range of 32 to 35 °C (Kim et al., 2007). Maize, therefore, can grow at higher temperatures in comparison to the other cereal crops and is therefore suitable for warmer conditions. However, excessively hot temperature or even moderately cool night temperature can become a limiting factor which impacts on maize growth processes such as photosynthesis. Especially, heat negatively affects fertility during pollination, with negative consequences for grain yield. The canopy exchange rate (in line photosynthesis activity) of maize starts to decrease at temperatures over 35 °C and extremely decreases in the case temperature is more than 38-39 °C (Kim et al., 2007). Likewise, maize seed emergence is best derived under the ceiling temperature conditions from 28.9 to 30.0 °C and starts to decrease at 39.1-40 °C (for leaf production), as a result in a study case in Iran (Edalat & Kazemeini, 2014) while the minimum soil temperature for germination is from 8-9 °C (European cultivars). Generally, the major impact of warmer temperatures is on the reproductive stage of development (Hat & Prueger, 2015). However, in some cases, heat stress does not affect the silking stage, at least in the range of air temperature up to 42.9 °C on the field and 52.5 °C in the greenhouse (Lizaso et al., 2018) or have no effects on the silking-anthesis interval (Shim et al., 2017).

In addition to the influence of temperature, water is considered one of the most important elements which strongly affect maize growth. In theory, the rainfed maize is cultivated successfully in Thai Nguyen because maize requires 300-700 mm well distributed precipitation during growing period (depending on yield level, soil and climate conditions) (Eitzinger et al., 2009).

Being the primary feeding source for livestock and poultry production, maize is the second most important cereal crop in Vietnam. However, caused by typical climate systems and topographic characteristics, maize is mostly cultivated in the north of Vietnam, sharing 70% of the total maize area, in which 50% is cultivated in northern Midlands and mountainous areas with two or three crops per year (USDA, 2012; USDA, 2014; USDA, 2015). In addition, maize is grown under rainfed conditions or limited irrigated conditions in Vietnam instead of the optimum irrigated conditions.

1.1.4 Types and uses of maize

Maize can be used for a variety of food and industrial products because maize contains approximately 72% starch, 10% protein and 4% fat (Ranum et al., 2014). The protein quality (relative content of casein) of a common maize is at 32 %, which is much lower than rice, and approximately equals to wheat and sorghum with 79.3, 38.7, and 32.5 %, respectively (FAO: http://www.fao.org/docrep/T0395E/T0395E03.htm). In addition, a yellow-maize contains a high concentration of pro-vitamin A that can be converted into vitamins by animal tissues. Therefore, maize is used as human food. Moreover, maize is also used in the pharmaceutical industry and drink industry. In addition to human food and animal feeding application, maize is used in paper and textile industries to enhance the strength of papers or warp yarns. That's why maize currently becomes a very important crop to meet the demand of food, feed, and biofuel. In 2013, maize is the second of top five crops produced after sugar cane (FAO, 2015).

In Vietnam, farmers currently use various maize types and cultivars, comprising different ripening groups (Fig. 3 a-d). Hybrid maize is usually used for livestock because hybrid maize grains are typically harder, bigger, and have suitable physical properties in dry milling than the other cultivars' grains. With the dark yellow kernels, hybrid maize cultivars are easily distinguished with the others (Fig. 3a).

a) Hybrid maize namely LVN61
(Source: http://hpstic.vn/news/Giong-ngo-lai-LVN61-16696.html)

b) White sticky maize namely NL556
(Source: http://news.kit.com.vn/2018/02/28/giong-ngo-nep-vn556/)

c) Yellow sweet maize
(Source: https://hatgionglucky.com/san-pham/ngo-ngot-thai-lan/)

d) Purple sticky maize
(Source:https://hatgiongbansi.com/san-pham/hat-giong-ngo-nep-tim-2/)

Fig. 3 a-d. Various maize types grown in Vietnam

A hybrid-maize is widely grown with flexible planting dates and different topographies in Thai Nguyen, Vietnam. Therefore, in comparison with sticky maize, a hybrid-maize has a longer growing period and more tolerant of drought stresses. Similar to a hybrid-maize, a sweet-maize has light yellow kernels. Nevertheless, sweet maize kernels are soft and sweet. A sweet-maize is commonly planted in recent years in local regions, especially in winter season. A white-sticky-maize is the local cultivar that is often used for human food. Its physical properties are similar to sweet maize however, they have different colors and are sticky. A white-sticky-maize is usually grown in the winter season while the purple sticky maize is newly and rarely found in Vietnam. In the 2010s, Vietnamese scientists and farmers improved various hybrid genotypes with shorter growing periods than before. Those new genotypes were examined in experiment fields before transferred to farmers in large scales. Most of the varieties require 117-130 days from sowing to harvest (Nguyen and Phan, 2010; Tran et al., 2012).

1.1.5 Agriculture and cropping systems in Nguyen province

Within 6 years (2005-2010), agriculture occupied approximately 95% of total gross outputs of agricultural sectors which involved forestry and fishery sectors in Thai Nguyen province, therein, the value of cereal crops (rice and maize) was approximately 50% of total output cultivation value that involved other crop groups such as perennial crops/industrial crops, fruit crops, vegetable crops (Thai Nguyen, 2010). Meanwhile, the planted maize areas occupy approximately by 20% in the total planted cereal crop area (Thai Nguyen, 2010).

Farmers mostly bred and used local varieties by themselves in the past. However, in recent decades, farmers have started using hybrid genotypes instead of local cultivars. The reason is that the hybrid maize has improved characteristics such as high yield and high content of starch. However, they have less flavor and too hard for the human diet. Due to the maize varieties, maize is partly used for human food and mostly used for livestock feed in the local region.

In the hilly area, perennial crops such as tea and cassava (Fig. 4a,b), are usually prior to growing instead of vegetable crops (Fig. 4d,e) or rice (Fig. 4c) because they require lower investment of irrigation systems. Therefore, in the highland of the province, maize is a sole crop which mostly grown under rainfed condition (Fig. 4f). In the flat area, rice, maize, and other vegetable crops are usually cultivated in 3-seasonal-crop rotations. However, rice is prior to cultivating in summer which is the rainy season because of a higher market price. Maize is therefore mainly grown at the other growing seasons which are winter (September or October to next January) and spring (February to May) with planting dates are set up due to specific weather conditions, field locations, irrigation conditions, soil conditions, and seasonal cropping systems. Hence, there are various maize planting dates in the local fields.

a) Tea

b) Casava

c) Rice

d) Vegetables

e) Soybean

f) Maize

Fig. 4. (a-f) Some various crop productions in Thai Nguyen province, Vietnam (Source: photo (a-e): Josef Eitzinger et al., 2018; photo (f): Thi Mai Anh Tran, 2016)

The planted maize area has been increased over the years. Over 20 years from 1995-2015, the planted maize area was increased 4 times from 5.2 thousand ha in 1995 to 21.0 thousand ha in 2015. As a consequence, maize production increased significantly from 10.1 thousand tonnes in 1995 to 88.0 thousand tonnes in 2015. In combination with the increase of the planted area, some other factors such as new varieties, new methodologies, and a higher investment might also contributed to an increase in maize production as well as an increase in maize yield (Tab. 1)

Table 1. Maize production in Thai Nguyen province, Vietnam

Agro-ecology	1995	2000	2005	2010	2015
Area (thousand ha)	5.2	10.7	15.9	17.9	21.0
Production (thousand tonnes)	10.1	30.8	55.1	75.2	88.0
Yield (kg/ha)	1940	2880	3470	4200	4190

(Data based on https://www.gso.gov.vn)

1.2 Problem statement

Indeed, Vietnam is well-known as one of the abundant biodiversity countries with ideal opportunities for bio-economic development, particularly the agricultural sector. However, numerous studies have been determined that Vietnam is one of the most vulnerable countries regarding climate change and climate variability because Vietnam is currently affected by adverse impacts of natural hazards such as droughts, floods, typhoons, and heavy rain (IPCC, 2007; FAO, 2014). One of the reasons is that Vietnam is a coastal country to the west of the Pacific Ocean in the eastern region of Southeast Asia. By a long coastline in the tropical monsoon belt to the east, Vietnam is therefore extremely affected by intense tropical cyclones.

In average, there are six to eight cyclones, affecting Vietnam every year, as reported by The United Nations Development Program. Since 1954, Vietnam has witnessed about 212 storms which left the country enormous damages in terms of population, infrastructure, houses, industrial areas, and seafood farms. Over the last few decades, the frequency and intensity of tropical cyclones originating in the Pacific have increased even more than ever (Daidu & Congxian, 2006). Most tropical cyclones cause strong winds and heavy rains that can drive into secondary hazards such as floods, typhoons, and salinization in Vietnam. Since 2015, the rising sea level has caused extreme salinization of coastal aquifers (Briefs & Earth, 2015). From 1985-1989, the number of typhoons hitting Vietnam was almost half that of the Philippines, but higher than Thailand. These hazards strongly influenced human life in Vietnam, especially farmers' livelihood who living from fishery (Kuntiyawichai et al., 2015). In addition to floods and typhoons, the frequency of heavy rains has been recently also higher than before in most sub-regions of Vietnam. Over the past 50 years, in the south of Vietnam rainfall showed a strong increase from 5 to 20% throughout the year (Russell, 2011). The number of heavy precipitation above 50 mm with increasing very wet days was detected to increase at most stations, left the country 4,884 deaths by floods, cost 3.7 million USD (data based on EM-DAT, 2015; https://www.emdat.be/). In 2016, heavy rain events were one of the main causes of extreme urban flooding in Ho Chi Minh city (Nguyen & Thi, 2016).

In contrast, in the north of Vietnam, rainfall decreased by 5 to 10% in wet seasons (Russell, 2011). This declination of precipitation in the north and the central highlands of Vietnam was recently detected the main reason of drought in the other studies (Thi-Minh-Ha et al., 2011, Briefs & Earth, 2015, Dijk & Rooij, 2014). Droughts occur in dry seasons while floods occur in rainy seasons. Moreover, the adverse influence of this prevailing condition is notable to the regions in which high temperature combined with a long duration under water stress.

Overall, the high temperature is common in summer combined with heavy rain in Vietnam. In recent years, the maximum temperature has reached nearly 40 °C, which was higher than the average level over the last decades. Nguyen et al. (2013) indicated that the average of temperature increased 0.26 °C per decade since the 1970s, possibly related to El Niño -Southern Oscillation across the country (Nguyen et al., 2014). On the other hand, the temperature increases not only due to elevated global atmospheric greenhouse gas (GHG) levels but also due to land use change effects. Indeed, land use change can have strong regional effects on air temperature, as it was shown that in tropical regions, land use change from forests to agriculture can increase regional air temperature due to change (Hu et al., 2015). Also increasing urban areas can lead to regional temperature increase albedo (urban heat island effect) (Zhang & Liang, 2018). In China, urbanization and other land use changes such as deforestation were found out to contribute to an increase in the daily mean temperature of 0.12 °C per decade (Jingyong et al., 2005). This finding was proved by many other studies all over the world. Land use change which drives an increase in temperature of 0.5 °C and a reduction in rainfall of 0.17 mm/day across the Amazonian regions, likely figured out by the declination of the extent of Amazon rainforest (Lejeune et al., 2015). Besides, a dramatic decrease in deforestation during the long period of more than 34 years correlated significantly to spatial variabilities of the number of rainy days and to increased temperatures in the Central Rift Valley of Ethiopia (Muluneh et al., 2017). The influence of prevailing weather conditions has been more or less negatively impacting on agriculture, particularly irrigation in Vietnam (Trinh et al., 2014). Besides, the land area is considered a limiting factor of food production. Therefore, to increase the total productivity under natural resource limitations is a extremely challenge (MONRE, 2008).

Under local conditions, soil properties are mostly poor in quality, therefore become a limiting factor which adversely impacts on agriculture, especially in terms of arable land use. These characteristics of the soils are obviously found in two main soil types, namely Ferralsol and Acrisol (Thai Nguyen, 2015). Defined by FAO, Ferralsols having the organic horizons with the thickness of less than 40 cm is the typical characteristic which formed under free drainage. Its parent materials can be freely leached out, leading immobilized iron in the oxidized stage, causing the smallest soil particles with yellowish or reddish colors. The oxidized iron contributes to creating a well-aerated structure with a number of porosities and most oxic horizons in clay and silt soil, leading to circulating freely of air and water though Ferralsols. In comparison with other soils, rainfall is quickly absorbed through Ferralsols soil, being convenient for root systems. However, rainfall also leaches quite faster to deeper layers as the consequence, leading to the limitation in fertilizer efficiency application. Therefore, the retention of nutrients to protect soil against losses is important in using this kind of soil type. Under the local climate conditions characterized by a huge amount of rain and the sloping topography, most of the soil types are characterized by acid property with low pH, leading to low organic matter in the north of Vietnam (MONRE, 2008). Similar to Ferralsols, Acrisols are present in hilly and mountainous areas under the humid climatic condition. They mostly have a limitation in their structure in the accumulation zone (Quesada et. al., 2010). Under local conditions, Acrisols are formed under high precipitation, high air humidity, and hilly topography conditions (Thai Nguyen, 2015).

Generally, arable land area (ALA) in Vietnam was increasing over five decades since 1961. The process of the ALA changes in Vietnam is shown in Fig. 5 (https://data.worldbank.org). In 2015, the ALA for the agricultural sector was approximately 7 millions square kilometers (m.sq.km), which was higher than the arable land area in 1961 nearly by 1.5 m.sq.km. However, in the first 30 years of the period, the ALA was not increasing but even decreasing slightly, mainly because of the expansion of urban areas. Strong increases in the ALA have been recorded in recent years. In 1990, the ALA was 5.3 m.sq.km, however it only increased by 1 m.sq.km in the short period of 10 years. From 2001 to 2010, the ALA had a slight fluctuation before increased again until 2015. The number of the increased ALA was mainly caused by deforestation in the mountainous areas in Vietnam. At present, in term of the economic aspect, the increased arable land area generously contributed to an increase in the total food production. However, in terms of sustainable development, a decline of the total forest area has caused enormous challenges which are happening nowadays. For instance, flooding in the mountainous areas occurs more frequently and intensively in a correlation with numerous different hazards that costed much more than the value of agriculture that can benefit for residents living there.

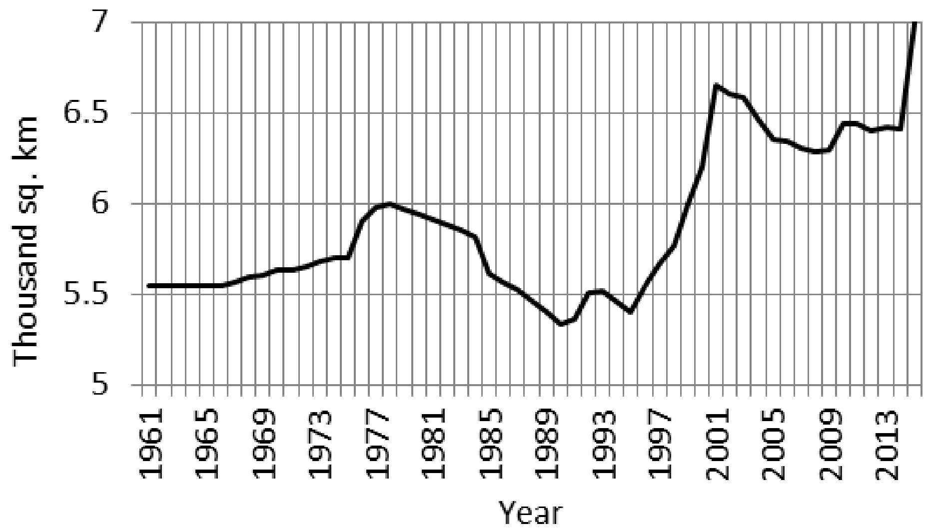


Fig. 5. Arable land use area in Vietnam. (Data based on https://data.worldbank.org)

Additionally, Vietnam is presently challenging with rapidly increasing population and environmental pollutions. In 1979, Vietnam' population was 52.7 million people. Inn 2004, the population climbed up to 81.6 million people. It is even predicted to reach 122 million in 2050 (MONRE, 2008). The huge size of residents drives the country to the secondary challenges that are partly related to pollutions and food security. As the report from Vietnam government, environmental quality, in general, is degrading to pollutions from agriculture which caused by undisposed wastes and pesticides. These issues even more notable nowadays than ever because of destroying biodiversity and reducing numbers of individuals, directly damaging many wildlife habitats, and extremely impact Vietnam socio-economic conditions (MONRE, 2008).

To cope with those challenges as well as to meet the demand of increasing population, Vietnam government has had various solutions to mitigate these severe effects. One of the major prior orientations is to increase the production efficiency, especially in the agricultural sector. On the other hand, farmers, therefore, were forced to change their traditional pathway in agriculture such as change of crop rotation, and replace wetland rice to maize because of lack of rainfall in dry season in the north of Vietnam. Over the past two decades, the arable land area of rice decreased by 27% while the total of maize cultivation was nearly triple (Keil et al., 2008). Besides, Vietnamese farmers currently tend to invest much more for their farms than in the past, especially in terms of methods and technologies to get higher productivity. However, the local maize production has still been not able to satisfy the demand in recent years (Dang et al., 2002). The reason may cause by the unfavorable weather conditions in combination with damages from insects and weeds, leading to low maize yields. Therefore, calculating and predicting effects of climate change on crop yields is important for topics ranging from food security to the socio-economic viability of the province.

1.3 Research questions

* How was the trend of climate in the last three decades in Thai Nguyen province, the mountainous area in the north of Vietnam?

* Did historical climate conditions have a positive impact on maize production over the past 30 years in the study area?

* Will climate conditions be more severe in the future than in the past? How will it impact maize production and what will be suitable adaptation options?

1.4 Research Objectives

To analyze how climate change impacts on maize production in Thai Nguyen province, Vietnam, three specific objectives are set:

(1) Analyze changing climate variability by statistical (indicator based) model AGRICLIM under current and future climate conditions (climate scenarios) in the case of the study area.

(2) Apply CERES-Maize model to simulate and analyze crop growth and yields as well as main growth limiting factors (nitrogen and water balance) under the different climatic scenarios, soil, genetic and management conditions.

(3) Analyze the potential of maize production under climate change scenarios within 100 years (2001 – 2100) and develop recommendations for adaptation options in crop management.

II. LITERATURE REVIEW

“Weather”, the short term variability of weather parameters, is commonly mentioned in human daily life to describe the actual states of the atmosphere, while “climate” in a narrow sense is usually defined as the “average weather” over a range of years (ideally a predefined 30-year period for allowing comparisons between sites) (Source: http://www.wmo.int/pages/prog/wcp/ccl/faq/faq_doc_en.html). In some regions, the weather is more or less homogeneous during the day and only exposes the difference every half of the year such as regions surround Earth' Poles. However, in most other regions on the Earth, it is visible to see the difference of weather every day caused by the appearance of sunlight during the day. Besides, there is the difference between day and night. For instance, the weather may be warmer during the day but cooler than that during the night. In addition, to present the periodic changes such as El Niño, La Niña, climate variability is defined as a short-term fluctuation on the seasonal or multi-seasonal scale. The time duration could be months to decades. To express the variation of climate in a longer duration, from decades to millennia, it is defined as climate change.

2.1 Dry and rainy seasons

2.1.1 Monsoon and its effect in East Asian countries

Summer monsoon affects East Asia including China, Japan, Korea, Indo-China peninsula (including Vietnam), and Philippines (Wang et al., 2013). The onset of summer monsoon happens in late May or June and ends in September every year (Cruz et al., 2013). In addition, some other Asian countries which are located in southeast Asia including East India, South China, Myanmar, Thailand, Vietnam, Laos, Kampuchea, Malaysia, Singapore, Indonesia, Borneo, Philippines islands, Portuguese, Timor and western New Guinea are not only affected by summer monsoon regime but are also affected by winter monsoon regime, which are namely the northeast monsoon and southwest monsoon, respectively. The northeast (summer) monsoon usually starts from late May and ends in September while the southwest (winter) monsoon usually starts from November and ends in March (Loo et al., 2015). Monsoon bring needed moisture by rainfall for agriculture, forests and habitants of the regions.

On the other hand, monsoons have some potential to cause extreme weather phenomenon, driving to secondary hazards such as flooding and soil erosion. China is affected strongly by the East Asian monsoon which brings disasters such as droughts, floods, and cold surges which adversely impacts on local life. Those disasters lead to the damages and losses of domestic products (Xue et al., 2015). Likewise, the summer monsoon brings heavy rain in summer with extreme daily rainfall events in India (May, 2004). However, in contrast to the state of monsoon in China and India, southwest (winter) monsoon over the western Philippines showed a enormous decrease in total amount of rainfall in most stations over the past 50 years, resulting in a decrease of the number of days without rainfall (Cruz et al., 2013). In addition, few studies detected a decrease of precipitation during winter monsoon season. However, in most cases, a regional precipitation increase is more common than a decrease. In addition to an increase in the average amount of precipitation, an increased trend of rainfall variability which affected by summer monsoon is also revealed in southeast Asia (IPCC, 2001b, IPCC, 2007).

2.1.2 Monsoon and its effect in Vietnam

Vietnam lies in the tropical climate zone with two main monsoon circulation systems which are the winter monsoon and the summer monsoon. They are also known as North Asian monsoon and South Asian monsoon. However, South Asian monsoon has stronger influence on Vietnam' climate than North Asian monsoon (Nguyen et al., 2014).

The onset of the winter monsoon is usually from August-September to December-January in the southern north and the center of Vietnam, meanwhile, the onset of the summer monsoon is from April-May to September-October. In Vietnam, the summer monsoon brings rainfall to most of regions. The appearance of the summer monsoon is notably in the upper northern regions of Vietnam including R1, R2, and R3 (see Fig. 1). However, there is not a clear difference between the dry season and rainy season in the north of Vietnam because there is no notable reversal of prevailing winds but light rains by the end of the dry season (April-May) (ISPONRE, 2009). Downwards to the south of Vietnam, the combination of two monsoon regimes drives to rainy season appearing in the late period of years, however, affected remarkably by summer monsoon. The summer monsoon is characterized by the deep moist convection and the change in direction of prevailing winds. The signal of the summer monsoon onset was defined therefore by the change of prevailing winds (Pham et al., 2010). Flooding is considered the consequence of monsoon dynamics over the country.

2.1.3 Pacific El Nino Southern Oscillation (ENSO)

During El-Nino years, a drier and warmer were reported to show an association with the inter-annual variations in southeast Asia (GFDRR, 2011). Nguyen et al. (2014) carried out a study which used weather data from 40 weather stations in Vietnam to indicate that averaged temperature in Vietnam had increased a range of 0.26 per decade since the 1970s, possibly related to El- Nino-Southern Oscillation across the country (Nguyen et al., 2014), shown in Fig. 6. The frequency of El-Nino was projected to increase in central equatorial Pacific, leading to increasing of Pacific El Nino Southern Oscillation (ENSO) related precipitation (Tran Thuc, 2013).

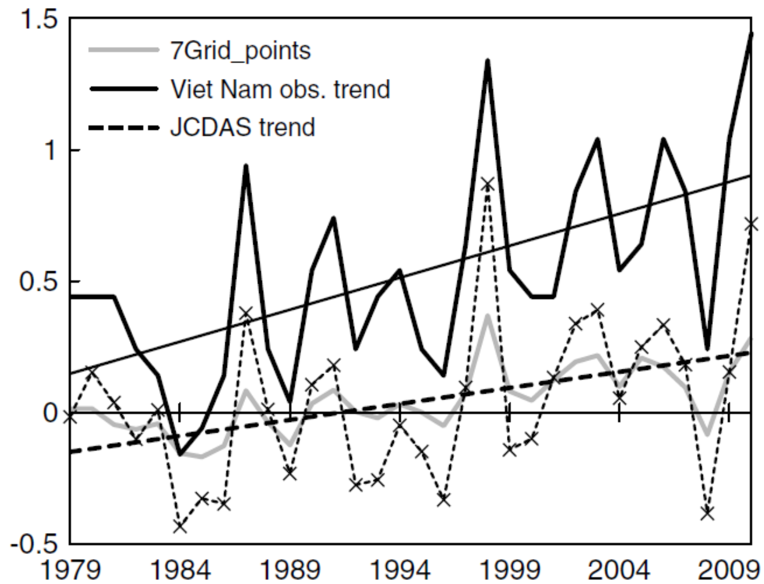


Fig. 6. Variation of observed annual average temperature anomaly (Celsius degree) (Nguyen et al., 2014)

2.2 Climate change and climate variability

Climate change and climate variability are more and more notably nowadays. Their states are mainly presented via global warming which is commonly known as the main consequence of climate change. Global warming refers to the gradual increase of observed or projected global surface temperature. Evidence of climate change and its impacts on natural systems have been proved by a huge number of studies (IPCC, 1993; IPCC, 2007; IPCC, 2013). Climate change is also widely projected for most regions on the Earth (Houghton et al., 1995; Metz & Davidson, 2007; F.Stocker et al., 2013).

Since the first assessment report of the Intergovernmental Panel on Climate Change (IPCC, 1993) which was completed in August 1990, the proofs of climate change has been more clearly in the other continuous IPCC reports (Houghton et al., 1995; Metz & Davidson, 2007; F.Stocker et al., 2013). Besides, climate change has been documented over 30 years in plenty regions in Africa such as in the West African Sahel, especially in terms of rainfall (van Duivenbooden et al., 2002), in Europe (Baldock et al., 2000), in America (W. Steffen et al., 2015) as well as in Asia and the other regions (IPCC 2001b,; IPCC, 2007; IPCC, 2013). In Canada, a roughly 30-year database demonstrated a slightly increasing trend of daily maximum temperature and a notably decreasing trend of precipitation in the months of February and March (Valeo et al., 2003).

Climate change is considered as the main reason for secondary hazards such as droughts and flooding. El Niño is one of the most common climate phenomena which is associated with anomaly climate events. For example, El Niño is frequently linked to monsoon failures in India, drought in Indonesia, flooding and heavy rains in the southwestern United States, and warmer- and drier-than-normal weather in Australia. Most of the drought events were considered as the consequences of El Niño in Australia (Johansson et al., 2015). In Africa and South America, climate change is projected to exacerbate water stress notably (Steffen et al., 2015). In many regions of Europe, climate change is projected to broaden the drought periods and aggravate resource pressures. Winter rainfall will increase, meanwhile, summer rainfall and low-flow discharges of many rivers are predicted to decrease during the dry season in some northern European countries including France, the UK, and Germany, which potentially accompanied by a huge water demand for irrigation due to more frequent droughts (Baldock et al., 2000).

Besides, climate change is responsible for a maximum monthly stream flow while decreasing organic nitrogen (El-Khoury et al., 2015), has an adverse impact on freshwater (Bates et al., 2008) and leads to the sea ice melting in high latitudes which is considered specifically as the consequence of higher temperature (Steffen et al., 2015). Thawing ice leads to less reflection of solar radiation, driving earth surfaces due to lower albedo to a higher temperature. In addition to the phenomenon of mean climate change, changing climate variability is also recorded in numerous regions worldwide.

Generally, extreme events such as droughts, floods, heat waves, and fires have been increasing in many regions. Globally, extreme weather events are expected to increase worldwide (Powell & Reinhard, 2015). However, the adverse impacts of climate change are projected more than the benefits, especially in term of fresh water and agricultural production potentials, and indirectly impacts of population growth, changing economic activity, land use change and urbanization (Bates et al., 2008).

2.1.1 Climate change and its influence in Southeast Asia

In Southeast Asia, aquaculture is critical to food security, particularly among communities in coastal areas such as in Vietnam (FAO, 2006), therefore, climate change and its influence are more notably than ever.

Average precipitation and intense rainfall events generally are expected to increase in tropical regions but decrease in the sub-tropics, except in eastern Asia. A decreasing trends in annual mean rainfall were observed in Russia, north-east and north China and the coastal belts. In addition to a change of precipitation, a gradual increase of temperature in combination with increasing drought (decreasing precipitation) was documented in Asia as presented by IPCC (2013), (Fig. 7 a,b). By this way, climate change was widespread to stress on irrigation requirement in Asia from 1900 to 2005. This issue is projected to continue in the future. Globally, an increase of irrigation requirement is predicted between 5% and 8% by 2070, with a larger amount of about 15% in Southeast Asia (IPCC, 2007; IPCC, 2013). Besides, during few last decades in Asia, changes in inter-seasonal, inter-annual and variability of rainfall has been recorded and reported (IPCC, 2007; IPCC, 2013). Besides, a decrease of the groundwater level was also recorded such as a case in Thailand. Groundwater levels decreased in Thailand coastal areas which store water diversion for shrimp ponds (Bates et al., 2008).

Generally, the negative effect of climate change is more visible in Southeast Asia, which shown by multiple socio-economic aspects, especially in terms of crop production and fishery.

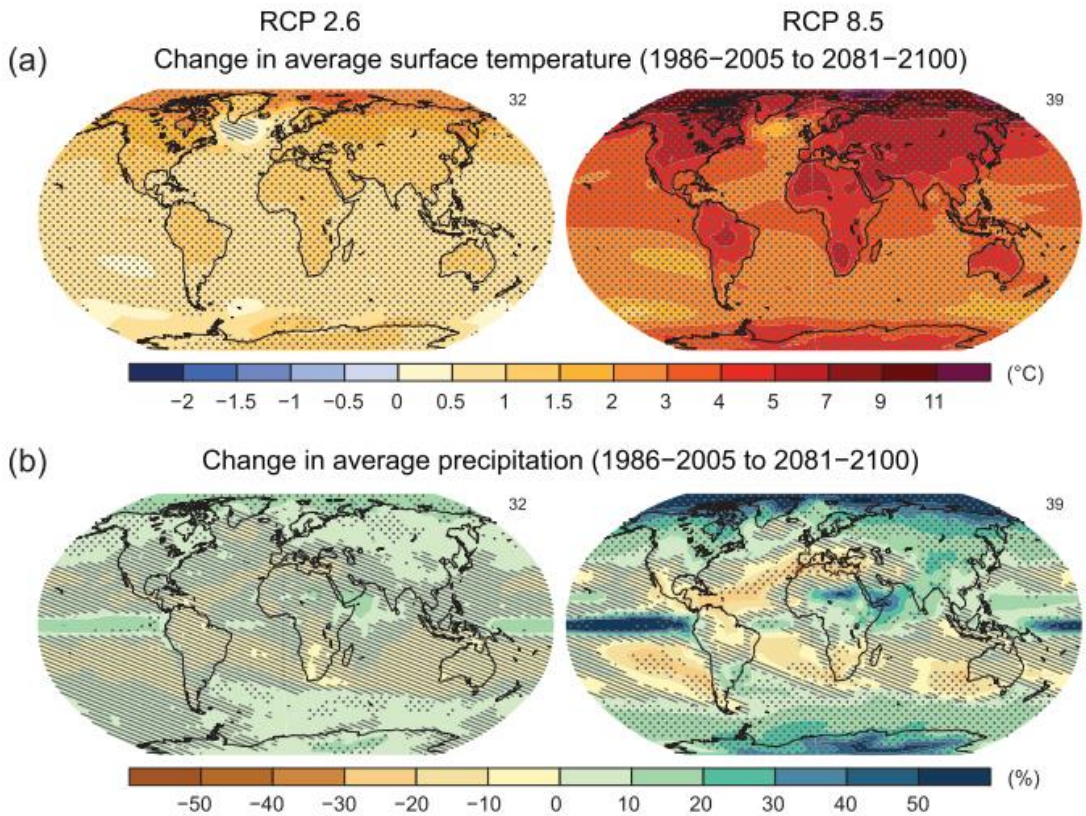


Fig. 7 a,b. Global change in average surface temperature and precipitation (IPCC, 2013)

2.1.2 Climate change and climate variability in Vietnam

Located in Southeast Asia tropical belt, Vietnam climate system is affected by two main monsoon regimes, namely winter monsoon and summer monsoon. These Pacific tropical cyclones bring rainfall across the country but in a different period of the year, winter rainfall in the central and southern region and summer rainfall in the north. Changes in rainfall varied widely among regions, with a decreasing tendency in the northern coast and an increasing trend in the central and southern coastal regions.

Rainfall recently has been recorded more heavy and frequent than in the past, leading to the secondary phenomenon such as floods, typhoons occur more often over the country in the rainy season, especially in the center, the south and some regions which located near the coastal line in the north of Vietnam. In the south of Vietnam, higher intensity typhoons and sea level were figured out to increase. At Vung Tau station, the average sea level was recorded by an increase of 0.398 cm per year (1981-2006) (GFDRR, 2011). These issues lead to other challenges, especially for agriculture. If sea level increases 1 meter, this would cause 17 million people under flooding risk and cause damages of up to US$17 billion with substantial impacts penetrating inland beyond the coastal zone (Bates et al., 2008). Moreover, many watersheds in Vietnam are highly vulnerable to climate change as the consequence of deforestation, indiscriminate land conversion, excessive soil erosion and declining land productivity (Bates et al., 2008).

In addition to the heavy rain, floods, typhoons, the number of days, and nights under extremely high temperature are also higher than in previous decades. In 2014, average annual temperature in the coastal regions of Vietnam was reported to get an increase of 0.28°C per decade. The data used were collected from 23 meteorological stations in Vietnam. In the north of Vietnam, not only the maximum of daily temperature showed the uptrend of an increase but also the minimum of daily temperatures. The intensity, frequency, and duration of extreme weather phenomena such as droughts are expected even to increase in the dry season. As a consequence of warming, the frequency of cold day and night has decreased sligtly over the past four decades.

Generally, climate change causes extreme threats to the livelihoods of people living, driving a lot of damages to housing, transportation and economy in Vietnam, for instance (Huynh & Stringer, 2018; Luu et al., 2018).

2.2 Impacts of climate change in the study area

Thai Nguyen has been informed about the impact of climate change in recent years by some reports from Vietnamese government in Vietnamese language. Therein, climate change was determined to have negative impacts human life via drought events which indirectly influenced one third land use area, agriculture, and more than 1 million of people who living in mountainous area of the province (http://www.tnmtthainguyen.gov.vn/home/cng-thong-tin-a-ly/1870-2013-11-14-08-37-48.html). In 2014, based on the analysis of soil properties which carried out by Thai Nguyen Department of Natural Resources and Environment, some extremely negative impacts of climate conditions on soil quality were found out. However, there has not had any specific scientific study about impact of climate change which published worldwide in the study area.

2.2.1 Droughts and its effect

In Thai Nguyen province, the land area under water stress conditions was measured by 32.01% in 2014 (Thai Nguyen, 2015). Drought events mostly happened in the highland of the province, particularly in Dinh Hoa district (Fig. 8 a,b). They were determined to be one of the reasons leading to a decrease of soil quality which directly influenced to chemical-biological process in the soil.

The drought was found out as the reason for an increase of acid level in the soil. In some maize fields with calcic ferralic Acrisols, pH decreased from 6.63 in 2005 to 3.67 in 2014 (Thai Nguyen, 2015). Likewise, a slight decrease in pH was documented in other regions. Besides, the decrease of total nitrogen, phosphorus, potassium, and organic matter in the soil was also recorded in most of the soil types (Thai Nguyen, 2015).

a) Moderate dry soil (Dong Hy, 2014) b) Moderate dry soil (Dai Tu, 2014)

Fig. 8 (a,b). Drought events in Thai Nguyen, Vietnam

Source: (Thai Nguyen, 2015)

2.2.2 Erosion and land degradation

In Thai Nguyen province, about 54% of the natural land area has a greater slope than 15^{o} which indicates potential erosion under high precipitation conditions (Thai Nguyen, 2015). In 2014, the eroded soil area was measured by 20.84% of the total provincial area, therein, approximately a half of the eroded area located in the hilly area of the province (Thai Nguyen, 2015). The strongest erosion happened in the area with the greater slope than 25^{o}, without grass cover and caused by heavy rain (Fig. 9 a).

Erosion combined with drought and heavy rain were determined the reason of extreme land degradation, with approximately 75% of total land provincial area, therein, the most extreme land degradation happened in the mountainous area with 10.15%. In terms of arable land area, the land degradation area was accounted by 17.53%, which located mostly in Vo Nhai and Phu Luong district.

a) Extreme land degradation (Dinh Hoa, 2014) b) Strong soil erosion (Dinh Hoa, 2014)

Fig. 9 a,b. Soil erosion and land degradation Source: (Thai Nguyen, 2015)

2.3 Climate change scenarios

Climate change scenarios (CCSs) are usually defined as projections which aim to reduce or stabilize the greenhouse gas emissions (GHG). Stabilization is a mitigation scenario but aim to a pre-specified GHG budget target based on the analysis of many factors such as future population levels, economic activity, energy intensity, social values and even land use. CCSs are reported by Intergovernmental Panel on Climate Change (IPCC). Since the first report was launched in 1993, all of IPCC reports are used widely for policymakers, scientists and other experts by hundreds of specialists all over the world.

Generally, climate change scenarios are developed with mathematical models or computational tools (IPCC, 1993), due to various purposes and hypothesis. In 1992, IS92 scenarios including IS92a, IS92b, IS92c, IS92d, IS92f, and IS92e were not created to analyze and reduce GHG, but examine the consequences of the impact of GHG if not acting to reduce. Most IS92 scenarios showed an increase in energy-related CO_2 emissions over the next century, except IS92c which showed a decrease in total CO2 between 1900 and 2100. Generally, the IS92 scenarios were fairly representative of other global scenarios but not of regional scenarios.

The next generation of climate change scenarios was SRES, termed Special Report on Emission Scenarios. The SRES scenarios cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. The set of SRES includes four storylines which are considered as four sets of scenarios called A1, A2, B1, and B2. These storylines then are developed by six modeling teams in order to get six scenario groups namely A1FI (fossil fuel intensive), A1T (predominantly non-fossil fuel), A1B (balance), A2, B1, and B2. Each scenario group afterwards is developed into two categories, namely HS (harmonized) and OS (denotes).

Unlike the scenarios developed by IPCC in 2007, the latest climate scenarios reported by IPCC in 2013 (IPCC, 2013) stabilize scenarios to achieve the goal of pre-specified greenhouse gases (GHGs) budget target. These are called Representative Concentration Pathways (RCPs), which comprise four emission pathways for stabilization, RCP 2.6, 4.5, 6.0 and RCP 8.5 scenarios (IPCC, 2013). They cover a range of forcing levels at 2.6, 4.5, 6.0 and 8.5W m^{-2}, respectively till the year 2100. The RCPs were designed to support research on impacts of climate change and simultaneously support research on policy. RCP 2.6, RCP 4.5, RCP 8.5 were used to induce variations of climate change in Canada (Alam & Elshorbagy, 2015). Under the Representative Concentration Pathways (RCP 6.0), the sea temperature is projected to increase by 1.28 °C in 2050, 1.65 °C in 2080 and 2.0 °C in 2100 in Southeast Asia (Lassa et al., 2016). Each of RCPs has its own reference based on the assessment model.

To reach the aim of reducing greenhouse gas emissions to stabilize atmospheric radiative forcing at 4.5 Wm^{-2} in 2100, the RCP4.5 scenario was created by using the reference scenario GCAM, termed Global Change Assessment Model. GCAM is a globally integrated assessment model and a direct descendant of the MiniCAM model. GCAM presents the global economy, energy systems, agriculture and land use, with the representation of terrestrial and ocean carbon cycles, a suite of coupled gas-cycle, climate change, and ice-melt models. GCAM describes the size of population of more than 9 billion in 2065 and then decrease to 8.7 billion in 2100. RCP4.5 results in an atmospheric CO2 concentration of 526 ppm in 2100. One of the influenced factors to mitigate the greenhouse gas emission is by declining meat consumption, a decrease in overall energy use, as well as declines in fossil fuel use compared to the reference scenario (GCAM).

Similar to the RCP 4.5, RCP 8.5 used IPCC A2 scenario as a reference scenario. It corresponds to the pathway of A2 scenario with highest greenhouse gas emissions (GHG), combined with high population and relatively low-income growth. GHG grows mainly by high demand and high fossil-intensity of the energy sector as well as increasing of population and associated high demand for food. RCP 8.5 aims to stabilize atmospheric radiative forcing at 8.5 Wm^{-2} in 2100.

2.3.1 Climate change scenarios for South Asia

Under the SRES B2 scenario, approximately 30% N_2O emission is contributed from East Asia. This number is projected to increase continuously till 2020 by 3%, significantly triggered by South Asia. Likewise, wastewater CH_4 (methan) emissions were mostly from Asia by nearly half of global CH_4 emission, given by 20% and 38% in South Asia and East Asia, respectively. As similar to N_2O emission, the wastewater CH_4 is also getting to increase in 2020, but only because of increasing emission from South Asia (IPCC, 2007). In the SRES A1B scenario, which shows a rapid economic growth, an increase of carbon dioxide (CO_2) emissions was found to happen in the developing world. Overall, average annual CO_2 emission growth between 2004 and 2030 is 1.5% in scenario B2 and 2.4% in Scenario A1B.

As a consequence of increasing greenhouse gasses (GHGs), Mori et al. (2006) investigated that global temperature may increase by 2.5 °C with the sensitivity in the range of 1.5-4.5 °C by Maria model (IPCC, 2007). This can lead to several interlinked effects. For example, the efficiency and capacity ratings of fossil-fuel-powered combustion turbines may be negatively affected by higher temperatures. Hamper offshore oil and gas may be affected by sea level rise, tropical cyclones, and large ocean waves. Lower water levels in lakes or rivers caused by lower precipitation and higher evaporation due to higher ambient temperatures, will decrease the outputs of hydro-electric power stations. In South Asia, particularly in monsoon regions, the heavy precipitation intensity is projected to increase by 10% in case of the temperature increases by 2 °C (Schleussner, 2016).

2.3.2 Climate change scenarios for Vietnam

The climate change scenarios for Vietnam were reported four times, in 1994, 1998, 2007 (updated 2009) and 2012 (Thi-Minh-Ha et al., 2011; ISPONRE, 2009; Ngo-Duc, 2014). Among them, details of the methods for building the 1994 and 1998 scenarios were not well documented.

Recent Vietnam' climate scenarios show that a decrease in precipitation will continuously occur in the northern parts, especially in the northwest of Vietnam in next 50 years. Meanwhile, an increase in the total amount of precipitation is detected over the other sub-regions combined with increasing number of hot days and the decreasing cold nights, especially the southern part of Vietnam based on the IPCC SRES A1B and A2 scenarios (Thi-Minh-Ha et al., 2011; ISPONRE, 2009; Tran Thuc, 2013). Besides, a variety of different future climate scenarios for the coastal regions of Vietnam are also discussed in the study which was carried out in 2014. Ngo Duc (2014) used two downscaling methods, statistical downscaling and dynamical downscaling, to build future scenarios for Vietnam (Ngo-Duc, 2014).

Another recent study, in 2017, using the PRECIS model (a regional climate modeling system that developed by the Hadley Center in the UK), the results showed that both increases and decreases in the mean temperatures over different regions of Vietnam. Besides, the total number of wet days decreases of about 5–10% all over Vietnam (Opitz-Stapleton et al., 2016).

In conclusion, it is clear to see that Vietnam is one of the most vulnerable coastal countries in terms of climate change impacts and sea level rise (Dung & Sharma, 2017). Climate change impacts strongly agriculture production (Duong et al., 2017), particularly in terms of aquaculture households but in some cases, climate change has also brought benefits for fishing groups (Ha & Thang, 2017).

2.4 The interaction between climate change and agriculture

Agricultural activities adversely impact climate change by releasing greenhouse gases (GHGs), CO_2, methane (CH_4), and nitrous oxide (N_2O) through the production process to the atmosphere (IPCC, 2001; IPCC, 2007). CO_2 is released largely from microbial decay or burning of plant litter and soil organic matter. N_2O, CH_4 emissions are major emitted from livestock and N-fertilization. In 2005 agriculture accounted for 10-12% of total global anthropogenic emissions of GHGs (IPCC, 2007).

Over the last three decades, annual GHG emissions have increased by an average of 1.6% per year and are expected to increase in coming decades due to demands on food and shifts of diet (IPCC, 2007); CH_4 and N_2O emissions have increased by nearly 17% from 1990-2005. N_2O is projected to increase by 35-60% up to 2030 contributed by larger herds of beef cattle, increasing of fertilizer application (IPCC, 2007). Meanwhile, the population growth drives sharply increasing food demand, therefore the expense of pressure on the environment, and depletion of resources (IPCC, 2007).

In many regions, climate change can have positive effects, affecting for example frost frequency, cold waves which will be reduced and food production is potentially improved (IPCC, 2001b). In these regions, the future warmer conditions for maize growing will be more suitable than in the past. A positive impact on agriculture was found in a study case in southwestern Ontario, Canada. The average crop yield will increase with warmer temperatures and a longer growing season in such regions where too cold temperatures are main limiting growing factors (Cabas et al., 2010).

In some other regions, climate change was recorded to have both positive and negative influence on crop production. For instance, In China, El Niño was recorded to influence positively and negatively on maize production. During El Niño years, an increase of maize yield was experienced in the north, whereas a decrease in yields was found in some areas in the South (Shuai et al., 2016). The same results were found in southeastern Australia. During the 2002 and 2006 growing seasons, El Niño-related droughts plagued portions of the Australian wheat belt, slashing national wheat production by nearly 50% relative to the previous year. However, not all El Niño events led to notable precipitation and temperature anomalies on local and regional levels. In 1997, a relatively good yielding crop compared with historical production was reported by a near-normal rainfall which related to the strongest El Niño (Johansson et al., 2015).

Generally, climate change will reinforce the trend towards to more extremely negative influence on agriculture (Muldowney et al., 2013). In the Netherlands, wheat yields were found to highly decrease by an increase of temperature since the early 1990s (Powell & Reinhard, 2015). As the same consequence of natural disasters in Americas, Asia and Australia above, farmers in West African Sahel have also undergone the same risks from various climatic changes, especially in terms of rainfall across past 30 years. Those issues impact more drastically on poor-resource farmers (van Duivenbooden et al., 2002). Another study, which was carried out in Sub-Sahara Africa investigated that crop yields change significantly through 2100 under alternative climate change scenarios. According to this study, cassava yield will be near zero in 2100 because of the excessive water from floods. Likewise, millet and sorgum yields are affected negatively by an increased temperature and drought, which range from –38% to –13%, and from –47% to –7% respectively, meanwhile, maize range from –19% to +6% (Blanc, 2012).

2.5 Maize production under climate change conditions

Many plant physiological processes have clear non-linear relationships to temperature. For example, temperature effects on the rates of biochemical reactions such as an exponentially increasing rate of the forward reaction and an exponential decay resulting from enzyme denaturation as temperatures increase (Fig. 10). Temperature can inhibit the cellular metabolism of C3 plants in cool seasons but may not inhibit the same procedure of C3 plants in the warm season as well as C4 plants such as maize. In cool temperate climates, low temperature prolongs during growth duration may reduce crop growth rate, and increases the risk of frost terminating grain filling prematurely. Likewise, warmer temperature either influences critical episodes such as pollination period of maize growth (Wheeler et al., 2000), or during silking which are both considered as having an inordinately extremely effect on maize grain yield (Suwa et al., 2010).

In terms of grain yields, maize grain yields under warmer regimes strongly decreased in comparison with the derived yield from a normal temperature regime in the case study by Hat and Prueger in 2015 (Hat and Prueger, 2015). Similarly, a study in France also indicated a decline in maize yield and production during the 2003 heat wave and associated drought. National 2003 maize yield loss equaled ∼1.5 t ha^{-1} compared to the 2000–2006 average (van der Velde et al., 2010). In the North China Plain, the weather data over the past six decades showed an increase in temperature while solar radiation and precipitation showed a decreasing trend. These conditions led to some negative influence on maize yield, particularly for short growing cultivar (low maturity group) (Huang et al., 2018).

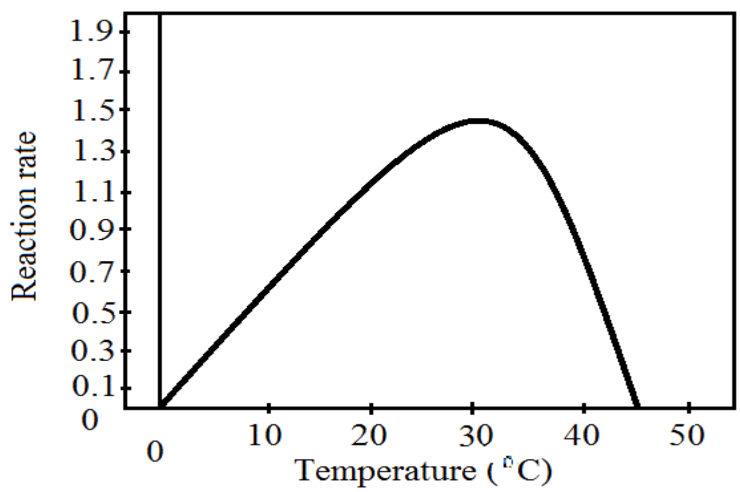


Fig. 10. Rate of reaction as a function of temperature add equation (Y= exp $(aX)^{-1}$)*(2-exp (bX))

(Source: FAO: http://www.fao.org/docrep/w5183e/w5183e08.htm)

In contrast, under increasing air temperature, maize yields in South Africa increased when production inputs such as labor, seed, fertilizer, and especially irrigation were optimized. Irrigation was considered as the most important driver of maize yields, shown by a reduction of maize yield of 4% when the average irrigation amount was reduced by 10% (Akpalu et al., 2003).

Besides, there are a lot of abiotic and biotic factors that influence maize growth in relation to the conditions of weather, soil and crop management factors. Although they could impact directly or indirectly, they are all important in a closed cycle relationship and contribute to final grain yield.

For example, water shortage has been a challenge to the sustainability of maize production in many irrigated agriculture regions (Zhao et al., 2018).

To adapt with the warmer weather condition, a combination of sowing dates with appropriate nitrogen rates could increase grain yields (Srivastava et al., 2018). Maize yield could increase by at least 14% through drip-irrigation systems in comparison to rainfed conditions (Liu et al. 2018). Additionally, organic manure could improve soil water potential in dryland agriculture, resulting in improving maize yield (Wang et al., 2017). However, excessive exchangeable Na^+, high pH (Wang et al., 2017) as well as the imbalanced application of nitrogen (N) and phosphorus (P) fertilizers can result in low crop yields, caused by low nutrient use efficiency (Zhang et al., 2016).

2.6 Maize production in Vietnam

In Vietnam, maize production has an important role in farmer's lives because maize is not only the cereal crop but also a cash crop. Its importance is only after rice because maize is mainly used for livestock feed and a small portion only for human meal such as vegetable and starch.

Because of the differences in topographies, soil types, climatic zones as well as the difference of crop managements such as irrigation regimes, fertilizer application, maize management between highland and lowland regions of Vietnam are different. In the highland regions, tillage was done primarily by hand with some animal power, which was the only option for farmers with unfavorable field conditions such as slopes or rocky areas. In the lowland area, tillage is done by either animal or machine power. Plow marks are the most common method of maize seeding in Vietnam. Seeds are sown in small holes dug by a stick or a small hoe in the high, sloping, and steep area. The amount of seeds often ranges from 17 kg/ha in the southeast-Mekong Delta upland areas to 24 kg/ha in the northern upland areas. The highest amount is observed in the northern lowland agro-ecology with 27 kg/ha (Dang et al., 2002). Chemical fertilizer used by farmers (urea, NPK, phosphorus, potassium, ammonium sulfate) varied widely in a relatively high amount. In the northern upland of Vietnam, the total chemical fertilizer was applied by 604 kg/ha, meanwhile, it was 810 kg/ha in the northern lowland (Dang et al., 2002). Besides, the quantity of chemical fertilizer not only depends on specific soil conditions, but also reflects the different levels of farmers' knowledge of the crop nutrient requirements. A relatively different in amount of nitrogen fertilizer use was not only recorded in differ landscapes, but also was different between farmers. By contrast, organic fertilizer is more frequently using in lowland than in the upland agro-ecologies. The amount of organic fertilizer was recorded by farmers' interviews in the north of Vietnam was in a range from 4.7-8.1t/ha which differed between the northern upland and northern lowland. In high land regions, organic fertilizer is prior to use for high value crops such as rice, vegetables (Dang et al., 2002).

Additionally, there are a plenty of crop cultivation calendars with various cropping patterns across the country. In the some regions of the north, local farmers can cultivate maize three times per year. A 3-crop rotation is often started with the spring maize crop. The spring maize is cultivated in January/February and harvested in May. The second possible maize crop is called summer maize that is usually planted in April/May and harvested in August. The last seasonal crop, namely winter maize, is possibly sown in September/October and harvested in next January. Besides, farmers also grow maize at the end of July or early August and harvest in November, namely autumn maize; however, this autumn maize area is very small to take into account of total maize production area and normally combined with two rice crops which is one of the most important intercrop patterns in Vietnam.

Considering the contribution of seasonal maize crops, winter-maize contributes about 45.5% of the total land use for maize followed by the spring-summer maize by 17.8% which are nevertheless only cultivated in Red river Delta in Vietnam under irrigated condition. The sole-spring maize grown is more common under rain-fed conditions, which is covered by 22.1% of total land area for maize production in the upland agro-ecology of Vietnam. The other patterns which are usually cultivated in the upland regions is responsible for 12.6% (Dang et al., 2002). Besides, beans and groundnuts are also cultivated with maize in crop rotation to protect and enhance soil quality.

In 1961, the total land area for maize cultivation was only 260,200 ha but it was increased up to 389,600 ha in 1980. Most of the maize varieties were the local cultivars. A few imported hybrid maize varieties were grown in a small area resulting in a low yield average of about 1100 kg ha^{-1}. In the next period of about 10 years, land use area for maize production was continuously increased up to approximately 478,000 ha and the grain yield also was higher than the last period. In 1992, the maize yield reached 1560 kg ha^{-1}, higher than 460 kg ha^{-1} in comparison with the yield in 1980. However, this average yield still was low in comparison with the number of average maize yield worldwide. This issue gave the Vietnamese Government a push in the investment of maize productivity. Particularly in terms of hybrid maize varieties to enhance the maize production, the Vietnamese Government introduced development policy specifically for maize variety translation since 1991. Since then, hybrid maize varieties have widely adopted by farmers to replace low yielding local/ traditional and open-pollinated varieties. In 2000, the total land area was covered by maize about 730,200 ha with the average yield of about 2750 kg ha^{-1} (Table 2) (Dang et al., 2002). Nowadays, the hybrid maize cultivation is strongly developing in Vietnam. There are a lot of new hybrid maize varieties such as LVN 10, DK 888, DK 999, LVN 20 which were released by private companies such as Pacific, Bio-seed, and Cargill (Dang et al., 2002). However, farmers have not adopted Bio-seed and Pacific hybrid maize varieties because the seed price is quite higher than the average cost which farmers could invest.

From 1995 to 2015, the maize productivity was increasing; however, it partly increased by expanding of arable land use for maize production. To expand the cultivation areas, farmers used to deforest, especially in some highland areas in the north, some ethnic group peoples are still expanding their arable land by slashing and burning forest in combination with hand tools sometimes, even though conversion of forest to agricultural land for maize cultivation is known to negatively affect soil fertility in Vietnam (Schweizer et al., 2017).

Table 2. Area, production and yield of maize in Vietnam, 1995-2015.

Agro-ecology	1995	2000	2005	2010	2015
Area (thousand ha)	557	730	1,052.6	1,125.7	1,178.9
Production (thousand tonnes)	1,177.2	2,005.9	3,787.1	4,625.7	5,287.2
Yield (kg/ha)	2110	2750	3600	4100	4480

Currently, in the central of Vietnam, maize yields decreased because of the drought season, in Dakrong district – a highland district of Central Vietnam in 2015, for instance; droughts impacted strongly negatively maize production which led the local farmers had to change the traditional land use system (involving maize) to other crops such as peanut, cassava, or green bean (Uy et al., 2015). In all lowland agro-ecologies, especially in regions near the Red River and Mekong Deltas, flooding is a major problem. Additionally, farmers reported an increase in pesticide use to combat maize pests and diseases such as stem borer, maize ear borer, maize bug, grasshopper, field rats, blight, and root and stalk rot when cultivating hybrid maize crops because the upward trend of insects and diseases due to severe climate conditions. Meanwhile, in the northern upland agro-ecology, droughts, soil erosion, poor soil fertilities and irregular rainfall mostly lead to the decline of maize yields. This backward development has therefore caused much more challenges for agricultural future which requires the Vietnamese government have a sustainable development policy to protect and rehabilitate soil quality.

Thai Nguyen locates in the northern upland areas where maize is a traditional cereal crop with the crop management is fairly similar to other regions in the north of Vietnam (Fig. 11a,b).

a) b)

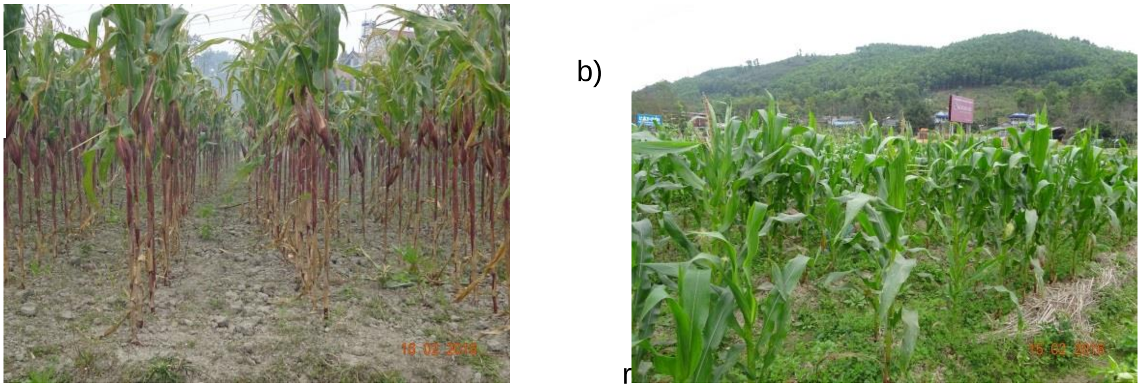


Fig. 11a-b. Maize fields in Thai Nguyen province

2.7 Crop modelling

Process-oriented crop models are widely used in research to identify and analyze climate change or weather impacts on crop growth dynamics, crop yields, nutrient balance and effects of crop management options (e.g. Devkota et al., 2013a; Ebrahimi et al., 2016; Eitzinger et al., 2013b) and also for strategic decision-making (Manschadi, 2017). The model used in this study, DSSAT 4.5 (Decision Support System for Agrotechnology Transfer, version 4.5) (Jones et al., 2003), a crop simulation environment consisting of several crop models, has been used for 30 years worldwide for various purposes such as providing considerable opportunities. DSSAT model can be downloaded by users from the website https://dssat.net/. DSSAT comprises over 40 crops in a huge range of applications. DSSAT model includes five main apps to input weather, soil, crop genetic, crop management and observed experiment data. The model can be used by different types of users and purposes such as a model developer or farmers for solving problems at fields, farms, and higher levels (Jones et al., 2003).

DSSAT shell and its implemented crop models, as many other mechanistic crop models, is designed for simulation of several crop management options, and under climate change scenarios used for visions for farming in future. It is improved by updated versions to getting more accurate in crop simulation. Since then, farmers could analyze the potential of their field under natural resource conditions such as soil and weather conditions. DSSAT models work as a tool for calculation expected growth and development of crops based on equations and mathematical functions. DSSAT deals with annual crops such as wheat, rice (Kadiyala et al., 2015), maize and various grain legumes and herbaceous perennials such as forage legumes and grasses. Besides crop growth and development, DSSAT can be applied for other study purposes such as to simulate water and nutrient dynamics in the soil (O'Neal et al., 2002, Timsina et al., 2008, Dokoohaki et al., 2017). In most studies, DSSAT models have been approved that it is a useful tool for crop simulation (SOLER et al., 2011; Geng et al., 2017,; Corbeels et al., 2016; Kadiyala et al., 2015). Analysis of the performance and the sensitivity of DSSAT model was carried out in several studies as well (Eitzinger et al., 2004; Yakoub et al., 2017; Kisekka et al., 2017; Eitzinger et al., 2013; Wang et al., 2018).

2.7.1 DSSAT model application

DSSAT cereal models (CERES models) can be used for many applications such as to simulate the grain yield, maximize the maize yield and help to avoid yield losses (Geng et al., 2017), for mulching effects simulation, such as plough pan formation (Corbeels et al., 2016), for accurately forecasting yield months before harvest (Quiring and Legates, 2008), and even successfully in biomass simulation of a new hybrid model which was due to better soil water simulations (Dokoohaki et al., 2016). Likewise, the potential of maize yield and the gap between the potential and the actual crop yield also were estimated by DSSAT models (Iyanda et al., 2014; Jing et al. 2017; MacCarthy et al., 2017). CERES models mimicked the soil water content dynamics well in the top 0.3 m of the soil (Eitzinger et al., 2004), Besides, DSSAT models could be combined with other software such as GIS (Geographical Information System) to assist agronomic decision making (e.g. Kadiyala et al., 2015; Basso et al., 2007). It was, for example, also combined with Apollo (DSS) to simulate and analyze spatially variable and management (Thorp et al., 2008) or embedded in the RZWQM2 model in combination with long-term climatic data (Kisekka et al., 2017). Particularly, DSSAT models also soil processes, which can predict N release, e.g. from a legume cover crop (Hasegawa et al., 1999), to assess the response of nitrogen (N) fertilizer and varieties in order to explore potential target zones for improved maize varieties (Jagtap et al., 1999; He et al., 2012), or optimize fertilizer application to minimize nutrient losses (e.g. by N-leaching) and increase crop yield (Liu et al., 2012). Therefore, DSSAT models are considered as a useful tool for optimizing fertilizer management simultaneously minimizing nutrient losses (Liu et al., 2012). In term of irrigation and water balance processes in soil, DSSAT is considered as a successful tool for evaluating alternative management options aimed to maintain yield and saving water such as in rice-maize systems in semi-arid regions (Kadiyala et al., 2015). Besides, DSSAT can be used to assess the irrigation water demand for crop growth, optimizing water use and therefore saving water supply for a crop in combination with other agricultural water management technologies and strategies such as soil water monitoring, drip irrigation, and residue management (Kisekka et al., 2017; DeJonge et al., 2012).

2.7.2 Limitations of DSSAT crop models applications

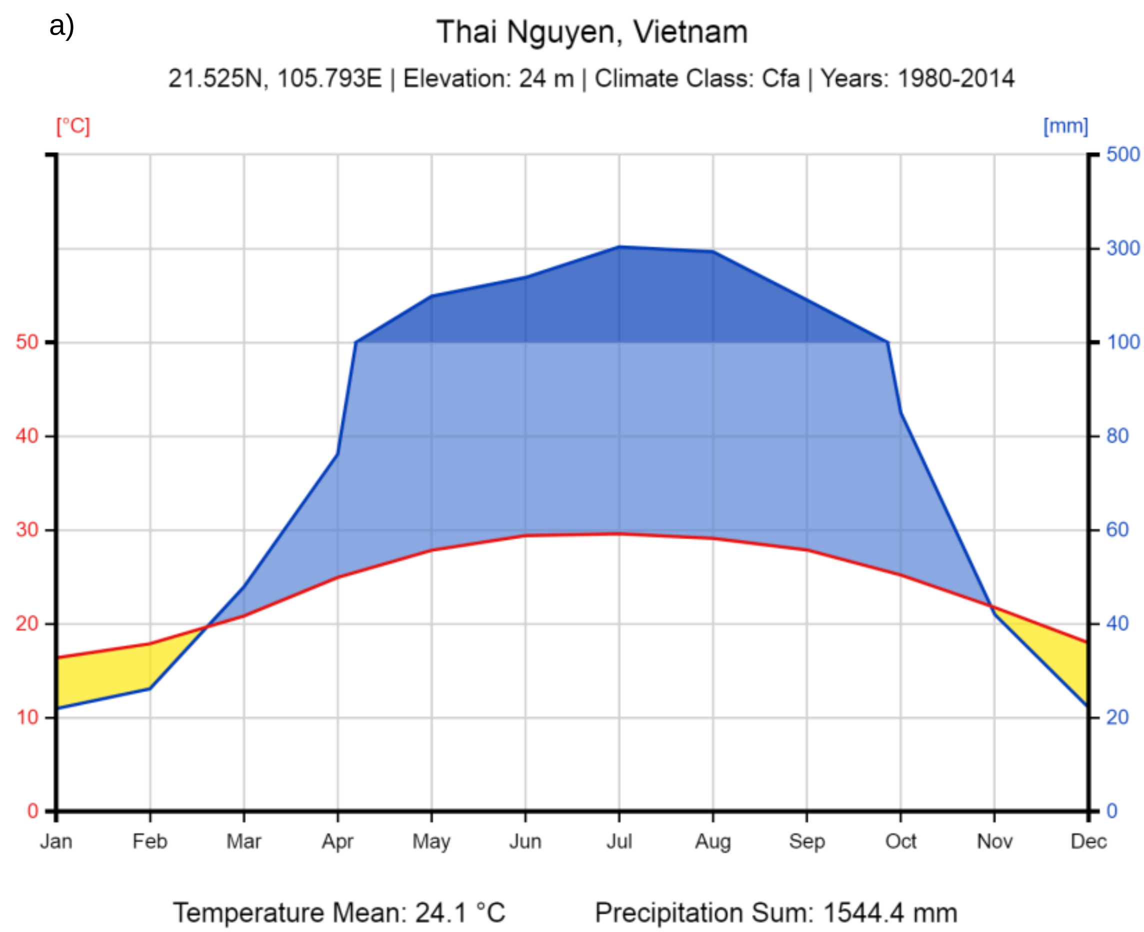
Crop models are useful tools for crop simulation. However, it still has some limitations which have been estimated by evaluating the performance of CSM-CERES-Maize, for example. Ngwira et al. (2014) proved that DSSAT simulation was successful for no-till and crop residue but poor for crop rotation. This could be caused by crop rotation algorithm in DSSAT (Ngwira et al., 2014). Another flaw was shown by a study which used CERES-Maize to measure the number and the weight of maize kernels. The error was about the difference between observed data and simulated data as well as the low accuracy at a higher temperature (Ban et al., 2015). Other uncertainties, in common with many other crop models are the determination of root growth dynamics, and related water and nutrient uptake abilities. Further, extreme weather impacts are often difficult to depict or not considered at all (e.g. hail damage). Other crop yield impacts such as pests diseases, weed pressure, impacts of environmental poisoning (e.g. from ozone) are also mainly not considered in current crop models. In consequence, they are a useful tool for simulating potential yields, but only with limitations estimators of the actual, real yields. Finally, it depends on the growing environment which limitations actually will play a role, and that needs careful check, background knowledge and experience with model application.

III. MATERIALS AND METHODS

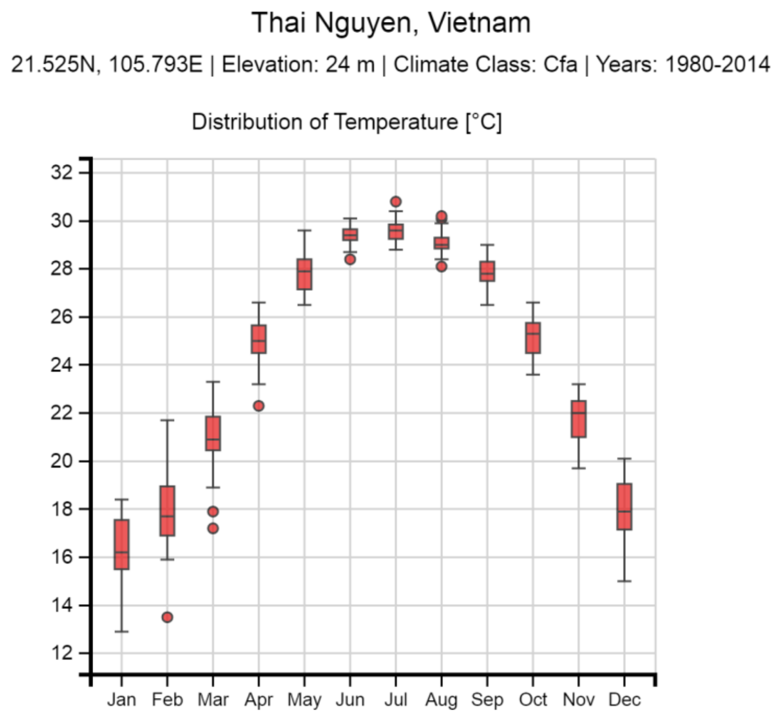
3.1 Study area and weather stations

In Thai Nguyen, Vietnam, there are four seasons in a year, spring (February, March, and April), summer (May, June, and July), autumn (August, September, and October) and winter (November, December and January). In the period of 35 years (1980-2014), the annual average temperature was around 24.1 °C while the yearly average precipitation was 1544.4 mm (data based on https://climatecharts.net/) (Fig. 12a). The temperature is getting higher in summer and reducing gradually to the lowest points in winter (January). Generally, summer is the rainy season which is affected by the summer monsoon. The maximum amount of rainfall is usually in July combined with strong winds, as shown in Fig. 12a-c.

a)



b)



c)

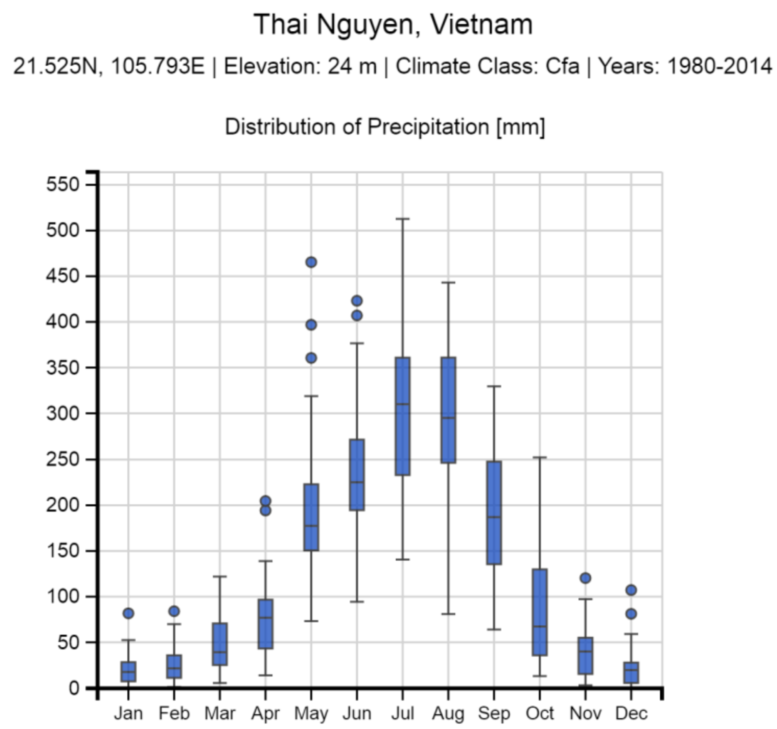


Fig. 12 a-c. Climate conditions in Thai Nguyen province (data based on https://climatecharts.net/).

The meteorological data are produced by two weather stations (Table 3), which are namely Dinh Hoa station and Thai Nguyen station. Both weather stations are managed by Thai Nguyen center for Hydro-Meteorological Forecasting, Vietnam that is responsible to supply the weather data for the province as well as for this study. Their locations are shown in Fig. 13. The distance between two stations is about 45 km. Dinh Hoa station is set up in the mountainous area to northwestern of Thai Nguyen province while Thai Nguyen station is set up at a flat area, in the center of Thai Nguyen province. The density per weather station in Thai Nguyen is about 1768.2 km^2. It shows the limitation in collecting the weather data and affects the accuracy of the local weather forecast. Moreover, in some periods missing data creates problems to analyze the local weather condition.

Table 3. Weather stations in Thai Nguyen province.

Stations	Latitude	Longitude	Height *(m a.s.l)*	Period *(daily data)*	Weather variables				
					Sun *(hours)*	Temperature *(°C)*		Rain *(mm)*	Humidity *(%)*
						Max	Min		
Thai Nguyen	21^{0}36” N	105^{0}50”	35.3	1990-2015	+	+	+	+	+
Dinh Hoa	21^{0}53” N	105^{0}38”	98.0	1961-1990	-	+	+	+	+

(+) Available data *(-) Unavailable data*

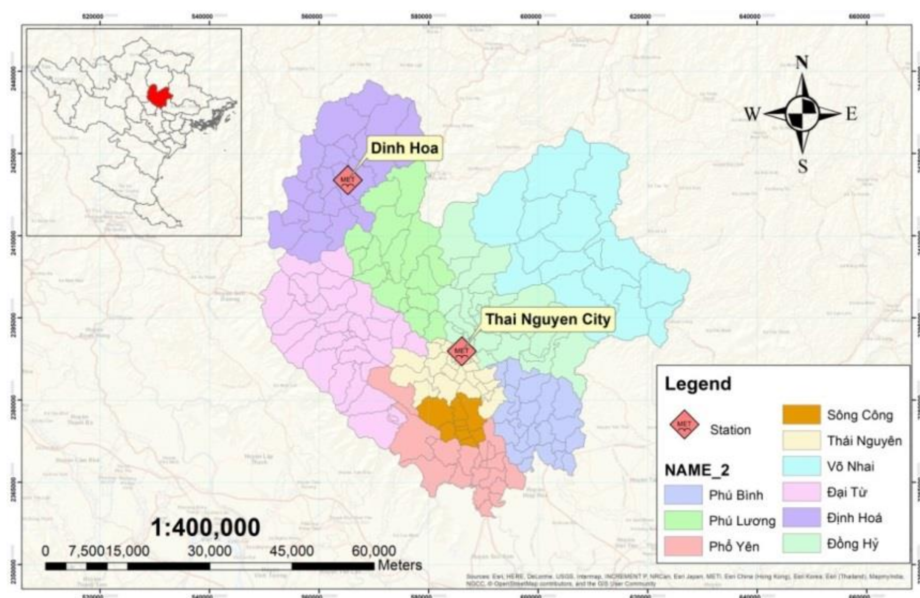


Fig. 13. Weather stations in Thai Nguyen province, Vietnam (author: Tran Thi Mai Anh).

3.2 Data collection and analysis

Data which are needed to run the applied models involve soil properties, crop management, experiment field (CERES-Maize), and weather data (CERES-Maize and AGRICLIM). Most of them were moderately good and collected from Thai Nguyen Department of Environment and Resources and Thai Nguyen center for Hydro-Meteorological Forecasting, excepting the field experiment data. However, some datum limitations remain existing (see Table 4).

The experiment field was set by the college in Thai Nguyen University of Agriculture and Forestry in 2008 for two maize growing seasons (section 3.2.3). The data quality was highly adequate for the model run. However, the author did not analyze the soil properties as well as record the irrigation amount, led to some difficulties in simulation, for example. Additionally, the database had some other limitation caused by crop managements changing by the time. For example, people did not use chemical fertilizer for two last decades as much as nowadays. Additionally, crop systems and crop varieties were considerably changed during the last period. Modern farmers are currently using new hybrid varieties that bring higher yields compared to local varieties.

In fact, soil properties are moderately homogeneous by more than 70% of Ferralsol soil. Additionally, maize is commonly cultivated in various types of soil such as Fluvisols, Acrisols, and Ferralsol. Therefore, to improve the accuracy of crop simulation, soil properties were additionally analyzed by digging soil profiles at which soil types on the maize fields (section 3.2.2.2) in combination with interviewing farmers, and local experts to fill datum gaps of crop management data (Fig. 14).

a)

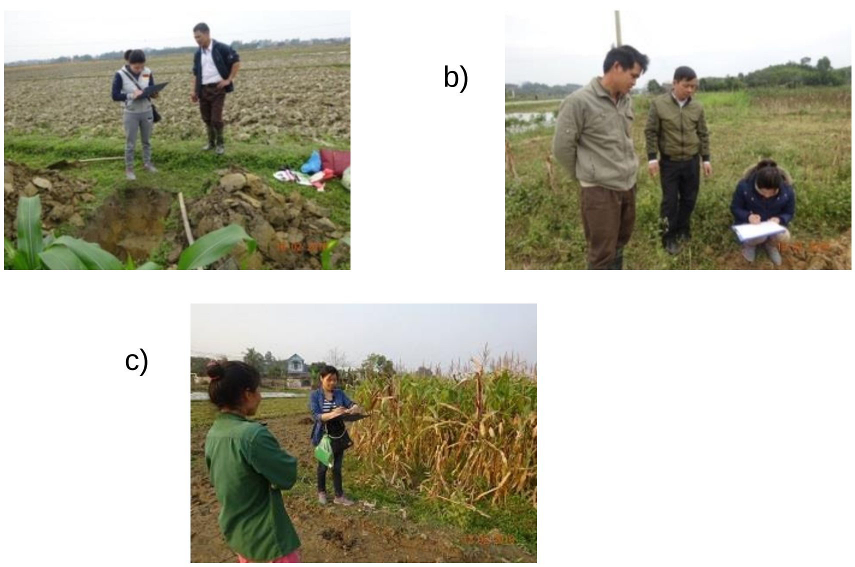


Fig. 14 a-c. Interviewing local experts and farmers

Table 4. Type and quality of model input data and implemented quality assurance measures.

Data	Name	Source	Information Quality
Weather	Maximum temperature (ºC)	Thai Nguyen Centre for Hydro-Meteorological Forecasting, Vietnam Address: Thai Nguyen city, Vietnam Email: ttkttvtn@vnn.vn	Errors (e.g Tmin > Tmax)
	Minimum temperature (ºC)		
	Rainfall (mm)		Good
	Relative humidity (%)		Good
	Solar radiation (MJ m^{-2} day^{-1})		Good Unit (hours)
Soil	Soil map	Thai Nguyen Department of Natural Resources and Environment Address: 132 Hoang Van Thu, Thai Nguyen city, Vietnam. http//:tnmtthainguyen.gov.vn	Very good
	Soil profile (soil depth)	(Tran Thi Mai Anh, 2016); (FAO, 2006) *(Based on local names and FAO' soil classification, 1988 and FAO' Guidelines Soil Description, 2006)*	Good
	Soil name, soil classification, soil texture (%)		
	Physical properties: Organic carbon (%), pH in water, Cation exchange, total nitrogen, bulk density (g/cm^3)	Thai Nguyen Center of Analysis and Environmental Technology	Good
	Chemical propertiesPhosphorus extractable (mg/kg), Potassium exchangeable (cmol), Stable Organic Carbon (%)		None
Crop management	Previous crop information	Farmers	Poor
	Cultivar	Local names (defined by model)	Good
	Planting data; Irrigation; Fertilizer; Organic Amendments; Tillage; Harvest; Chemical Applications	Farmers, Experts and experiment field (N.H Hong, 2008)	Moderate
Experiment data	Crop indices and recommended crop management	(N.H Hong, 2008)	Good (published in Vietnamese)

3.2.1 Weather data

Historical weather data were obtained from two local meteorological stations for 55 baseline years from 1961 to 2015 (their sources shown section 3.1 and table 4.). They both comprised five main individual elements, which involve maximum temperature, minimum temperature, solar radiation, rainfall, and relative humidity. However, the observed daily weather from Dinh Hoa weather station was only available for 30 years from 1961-1990 while the daily data from Thai Nguyen weather station were recorded for 25 years from 1990-2015. However, the monthly weather data from Thai Nguyen weather station was available for 35 years from 1980-2015, producing an overlapping period from 1980-1990 to ensure the accuracy of climate system change in Thai Nguyen province.

Another limitation of observed local weather data was about solar radiation data which were only available in hourly sunshine duration, which do not fit the requirement of the model. Hence, the solar radiation data were re-calculated based on Rs and Ra equations (by FAO, http://www.fao.org/docrep/x0490e/x0490e07.htm#radiation) to receive an energy equivalent unit as follows:

The Extraterrestrial radiation, Ra, for each day of the year shown by Equation 1:

$$\mathrm{Ra} = \frac{12(60)}{\pi} G_{SC} d_r [\omega_s \sin(\varphi) \sin(\delta) + \cos(\varphi) \cos(\delta) \sin(\omega_s)] \quad (1)$$

Where

Ra extraterrestrial radiation in the hour (or shorter) period [MJ m^{-2} day^{-1}]

Gsc solar constant = 0.082 MJ m^{-2} min^{-1},

dr inverse relative distance Earth-Sun,

ω_s sunset hour angle [rad],

φ latitude [rad],

δ solar decimation [rad].

Ra is expressed in the above equation in MJ m^{-2} day^{-1}. The corresponding equivalent evaporation in mm day^{-1} is obtained by multiplying Ra by 0.408. The latitude, j, expressed in radians is positive for the northern hemisphere and negative for the southern hemisphere. The conversion from decimal degrees to radians is given by:

$$\varphi = \frac{\pi}{180} [\mathrm{decimaldegrees}] \quad (2)$$

$$dr = 1 + 0.033 \cos\left(\frac{2\pi}{365} J\right) \quad (3)$$

$$\delta = 0.409 \sin\left(\frac{2\pi}{365} J - 1.39\right) \quad (4)$$

$$\omega_s = \frac{\mu}{2} - \arctan\left[\frac{-\tan(\varphi)\tan(\delta)}{X^{0.5}}\right] \quad (5)$$

Where: J is the number of the day in the year between 1(1 January) and 365 or 366 (31 December). Values for J for all days of the year and an equation for estimating J are given in Appendix (Table 14).

Solar radiation (Rs) afterwards can be calculated with the Angstrom formula which relates solar radiation to extraterrestrial radiation and relative sunshine duration:

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a \quad (6)$$

Where:

R_s solar or shortwave radiation [MJ m^{-2} day-1]

n actual duration of sunshine [hour],

N maximum possible duration of sunshine or daylight hours [hour],

n/N relative sunshine duration [s]

Ra extraterrestrial radiation [MJ m^{-2} day^{-1}]

a_s regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n=0),

a_s+b_s fraction of extraterrestrial radiation reaching the earth on clear day (n=N)

Rs is expressed in the above equation in MJ m^{-2} day^{-1}. The corresponding equivalent evaporation in mm day^{-1} is obtained by multiplying R_s by 0.408. Depending on atmospheric conditions (humidity, dust) and solar declination (latitude and month), the Angstrom values a_s and b_s will vary. Where no actual solar radiation data are available and no calibration has been carried out for improved a_s and b_s parameters, the values a_s=0.25 and b_s=0.50 are recommended.

3.2.2 Soil data

3.2.2.1 Soil types in study area

Vietnam has more than 53% of ferralic soils as presented in the country report in 2014 (USDA, 2014). In Thai Nguyen province, Ferralsols was accounted for 75% based on the old soil map in 2005 and the local reports in 2012. However, according to the FAO soil classification, local soil properties in some regions may appropriate for Acrisols classification. The contributions of soil types are shown in Fig. 15 with names of soil types were translated from the local reports. The examination of soil profiles and soil properties are shown in Fig. 16 and table 6.

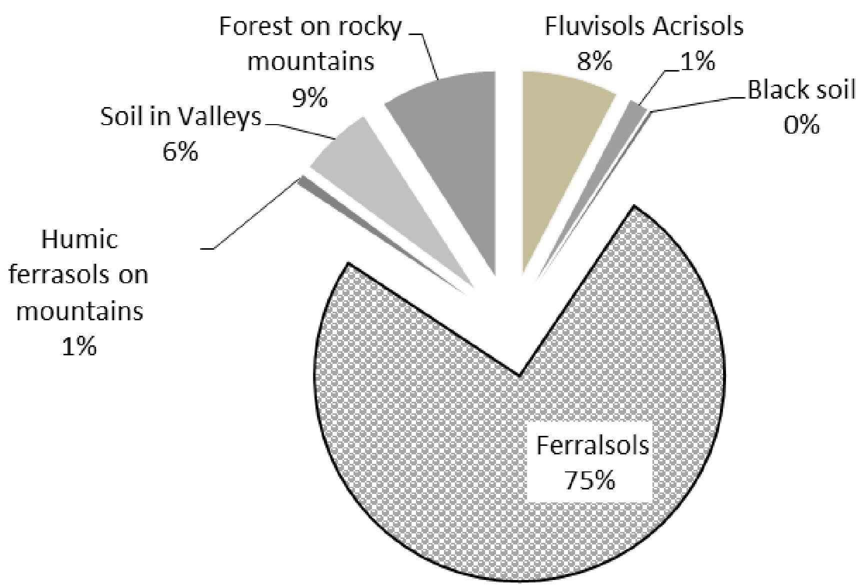


Fig. 15. Percentage of various soils in Thai Nguyen, Vietnam

(Source: Ministry of Agriculture and Rural Development, 2012.

More reference Vietnam soil type in country report 2015 - http://www.fao.org/fileadmin/user_upload/GSP/docs/asia_2015/Vietnam.pdf)

In local regions, Ferralsols and Acrisols are two main soil types. In addition to two main soil types, other soil types such as Fluvisols and Gleysols are also found, however they occupy tiny proportions. Fluvisols and Gleysols are commonly found near to the river bank and strongly affected by flooding in the rainy season in the case of poor water-drainage systems. In addition, Gleysols are also found in the area and have the high level of groundwater, leading some limitations for cultivation such as tillage and rooting development.

3.2.2.2 Examination of some soil profiles and soil properties

In order to run the crop model, all information which is needed to run the S-build application (to build the soil input file) includes: soil general information (soil location with soil profile name, soil color, drainage, runoff, percentage of slope, fertilizer factor (0-1), runoff potential) and soil physical and chemical soil parameters which are composed of depth, master horizon, % clay, % silt, % stones, organic carbon, pH in water, cation exchange capacity (mol/kg) and total nitrogen (%).

Soil types and their properties were taken mainly from the old soil map which was created in 1961. However, due to the soil data model input requirement, previously analyzed soil data from Thai Nguyen center of analysis and environmental were used in combination with some physical and chemical soil properties from four different examined soil profiles which carried out at the moment of the study.

These profiles were located in 4 different districts sparsely to the north, the center and the south of Thai Nguyen province. The selection of soil profiles was based on the land use map in order to examine the physical properties of the typical soil characteristics for maize. Their names were defined based on the comparison between local names and those from FAO-UNESCO soil classification (1988). Each soil profile was dug about 1.2m deep and 0.8x0.8m wide under maize fields. Each soil profile had three soil horizontal layers. Soil samples were taken from each soil horizons and were measured afterward to identify horizontal depth, soil color, soil structure, soil texture, and some other chemical soil indices (see Fig. 16,17).

To identify soil color, an undisturbed soil ped was taken in one hand, then opened carefully the ped. If the soil is dry, then moisten the soil with water. The color of each ped was compared with the colors on the Munsell color chart. To measure soil texture, quick field tests which namely the manipulative test was applied. However, they were improved by laboratory tests by previous analyzed soil data from Thai Nguyen center of analysis and environmental (table 16). The methods to measure soil structure and soil texture were followed step by step by FAO (available: http://www.fao.org/fishery/static/FAO_Training/FAO_Training/General/x6706e/x6706e06.htm?fbclid=IwAR31hf_77sAj413VGIjAFECaugO1sItusjjg5pZy1E0ey-MtyXMOBe-kl-U). The system of particle-size classification was used by US Department of Agriculture (USDA).

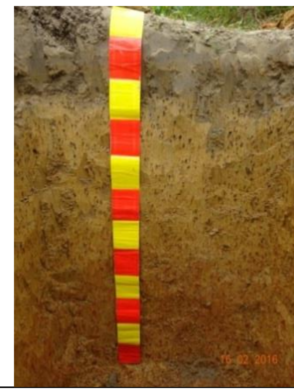
a)Site A Name (FAO-UNESCO): Gleyic (clay mineral) Acrisol Xop Village, Huong Thuong Commune, Dong Hy District, Thai ($21^0$43N”, $105^0$42”E, 152m a.s.l)		
b)Site B Name (FAO-UNESCO): Calcic-Acric Ferralsol La Dong, La Hien, Vo Nhai District, Thai Nguyen province ($21^0$46’N, $105^0$28’E, 350m a.s.l)		
c)Site C Name (FAO-UNESCO): Acric Ferralsol Trang Hoc, Du, Phu Luong District, Thai Nguyen Province Nguyen province ($21^0$35”, $105^0$52”, 55m a.s.l)		
d)Site D Name (FAO-UNESCO): Gleyic Fluvisols Lang Village, Uc Ky Commune, Phu Binh District, Thai Nguyen Province ($21^0$30’, $105^0$36’, 22m a.s.l)		

Fig. 16 a-d. Some soil profiles and horizons in Thai Nguyen province, Vietnam (February, 2016).

The first profile A (Fig. 16a) was chosen in Dong Hy District ($21^0$35”, $105^0$52”, 55m a.s.l). The district is located near Cau River which flows along the center of Thai Nguyen province. The topography is characterized by a flat horizon. The dominating soil type in this location is classified as Acric Ferralsol.

The second soil profile B (Fig. 16b) was in Vo Nhai ($21^0$42’13”N, $105^0$55’25”E, 55.47 m a.s.l). Vo Nhai is the northern district of Thai Nguyen province, which is not only one of the major areas for maize production, but also one of the special regions by special soil characteristics. Vo Nhai is a mountainous area of approximately 845.10 km^2 with great variation in elevation, ranging from 50 m to 600 m and many calcic hills around the fields. The climate of the region is influenced therefore by nearby mountains, increasing variation of regional precipitation. The dominating soil type in this area is classified as calcic-acric Ferralsol (FAO-UNESCO 1988) (Calcic layer in light grey in A-horizon, the strong accumulation of clay in the B-horizon (light yellow) and not dark in color. The annual rainfall averaged over 1961-2004 was 1539 mm (representative weather station Dinh Hoa, $21^0$46’N, $105^0$28’E, 350ft a.s.l). In dry season, soil is dramatically dry and hard, leading to some difficulties in tillage.

The third soil profile C (Fig. 16c) was determined in Phu Luong district ($21^0$43N’, $105^0$42’E, 152 m a.s.l) which is located in the Northwest of Thai Nguyen. Its topography is characterized by gently rolling terrains and hills. Therefore, the accumulation of iron and aluminum in arable land is higher than the other regions. In some parts of the district, the high level of ground water is the reason leading to gleyic process, driving the yellowish and greyish colors in some spots in soil. Additionally, soil texture is mainly characterized by small sandy particles at the surface. Hence, the soil is classified as a Gleyic Acrisol (FAO-UNESCO 1988).

The final soil profile D (Fig. 16d) was dug in Phu Binh district which locates in the south of Thai Nguyen province ($21^0$30”, $105^0$36”, 22m a.s.l). As similar to the soil profile C, its location is near Cau river where the land area was almost flat with large plains used for rice and maize crop. However, the cut surface of soil profile D shows that there is a difference between profile C and profile D. It is easy to see that the profile D has a kind of smooth, silty, clayic cut surface while profile C has lots of gravels and is kind of sandy soil. Moreover, the brown color in profile D presents a distinct topsoil horizon which mostly created by fluvial materials concentration while the yellow horizon presents the GLEY process over the flooded periodically. Based on those typical characteristics the soil is easily defined as Fluvisols (FAO-UNESCO 1988). The representative weather station is located in Thai Nguyen ($21^0$36”,$105^0$50”, 39m a.s.l).

Fig. 17. Groups of soil samples from four soil profiles in Thai Nguyen province, Vietnam. (01-03: Site A-Dong Hy, 04-06: Site B- Vo Nhai, 07-09: Site C- Phu Luong, 10-12: Site D-Phu Binh)

To measure some chemical soil properties, basic methods were applied and took place at the laboratory in Thai Nguyen Agriculture and Forestry, Vietnam (Fig. 49), with the support from the technical staff (Mr. Hung) and Thai Nguyen center of analysis and environmental. Methods for each soil indices were shown in table 5.

Table 5. Measurement of some chemical soil properties

Chemical soil properties	Name of method
Organic matter (humus)	Tiurin method (J. Mebius, 1960)
Total nitrogen	Kjeudahl method (Gibson, 1904)
Phosphorus	Molybdate blue–ascorbic acid colorimetric method (Adesanwo et al., 2013)
Cation exchanges	Amoni axetat method (TCVN 8569:2010) (Vietnam, 127/2007/NĐ-CP, 2007)

The measured soil properties of four soil profiles afterwards were matched with previous analyzed soil data from Thai Nguyen center of analysis and environmental to improve the accuracy of typical soil indices for maize. However, there were two soil profiles having the same properties, therefore, three of them were used to calibrate and simulate the maize yield (table 6).

Table 6. Soil properties of examined soil profiles within the study region

Profile	Depth (bottom)	Texture (%)		pH	OM	Total N	CEC	Drained		Bulk density
	(cm)	< 0.002	0.02-0.002	(KCl)	(%)	(%)	(cmol/kg)	Lower limit	Upper limit	g/cm^3
Profile A – Dong Hy	0-20	15.1	49.8	5.2	1.49	0.05	11.5	0.064	0.143	1.2
Gleyic Acrisol	20-90	23.7	9.8	4.2	0.44	0.04	5.7	0.052	0.078	1.56
	90-120	23.7	9.1	4.3	0.37	0.03	4.3	0.051	0.075	1.58
Profile B - Vo Nhai	0-20	15.2	33.3	4.5	0.6	0.03	11.5	0.065	0.132	1.42
Calcic-Acric-Ferralsols	20-80	16.5	30.1	4.2	0.3	0.01	5.7	0.07	0.135	1.48
	80-120	16.9	30.9	4.4	0.1	0.01	4.3	0.057	0.11	1.51
Profile D - Phu Binh	0-20	18.2	33.5	6.0	1.7	0.06	18.1	0.147	0.283	1.29
Fluvisols	20-60	20.1	32.9	5.5	0.3	0.03	11.1	0.121	0.226	1.47
	60-120	17.8	35.1	5.0	0.1	0.01	9.4	0.106	0.209	1.48

(OM: Total organic matter; CEC: Cation exchange capacity)

3.2.3 Experiment fields and crop management data

The experiment fields were conducted by Nguyen Huu Hong in 2008 in Thai Nguyen province, Vietnam for winter and spring maize seasonal crops. The results of the field experiment were published in Thai Nguyen scientific journal in 2008 (H. H. Nguyen, 2008) In the field experiment, maize was grown in spring and winter seasons with eight new hybrid maize genotypes and one local maize genotype under irrigated condition and optimized maize fertilizer application (Tab. 7). The results showed that maize yields of hybrid genotypes were higher than the control genotype which was also the local genotype for a long time. Hybrid maize yields ranged from 5770 to 7340 kg ha^{-1} and 5380 to 7370 kg ha^{-1} in spring and winter season, respectively. Meanwhile, the local maize genotype derived only 4720 kg ha^{-1} in the spring season and 5790 kg ha^{-1} in the winter season (H. H. Nguyen, 2008). Leaf area index in the spring season is mostly higher than a winter season from 0.2 to 1.5 with a number of leaves per plant of around 18-21 (H. H. Nguyen, 2008; Tran et al., 2012).

In local fields, farmers still use buffalos to do tillage and expose to chemical pesticides because of mixing, loading, and spraying directly by hand because of the small size of cropland and the low level of technical development. This issue therefore takes more human efforts and increases health risk in crop cultivation practices. However, there was a difference in terms of maize varieties over the time. In the past, local maize genotypes mostly were the white sticky maize (Fig. 3b). Currently, due to the increased demand for maize in the livestock sector, most maize genotypes used by farmers in Thai Nguyen province are hybrid genotypes (Fig. 3a). It is also the reason why local agronomists mainly focus on hybrid maize genotypes.

To improve the realistic results of crop management data, the study interviewed farmers, and local experts about agronomic managements such as tillage, N application, manure, or pesticide applications. The results showed that there was a difference of nitrogen applications. 100 kg N ha^{-1} was the common level of N application by farmers in Thai Nguyen province while 150-200 kg N ha^{-1} was the recommended rate from local experts (H .H. Nguyen, 2008). Besides, in some parts of the province, farmers commonly use chemical fertilizer such as Urea-$CO(NH_2)_2$, ammonium nitrate (NH_4NO_3) because of quick impact on crop growth. In other villages, farmers use chemical fertilizers combined with organic amendments from organic wastes, poultry and animal manure from chickens, cattle, or horses to save costs. Manure was normally applied after tillage and before sowing. Other information on crop management was listed in table 7.

Table 7. General crop management details of maize growth, Thai Nguyen province, Vietnam.

Stage		Days after sowing		Management				
		Spring season	Winter season	Tillage		Organic amendments (kg/ha)		P (Phosphorus) (kg/ha)
Prepare				Cultivator, field	Animal drawn implements	5550 (manure)		50
Planting date		February	September					
1	Sowing	0	0	Planting method	Planting distribution	Plant population (plant/m^2)	Row spacing (cm)	Planting depth (cm)
				Dry seed	Rows	70	25	2-10
2	Emergence	-	-		Irrigation*			
3	2 leaves fully emerged							
4	5 leaves - Tassel and ear initiation	-	-	1/3 N+1/2 K	Irrigation*	Farmer surveys: Fertilizer application for 1 ha: 5550 kg organic fertilizer + 100kg N+ 50kg P+ 45kg K Experiment field data: 1500** kg compost + 200N+100 P+ 90K -		
5	8 leaves	-	-	1/3 N+1/2 K	Irrigation*			
6	16 leaves	-	-	Chemical application	Irrigation*			
7	Pollination (20 leaves)	-	-	1/3 N	Irrigation*			
8	Tasselling/ Silking	75/77*	68/69*		Irrigation*			
9	Maturity	124*	130*		Irrigation*			
Harvest		May	December					

* Recommended

** Experiment field data

3.3 DSSAT CERES – Maize application

In this study, Decision Support System for Agrotechnology Transfer (DSSAT V4.5 and DSSAT V4.6) was used to simulate maize yields under the variable weather and various main soil properties.

In order to simulate maize growth in the study region, maize was simulated in spring (as spring maize from February till May) and in winter (as winter maize from September till January) due to the main maize seasons Thai Nguyen, Vietnam (H. H. Nguyen, 2008). Data of planting dates and N (nitrogen) applications were derived from farmer surveys based on empirical experience and annual reports from the Department of Agriculture and Rural Development, Thai Nguyen, Vietnam. In this study, model validation and crop simulation were implemented for three soil types with the average amount of fertilizer application (100kg N, 50kg P, and 45kg K per ha) for each maize growing season, whereas, model calibration which followed crop indices and crop management of experiment fields (see section 3.2.3 and table 7).

However, DSSAT CERES – Maize was first calibrated using crop growth and development parameters which obtained from the experiment field (see more in section 3.2.3). The calibration was created by five genetic coefficients, including total numbers of leaves per stem (LAIH), beginning peg stages (days after sowing) (R2AT), physiological maturity days (harvest days) (MDAPs), leaf area index (LAIXS) and grain yields (HWAMS) for three maize hybrids which are SX2010, SX5012 and LVN47 from the experiment fields. Additionally, three main soil types of maize fields (Ferralsols, Acrisols and Fluvisols, see section 3.2.2 and table 6) were considered to improve the accuracy of calibration and validation of the model and mitigate the uncertainty of simulation in response to see the influence of climate on maize production in the future.

3.3.1 Calibration and validation of DSSAT model

Calibration is considered as model parameter estimation. Calibration is a critical aspect of crop modeling project because the accuracy of results is heavily dependent on the parameter values used in the model, especially crop parameters. Validation is the second most important aspect to improve the accuracy of model application for simulation goal, by using independent data from the calibration data set.

ATCreate and GenSelect (GENCALC) apps in the DSSAT shell were used to calculate the crop genetic coefficients. Beginning with ATCreate, five crop growth indicators from the experiment field were filled to create the file.MZA. Afterward, a simulation file of experiment field (*.MZA) was created by “Crop management data” tool to run the crop model. Finally, the measured crop growth results were compared with observed data from the experiment field. That soil was chosen to calibrate the DSSAT model is Acrisols (Tab. 6). The calibration was carried out for three varieties: SX2010, SX 5012, and LVN 47. Crop management data were taken out from experiment field data.

To validate the DSSAT model, data including historical weather, soil, and management data were used to simulate maize yields. The input management data were collected from Farmers Surveys and Agriculture and Rural Development Department in the local area. Further, statistics on annual maize yields/production were collected from the local statistic report book. The maize yields were calculated for three main soil types of the province (Tab. 6) with the percentage of Ferrasols, Acrisols, and Fluvisols by 75.68%, 1%, and 8%. However, to accruate the average maize yield for provincial case, the study combined the percentage of other soil types to Acrisols portion to have the total number of soil types is 100%. The formula to calculate the average maize yield was presented in the section 3.3.2. After simulation, the simulated maize yields were compared with the annual maize yield statistics by NRMSE (Normalized Root Square Error) to estimate the performance of the simulation. Moreover, the sensitivity of the DSSAT model was tested against weather input parameters (temperature, precipitation).

3.3.2 Crop simulation

For further evaluation of the simulation results against reported annual maize production statistics, the simulated maize yields (including two growing seasons) were weighted between the share of three soil types within the case study region as follows:

$$Y = (\overline{F_X} + \bar{F}_Y) = (a_1x_1 + a_2x_2 + \dots + a_ix_i) + (a_1y_1 + a_2y_2 + \dots + a_iy_i) \quad (7)$$

$$x_i = (x_r + x_w)/2 \quad (7a)$$

$$y_i = (y_r + y_w)/2 \quad (7b)$$

Y: annual maize production

$\overline{F_X}$: maize yield in spring season

$\bar{F}_Y$: maize yield in winter season

a_1 ... a_i: constant arable area of each soil types

x_1 ... x_i: averaged maize yield in spring

y_1 ... y_i : averaged maize yield in winter

$x_r(y_r)$: simulated maize yield in spring (winter) under rainfed condition

$x_w(y_w)$: simulated maize yield in spring (winter) without water stress (irrigated)

3.3.3 Performance of DSSAT-CERES Maize model

3.3.3.1 Validation of CERES-Maize

The Normalized Rood Square Error (NRMSE) was used to evaluate the performance of CERES_Maize model using the simulated and observed maize yield as follows:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(o_i - s_i)^2} \qquad (8)$$

$$\text{NRMSE} = \frac{RMSE}{\bar{O}} * 100 \qquad (9)$$

Where

RMSE: root mean square error

NRMSE: normalized root mean square error

n: a number of different simulation

s_i : simulated maize yield in year i

o_i: observed maize yield in year i

$\bar{o}$: the mean of observed maize yield

The smaller RMSE is, the better becomes model performance where its minimum of zero implies perfect model fit.

NRMSE gives a relative measure (%) of the difference between simulated and observed data. The simulation is considered excellent with a NRMSE less than 10%, good if the normalized RMSE is greater than 10% and less than 20%, fair if the NRMSE is greater than 20% and less than 30%, poor if the NRMSE is greater than 30% (Bannayan & Hoogenboom, 2009).

Another indicator used for estimating model performance was the Index of Agreement (d):

$$d = 1 - \frac{\sum_i^n (O_i - S_i)^2}{\sum_i^n (|S_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (10)$$

Where d: index of agreement

O_i: Observed yield in year i

S_i: Simulated yield in year i

$\bar{o}$: the mean of observed maize yield

The Index of Agreement (d) developed by Willmott (1981) is a standardized measure of the degree of model prediction error and varies between 0 and 1. A value of 1 indicates a perfect match, and 0 indicates no agreement at all (Willmott, 1981). Besides, the index of agreement can detect additive and proportional differences in the observed and simulated means and variances; however, it is overly sensitive to extreme values due to the squared differences (Legates and McCabe, 1999).

3.3.3.2 Sensitivity analysis of CERES Maize model under various weather conditions

Crop model sensitivity analysis was carried out by changing the historical weather (observed) conditions for 6 regimes (table 6).

Table 8. Climatic regimes for analysis the sensitivity of DSSAT model.

Regimes		Define
1	+2 °C	Increase temperature 2 °C
2	+2 °C,-25%	Increase temperature 2 °C and decrease precipitation 25%
3	+2 °C,+25%	Increase temperature 2 °C and increase precipitation 25%
4	+4 °C	Increase temperature 4 °C
5	+4 °C,-25%	Increase temperature 4 °C and decrease precipitation 25%
6	+4 °C,+25%	Increase temperature 4 °C and increase precipitation 25%
7	-25%	Decrease precipitation 25%
8	+25%	Increase precipitation 25%

3.3.4 Maize yield simulation under climate change scenarios

3.3.4.1 GCMs scenarios

The weather data used for this study were created by Danish Meteorology Institute and derived from CORDEX (coordinated Regional Climate Downscaling Experiment https://esg-dn1.nsc.liu.se/search/cordex/). The scenarios were based on the driving GCM (global circulation model), namely ICHEC-EC-EARTH and the RCM (regional climate model) DMI-HIRHAM5. Both, RCP4.5 and RCP8.5 climate scenarios for the period 2001-2100 were applied in the study.

3.3.4.2 Simulation of maize yields during 2001-2100

The simulation of spring and winter maize, respectively, was carried out for 100 years (2001-2100) for each soil type and climate scenario combination with the average amount of fertilizer application (100kg N, 50kg P, and 45kg K per ha) for seasonal maize crops (spring and winter maize, respectively). The annual yields were calculated by Equation (7).

3.4 AGRICLIM - Agroclimatic Indexes model

AGRICLIM is an agrometeorological software which includes 4 main sub-models which are ETo (reference evapotranspiration) model, Snow model (snow layer occurrence and depth), FAO model (actual evapotranspiration and crop soil water balance parameters), and Agro model (many other agroclimatic risk indicators, such as frost risk, heat waves at various seasonal time scales etc.). The model is used as a tool to calculate plenty of agrometeorological indexes (see Appendix for details, Table 15) such as the number of dry days, number of snow days, duration of heat waves, and many other indices which are useful to identifying weather-related cropping risks. The input data include daily data of solar radiation, maximum and minimum temperature, evapotranspiration, rainfall e.g. To run the model, users need to set up parameters for each sub-models, for example, units, solar constants, or albedo which are needed for the Eto model.

IV. RESULTS AND DISCUSSION

4.1 Past climate characteristics of Thai Nguyen province

4.1.1 Climatic trends in Thai Nguyen province over 35 years (1980-2015)

From 1961-2010, the mean monthly temperatures in the north of Vietnam showed an increasing trend while precipitation tended to decrease in almost all of the observation stations in the north (Tran Thuc, 2013). By observed local weather data over the past 35 years (1980-2015), it can be seen that local climatic conditions had also gradually changed in Thai Nguyen province, Vietnam, particularly shown by an increasing temperature trend.

The monthly average temperature over the first decade of 35 years (1980-2015) was 23.1 °C. In the second decade, the average temperature showed an increase of 0.4 °C compared to the first decade. This pronounced tendency was present until the third decade, which had an increase of temperature by 0.3 °C. Besides, the highest and the lowest monthly average temperatures (monthly based) were found by 29.7 °C in July 2010 and 11.9 °C in January 2011, respectively, indicating a large variation of temperature in the last 5 years of the period (1980-2015). However, in contrast to temperature, annual solar radiation seemed to decrease slightly over the period with R^2(R-square) value of 0.44. The increased concentrations of carbon dioxide and other greenhouse gases were expected to be the initial reason leading to higher temperatures without increasing solar radiation. From 1975-1999, CO_2 concentration based forcing increased from 0 Wm^{-2} to approximately 2.5 Wm^{-2}, providing the biggest contribution to the radiative forcing, accounting for 61% (Shine et al., 2001). Besides, the declining trend of global radiation could be dedicated to increasing air pollution (solar dimming) in the region, where decreasing trend in air humidity could be explained by the declining precipitation (Wild & Ohmura, 2009). In addition, El Niño, the active volcano eruption in the Pacific Ocean and environmental pollution may be the further possible reasons leading to higher temperatures in the local troposphere.

Similar to annual solar radiation, annual precipitation and annual relative humidity showed fallen trends from 1980 to 2015 with R^2(R-square) values of 0.1907 and 0.3917, respectively. The average annual rainfall was 1897.8 mm over 35 years while the monthly average rainfall was 158.2 mm. A higher variation of precipitation was observed in few last years of the period 1980-2015. The rainfall in 2013 reached the highest amount, with a total rainfall of 2572.6 mm out of the 35-year historical period (1980-2015), which was higher by 60 mm compared to the second highest amount of rainfall in 1986. Meanwhile, the lowest total annual rainfall was observed in 2003 as only 1689.9 mm. As a consequence, the relative air humidity also declined to the lowest level as 79% in 2003, which was lower by 5% in comparison with the highest level of air humidity in 2000 and lower by 3% compared with the average of relative humidity over 35 years.

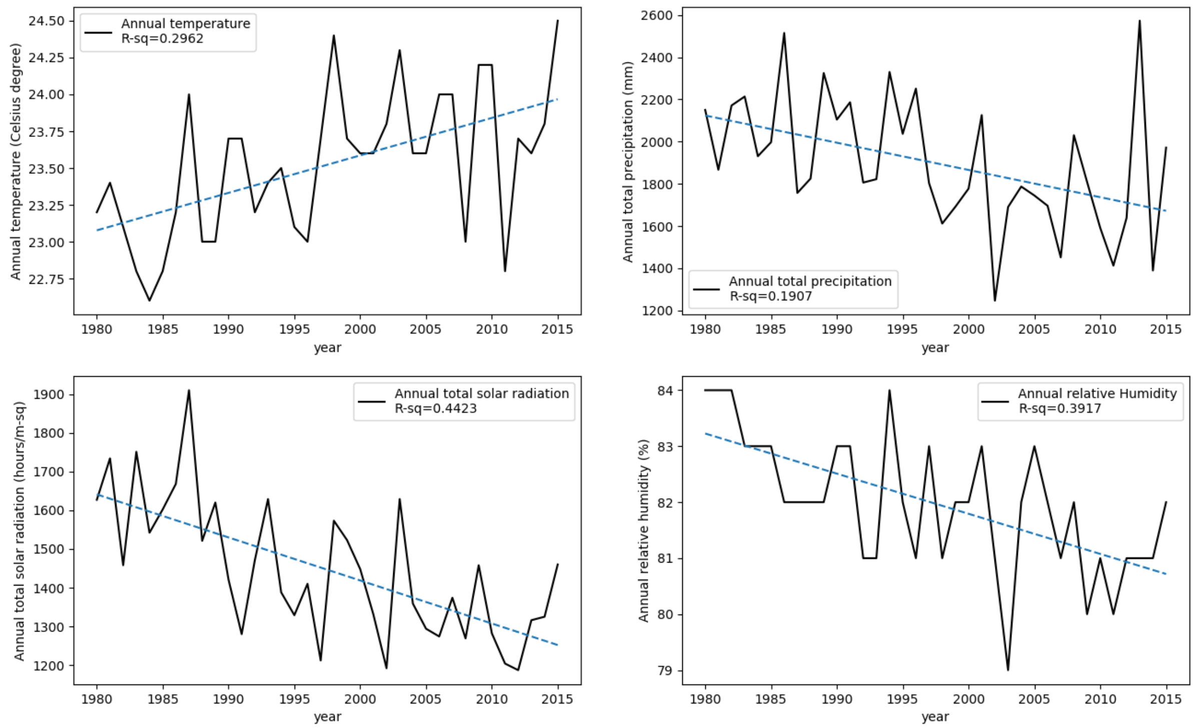


Fig. 18. Annual weather data (temperature, precipitation, global radiation and air humidity) from 1980-2014 Thai Nguyen, Vietnam (R-sq termed R square).

In addition, the number of days without rainfall during the spring (February to May) from 2000 to 2015 (Fig. 19) in association with a decreasing trend in annual rainfall (Fig. 18) indicated that there is an increasing trend of drought. This fact may cause problems for agriculture, particularly in terms of water supply during the drought period.

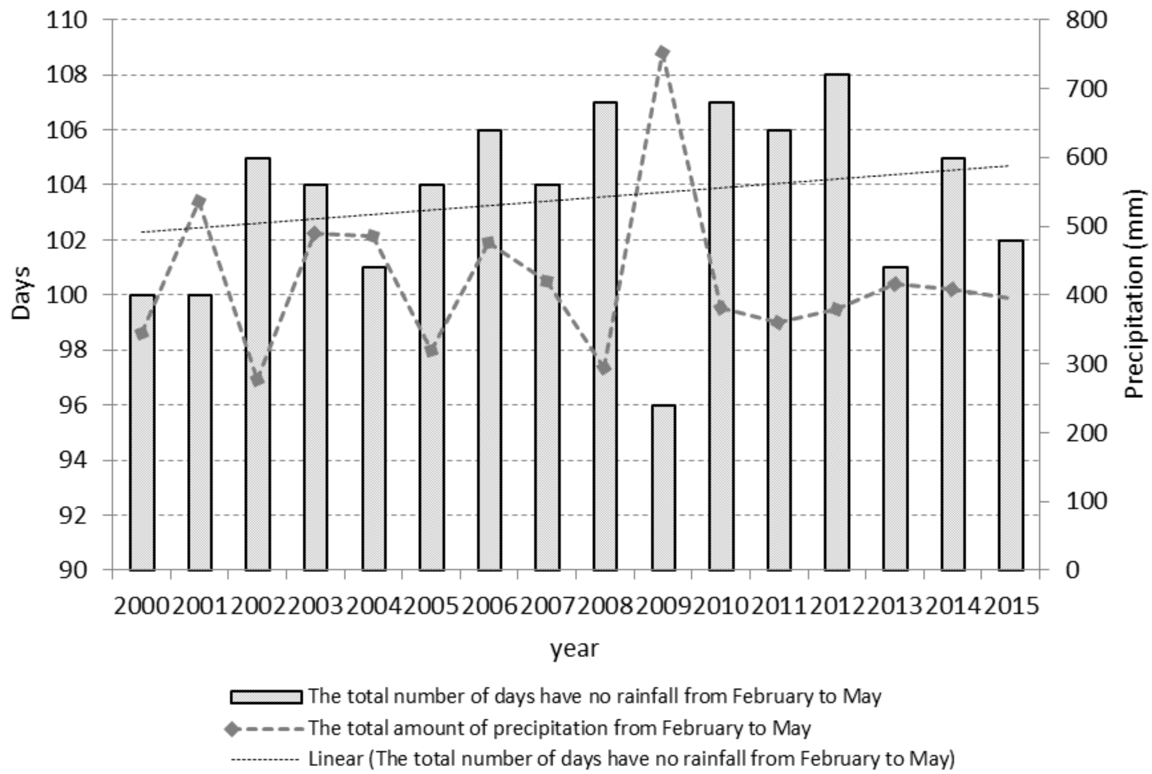


Fig. 19. The total number of days without rainfall and precipitation amount in spring maize growing seasons 2000-2015.

In conclusion, the local climate data provide evidence of climate change on a regional scale, in Thai Nguyen, Vietnam. The local weather shows simultaneous changes in all aspects of climatic conditions but in different trends. Combined with increasing temperatures, the extreme weather intensity was also reported to be more frequent with heavy rain, extreme hot temperature and an increasing trend of prolonged dry periods over the past 35 years.

4.1.2 Monsoon season and the potential of maize production under local weather conditions in Thai Nguyen province, Vietnam

Thai Nguyen province is located in the northwest of Vietnam, and is frequently influenced by the summer monsoon. Therefore, the onset time of the rainy season in the study area is commonly from April or early May and prolongs until September. Over the period 1980-2015, the total annual amount of precipitation was mostly contributed by summer rainfall which mostly accounted for over 50% of total annual precipitation in average. In 2009, the amount of precipitation from October to January dropped to 80.3 mm while it was approximately 9 and 12 times higher than that in spring and summer, respectively, showing a high inter-annual seasonal variability of precipitation. Overall, the total amount of precipitation in summer was higher than in winter approximately by 6 times on average over 35 years (Fig. 20).

Generally, early spring and late winter are considered the dry season in Thai Nguyen, Vietnam. During 1980-2015, the average amount of precipitation was only approximately 200 mm as shown in Fig. 20. Therefore, spring maize usually might face some adverse conditions during germination period in early spring while winter maize had to combat with drought stress phases during pollination (in the middle of winter because of low amount of precipitation or long dry periods).

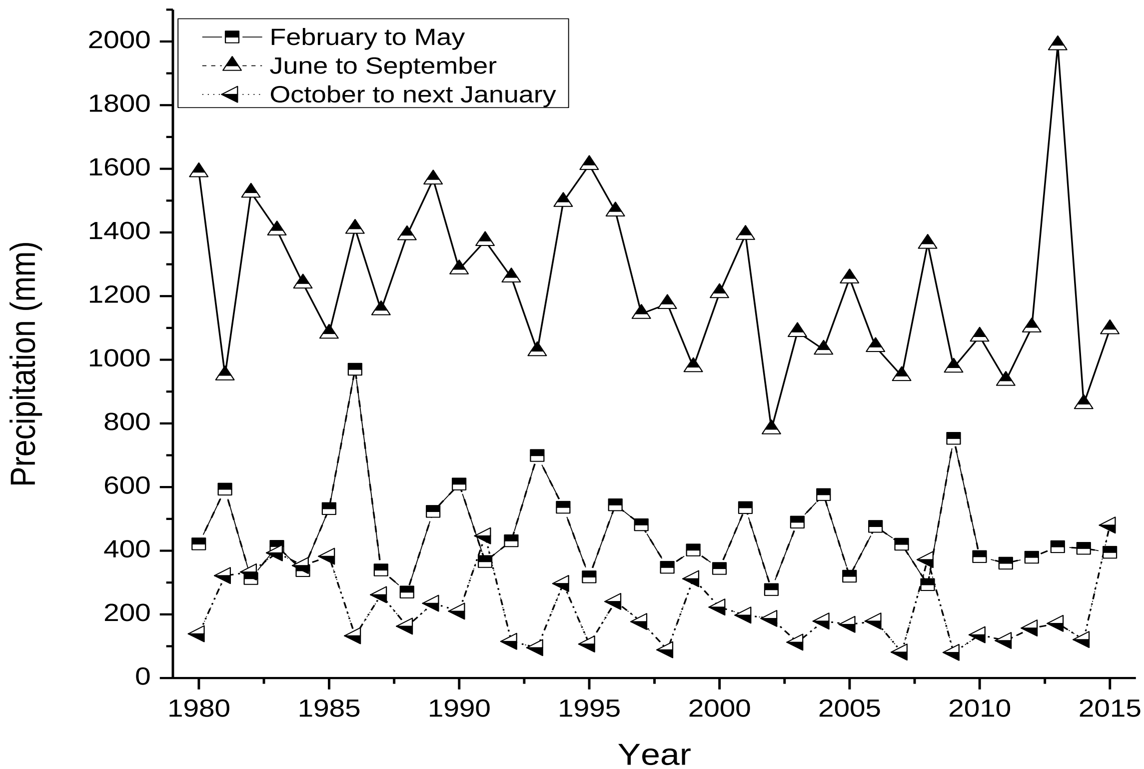


Fig. 20. Distribution of rainfall in Thai Nguyen, Vietnam.

4.1.3 The signs of climate change in Thai Nguyen province, Vietnam

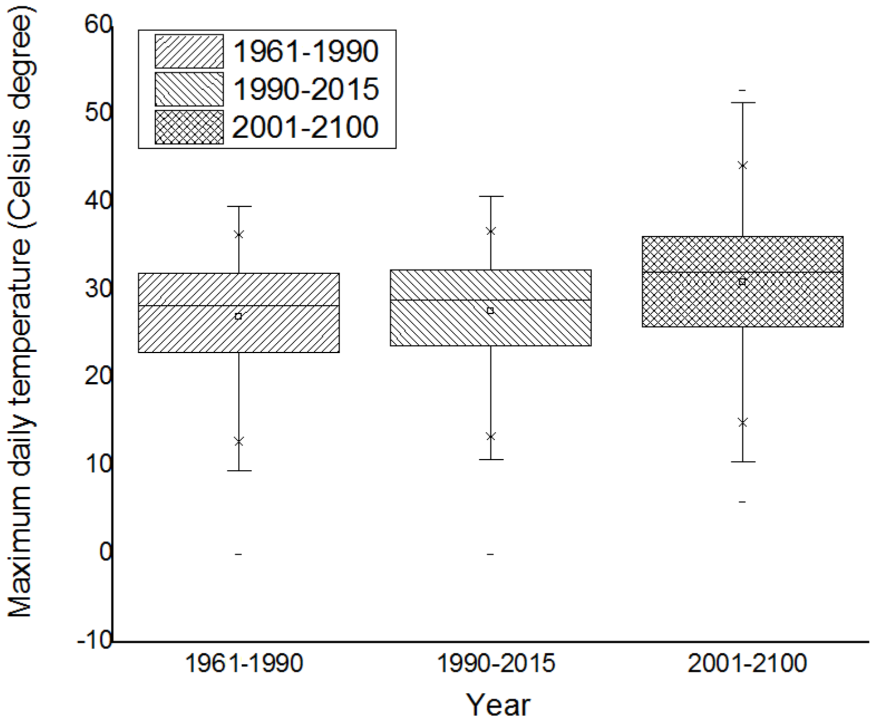
The northwest of Vietnam involving Thai nguyen province may increase in temperature even more than in other regions of Vietnam, while a decrease in precipitation will continuously occur in the next 50 years under Vietnam climate change scenarios (Thi-Minh-Ha et al., 2011; ISPONRE, 2009; Tran Thuc, 2013). Besides, the lowest temperature in winter and in summer was projected to increase by 2-3 °C and 2-3.5 °C (SRES A1B and A2), respectively, untill the end of the 21 century (UNDP, 2013).

Based on the observed weather data from two weather stations over 1961-2015 (Thai Nguyen and Dinh Hoa) (Tab. 3), a minor difference of temperature, and a noticeable difference of precipitation between two station' data were found out. The difference of annual temperature between two stations over two periods was ± 1 °C (see Tab. 9), which may cause by the difference of lattitude and topography. However, a further finding is that the mean annual temperature of both weather stations in the overlapping period from 1980 to 1990 seems to be remarkably similar (Fig. 22), although the weather stations are not near each other and in differ topography (Fig. 21). Therefore, it indicates that during the overlapping period, the increasing trend of temperature was proved in advance.

In the first 30 years of observed analysis (1961-1990), the maximum daily temperature was 39.6 °C in December 1966. However, under the climate the change scenario RCP 8.5, the maximum daily temperature reached incredibly 52.8 °C. Meanwhile, the average maximum temperature also increased significantly from 27.1 °C (1961-1990) to 31.0 °C (2001-2100). Likewise, the averaged minimum temperatures during 2001-2100 were projected to be higher at approximately 2 °C compared to the averaged minimum temperature during 1961-1990. Similar results were reached by the Vietnam climate change scenario updates in 2012 (Ngo, 2014).

a)

b)



c)

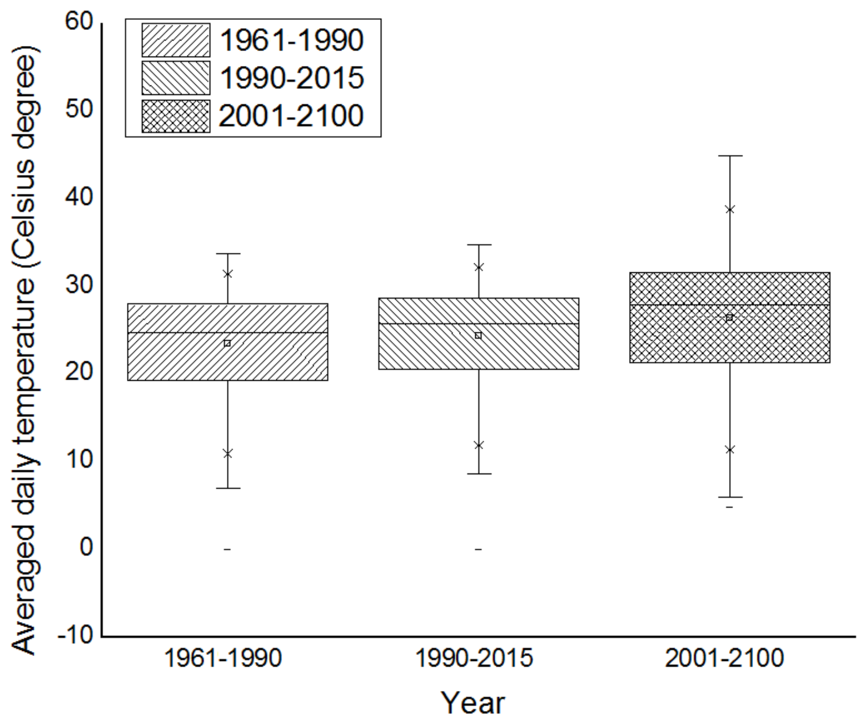


Fig. 21 a-c. Temperature change in Thai Nguyen province, Vietnam

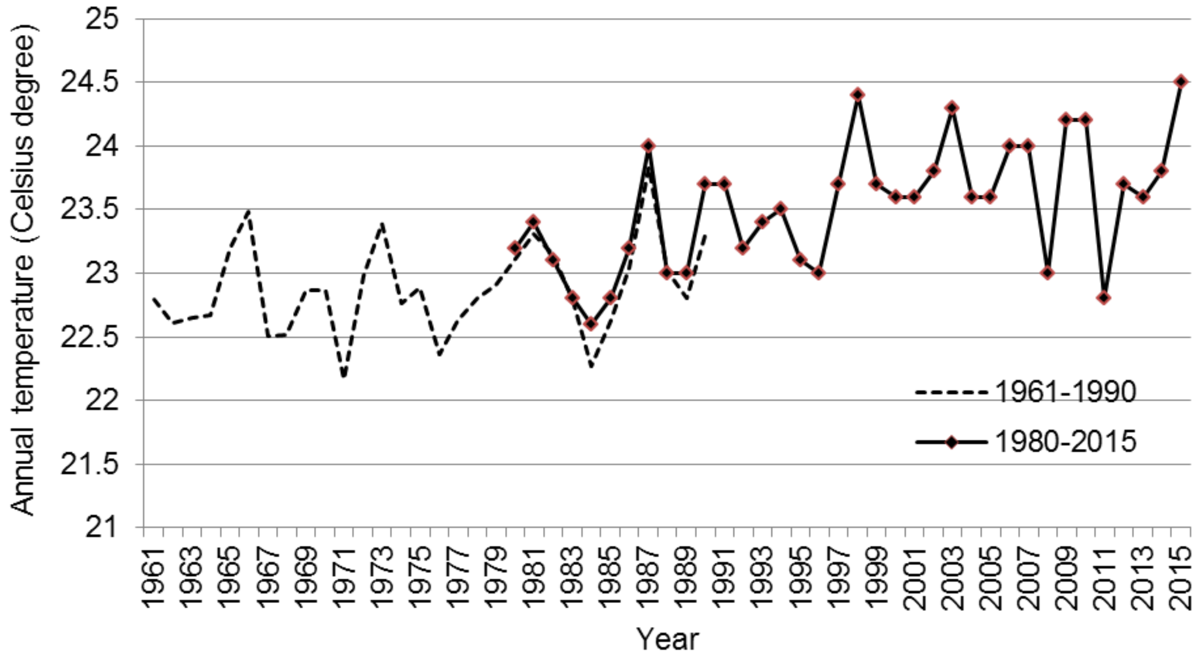


Fig. 22. Mean annual temperature in the overlapping period 1980-1990

The annual precipitation was different about ±15% (see tab. 9).

In contrast, the average daily rainfall decreased under both climate change scenarios RCP 4.5 and RCP 8.5. The average of daily rainfall was approximately 4.64 mm from 1961-1990 and was more or less unchanged from 1990-2015. However, one limitation is found in this case, when the overlapping period of rainfall between two weather stations seemed not fit completely together, especially in 1987 and 1988, most likely due to small scale convective precipitation events (Fig. 23). In 1987, at Dinh Hoa station, the annual precipitation was measured by 109.5 mm while at Thai Nguyen station, it was 152.1 mm. Similarly, in 1988, the annual precipitation in Dinh Hoa station was much lower than in Thai Nguyen station with 135.3 mm and 193.7 mm, respectively. However, in 1990, the annual precipitation at the two stations was similar with 188.4 mm and 175.3 mm, at Dinh Hoa station and Thai Nguyen station, respectively. This would be caused by the difference in topography between the two stations as mentioned above in chapter 3.1. However, the general range of annual precipitation at both sites (ca. 150-200 mm in the overlapping period) proved a similar precipitation climate pattern.

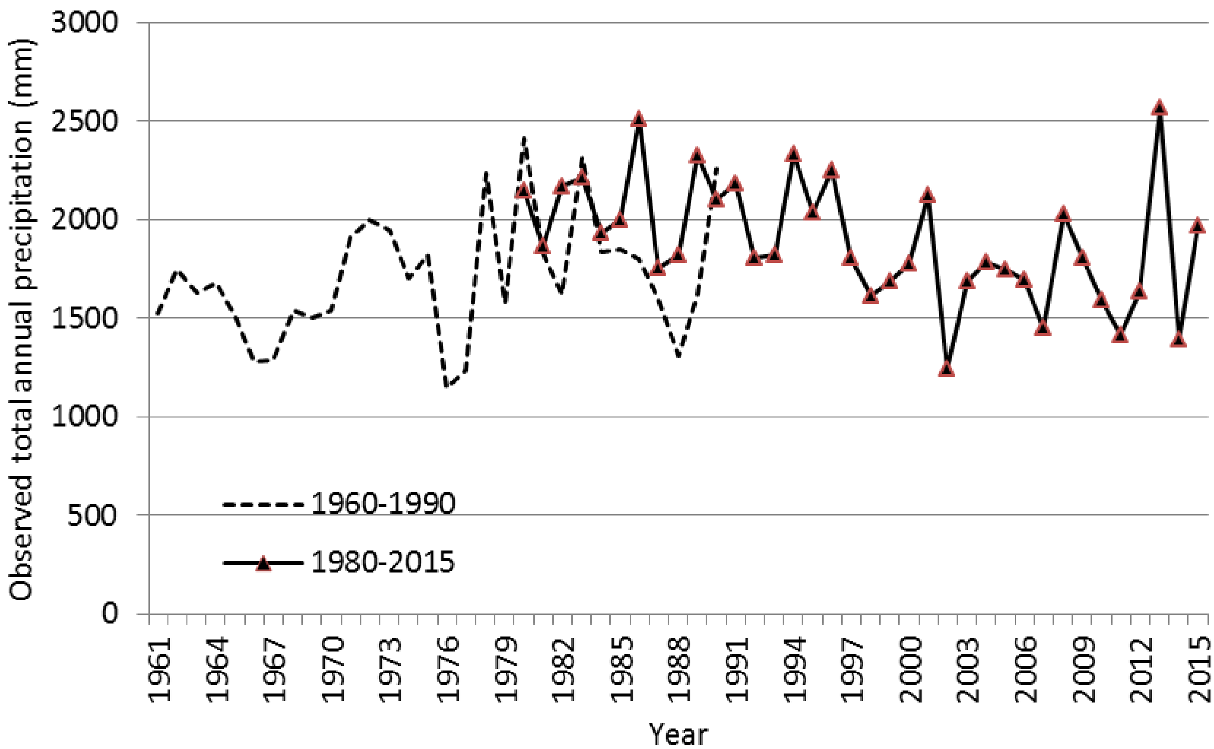
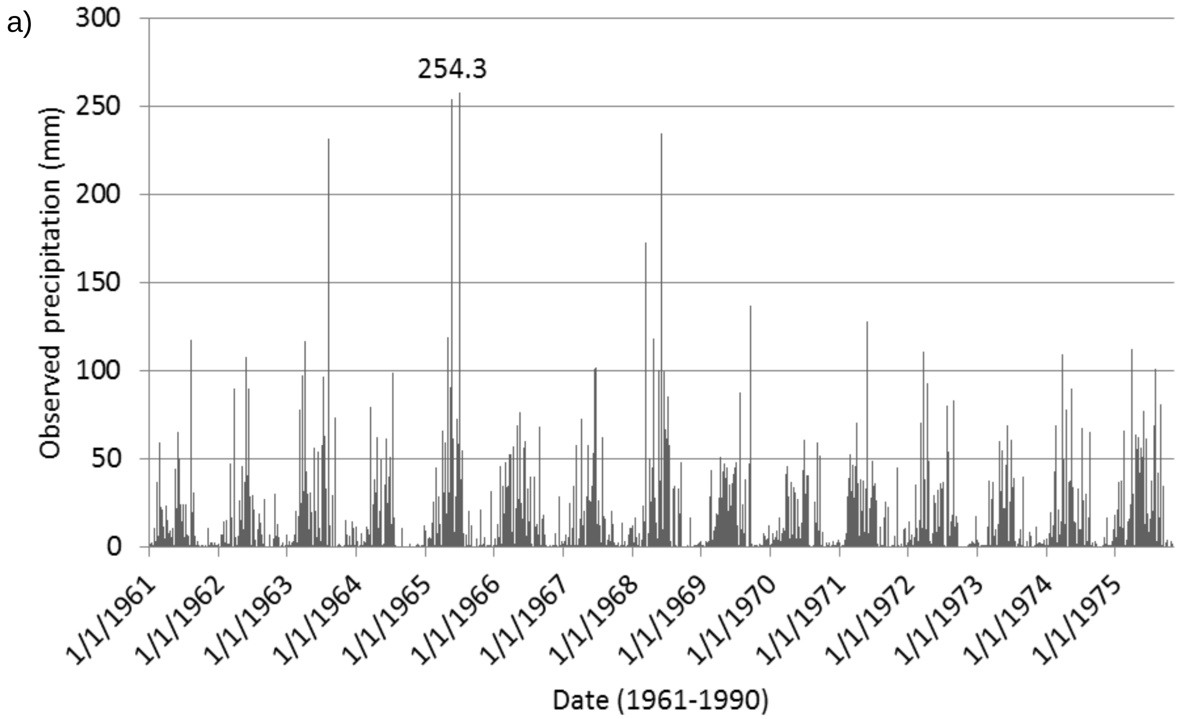
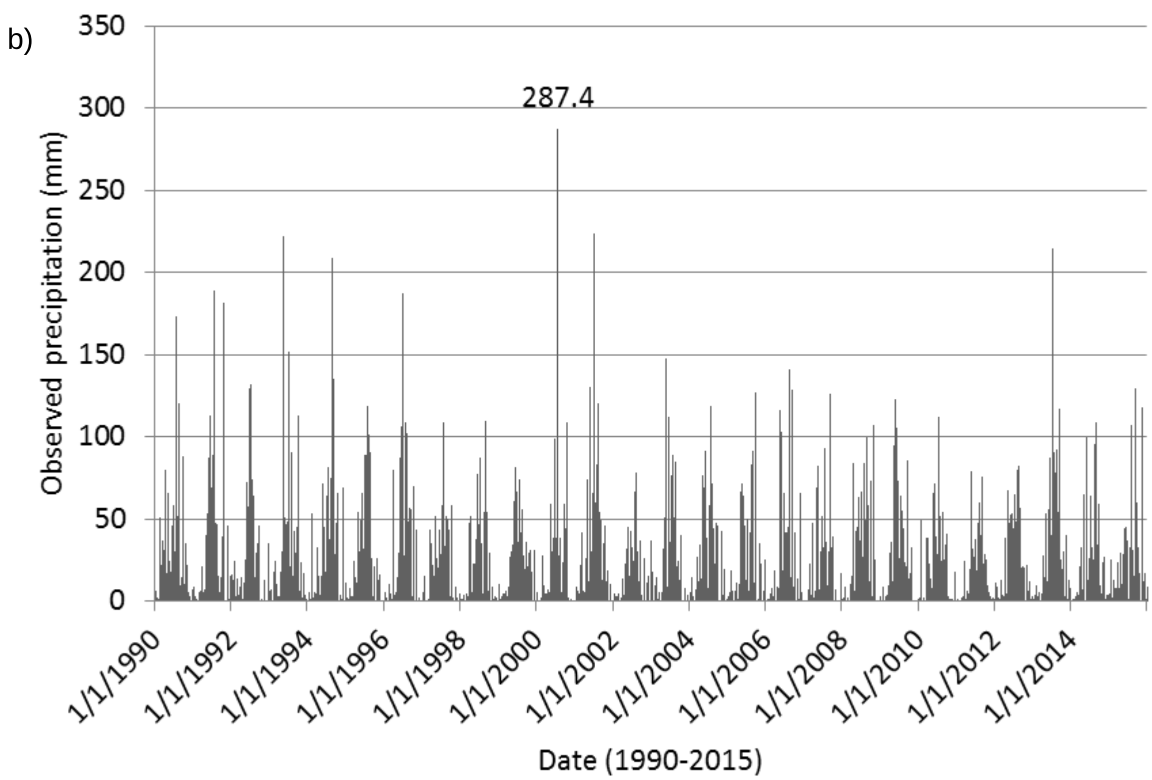


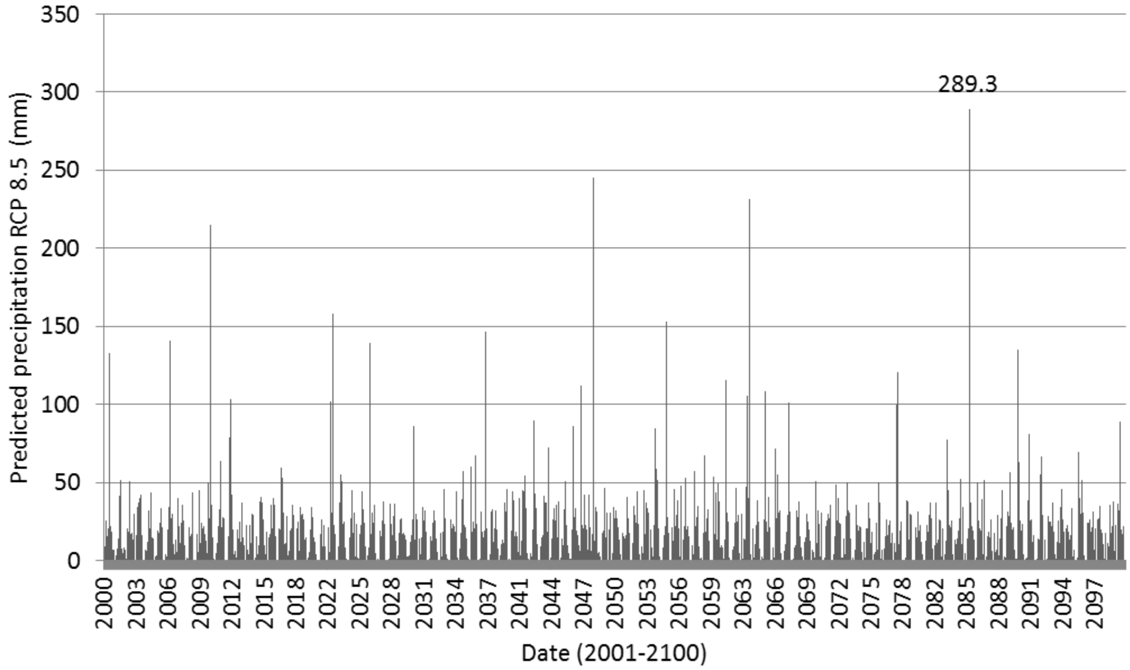
Fig. 23. Mean total annual precipitation in the overlapping period (1961-2015)

Under the climate scenario RCP 8.5, the average daily rainfall was projected to be significantly reduced by 1.85 mm from 2001-2100, which equals a 60% reduction in comparison with the average amount of daily rainfall from 1961-2015. The reduction of precipitation under RCP4.5 was even less than that under RCP 8.5, which was predicted at 1.7 mm. Generally, both scenarios therefore showed extremely low amount of rainfall combined with a high temperature in the future which is expected to have an adverse impact on rainfed maize production potential. This result is consistent with a decrease in the number of wet days by approximately 5–10% in Vietnam (Opitz-Stapleton et al., 2016).


a)
254.3
Observed precipitation (mm)
0
50
100
150
200
250
300
1/1/1961
1/1/1962
1/1/1963
1/1/1964
1/1/1965
1/1/1966
1/1/1967
1/1/1968
1/1/1969
1/1/1970
1/1/1971
1/1/1972
1/1/1973
1/1/1974
1/1/1975
Date (1961-1990)


b)
287.4
Observed precipitation (mm)
0
50
100
150
200
250
300
350
1/1/1990
1/1/1992
1/1/1994
1/1/1996
1/1/1998
1/1/2000
1/1/2002
1/1/2004
1/1/2006
1/1/2008
1/1/2010
1/1/2012
1/1/2014
Date (1990-2015)

c)



d)

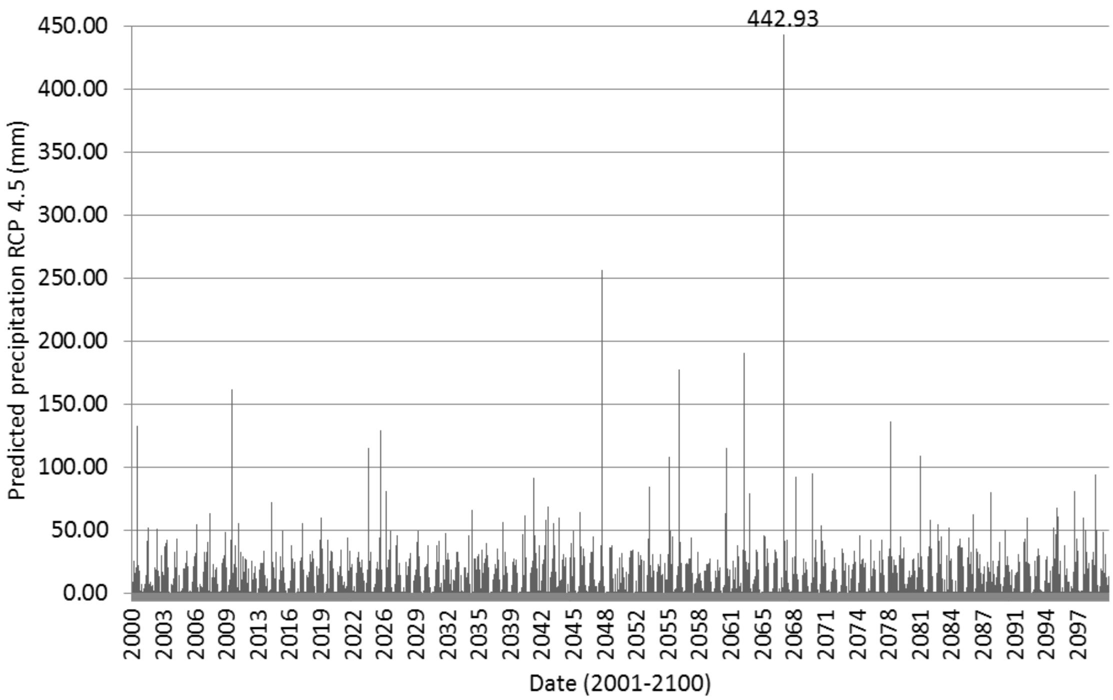


Fig. 24 a-d. Precipitation variability over two climatic periods (a,b), climate scenarios RCP 8.5 and RCP 4.5 (c,d) in Thai Nguyen province, Vietnam.

In addition to the reduction of daily rainfall in the future, the sign of climate change was also shown by the reduction of monthly averages of precipitation (Fig. 25) and the increase of heavy rainfall events under both climate change scenarios RCP 4.5 and RCP 8.5. There was no rain event with the amount of precipitation higher than 300 mm during the past 35 years (1980-2015) while the number of heavy rain events with the amount of over 300 mm under both climate change scenarios (RCP 4.5 and RCP 8.5) was indicated to be higher than the past period. The highest amount of daily heavy rainfall even reached 442.9 mm in 2067 as under RCP 4.5. However, the probability of heavy rainfall events over various rainfall amounts in the future climate scenarios is indicated to be less than in the past, particularly under RCP 4.5 (Fig. 28a-d).

Moreover, the decreasing trend of precipitation seemed logical by the increase of annual and monthly percentage of dry days (Fig. 26 and Fig. 27). The total number of dry days was projected to increase, especially under RCP 4.5 by 72.3%.

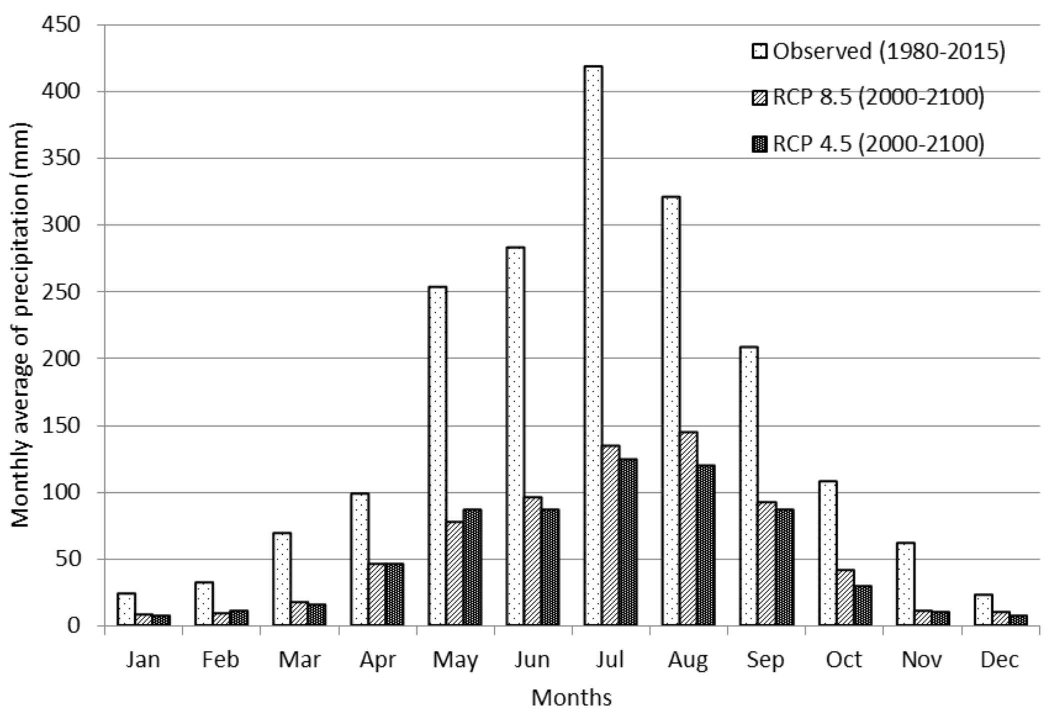


Fig. 25. Average of monthly precipitation

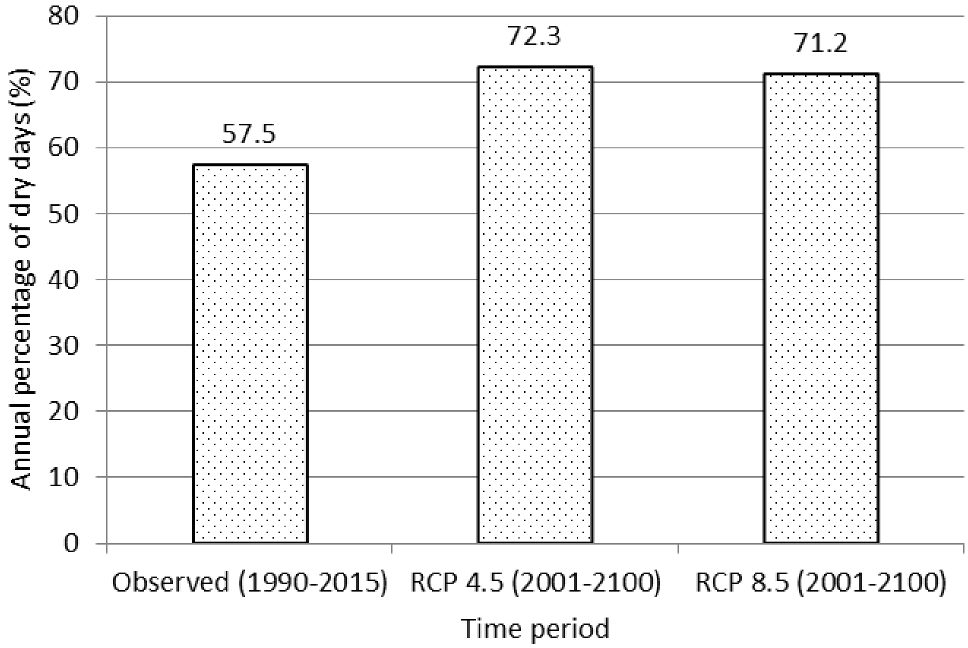


Fig. 26. Annual percentages of dry days

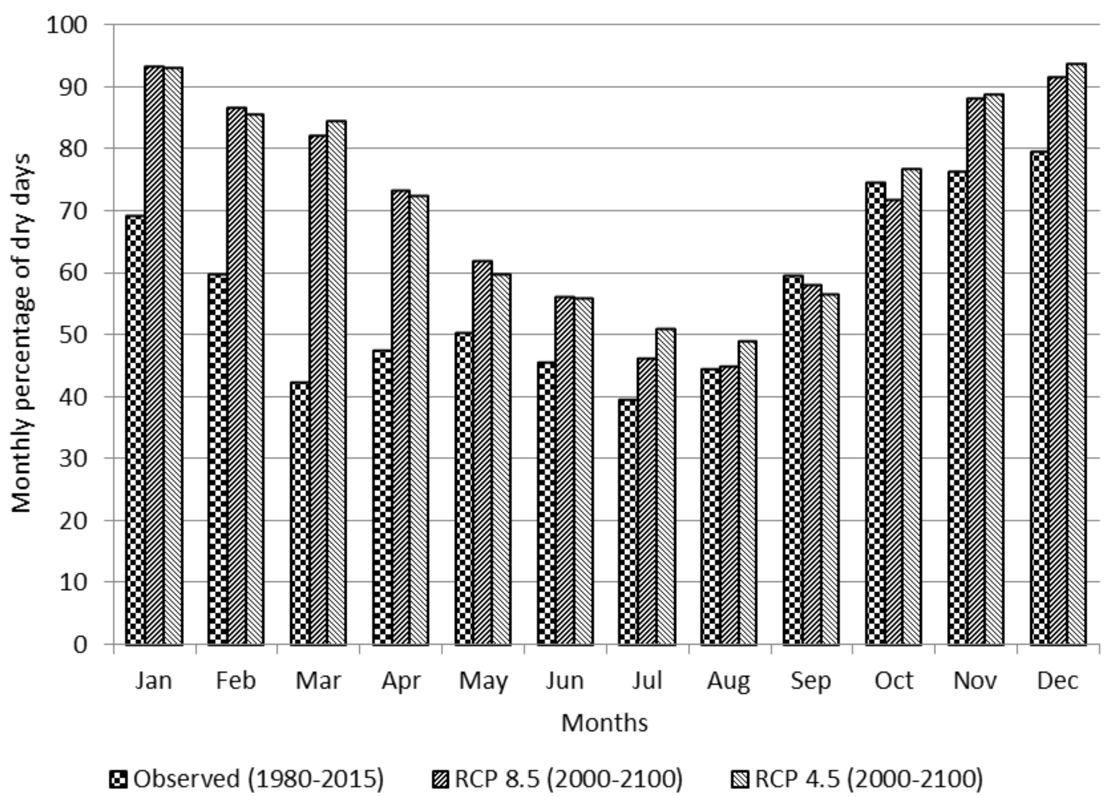
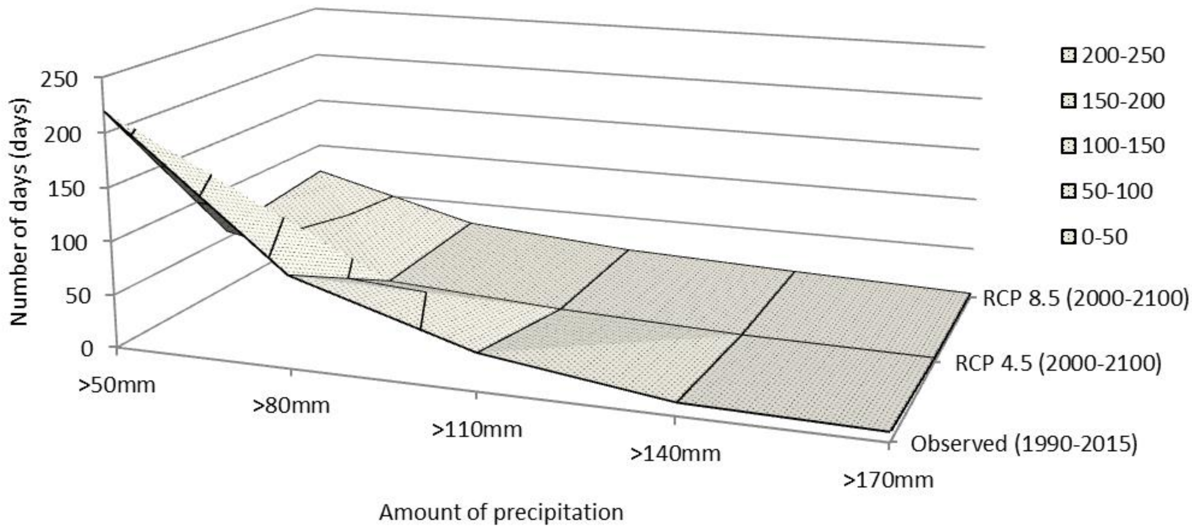
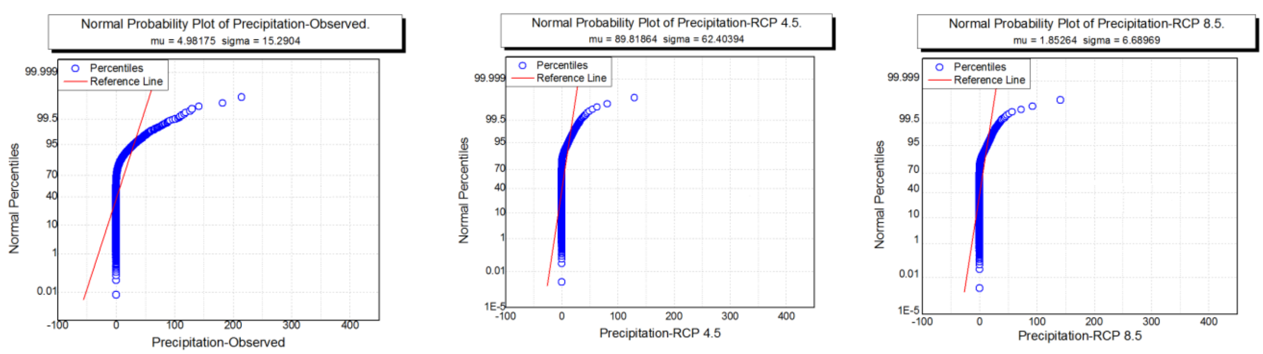


Fig. 27. Monthly percentages of dry days

a)



	Maximum precipitation (mm)
Observed (1990-2015)	287.4
RCP 4.5 (2001-2100)	442.9
RCP 8.5 (2001-2100)	289.3



b) c) d)

Fig. 28 a-d. Distribution and probability of heavy rain

4.2 Local weather condition analysis by AGRICLIM model

4.2.1 Historical periods and an overlapping period under climate change scenario

4.2.1.1. Local weather over the period 1961-2015

Over past 50 years in Thai Nguyen province, the AGRICLIM output results revealed a difference in the effective global radiation sum (SRAD_LGPt5) between the two stations, also between two periods of time (table 9). The SRAD_LGPt5 for every crop was recorded in the Dinh Hoa weather station was less than in the Thai Nguyen weather station, especially SRAD_LGPt5 for winter crop. The increased of SRAD_LGPt5 roughly was proportional to all of other indices which related to heat as heat stress, total duration of heat waves, and the total amount of effective temperature per year, also leading to a slight higher temperature in period 1990-2015 in comparison with the period 1961-1990 by +1°C (tab 9).

Moreover, among three different crop seasons, winter crop was received the highest level of SRAD_LGPt5, which followed by spring crop season and fodder crop season over 1961-2015 (Fig. 29 and tables 9).

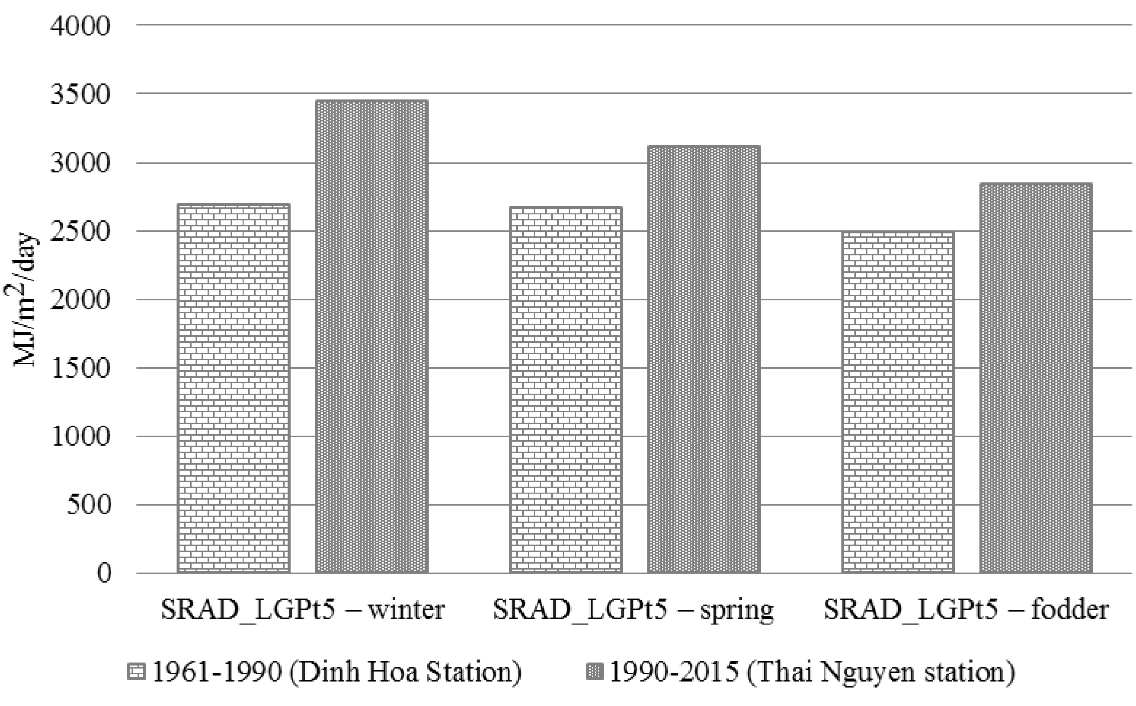


Fig. 29. Comparison of annual effective solar radiation between two historical periods for winter and spring cereal and fodder permanent crop.

Table 9. Overview of agrometeorological indices of two past decades (of available data records) of two weather stations and of two climate change scenarios during 2001-2030 in Thai Nguyen province, Vietnam.

Indices	Name of stations	Dinh Hoa	Thai Nguyen	Thai Nguyen	Thai Nguyen
	Unit	1961-1990 *(Observed)*	1990-2015 *(Observed)*	2001-2030 (Scenario 4.5)	2001-2030 (Scenario 8.5)
SRAD_LGPt5 – winter crop (annual)	MJ/m2	2694.63	3449.36	1952.82	2256.28
SRAD_LGPt5 – spring crop (annual)	MJ/m2	2672.47	3115.82	1833.43	2010.76
SRAD_LGPt5 – fodder crop (annual)	MJ/m2	2492.91	2838.24	1129.29	1361.82
DryI_AJ_Fodder crop	number of days	6.07	21.65	68.39	69.84
DryI_AJ _Winter crop	number of days	4.87	21.77	65.97	66.90
DryI_AJ _Spring crop	number of days -	6.9	28.69	65.77	67.03
DryI_AS_Spring crop	number of days	7.03	38.73	104.29	97.68
DryI_AS_Winter crop	number of days	5	31.81	104.45	97.52
DryI_AS_Fodder crop	number of days	11.43	47.27	143.71	134.65
Harvest_July_Winter crop	number of days	1.37	3.38	14.23	7.9
Harvest_July_Spring crop	number of days	1.37	3.38	14.23	10.84
Harvest_July_Fodder crop	number of days	0.57	1	11.55	10.84
Harvest_June_fodder crop	number of days	1.63	3.08	16.26	15.52
Harvest_June_winter crop	number of days	2.03	5.54	16.65	16.23
Harvest_June_Spring crop	number of days	2.03	5.54	16.65	16.23
HeatStress_Early (28)	number of days	31.43	31.5	71.45	72.32
SumEf_10	°C	4781.37	5200.44	5423.11	5348.85
Mean annual temperature	°C (°C deviation)	23.4 (-1)	24.4 (Ref)	25.2 (+0.8)	25.0(+0.6)
Mean annual precipitation	mm (% deviation)	1695.3 (-15.3%)	1892.3 (Ref)	593.5 (-66.6%)	662.9 (-48.6%)
WatBal_AJ	sum (mm)	344.66	100.6	-297	-305.67
WatBal_AS	sum (mm)	894.40	425.18	-459	-389.50

Because of the limitation in collecting observed weather data, the difference in the effective global radiation sum (SRAD_LGPt5) between the two stations over past 50 years in Thai Nguyen province (table 9) revealed an uncertainty which may be caused by the temporal and spatial reasons. Dinh Hoa weather station is located in the mountainous area and further to the equator in comparison with Thai Nguyen station which is located in the flatland and nearer the equator than Dinh Hoa weather station.

In terms of drought stress, the output results from AGRICLIM show that the number of days with intensive water deficit (dry days) increased during the period 1961-2015 (Fig. 30). A dry day is defined as a day with the rate of actual evapotranspiion vs. reference evapotranspiration (AET/ET0) smaller than 0.4. The number of dry days for all three crop seasons was increased. During 1961-1990, followed by the highest number of dry days from April to June (DryI_AJ) for the spring crop season, that was the number of dry days for the fodder crop season and the winter crop season. From 1990-2015, there was a similarity between the number of dry days from April to June (DryI_AJ) for winter and fodder crop while the number of dry days for spring crop was still at the highest level.

Considering dry days from April to June (DryI_AJ), the number of dry days was 20 days lower compared to the period from April to September (DryI_AS). The number of dry days in the period 1990-2015 was in maximum 6 times higher than those in the last periods (1961-1990) at Dinh Hoa station. The number of days from April to September (DryI_AS) for spring still higher than those for winter crop but lower than for fodder crop. This difference might parlty caused by the difference in location and topography. The lower the elevation downward to the south, the number of dry days is getting higher in Thai Nguyen province, Vietnam. However, it would also caused by the warmer temperature and the decreased of precipitation over years (Fig. 18).

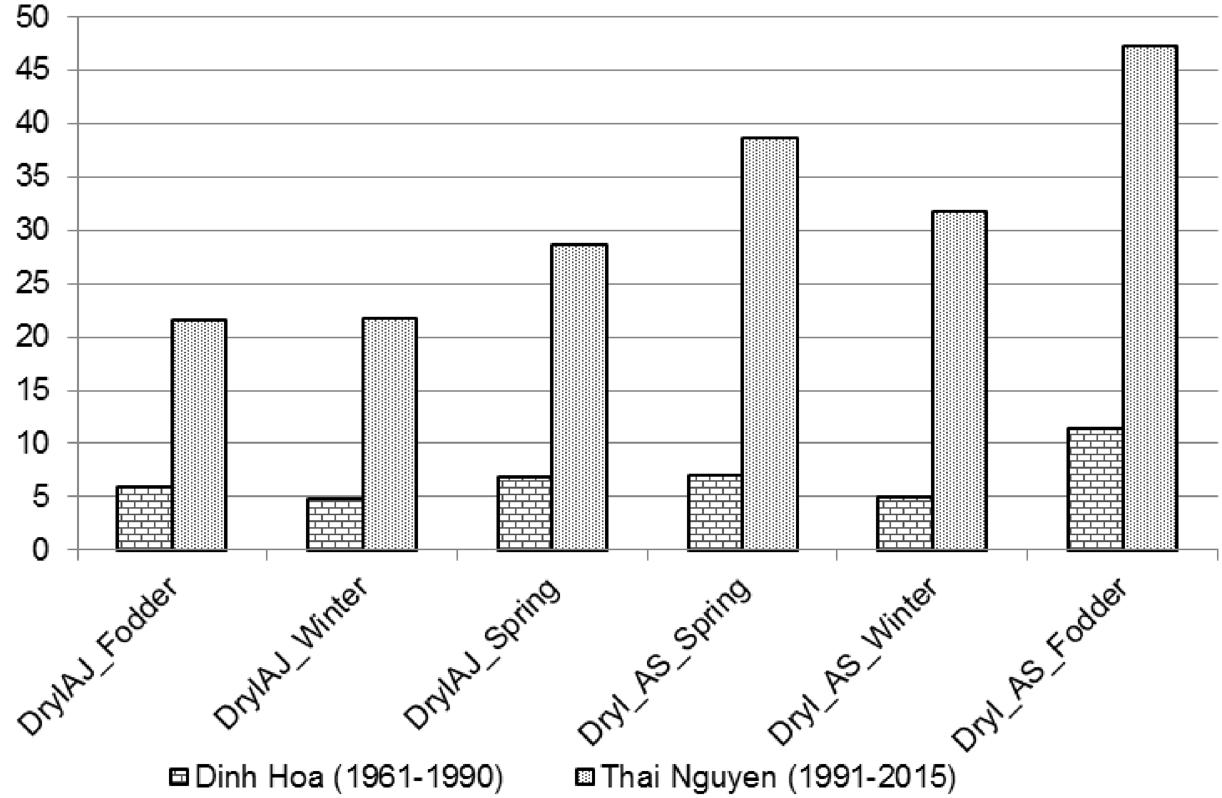


Fig. 30. Comparison of the number of dry days between two weather stations in two historical periods for winter and spring cereal and fodder permanent crop of April-June (AJ) and April-September (AS), respectively.

Furthermore, AGRICLIM calculated the number of days that are suitable for harvest, as shown in Fig. 31. The harvest days are defined as the number of days per month when daily precipitation on day N < 0.5 mm; daily sum of precipitation on day N- 1 is < 5 mm; daily sum of precipitation on day N-2 < 10 mm and daily sum of precipitation on day N-3 < 20 mm in conjunction with water content in top 20 cm is between 0-70% of maximum soil water holding capacity. Therefore, the number of days for crop harvest was highest in June and less than that in the next month, July.

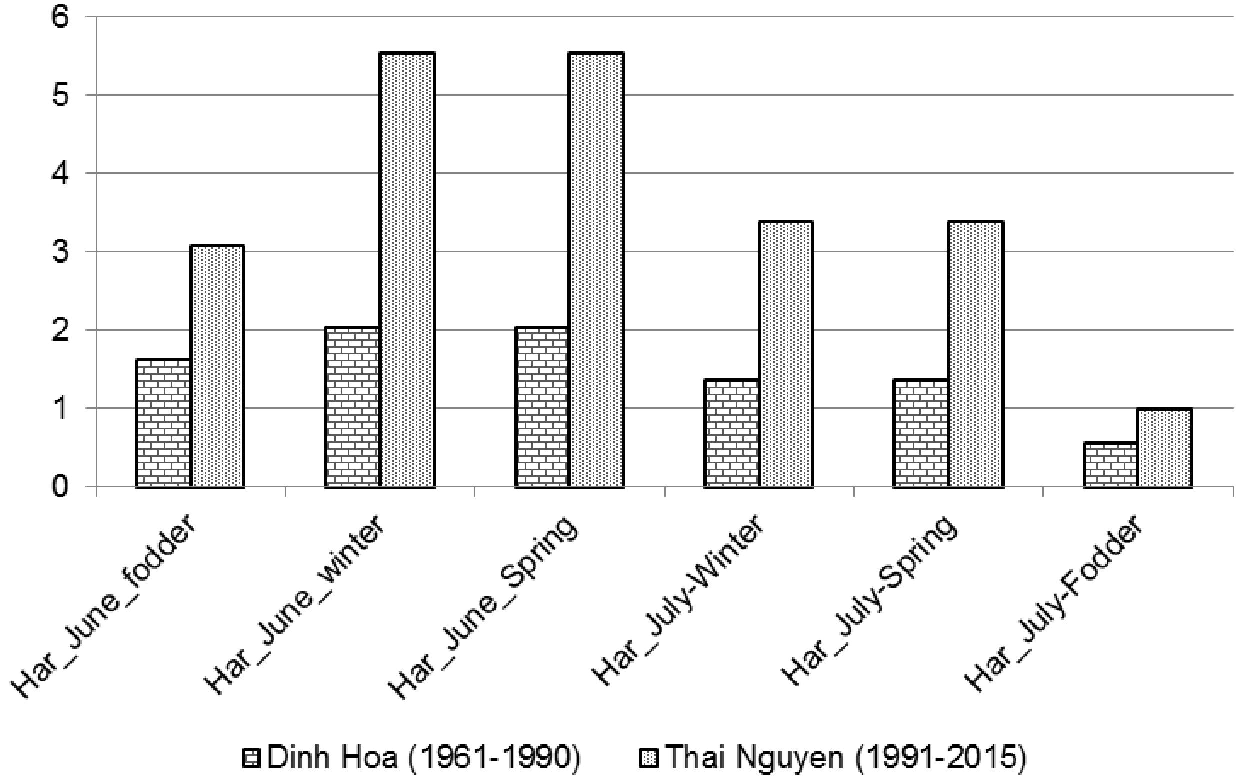


Fig. 31. Comparison of the number of days that are suitable for harvest over the period 1961-2015 for winter and spring cereal and fodder permanent crop

A further result over 25 years (1990-2015) was about the duration of the vegetation season. Its definition includes the following: number of days with mean temperatures continuously > 15°C and not drop below threshold for more than 3 days; minimum temperatures above 0°C; sum of effective temperatures (SumEf_10) above 10 °C. The results showed that the duration of vegetation was higher in the period 1990-2015 (Thai Nguyen station) than that in the period 1961-1990 (Dinh Hoa station). As a result, the water balance was reduced (became less positive) in Thai Nguyen weather (1990-2015) compared to Dinh Hoa weather station (1961-1990), (Tab. 9).

This suggests that in the center and southern regions in Thai Nguyen province (flatland), the number of days with a total duration of heat waves and the total amount of temperature per year were higher than those in the northern regions (Midland and Highland). As a consequence, the course for vegetation in summer in the center and the south of Thai Nguyen was shorter than in the northern region according to the output results. Similarly, the potential water balance in the flat land was much smaller than in the high land due to more dry days.

4.2.1.2 Climate change and overlapping period 2000-2015 between observed and scenario data

Together with the previous outcome of local weather in the observed-past period, it can be seen that temperature and solaradiation during the past period were proportionally increasing while it was adversely correlated under climate change scenarios (see tab 9). The increased temperature was shown by the increase of the total amount of the effecitve temperature per year in the future, the increase of Huglin index and the increase of the total duration of HeatW3. Interestingly, the annual rainfall during 1961-1990 was lower than during 1990-2015, whereas the water balance was decreasing since 1961. The decreasing trend was continuously present under climate change scenarios, especially under RCP 4.5. This phenomenon was consistent with an increasing trend of the number of dry days.

An enormous increase was found in the number of dry days. In the period 1961-1990, it only ranges from 4.87 to 11.3 days. This number increased dramatically in the period 1990-2015, where it ranged from 21.65 to 47.27. The increasing trend in number of dry days continues to increase under climate change scenarios. The number of dry days was approximately tripled over 2001-2030, with the maximum number of dry days by 143.71 days for the fodder crop season. This is somehow a consequence of a huge reduction of precipitation during the period 2001-2030 under climate change scenarios. The mean annual precipitation also decreased tripled in comparison with that in the past (table 9).

From the results, it is clear that the “dry” weather conditions in the future may be more extreme than in the past. During the overlapping period (2000-2010), the result showed that, the predicted temperatures under climate change scenarios were very similar to the local observed temperature. The mean annual temperature was only 22.87 °C from 1961-1990 and increased to 23.5 °C from 1990-2015. In the climate scenario it increases by 2.37-3.13 °C in the period from 2001 to 2030 compared to the measured period 1980-2015 and 1961-1990, respectively. By contrast, the overlapping period indicated a huge difference between the observed and climate change scenarios RCP 8.5 and RCP 4.5 precipitation (Fig. 32). This reveals an uncertainty of climate conditions in the future, especially in terms of precipiation under RCP 4.5. In comparison of climatic conditions between two climate change scenarios, the climate conditions of RCP 4.5 are more extreme precipitation than in RCP 8.5, while temperatures are similar between both scenarios. However, due to the increasing trend of temperature over 50 years in the past, and the decreasing trend of precipitation (the findings in chapter 4.1.1), we see more or less a warmer and dryer climate in future scenarios.

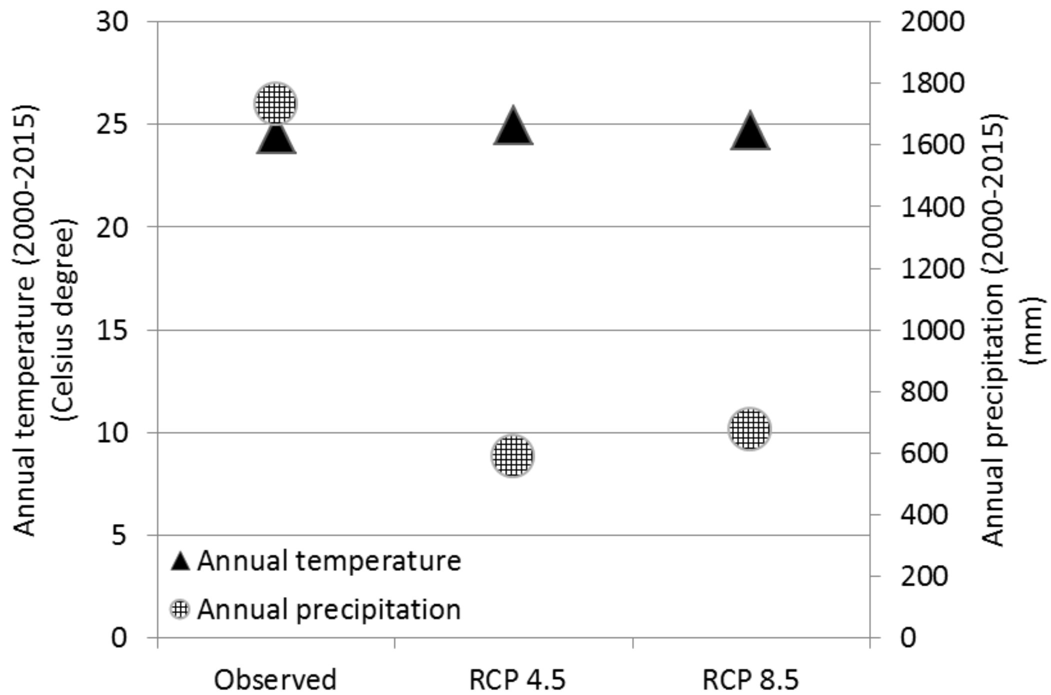


Fig. 32. Comparison between precipitation and temperature of the overlapping period (2000-2015) (=bias between observed and scenario)

4.2.2 Change of agroclimatic indicators under different climate scenario periods

Agrometeorological conditions simulated by the AGRICLIM model under the two applied climate change scenarios RCP 4.5 and RCP 8.5 and for different future periods are presented in table 10 and table 11.

The results show that there was a slight difference between the weather conditions in the future based on the two climate scenarios. In general, the total effective global radiation under RCP 8.5 is higher than that under RCP 4.5 (Fig. 33), in conjunction with a higher DvegSummer (duration of vegetation summer) and a higher SumEf_10 (total effective temperature). These conditions led to the higher heat stress under the RCP 8.5 scenario. However, this was not correlated to the number of dry days which are counted to be higher under the RCP 4.5 scenario in all of the crop seasons (winter, spring, and fodder).

Under the climate change scenario RCP 8.5, there was an increase in effective solar radiation effective solar radiation for all crops in the period 2035-2065 in comparison with the last 30-year periods 2001-2030, however, it afterward declined in the next 30-year period 2070-2100. Overall, the effective solar radiation for the winter crop increases while it decreases for the winter and the summer crop. Additionally, among three crop seasons, the effective solar radiation for the fodder crop is much lower than for the winter and the spring crop (Tab. 10). In contrast, the total effective temperature and mean annual temperature gradually were projected to increase from 2001-2100. The temperature was calculated as highest from 2070-2100. This was consistent with the highest heat stress from 2070-2100 and the highest mean annual temperature at 28.1 °C from 2070-2100, while it was only by 22.87 °C and 26.5 °C from 1961-1990 and 2001-2100, respectively. Likewise, the number of dry days from 2001-2100 for all crops also increases, especially for the fodder crop which was determined out to be the highest with 143.8 days from 2070-2100. It is higher by 38.4 days compared to the number of dry days for spring crops and 38.65 days compared to the number of dry days for winter crops in the same growing period (April to September) (table 10). This condition may be the reason which drives to the decrease in number of days that are suitable for fodder crop' harvest, meanwhile, the number of days that are suitable for the spring crop and the winter crop' harvest almost increase.

Table 10. Agrometeorological conditions under the climate change scenario RCP 8.5 over different periods from 2001-2100

Name	Unit	Thai Nguyen station-*under climate change scenarios RCP 8.5*			
		2001-2030	2035-2065	2070-2100	2001-2100
SRAD_LGPt5 – winter	MJ/m^2	2256.28	2445.83	2241.80	2299.29
SRAD_LGPt5 – spring	MJ/m^2	2010.76	2089.64	1929.44	1983.33
SRAD_LGPt5 – fodder	MJ/m^2	1361.82	1470.90	1195.75	1303.47
DryIAJ_Fodder	number of days	69.84	73.35	72.35	72.79
DryIAJ_Winter	number of days	66.90	68.26	66.77	67.69
DryIAJ_Spring	number of days	67.03	68.03	66.94	67.91
DryI_AS_Spring	number of days	97.68	99.39	105.42	101.13
DryI_AS_Winter	number of days	97.52	99.13	105.19	100.87
DryI_AS_Fodder	number of days	134.65	136.68	143.84	139.12
Harvest_July_Winter	number of days	7.9	12.23	13.23	12.20
Harvest_July_Spring	number of days	10.84	12.23	13.23	12.20

Harvest_July_Fodder	number of days	10.84	8.29	9.9	8.77
Harvest_June_Fodder	number of days	15.52	14.00	15.90	14.92
Harvest_June_winter	number of days	16.23	14.81	16.81	15.8
Harvest_June_Spring	number of days	16.23	14.81	16.81	15.80
HeatStress_Early (28)	number of days	72.32	78.42	86.77	79.49
SumEf_10	°C	5348.85	5900.36	6578.24	5945.22
Mean annual temperature	°C (deviation from 2000-2015)	25.0 (+0.6)	26.3(+1.9)	28.1 (+3.7)	26.5 (+2.1)
Mean annual precipitation	mm (% deviation from 2000-2015)	662.9 (-65%)	713.0(62.3%)	655.6(65.3%)	674.3(62.8%)
WatBal_AMJ	sum (mm)	-305.67	-304.75	-312.58	-310.91
WatBal_AS	sum (mm)	-389.50	-423.51	-505.11	-441.18

The differences in indicator values between the different scenario periods are similar to the RCP 4.5 scenario at different levels (table 9). The results of SRAD_LGPt5, DryIAJ, DryI_AS, SumEf_10, and WatBal show the same trends as those under RCP 8.5. However, most of them show a stronger severe climatic condition (Fig. 33-35).

Under the climate change scenario RCP 4.5, SRAD_LGPt5 is decreasing gradually from 2001 - 2100 for all crop seasons. The most extreme decrease in SRAD_LGPt5 is at 1003.39 WJ/m^2 for fodder crop from 2070-2100, which equals as approximately half of the highest SRAD_LGPt5 which is for winter crop. Likewise, the annual temperature is increasing from 2001-2100, with the highest annual temperature of 26.6 °C in the period 2070-2100. Additionally, the total effective temperature and the number of days under heat stress are also increasing from 2001-2100.

In terms of drought stress, under RCP 4.5, the number of dry days was projected to be much higher than in the past (1990-2015), which correlated with the strongly decrease in annual mean precipitation over 2001-2100 in comparison with the annual mean precipitation from 1990-2015 (Tab 11). However, the precipitation slightly fluctuates when it increase during the period 2035-2065 and decrease again in the next 30-year period 2070-2100.

Table 11. Agrometeorological conditions under climate change scenarios RCP 4.5 over different periods from 2001-2100

Name	Unit	Thai Nguyen station-*under climate change scenarios RCP 4.5*			
		2001-2030	2035-2065	2070-2100	2001-2100
SRAD_LGPt5 – winter	MJ/m2	1952.82	2006.32	1919.06	1909.06
SRAD_LGPt5 – spring	MJ/m2	1833.43	1790.54	1683.56	1773.32
SRAD_LGPt5 – fodder	MJ/m2	1129.29	1065.40	1003.39	1061.62
DryIAJ_Fodder	number of days	68.39	74.20	72.87	71.97
DryIAJ_Winter	number of days	65.97	71.00	66.58	67.68
DryIAJ_Spring	number of days	65.77	71.07	66.87	67.74
DryI_AS_Spring	number of days	104.29	108.40	112.23	107.22
DryI_AS_Winter	number of days	104.45	108.33	111.94	107.15
DryI_AS_Fodder	number of days	143.71	147.33	148.90	146.50
Harvest_July-Winter	number of days	14.23	13.40	15.16	13.96
Harvest_July-Spring	number of days	14.23	13.40	15.16	13.96
Harvest_July-Fodder	number of days	11.55	8.57	12.00	10.36
Harvest_June_Fodder	number of days	16.26	16.33	14.19	15.23
Harvest_June_Winter	number of days	16.65	16.63	15.71	16.06
Harvest_June_Spring	number of days	16.65	16.67	15.71	16.07
HeatStress_Early (28)	number of days	71.45	78.47	80.90	76.81
SumEf_10	°C	5423.11	5757.63	6008.49	5735.12
Mean annual temperature	°C (deviation from 2000-2015)	25.2 (+0.8)	26.0(+1.6)	26.6 (+2.2)	25.9 (+1.5)
Mean annual precipitation	mm (% deviation from 2000-2015)	593.5 (-68.6%)	625.0(-67%)	608.0 (-67.9%)	616.7(-67.4%)
WatBal_AMJ	sum (mm)	-297.49	-318.55	-304.83	-303.27
WatBal_AS	sum (mm)	-459.28	-462.35	-507.02	-469.90

Generally, from the observed data over the period 1961-2015 and projected data by two climate change scenarios, it was determined that the projected solar radiation in the future was generally lower than in the past, especially under the RCP 4.5 scenario. The amount of effective solar radiation reaches the lowest values for the fodder crops in the period 2070-2100 as 1003.4 Wm^{-2}. In comparison of the effective solar radiation between the two climate scenarios, RCP 8.5 shows a higher value, especially for the fodder crop (Fig. 33).

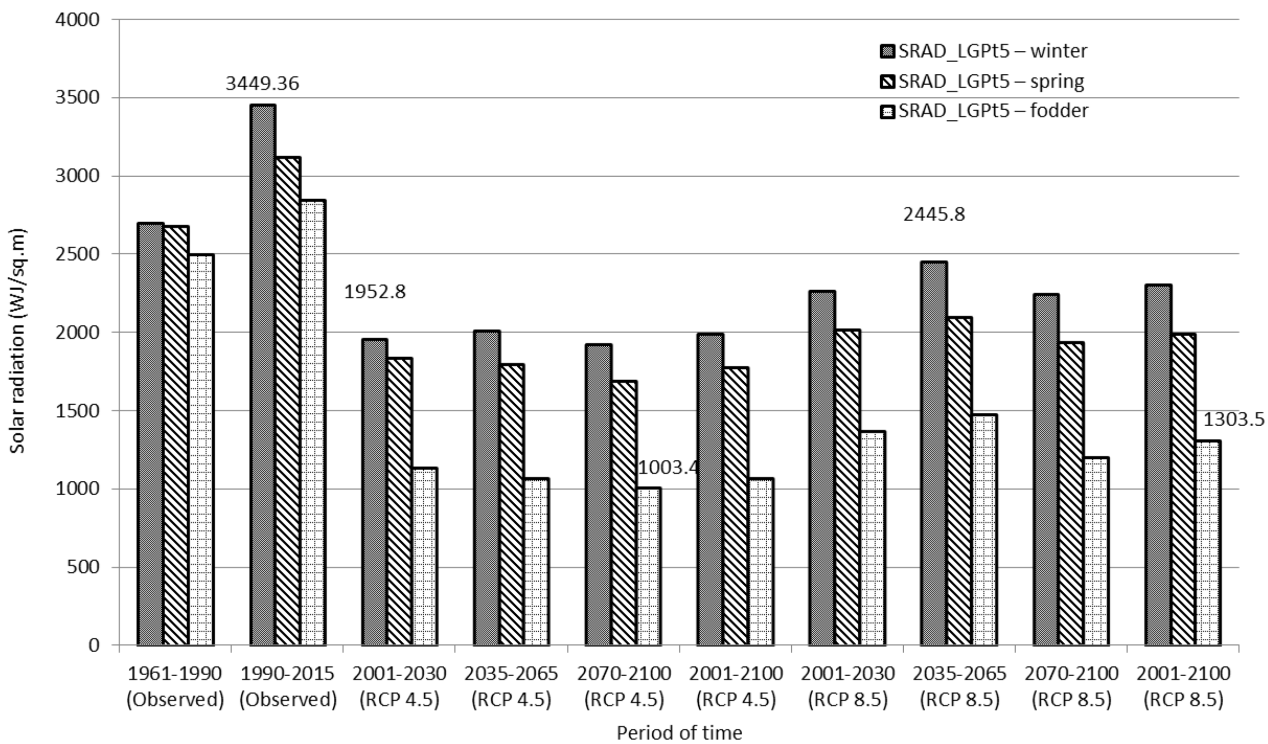


Fig. 33. Comparison of effective solar radiation over different measured and scenario periods.

In contrast, the average number of dry days in the period (2001-2100) under the two climate scenarios was projected to be much higher in comparison to 1961-2015, especially under the RCP 4.5 scenario (Fig. 34). It is clear that the highest number of dry days is concentrated in the fodder season, followed by the spring season and winter season.

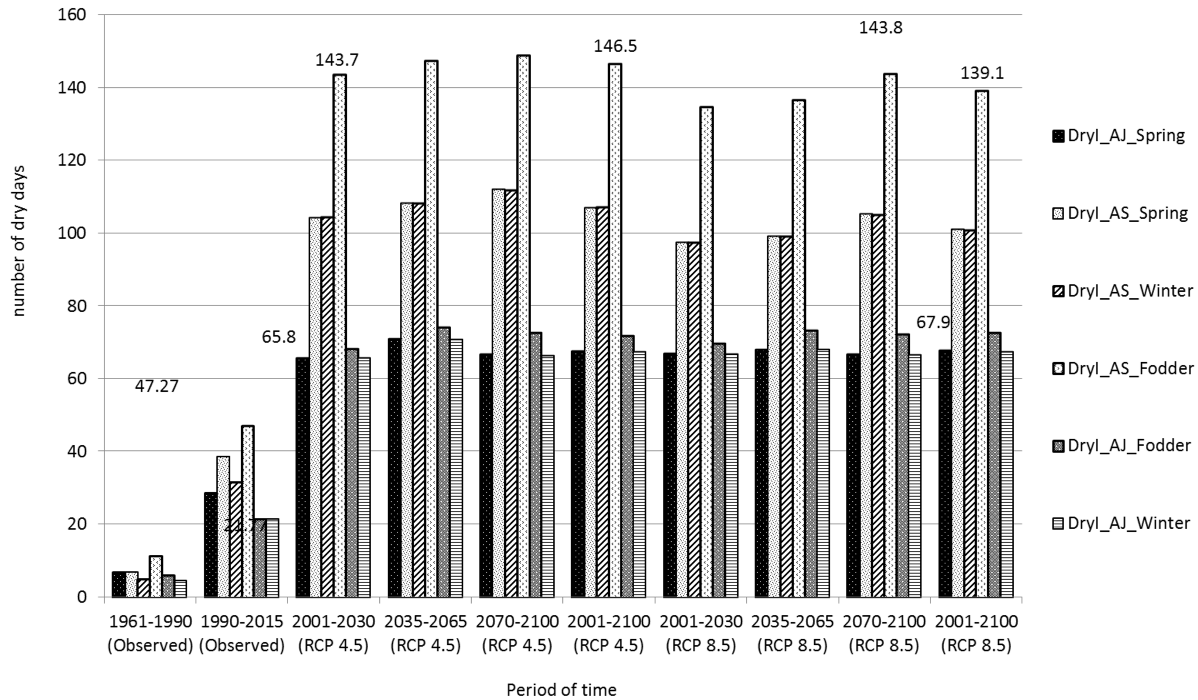


Fig. 34. Number of dry days over the observed periods (1961-2015) and the applied climate change scenario periods from April-September.

Additionally, precipitation decreases and increases in potential evaporation, and the water balance under the applied climate change scenarios becomes substantially negative during the spring and summer growing seasons in comparison with the last 2 decades of observations (Fig. 35 and Tables 9-11).

Moreover, the total water balance changed from a positive value of 50-400 mm from 1990-2015 to a negative value of 250-450 mm under the various climate change scenario periods, which means a dramatic drop in potential crop available water, leading to drought episodes that are more frequent and severe in the future and affecting available water resources as well.

Potentially, there might be a bias between the observations and the climate scenario estimate when we compare 2001-2014 observations with scenario period 2001-2030. However, there was a strong decreasing trend between 1961-1990 and 2001-2014 observation periods. Even with uncertain climate scenario bias we can therefore expect potential further decreasing water balance trends in the future.

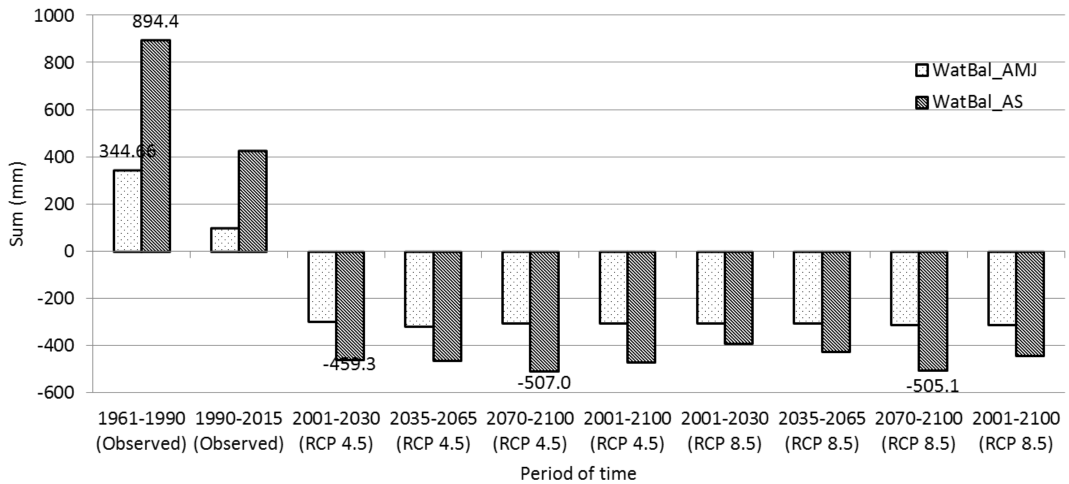
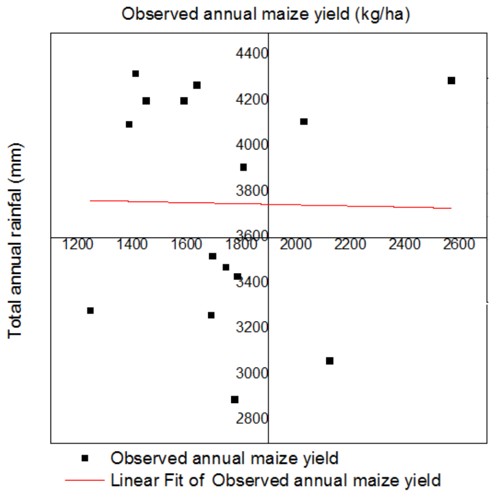


Fig. 35. State of seasonal water balance of the past observational and future climate scenario periods applied in the case study region.

4.2.3 Relation between past climate conditions and maize yields

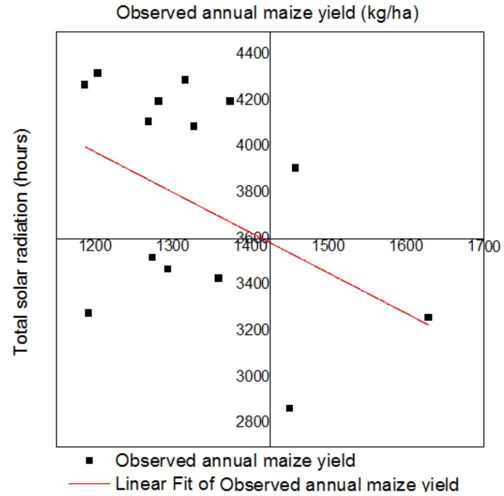
The observed annual statistical maize yields (containing all growing seasons in the case study region) over the 15-year historical period (2000-2014) (see Methods section) show advance in the average of 3000 kg/ha in 2000 to 4100 kg/ha in 2014. To indicate the correlation between the grain yields and daily weather data, the Pearson correlation and R-square (R2) value were used for each weather element including temperature, rainfall, air relative humidity, and solar radiation. The results showed that all of the weather parameters in single did not have a significant influence on maize yields with the highest Pearson's correlation coefficient was -0.40 for solar radiation (Fig. 36b), followed by relative air humidity and temperature with Pearson's correlation coefficients of -0.36 and 0.19, respectively (Fig. 36c,d). Finally, annual rainfall seemed to have no effect on maize yield with a Pearson's which of approximately 0.00 (Fig. 36a). The conclusion is that maize yields were limited in these observation periods mainly by other limiting factors than climatic parameters. However, solar radiation and temperature were reported as two main factors which affected yield potential based on the maize yield database in Nebraska USA and Southeast Asia (Setiyonoa et al., 2010). Moreover, under optimum conditions of water and nutrients, solar radiation was found as a limiting factor under late planting (July) through heavy cloud cover during the peak rainfall months of August and September in northern Ghana (MacCarthy et al., 2017). In our case, even there is no significance, less solar radiation hints also to a negative yield effect, where precipitation changes did not have an effect probably through the still positive water balance in the past decades.

a)



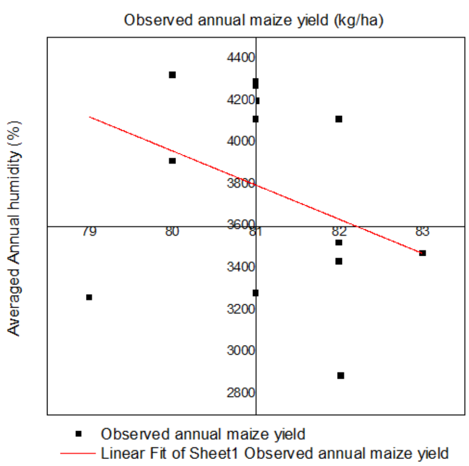
Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	3.48934E6		
Pearson's r	-0.01655		
Adj. R-Square	-0.07663		
		Value	Standard Error
Observed annual maize yield	Intercept	3795.96366	737.70335
	Slope	-0.02502	0.41919

b)



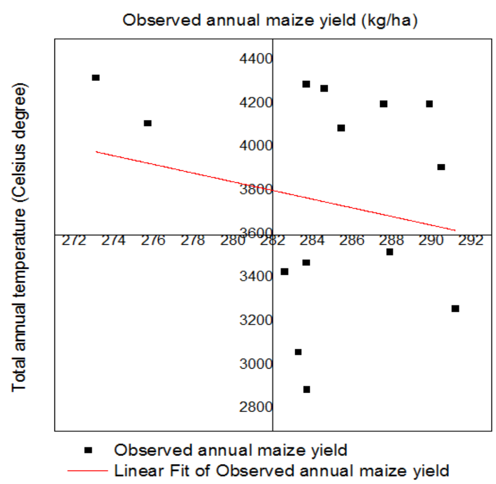
Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	2.9126E6		
Pearson's r	-0.40683		
Adj. R-Square	0.10132		
		Value	Standard Error
Observed annu	Intercept	6079.87951	1454.4372
Observed annual maize	Slope	-1.75049	1.09013

c)



Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	3.04022E6		
Pearson's r	-0.3591		
Adj. R-Square	0.06195		
		Value	Standard Error
Observed annual maize yield	Intercept	17001.69291	9551.2233
	Slope	-163.0315	117.51937

d)



Equation	y = a + b*x		
Weight	No Weighting		
Residual Sum of Squares	3.35282E6		
Pearson's r	-0.19846		
Adj. R-Square	-0.03451		
		Value	Standard Error
Observed annual maize yield	Intercept	9415.6769	7757.65403
	Slope	-19.9028	27.26059

Fig. 36. Relationship between weather parameters and historical maize yield in Thai Nguyen.

4.3 Crop model calibration and validation results

4.3.1 DSSAT model calibration

The calibration was carried out for two maize growing seasons, winter and spring maize, using ATcreate and GENCALC. The calibration data sets were presented in the method section. The comparison between observed (field experiment) and simulated crop growth indicators was afterward conducted. The results are shown in table 12 and table 13.

The planting date from the field experiment was not available but was set according to the common practice for the simulation.

Table 12. Calibration results of the DSSAT model by spring maize indicators

Crop indices \ Genotype	SX2010		SX5012		LVN47	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
Planting date (DOY)	Spring	53	Spring	53	Spring	53
Silking(Beginning Peg stage) (*)	77	70	75	62	77	70
Physiological maturity (Harvest) (*)	117	105	121	99	125	105
Leaf index, at harvest	3.6	5.72	3.9	5.59	4.0	5.98
Number of leaves per stem	20.2	15.62	20.2	14.18	20.1	15.29
Yield (kg/ha)	5720	5993	6350	6144	5990	6202

(*) (days after planting)

The results show that the DSSAT model was excellent for calculating the grain yields (HWAMS) in the spring season of 2008. The percentage similarity between the observed spring grain yield and simulated spring grain yield was from 95-97%. However, a moderate accuracy was derived for the leaf indicators between the observed and simulated data. The observed leaf area indices (LAIXS) were lower than the simulated ones, whereas the observed numbers of leaves per stem (LAIH) were higher than the simulated ones. Calibration showed that there was still a misbalance between leaf areas and the number of leaves due to specific leaf weight deviation.

Table 13. Calibration results of the DSSAT model by winter maize indicators

Crop indices \ Genotype	SX2010		SX5012		LVN47	
	Observed	Simulated	Observed	Simulated	Observed	Simulated
Planting date (DOY)	Winter	265	Winter	265	Winter	265
Silking (Beginning Peg stage) (*)	66	60	67	54	68	63
Physiological maturity (Harvest) (*)	120	133	123	122	123	136
Leaf index	2.9	5.66	2.4	5.68	2.9	5.76
Number of leaves per stem	19.6	15.49	19.9	16.22	19.5	16.07
Yield (kg/ha)	6440	7816	7370	8271	5660	8072

(*) (days after Planting date)

Table 14. Calibrated crop coefficients for Thai Nguyen, Vietnam

COEFF	Definitions	SX2010	SX5012	LVN47
P1	- Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8 °C) during which the plant is not response to change in photoperiod.	140.4	121.0	125.0
P2	– Extent to which development (express as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h).	0.3	0.0	0.0
P5	- Thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C).	685.0	685.0	685.0
G2	- Maximum possible number of kernels per plant.	907.9	907.9	907.9
G3	- Kernel filling rate during the linear grain filling stage and under optimum conditions (mg/day).	6.6	10.0	10.00
PHINT	– Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.	44.92	38.9	38.9

In winter maize season, the DSSAT model mostly showed a good agreement between observed grain yields and simulated grain yields with the highest percentage of similarity for the SX5012 cultivar approximately 87.8%, followed by the cultivar SX2010 and LVN47 with 76.8% and 57.4%, respectively. In contrast, a weak performance of the DSSAT model was found out in terms of leaf indices, especially the leaf area index.

In general, based on a limited data set for calibration, the calibrated results determine that the DSSAT model performs moderately good to calculate the maize growth and yield indicators; as a result, the benchmark varieties are accurately represented by the calibrated genetic coefficients, including P1, P2, P5, G2 and G5 as shown in Table 14.

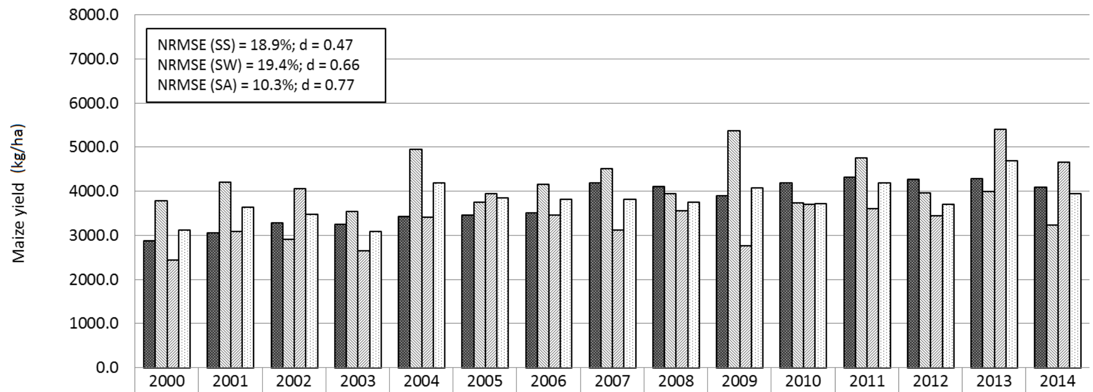
4.3.2 DSSAT model validation

4.3.2.1 DSSAT model validation under fixed irrigation

Validation was carried out for spring and winter season maize over 15 years (2000-2014). The performance was measured by NRMSE for annual yields and averaged grain yields of both seasons.

Generally, the performance of the DSSAT model was considered moderately good with NRMSE for the annual crop by 10.3%. However, the performance of the DSSAT model in the simulation of spring and winter maize yields were only fair with the NRMSE value of 18.9% and 19.4%, respectively (Fig. 37) when the simulated seasonal yields were compared with observed annual (yearly) yields. This limitation in model validation was caused by missing recorded seasonal maize yields that were not available in the local reports. Moreover, the recorded yields could have some mistakes that caused by local farmers and the local agriculture department. Another reason of deviations could be a difference of crop management between reality and simulation, for example, a different irrigation application between the simulation and reality in winter and spring seasons. In addition, the DSSAT model may not be robust in simulating grain yield under extreme weather conditions such as soil erosion occurring in the midland of the mountainous area or flooding which occurs in the fields which are located near the river. Further, caused by the fact that we did not simulate crop rotations, adds potential for result deviations (Ngwira et al., 2014).

Considering the performance of the DSSAT model by Index of Agreement (d), the results show a moderate match between observed (statistical) annual maize yield and simulated annual maize yield with the (d) value of 0.77 (Fig. 37).



	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Observed annual yield	2880.0	3060.0	3280.0	3260.0	3430.0	3470.0	3520.0	4200.0	4110.0	3910.0	4200.0	4320.0	4270.0	4290.0	4090.0
Simulated yield in spring (SS)	3794.2	4209.2	2913.2	3539.9	4956.9	3756.0	4165.6	4522.4	3953.7	5372.7	3745.2	4762.9	3961.6	3993.8	3233.8
Simulated yield in winter (SW)	2440.8	3094.1	4060.8	2652.8	3419.9	3955.7	3473.3	3123.9	3568.5	2775.3	3713.8	3611.8	3443.7	5410.6	4669.2
Simulated average annual yield (SA)	3117.5	3651.6	3487.0	3096.3	4188.4	3855.8	3819.4	3823.2	3761.1	4074.0	3729.5	4187.4	3702.7	4702.2	3951.5

Year

Fig. 37. Yield validation of spring and winter season maize 2000-2014 against statistically reported maize yields.

Furthermore, maize is usually cultivated with other crops in a flexible rotation to obtain the highest efficient productivity. Additionally, the real maize yield trend is also influenced by various elements that are not considered in the CERES-Maize model through a multiyear run, such as variable impact of diseases and pests, change in production methods and technologies such as fertilization, irrigation or new hybrid varieties or cultivars that are better adapted to drought conditions and bring much higher yields. All these effects are visible in our case study region.

To consider technological improvements in our comparison of simulated vs. observed yields to obtain a reliable comparison between real observed yield and simulated yield, the yield trends caused by increasing production technology were removed out by detrending the time and moving the year to year residuals, as shown in equation (11):

$$\mathrm{y} = \frac{x - \overline{x}}{\overline{x}} \times 100(\%) \tag{11}$$

Where Y is the residuals, x is the actual value, and $\overline{x}$ represents the smoothed 6- year running means.

Smoothed time series of observed maize yields were calculated with a 6-year running mean. It was assumed that the detrended results are removed from climate-related influences such as new technologies in crop management or better varieties. The result is shown in Fig. 38.

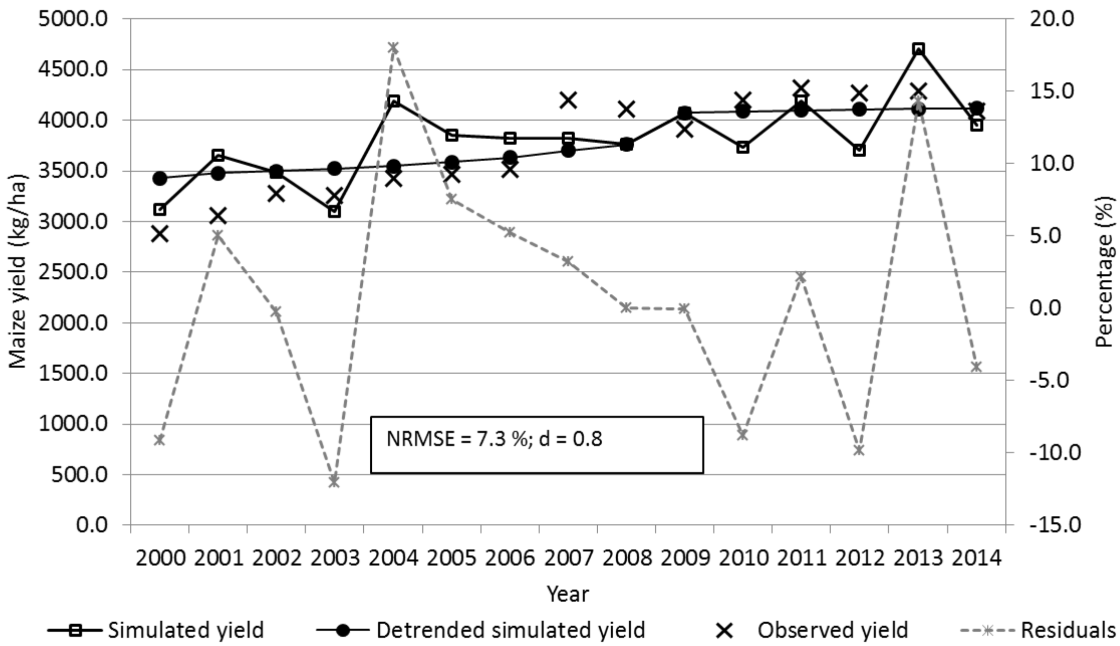


Fig. 38. Detrended simulated maize yield.

Concerning the performance of detrended simulated yield and observed yield, the results indicate a much better performance of in the CERES-Maize grain yield simulation compared to the performance calculated without detrended observed yield, shown by the NRMSE value of 7.3% and the d value of 0.8.

4.3.2.2 Sensitivity of simulated maize yield

4.3.2.2.1 Sensitivity of simulated maize yield to temperature and precipitation change

A model sensitivity analysis can reveal if a crop model responds in the correct direction or in an acceptable range against changes in critical inputs such as weather, crop and soil parameters. It is, for example, often used to intercompare different crop models, to identify weaknesses of crop models in certain environments or better to understand the results of simulated scenarios (e.g. Eitzinger et al., 2013a). In this study the sensitivity analysis was carried out for rainfed spring and winter maize at soils with suitable water storage capacity in comparison to irrigated the case (Fig. 39 a-c and Fig. 40). The results show that the CERES Maize model is sensitive to simulating the maize yield under different temperature and rainfall conditions. Simulated maize yields showed a strong response to increasing temperatures, where it decreased when temperature increased in comparison with the measured conditions (Observed) (period 2000-2015).

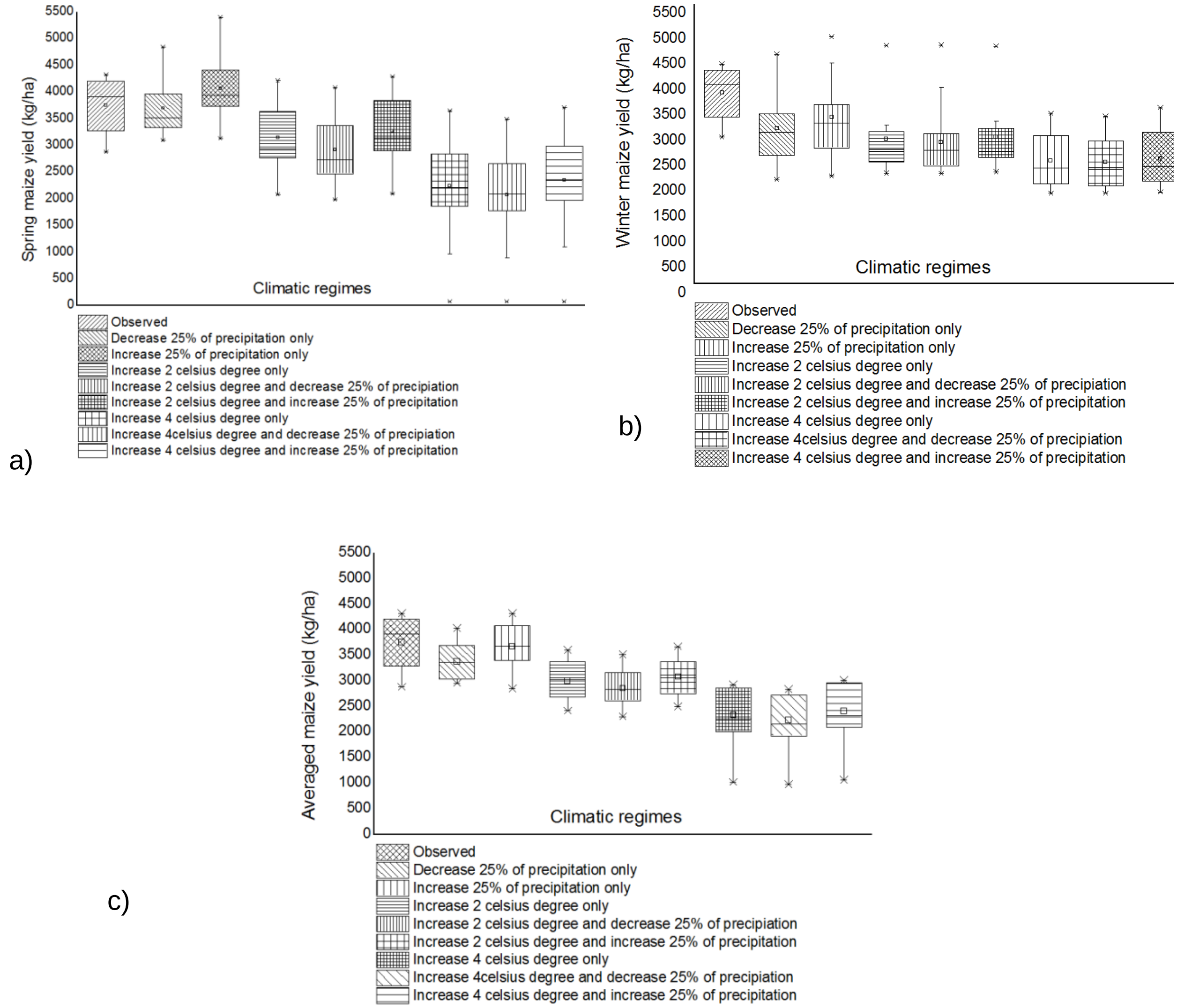


Fig. 39. a-c. Change of simulated maize yields under different temperature/precipitation sensitivity scenarios for spring, winter maize season, and annual averaged yields (irrigated case).

The annual maize yields decreased by 19% and 37% when the temperature increased by 2 and 4°C, respectively. Furthermore, the sensitivity of the DSSAT model to changes in rainfall was noticeable and showed a clear trend in combination with an increase in temperature. The highest decrease of simulated annual maize yields of approx. 40% were obtained at 4°C increase in temperature and 25% decrease in rainfall. However, the most notable change of maize yield was generally recorded by increases in temperature. Similarly, Shuai et al., 2016 reported that in China, an increase of 2 °C of temperature could affect maize yield more than a 20% change of precipitation. A greater change of precipitation led to more maize yield variability during El Niño years, especially in dry seasons.

Generally, in our case study region grain yield change is proportional to the amount of precipitation and is negatively affected by high temperature simultaneously, especially in the spring maize growing season. A strong effect of increasing temperatures on simulated irrigated maize yields (under current production technology) was shown by approximately 10% yield loss per 1 °C of warming (Fig. 40).

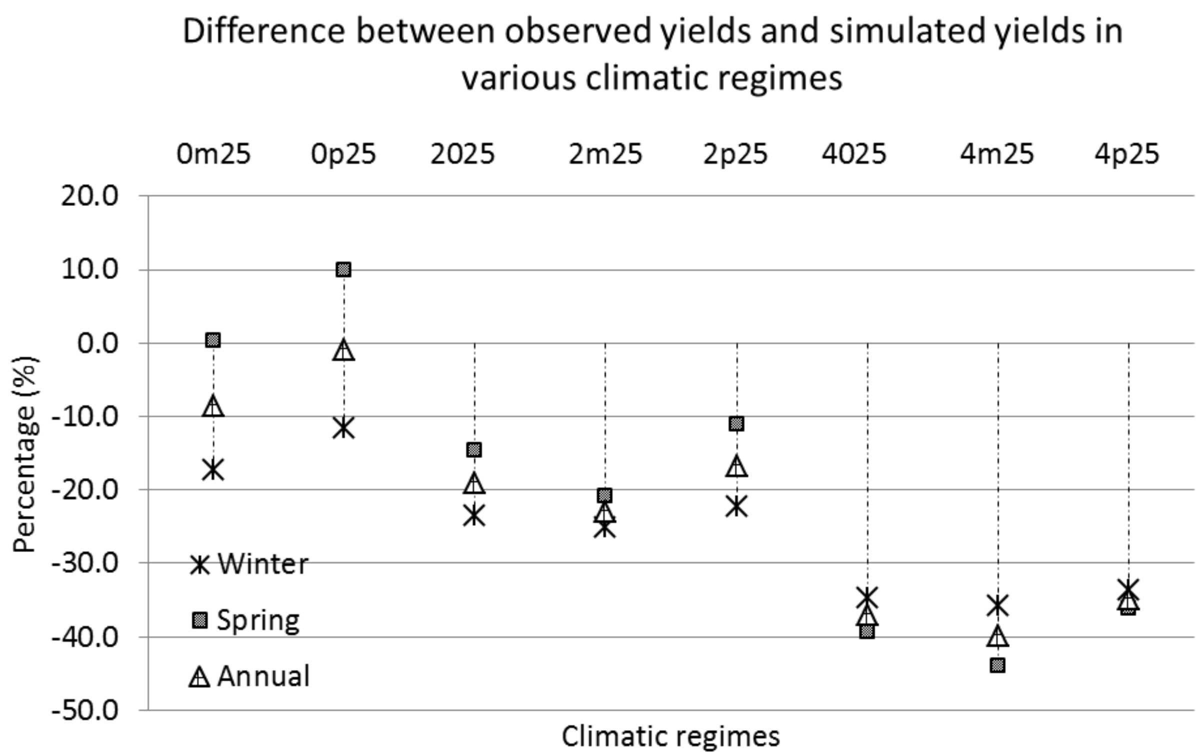


Fig. 40. Sensitivity of DSSAT model

On the other hand, due to the real practical in the local, it is unrealistic to simulate maize growth under rainfed conditions because the spring maize season is normally quite dry, especially at the beginning of the season. This dynamic requires farmers to irrigate their farms in some important periods of crop growth under drought stress; otherwise, crop will lose or obtain very low yields.

4.3.2.2.2. Sensitivity of simulated maize yield in regard to soil types

The sensitivity of the CERES-maize model with regard to the three main predefined regional soil types was estimated as follows. The three main soil types in Thai Nguyen include Acrisols, Ferralsol, and Fluvisols, whose soil characteristics were used as input for simulation of grain yield of the baseline period of 15 years (2000-2014). The simulation was carried out separately for spring and winter maize growing seasons (Fig. 41a-d).

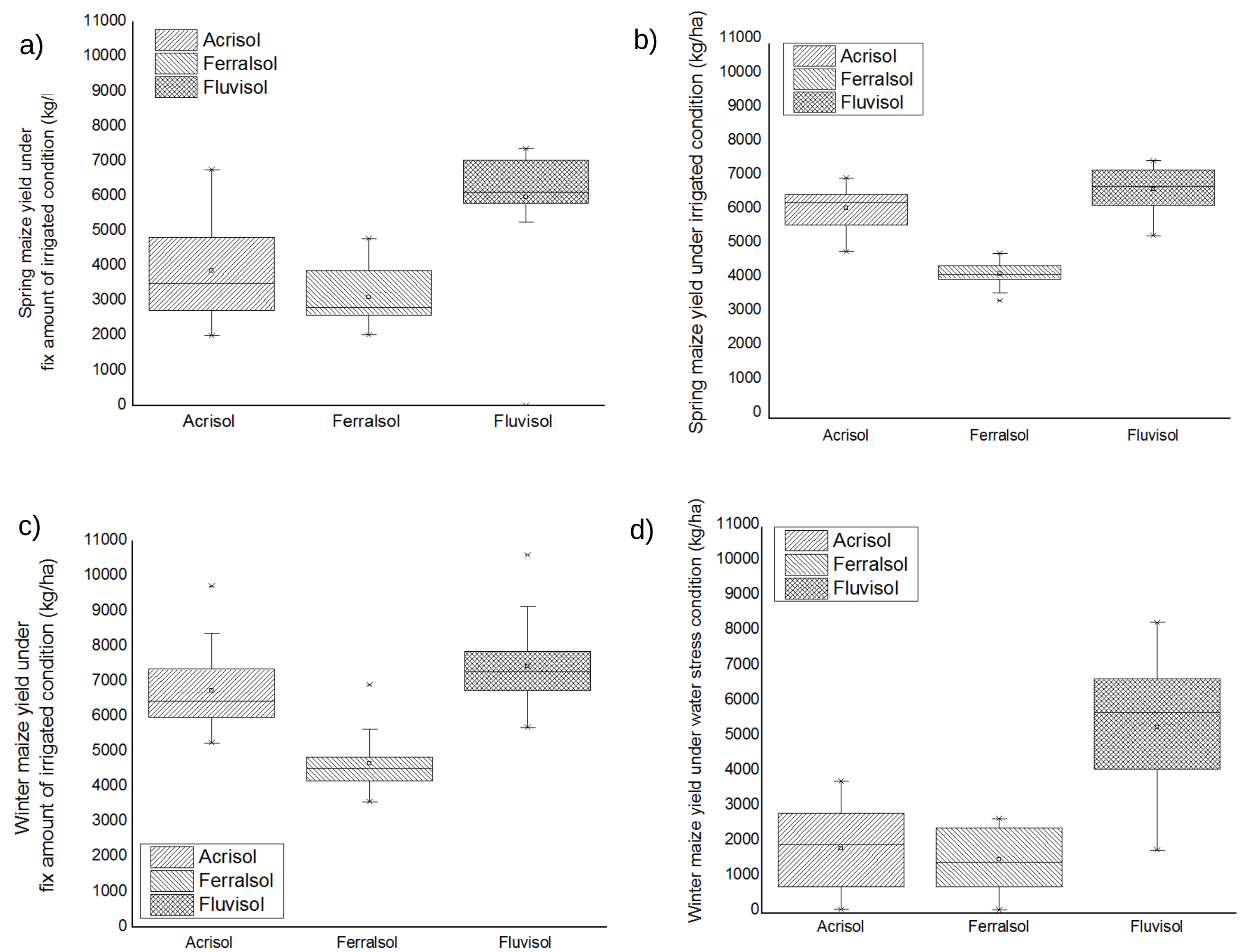


Fig. 41 a-d. Simulated maize yield under different soil conditions for spring and winter season during the period 2000-2014. Boxes are defined with solid line as the median and dashed line as the mean.

In general, the differences in simulated yields decreased between the soils under irrigated (no drought stress) conditions, which can be explained by the increasing impact of the soil water holding capacity on crop water availability under drought conditions.

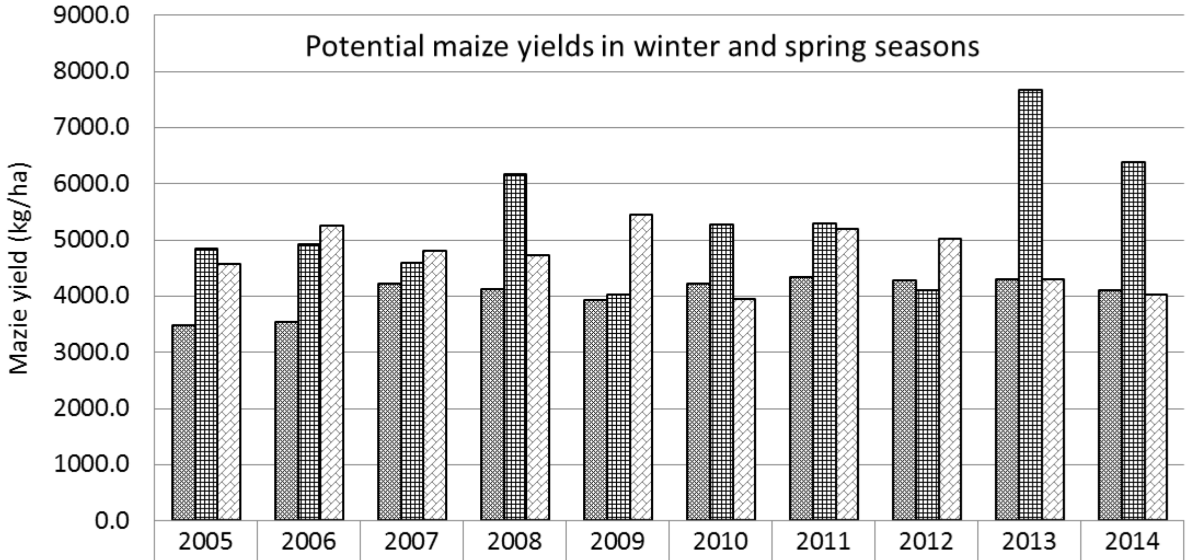
The simulated grain yield of **spring-sown maize** indicates that there is a difference between the three soil types but also between the years with lower interannual yield variability than for winter maize. Under the same yearly agronomic management, maize grown at Fluvisol reached high simulated yields at a range from 6000 to 7300 kg/ha during the period 2000-2009 but declined in the next period of 2010-2014, probably caused by adverse weather conditions. Similarly, there was less maize grain yield at Acrisol and Ferralsol soils across the period 2010-2014 in comparison with the period 2000-2009. Similarly, the simulated grain yields showed a large gap between annual grain yields under drought stress (rainfed) conditions and irrigated conditions. Generally, the irrigated maize grain yield is double that of grain yield under rainfed conditions, showing the important role of irrigation for maize production in that region.

In comparison with simulated **grain yield in the winter season**, the results showed that maize grown at Fluvisol also received much higher grain yield compared to maize grown on the other soils because of Fluvisols' highest soil water storage capacity. The simulated grain yield of Fluvisol in the winter season was also much higher than those grown in the spring season.

In general, the simulated grain yield in the winter season was higher than that in the spring season and much higher than the average annual maize yield, especially in the case of Fluvisol. This shows the potential of maize grown even through the winter season which is considered as the dry season. Under drought stress conditions (rainfed simulation), Acrisol and Ferralsol also show a difference in grain yield. The grain yields of Acrisol were higher than those of Ferralsol. The difference was expressed between different periods, probably caused by the difference in water-holding capacity. In the period (2010-2014), the grain yields were higher than the grain yield in the previous decade. The difference between the periods was most markedly in the case of Fluvisol.

4.3.2.3 Potential maize yield in Thai Nguyen

The crop simulation indicates that maize yields under rainfed conditions are much lower than the maize yield derived under irrigation. Under rainfed condition, the average of simulated maize yield over the period 2005-2015 was only 2903.2 kg/ha while the average of observed maize yield was 3811.8 kg/ha and the average of simulated irrigated maize yield was 5018.2 kg/ha (Fig. 42). In other words, the observed maize yield could be extremely low under the rainfed condition and be increased by around 24% under optimum irrigation because the observed maize yield still includes approximately 30% of irrigated maize area (Hung. comm., 2016; no data available).



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Observed	3470.0	3520.0	4200.0	4110.0	3910.0	4200.0	4320.0	4270.0	4290.0	4090.0
Winter	4835.2	4913.7	4583.0	6162.6	4020.5	5264.5	5283.4	4085.7	7664.2	6368.1
Spring	4565.6	5243.4	4784.2	4718.0	5429.8	3944.4	5177.4	5010.9	4295.6	4014.2

Fig. 42. Potential maize yields in Thai Nguyen, Vietnam

4.4 Simulated rainfed maize yields under climate change scenarios

4.4.1 Winter and spring maize yields for the period 2001-2100 under RCP 4.5 and RCP 8.5 climate change scenarios (CCSs)

In comparison between the average observed maize yield from 2000-2014 and the average maize yield under two climate change scenarios RCP 4.5 and RCP 8.5 from 2001-2100, the results showed an small increase under both CCSs in the future (Fig. 43,44) with a notable difference between two climate change scenarios in simulated maize yields was shown from 2070-2011. The average maize yield under RCP 4.5 is by 3957 kg/ha while the average of maize yield under RCP 8.5 is 3853.6 kg/ha. They are both higher than the average of observed maize yield from 2000-2014, contributed by the decrease in spring maize yields and an increase in winter maize yields (Fig. 43-45). The average increase of maize yields are contributed mostly by the increase of winter maize yields (Fig. 45). On the other hand, the results show a slight decreasing trend of maize yields under both CCSs, especially under RCP 8.5 at the third periodic of 30 years (1970-2100) (Fig. 34). The main reason is caused by the changes in temperature and precipitation (Fig. 25-28). The temperature was found to increase gradually while the precipitation was found to decrease under both CCSs from 2001-2100 (Tab. 9-11).

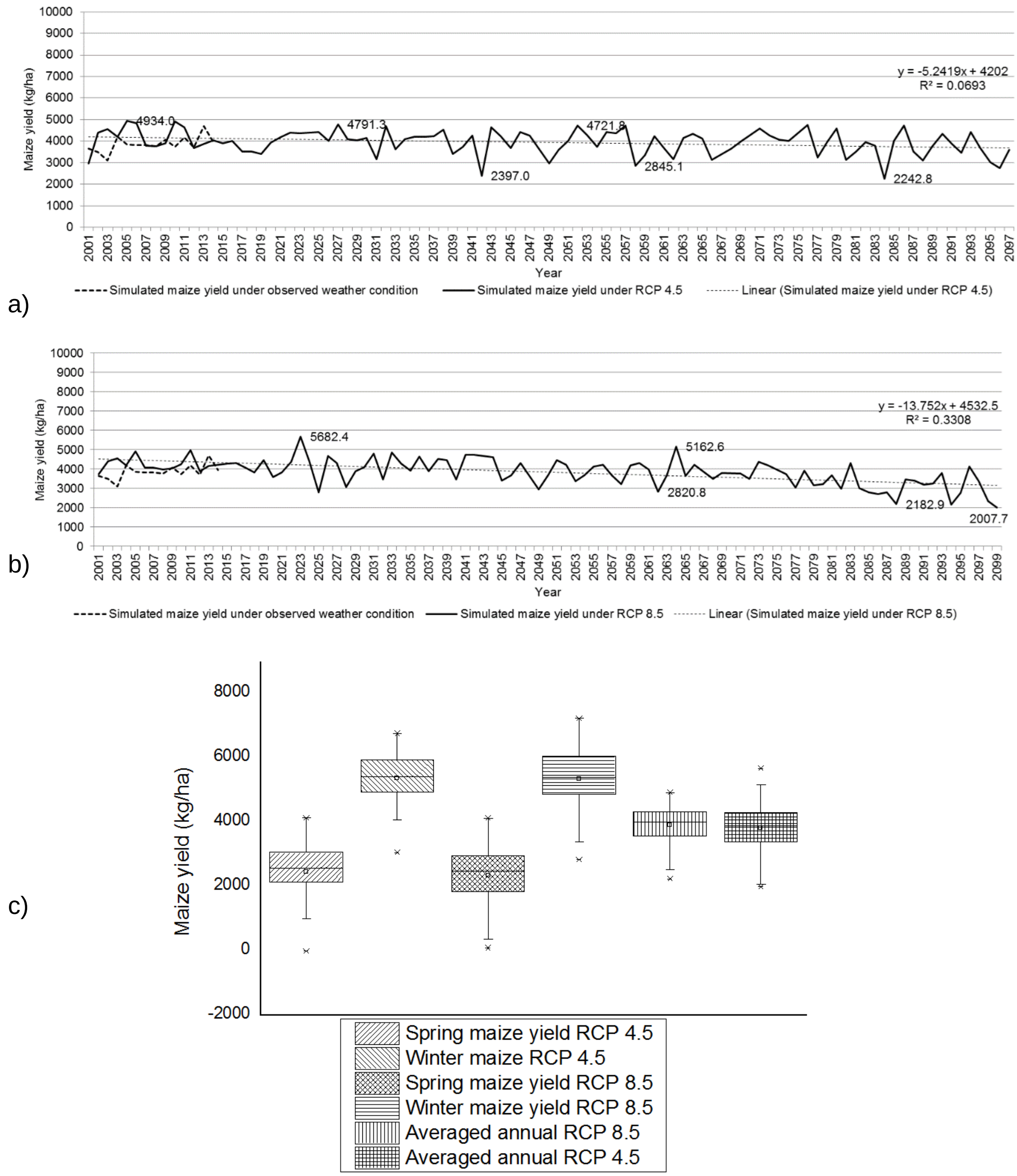


Fig. 43 a-c. Annual and seasonal simulated maize yield under two different climate scenarios RCP 4.5 and RCP 8.5 during the period 2001-2100 (Boxes present 50% of all cases, including a vertical line at the median and a dot at the mean and two courses of seasonal maize yields.

Concerning the trend of maize yields from 2001-2100, it shows that maize yields are mostly highest from 2035-2065, contributed by the highest average winter maize yields under both CCSs (Fig. 44). From 2001-2030, under RCP 4.5, the average spring maize yield and winter maize yield are at 2743.2 kg/ha and 5561.3 kg/ha, respectively; continuously, they are reduced to 2651.6 kg/ha and 5271.9 kg/ha, respectively from 2035-2065; however, only the average spring maize yield decreases to the lowest level at 2200.8 kg/ha while the winter maize yield increases by 5382.0 kg/ha from 2070-2100 compared to the last period (Fig. 45). The decrease of maize annual maize yield is lowest at 0 kg/ha. The main reason for this was found to be a very low rainfall during the growing season causing to germination problems and to complete yield failure. In comparison with the historical period (2000-2014), under RCP 4.5, mean annual maize yields over the 100 year period 2001-2100 increase by +3.6%, contributed by the increase in winter maize yields by +33.3% and a reduction of spring maize yields by -30.3%. The strongest decrease of spring maize under RCP 4.5 was projected by -38.2.8% in the period from 2070-2100 and the highest increase of winter maize is by +32.6% in the period from 2001-2030. Under RCP 8.5, spring maize mostly decreased in comparison with observed spring maize but more than under RCP 4.5, especially from 2070-2100 with -50.1%, meanwhile, the winter maize yield increase only by +18.2%, leading to the lower increase in average maize yield in this period compared to RCP 4.5. However, these variabilities also lead to an increase in the total of annual maize yield during period 2001-2100 by +1.1% in the RCP 8.5 scenario.

Moreover, under RCP 4.5, the average spring grain yield is calculated by 2483.3 kg/ha while the average winter grain yield is 5410.6 kg/ha. Likewise, under RCP 8.5, the average of grain yield in spring is at 2352.8 kg/ha while the average winter grain yield is at 5354.4 kg/ha. The combined influence of weather parameters was considered to be the main reason for the difference between them. Spring maize not only received lower effective global radiation sum (SRAD_LGPt5) but also less precipitation amount and higher number of dry days (see table 10-11). From 2001-2100, under RCP 8.5, the total sum of effective solar radiation was projected as 1983 MJ m^2 and 2299 MJ m2 in spring and winter, respectively. A lower total sum of effective solar radiation was also found under RCP 4.5, shown by 1773.3 MJ m^2 and 1909.1 MJ m^2 in spring and winter, respectively. These findings indicate that maize yields were proportional changing with effective solar radiation. Similarly, a study in China reported that maize yield reduction was considered as the consequence of vapor pressure deficit and drought stress affected by solar radiation, temperature, and precipitation (Shuai et al, 2016). In France, heat wave and associated drought resulted in a decline in maize yield and production in 2003 (van der Velde et al., 2010).

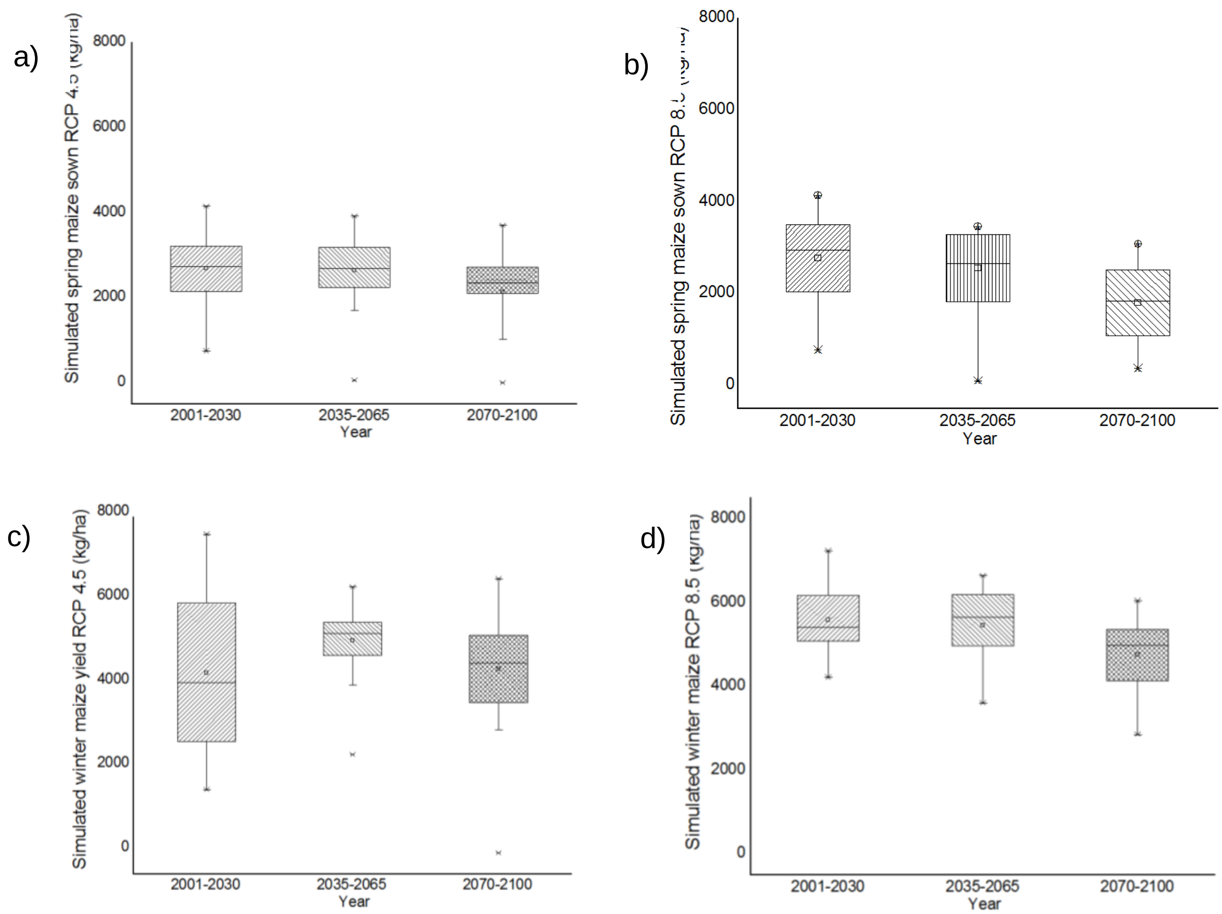
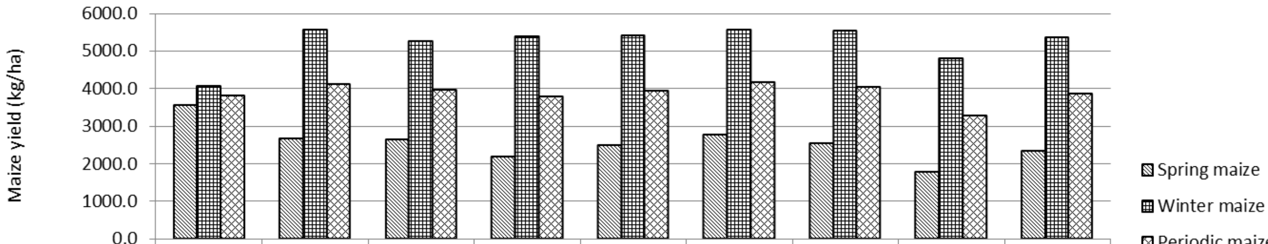


Fig. 44 a-d. Simulated spring and winter season maize yield under the two different scenarios RCP 4.5 and RCP 8.5 for Thai Nguyen province, Vietnam. Boxes present 50% of all cases, including a vertical line at the median and a dot at the mean.

Generally, winter grain yields are higher than spring grain yields because the number of dry days in spring crops was projected to be higher than in winter crops under climate change scenarios (Tab. 10,11). In addition, the winter maize is grown after the end of the rainy season, where soils have still high water content. During winter maize growing season, precipitation is continuously decreasing, and effective solar radiation increases, forming ideal conditions for yield formation. The spring maize, sown in February, with low soil water contents often suffers drought stress during vegetative period, limiting its yield potential, so the spring maize yield stays lower on average. Climate change is changing growing conditions in that it is improving winter growing conditions and adds more stress during the dry spring growing season.



	2000-2014	RCP 4.5 (2001-2030)	RCP 4.5 (2035-2065)	RCP 4.5 (2070-2100)	RCP 4.5 (2001-2100)	RCP 8.5 (2001-2030)	RCP 8.5 (2035-2065)	RCP 8.5 (2070-2100)	RCP 8.5 (2001-2100)
Spring maize	3560.9	2679.5	2651.6	2200.8	2483.3	2772.9	2549.8	1777.9	2352.8
Winter maize	4058.7	5561.3	5271.9	5382.0	5410.6	5576.8	5531.7	4796.6	5354.4
Periodic maize	3809.8	4120.4	3961.7	3791.4	3947.0	4174.8	4040.8	3287.3	3853.6

Fig. 45. Comparison of historical maize and simulated climate scenario periods maize yield

On the other hand, maize yields can be influenced by the amount of N leaching which is directly influenced by the amount of precipitation and soil properties. The results revealed that maize production on Fluvisol soil had mostly no effect on N leaching, but strong N leaching occurred on sandy soil such as Ferric-Acrisol and Acric-Ferralsol soils. Based on the climate change scenarios, N leaching was therefore expected to increase in winter maize season and decrease in spring maize season due to the rise of rainfall in winter season and the reduction of precipitation in spring (see tables 10-11). However, it does not mean that spring maize yield will obtain higher yield because of less N leaching, because spring maize yield is notably affected at the same time by decreasing precipitation and increasing negative water balance. N leaching was simulated in a range from 40-90 kg/ha and 50-70 kg ha^{-1} in the spring and winter seasons, respectively during the observed period (2000-2014), where higher total N-leaching rates were simulated in winter (Fig. 46a-b) due to much higher precipitation in the observed weather data. Under climate change scenarios, N leaching decreased dramatically in spring season (Fig. 46c-f), where it slightly increased in the winter season. This correlates with the higher number of dry days in the spring season compared to the winter season under both climate change scenarios (RCP 4.5 and RCP 8.5) (see Fig. 25). Approximately 70% of N leaching in springs is less than 41 kg ha-^{1} while 70% of N leaching in winter seasons is more than 56 kg ha^{-1} under RCP 4.5. Likewise, N leaching in spring seasons is lower than in winter seasons under RCP 8.5. These results are in line with a study from the North China Plain (NCP), where N leaching is determined out to concentrate in the summer maize season due to more precipitation than in winter. Additionally, the nitrogen loss showed a dependent rate on heavy rain events (of more than 100 mm day^{-1}). Moreover, light soil texture is also one of the factors that drastically influences nitrogen leaching in combination with a predominance of rainfall in summer. However, annual leaching only reached 38-60 kg ha^{-1} from conventional N management while the nitrogen accumulation was much higher in comparison to other regions in Europe such as Sweden, Italy, and Germany. The N accumulation in the NCP reached 762 kg N ha^{-1} at 0-1 m soil depth (Huang et al., 2017). This could also be the reason why maize yields in some specific years during the period from 2015-2030 under RCP 4.5 were simulated to be very low in comparison with maize yields received before and after that period (Fig. 46 a-d). This result is consistent with a case study in China. The study predicted that in the future, the runoff in most Chinese basins may decrease to different degrees. In addition, the decreasing runoff velocity is fastest in the RCP8.5 scenario, and the decreasing runoff trend slows down under the RCP4.5 and RCP2.6 scenarios (Chen et al., 2014).

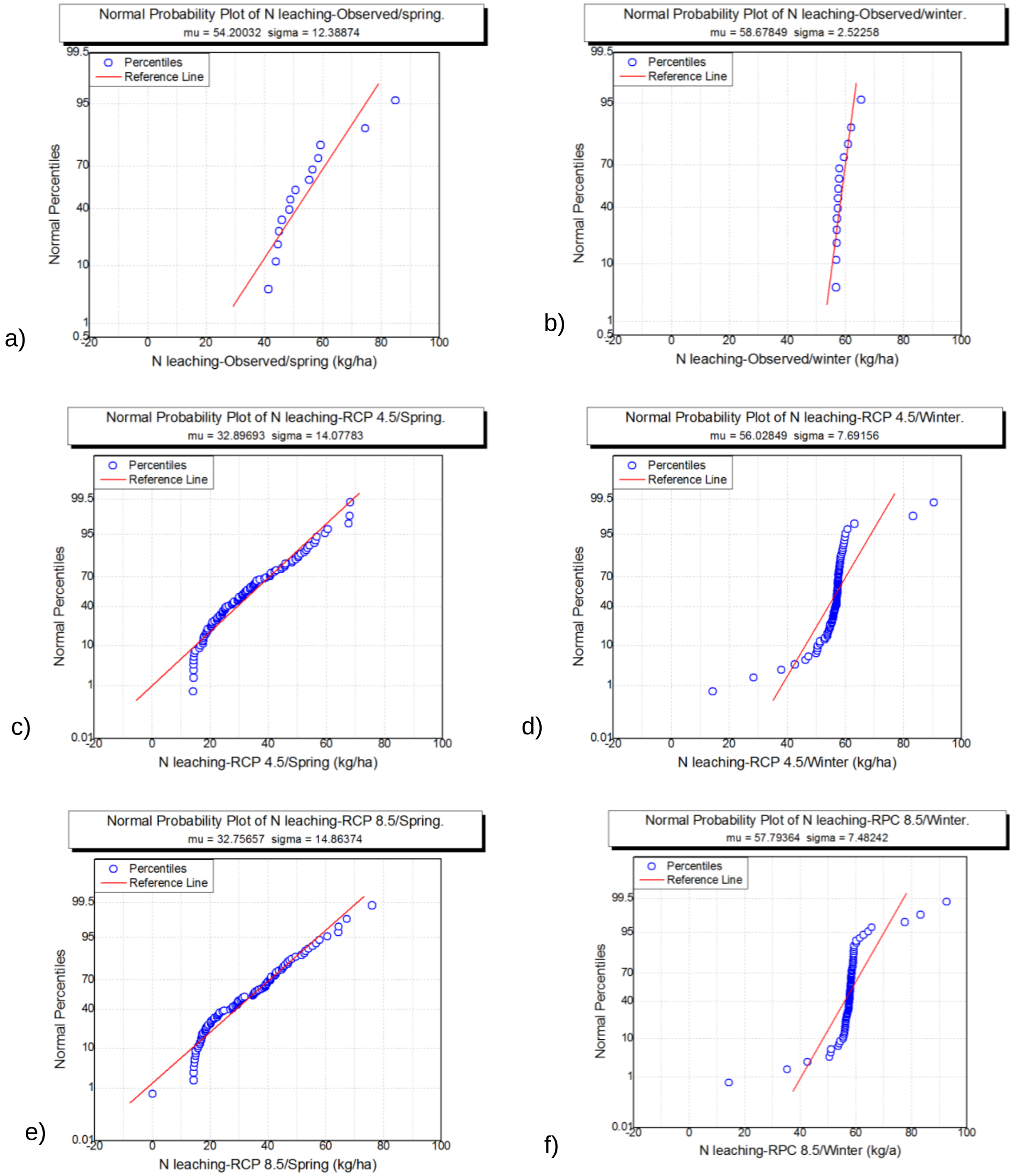


Fig. 46 a-f. Normal probability of N leaching for winter and spring maize growing season under current conditions (a-b) and RCP 4.5 (c-d) and RCP 8.5 (e-f) climate scenarios.

4.4.2 Uncertainty analysis and factors influencing maize yield simulation

4.4.2.1 The difference of the two applied climate scenarios

The results showed that there was a huge difference in some agroclimatic indicators between two climate change scenarios such as effective global radiation sums, the difference in the number of dry days, the number of days suitable for harvest and potential water balance. The effective global radiation sum under the climate change scenario RCP 8.5 is much higher than those under RCP 4.5. The highest difference was projected approximatley 38.1%. The number of days suitable for harvest for the winter crop in July is also notably different in comparison between two RCP 8.5 and RCP 4.5, especially from 2001-2030. Under RCP 8.5, the number of days suitable for harvest is lower by 44.5% in comparison with those under RCP 4.5 from 2001-2030. In addition, the moderate difference in terms of number of days suitable for harvest for spring and fodder crop in addition to a slight difference in terms of a number of dry days under RCP 8.5 and RCP 4.5 is also observed in given periods, as shown in Fig. 47.

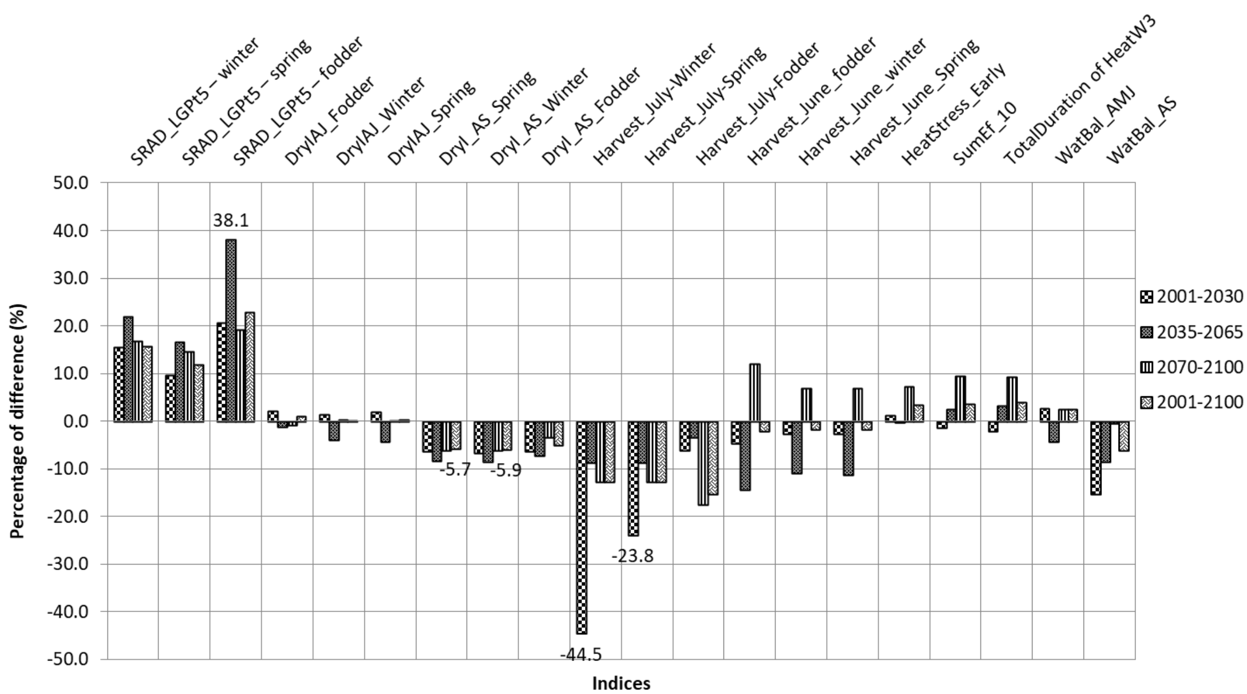


Fig. 47. Deviation of selected agroclimatic indicators under RCP 8.5 from RCP 4.5 as the reference

4.4.2.2 The contribution of other factors to maize yields in the study region

a) The type and rate of organic fertilizer applied and its effects

In the past, local farmers often produced manure for cultivation by themselves. However, the manure use in the cultivation of crops has recently been depleted in smallholder farms. The reason is that farmers prefer to use chemical fertilizer instead of organic fertilizer because of faster efficiency to enhance maize yield specifically and crop productivity generally. This led to higher income at the present but could result in difficulties in the future because of soil degradation and loss of soil fertility.

In fact, manure fertilizer has some negative aspects such as slow decomposition and nutrients may be released when the plant does not need them because manure mineralization is strongly affected by temperature and moisture content. However, nutrient content in manure is limited in comparison with chemical fertilizer. Furthermore, manure is also required in large quantities which may not be readily available to small farms. Therefore, the combination of organic and inorganic fertilizer is recommended to maintain a balance between farmers' income and environmental aspects (Tonfack et al., 2009). Chemical fertilizer has some typical advantages that manure does not have, such as quickly absorbing by the plant root system, thereby, rapidly increasing crop productivity (Sharma and Chetani, 2017). Moreover, there are also negative aspects of chemical fertilizers, such as too high fertilizer application rates and incorrect application timing can lead to N-leaching, loss of investment and environmental problems.

b) Various planting date and varieties

In reality, there are plenty of maize crop planting dates in the study region due to the soil properties, soil-water conditions, maize varieties, cropping patterns and finally due to high variability of annual weather conditions and monsoon occurrence. However, this study could only take into account the most common planting date for maize in combination with the most common varieties which are annually reported in local statistical reports. The influence of planting dates on maize growth and maize grain yield was detected from a bunch of studies around the world. Different planting dates drive different maize grain yields (Dahmardeh, 2012; Beiragi and Khorasani, 2011; Kharazmshahi, Zahedi and Alipour, 2015; Long *et al.*, 2017). However, it greatly depends on the seasonal crop and other factors such as topographical and climatic conditions, and how planting dates affect final yield. Most of the studies show an overall earlier planting driving a higher grain yield. Delayed planting dates such as in the Waikato and Manawatu regions of New Zealand led to a decrease of maize total biomass and harvest index due to the lower rainfall and lower solar radiation (Tsimba et al., 2013).

In addition, during the long period of maize crop development, the uncertainty in term of physiological mechanisms governing nutrient uptake may also be considered as an uncertainty because it is related to the whole plant nutrient uptake and its efficiency parameters (Ciampitti, 2012).

c) Errors from local report data

The uncertainty of climatic factors was considered as a limitation of CERES-Maize simulation (Bert et al., 2007). In addition, lack of data for model simulation is quite a common issue, especially in developing countries. The reason is that actual yield data (Y_a) reports are not well developed or reported and markedly different caused by different data sources over the years, regions within the same country. Besides, weather data and soil data are of poor quality. In addition to the lack of the data, preserving and nonpublic data are also an obstacle to crop modeling by some government agencies. These difficulties can lead to weak performance assessments of crop modeling studies in general. To address these issues, global databases can help to identify the crop sequence and management (Grassini et al., 2015). In Vietnam, due to the low level of technology improvement, reported data from local government officials were poor in quality. Moreover, growing by the time, the cultivation techniques were also altered by various innovations, such as change of varieties as well as other agronomic management. Hence, to fill the data gaps, it is important to understand the minimum data requirement of any model application. It can help to solve the problem to choose the second or the third alternative. For example, an alternative for filling gaps in station weather data such as T_{max} and T_{min} is the use of globally available gridded weather data. Currently, missing yield data, as one of the most required for any crop modal calibration and validation, can be retrieved directly from national statistics bureaus. Another alternative option is to estimate yields from existing data that are collected from farm surveys or by local agronomists administered by national agricultural agencies, institutions, departments, universities, private sector, or other on-going projects (Grassini et al., 2015). However, Vietnamese farmers often do not post their cropping management. Additionally, they do not measure exactly the productivity, or the amount of fertilizer that they have applied.

4.5 Adaptation to climate change impacts on maize production in Vietnam

Overall, under the two climate change scenarios in this study, RCP 4.5 and RCP 8.5, climate conditions are projected to be more extreme than in the past with higher temperature and lower seasonal precipitation. It is expected to negatively impact maize production, especially during the dry season. The influence of high temperature will become more extreme when it accompanies a low amount of rainfall. This condition leads to soil water deficiency, particularly in the long term of seasonal crops. In central Vietnam, maize yield decreased in drought seasons, driving farmers to change land use systems into other crops such as peanut, cassava or green bean (Uy et al., 2015).

Based on the current local farming conditions, some recommendations for maize adaptation under climate change conditions in the future can be derived. In the IPCC third assessment report (IPCC, 2001a), adaptation is defined as "an adjustment in the natural or human system in response to actual or expected climatic stimuli or their effect, which moderates harm or exploit beneficial opportunities". Irrigation is considered a crucial key to mitigating the influence of drought stress on maize growth in France (van der Velde et al., 2010). Irrigation is even more important under the climate change perspective, especially in South Asia (Döll, 2002). Drip-irrigation was found be an adaptation solution for enhancing of maize yield in a subhumid region with limited water resources for irrigation, China. However, due to the typical characteristics of topography and hydrologic conditions of Thai Nguyen, Vietnam, the irrigation system may expose to some difficulties in terms of water delivery in the dry season. Therefore, simultaneously building up an irrigation system, a system of dam or water storage in the local area might be a solution to store water in the rainy season and deliver water in the dry season.

In conjunction with irrigation, a shift in planting date also has some positive influence in reducing drought stress impacts on maize production due to the interaction between climate condition and soil condition. Abraha & Gårn (2016) investigated that flexible planting and rainwater harvesting have a substantial potential for reducing the negative impacts of climate change, and possibly even increased output (Abraha and Gårn, 2016). In Southern Mali, earlier planting date of maize cultivation in combination with recommended fertilizer options and long duration varieties for medium farms were projected to decrease the impact of warming by 2.9 to 3.3 °C. Under control-conditions, simulated maize grain yield even increased by 51-57% under current farmer fertilizer practices (Traore et al., 2017). In cooler mountainous regions, earlier sowing dates are also considered to obtain higher yields by rising the length of the growing season, as a result of a case study in southwestern US (Myoung et al., 2015). However, in another region, a later planting date to shift the plant water demand and lessen exposure to drought periods during silk-tasseling was determined out to be an adaptation option under climate change conditions (Harrison et al., 2011). Due to the local climate conditions in the Vietnam case study region (dry in early spring and during the winter season), the planting date, therefore, may shift to be later in the spring season and sooner in the winter season to avoid the most extreme dry periods in early spring and late winter. The adaptation is convinced by several studies that demonstrate the impact of temperature and precipitation on maize yield such as a study carried by Blanc in 2012. Its results show that an increase of 1.7% in maize yield is derived by an increase of 100 mm in precipitation at a temperature mean value of 24.3 °C (Blanc, 2012)

On the other hand, to improve soil water storage capacity, mulching may also be a convenient strategy, especially in combination with rotational tillage, thus progressing crop grain yield and water use efficiency (Wang et al., 2018). The positive effect of mulching on maize yield was shown by an increase of maize yield by 33.4% and 30% in the Loess Plateau, China. Furthermore, plastic mulching helped to increase soil water storage at the end of the fallow season and provide nonlimiting water conditions for early seedling growth, especially when rainfall was scarce in this region (Jia et al., 2018). Another case study in China investigated that soil water capacity in the mulching treatment was much better than that in the no-mulching treatment at 0–60 cm soil depth, however, it was not notably different from the 140–200 cm depth. Moreover, plastic film mulching including basal fertilizer improved maize yield at 10.6%, 9.5%, and 15.4%, and continuously enhanced the yield at 16.6%, 20.9%, and 12.2% over three consecutive years, respectively (Xiukang, 2015).

One key mechanism for plants to adapt to environmental conditions is the modulation of gene expression. Implementation of drought-tolerant hybrids and managing soil water efficiently throughout grain filling is important for maintaining high yield under water-limited conditions (Zhao et al., 2018). Hence, genetic and agronomic strategies to adapt to climate changes are proposed as the most efficient options. Heat-tolerant maize varieties have the potential to avoid severe yield loss due to heat damage and help farmers to adapt to climate change impacts (Tesfaye et al., 2016). In Vietnam, after five years conducting evaluations of risk assessments on genetically modified maize, scientists successfully created new genotypes producing double yield compared to conventional hybrid varieties (Dang et al., 2002).

Organic fertilizers are assumed to be another essential mechanism for plants to adapt to environmental challenges. There are many studies showing the benefits of manure in term of maize yield enhancement and soil property improvement. In China, dung application in combination with deep tillage could improve the maize yield by up to 43% and enhance the soil organic qualities in comparison with conventional tillage (Meng et al., 2016).

Similar results were also detected in northwestern China when using manure. It helped to increase the N (total nitrogen), P (available phosphorus), and SOM (soil organic matter) concentration in the soil layer of 50-150 cm by 25%, 198% and 41% respectively, improving the soil-water nutrient and brought the increased maize yields by 5-10% at the high planting density (Wang et al., 2017). Additionally, organic manure could recover soil water potential in dryland agriculture, resulting in improved maize yield (Wang et al., 2017). In addition, poultry application even helped to increase the leaf area and weight of tomato (*Solanum lycopersicum L.*), okra (*Abelmoschus esculentus*), pumpkin (*Telfaria occidentalis Hook F*) in a conjunction with improved soil physical and chemical properties as results from some study cases in Nigeria (Ewulo et al.,, 2008; Adekiya and Agbede, 2012). In another area in Africa with dominating sandy soils, poultry manure could support to enhance soil bulk density and improve the total porosity and soil moisture content (Khalid et al., 2014). Individually, in a study of analysing relationship between organic cow dung and chemical fertilizer (N.P.K) on maize production, the results showed that an increase of maize grain yield by using cow dung without using chemical fertilizer can be recommended considering the costs and environmental features in future (Wisdom, 2012).

Over and above, intercropping can reduce the negative impact of water stress during the dry season. In Africa, intercropping maize with a tree such as gliricidia increased maize grain yield and soil C in the soil surface layer (20 cm). Additionally, water use capacity was also higher in the intercrop maize with gliricidia (Gliricidia sepium) than in sole maize. The highest grain yield was derived at an 8 m horizontal distance from the gliricidia tree, gradually decreasing and dropping to the lowest point at a 1 m horizontal distance from the gliricidia tree (Smethurst et al., 2017). In Thai Lan, intercropping maize with other crops such as legumes (rice bean, cowpea, lablab, mung bean) helped to increase maize yield in general. The highest increase in maize yield derived from the intercropping of maize with lablab was 54%, followed by 34% with cowpea, rice bean, and mungbean. In addition, nitrogen accumulation also increased under the intercropping system as shown by the enrichment of soil biodiversity or Shannon diversity index. The maximum index was given by the intercropping of maize with rice bean, followed by cowpea, mungbean and finally with lablab.

Interestingly, the intercropping system further helped to decrease weed dry weight during crop seasons, reduce soil erosion on steep slopes and reduce exacerbated environmental issues such as haze atmosphere because of burning crop residue especially in the case of maize in the mountainous area (Punyalue et al, 2018). Exceptionally, maize can even be cultivated with gladiolus, cauliflower, pea, carrot, spinach, cotton to enhance land use efficiency in India. These studies support the high potential for intercropping maize with other crops. In reality, maize is often cultivated with rice or vegetable in a rotating system. However, under local conditions, maize could have considerable potential to be cultivated with other crops together in intercropping systems that have hardly ever experienced. Many examples from regions with similar soil and weather conditions as in Thai Lan, Africa, and India are given.

a)

Intercropping maize with soybean

(source: http://www.fao.org/docrep/009/a0100e/a0100e07.htm)

b)

Mulch application in maize

(Source: http://kiboko.nl/portfolio-item/intercropping/)

c)

Different planting date as adaptation

Fig. 48 a-c. Adaptation strategies for maize management in Thai Nguyen, Vietnam

Furthermore, there are a number of adaptation options that can be applied in the study area to minimize the negative impact of climate change on maize production such as optimizing production inputs such as labor and crop management timing, cultivars, fertilizing, and multicropping (Döll, 2002), but these need to be carefully evaluated. For example, in regard to reducing N-leaching and to improving N-use efficiency, irrigation methods can play an important role (e.g. Devkota et al., 2013b), which needs to be further investigated under specific environmental conditions. In addition, land use change and landscape structure improvement need to be considered in advance to reduce evapotranspiration by lowering the wind speed (Eitzinger and Kubu, 2010).

Finally, farmers need better education and training on new agricultural production techniques and methods, and about the market to ensure higher market-price stability of their agricultural products. They can improve sustainable planning and implementation of adaptation options by using appropriate tools. Those tools may be supported by the government such as political measures, ecological farming, establishing regional food production and local market organization. Additionally, farmers might also have some practical risk reduction tools such as insurance, diversification, and adaptation measures (Eitzinger and Kubu, 2010; EITZINGER, 2011).

Table 15. Adaptation options to climate change for maize production in Thai Nguyen, Vietnam

Regions	Observed trends in adaptations to climate change	Recommended feasible adaptation options to climate change	Mitigation effects	Identified limitations for adaptation options to climate change
General	Change of sowing dates (late spring and early winter season, see Fig. 48c), increase of irrigation, modified plant protection-programs. Crop issurance Weather forecasting services	Change of sowing dates; increase of irrigation requirements; optimize plant protection programs; changing fertilization requirements; intercropping cultivation; use organic fertilizer; decrease of plant density per unit area in dry plant growing systems, new hybrids/cultivars, adjust doses of fertilizers; performance of plant rotation; plant residues incorporation with nitrogen utilization; farming school.	Improve soil fertility; optimize fertilizing of cereals which will decrease soil, water, and food pollution; food security constraints.	Availability and cost of water resources; small farm size; farmers cooperation is at a very low level; technology imitations; financial resources; environmental hazards; scientific knowledge limitations (genetic improvement); marketing constraints. Low training and education levels of farmers.
Flatland	Optimized plant density per area; improved irrigation and drainage systems; changed cultivars and crops.	Optimal soil cultivation time, sowing date; improve the current irrigation and drainage systems; change cultivars and crops; minimize tillage.	Minimum tillage prevents soil compaction and increase carbon sequestration in soils.	High cost of machinery; high costs of irrigation system and education of farmers concerning practicing minimum tillage system.
Midland and high land	Using new productive cultivars and hybrids which adapt better with drought conditions	Using different further productive cultivars and hybrids which accommodate better with dryness circumstances; hill terracing.	Reduce the impact of water stress, soil water erosion in maize production.	Farmers have lack of information about effects of water erosion; droughts; dry winds; floods; mudflow floods which usually happen in ravine areas.

V. Conclusions and recommendations

5.1 Conclusions

5.1.1 Evidence of climate change in the study area and its projection in future

Local weather has steadily changed over 35 years, reputably shown by an increase in temperature and reduction in precipitation in Thai Nguyen province, Vietnam. The rise in temperature over the period of 35 years (1980-2015) was 0.7 °C in combination with decreases in precipitation. In the future, the average temperature is projected to increase from 24.5 °C during the observed period from 1990-2015 to 26.2 °C (2001-2100) under RCP 4.5 and 26.7 °C (2001-2100) under RCP 8.5. The maximum temperature is projected by 52.8 °C and 48.2 °C, while the minimum temperature is projected by 11.9 °C and 6.2 °C under climate change scenarios RCP 8.5 and RCP 4.5, respectively. This finding indicates considerable variability of temperature in the future. Consequently, it intimates that the weather in the local area may be more extreme than in the past, therefore, will lead to more struggles for crop production. In contrast to temperature, an enormous precipitation reduction was determined by approximately 60% in comparison with the average precipitation during the observed period from 1990-2015. It was calculated by 1.85 mm d^{-1} and only by 1.7 mm d^{-1} under RCP 8.5 and RCP 4.5, respectively.

5.1.2 Perspectives of maize production during the next decades up to 2100 under projected weather conditions

With the NRMSE value in a range between 19.4% and 10.3% and the index of agreement range between 0.47-0.77, the simulated results showed that the DSSAT-CERES-Maize model has good performance in estimating maize production, resource use, and risks of maize production in the study region. The simulated maize yield is therefore a useful trend information for farmers as well as policymakers in the future.

The study showed that maize yields in the future are slightly higher than in the past under both climate change scenarios RCP 4.5 and RCP 8.5. Taking into account the average of yearly maize yields over the whole period of 100 years, it was determined to be higher than the average of observed annual maize yields in the period (2000-2014) of about 1.1% under RCP 8.5 and 3.9% under RCP 4.5, mostly contributed by the increase of winter maize yields. Winter maize yields were calculated to increase up to 33.3% and 31.9% under RCP 4.5 and RCP 8.5, respectively while spring maize yields, in opposition, decrease under both climatic scenario conditions, RCP 4.5 and

RCP 8.5, by 30.3% and 33.9%, respectively. These results are mainly correlated with a higher number of dry days and less precipitation in spring compared with winter.

Under climate change scenarios, N leaching decreases extremely in the spring season, where it slightly increases in the winter season. Approximately 70% of N leaching in springs is less than 41 kg ha-^{1} while 70% of N leaching in winter seasons is more than 56 kg ha^{-1} under RCP 4.5. Likewise, N leaching in spring seasons is lower than in winter seasons under RCP 8.5. This is consistent with the higher number of dry days in spring seasons compared to winter season in the next decades up to 2100 under both climate change scenarios (RCP 4.5 and RCP 8.5), which were measured by Agriclim.

To cope with the negative impact of climate change on spring maize, it is necessary to apply various adaption methods for maize production such as change of planting date, intercropping cultivation, mulch application and especially more irrigation (if water resources are available) to mitigate the severe effect of increasing dry weather and improve the crop productivity.

The study suggested among others (table 15) that irrigation is the crucial key to reducing the influence of drought stress on maize in combination with other adaptation options such as constructing a water storage system or water storehouse. These latter systems may also a solution to deposit water in the rainy season and deliver water in the dry season. In addition, changing the planting date or application of different planting dates in the same season would be an option to reduce cropping risks. The sowing date, accordingly, may be delayed in the spring season and set sooner in the winter season to escape shift the most notably dry periods. Additionally, improvement of new cultivars should also be considered an innovation in terms of climate change adaptation in future.

5.2 Limitation and recommendations

Simultaneously, changes in weather conditions, agronomic management and varieties occur during the study period. Nevertheless, the results of maize yield simulation were executed by representative conditions with some limitations of data availability. Accordingly, it is recommended for next studies to use more genotypes and test various agronomic techniques during the crop simulations in addition to build up a database for future simulation studies in the fields.

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APPENDIX

Table 16. Soil properties in Thai Nguyen, Vietnam

FD	Depth (bottom)	Texture (%)			pH	OM	Total (%)			(meq/100 g)			Al3+	
	cm	2-0.02	0.02-0.002	< 0.002	KCl	%	N	P2O5	K2O	Ca	Mg	CEC	ldl/100g	mg/100g
TC.12	0-25	45.32	29.70	24.98	4.13	2.65	0.242	0.189	0.32	5.38	1.05	18.18	1.12	35.84
	25-60	36.95	20.04	43.01	4.03	0.48	0.044	0.062	0.45	1.27	0.20	10.66	1.72	41.44
	60-110	32.76	16.63	50.61	4.09	0.24	0.022	0.064	0.54	0.90	0.16	11.39	2.40	29.12
§T.1	0-20	58.72	23.46	17.82	4.61	1.75	0.128	0.067	0.89	1.41	0.43	10.43	0.80	79.32
	20-45	47.96	27.32	24.72	4.41	1.02	0.101	0.102	1.12	1.22	0.34	10.10	1.12	64.26
	45-100	47.90	25.19	26.91	4.35	1.02	0.089	0.103	0.95	1.18	0.32	9.94	1.32	51.52
§T.6	0-20	56.75	21.28	21.97	4.22	1.68	0.128	0.073	0.36	1.63	0.44	16.52	2.02	40.32
	20-50	57.55	17.53	24.92	4.22	1.10	0.095	0.071	0.35	1.09	0.20	10.02	1.52	58.24
	50-100	52.03	15.16	32.81	4.23	0.73	0.068	0.056	0.53	1.21	0.25	9.83	1.40	59.36
§T.8	0-15	40.42	35.61	23.97	3.90	1.68	0.134	0.087	1.24	1.43	0.20	17.38	2.32	54.88
	15-50	32.33	33.72	33.95	3.98	1.10	0.084	0.052	1.43	0.91	0.12	11.47	2.28	64.96
	50-120	32.33	32.05	35.62	4.02	0.66	0.056	0.051	1.44	0.87	0.13	11.29	1.76	60.48
§T.10	0-20	75.49	9.52	14.99	3.95	1.46	0.112	0.094	0.22	1.43	0.18	9.97	0.40	33.52
	20-60	65.75	9.65	24.60	4.30	1.17	0.101	0.181	0.18	1.02	0.13	6.28	1.12	40.32

	60-100	64.72	8.76	26.52	4.45	0.80	0.067	0.194	0.19	1.03	0.11	7.47	0.56	53.44
§T.14	0-20	41.59	23.42	34.99	4.17	1.24	0.117	0.045	0.34	1.69	0.18	12.22	1.60	59.36
	20-55	35.04	21.39	43.57	4.16	0.51	0.050	0.028	0.41	0.88	0.10	9.32	1.52	43.68
	55-120	30.27	21.66	48.07	4.20	0.44	0.039	0.036	0.67	1.10	0.13	9.53	2.08	38.08
TC.6	0-20	69.12	15.79	15.09	3.88	1.39	0.112	0.219	0.37	1.22	0.31	11.49	0.76	91.84
	20-40	66.51	9.77	23.72	4.21	0.44	0.044	0.064	0.54	1.11	0.27	5.66	0.88	59.36
	40-110	67.17	9.12	23.71	4.33	0.37	0.033	0.061	0.48	0.83	0.16	5.33	0.76	38.08
PL.1	0-30	34.48	32.19	33.33	3.87	2.04	0.151	0.183	1.12	2.60	0.50	19.65	2.40	97.44
	30-70	18.47	30.34	51.19	3.80	1.10	0.101	0.132	1.38	1.81	0.32	16.57	3.20	76.16
	70-100	18.09	26.02	55.89	3.79	0.51	0.050	0.146	1.76	1.63	0.22	14.34	2.20	41.44
PL.3	0-20	29.13	43.51	27.36	5.64	3.07	0.212	0.181	1.38	17.49	3.48	20.09	0	64.96
	20-40	23.85	38.73	37.42	5.01	0.88	0.078	0.072	1.34	7.01	1.59	14.36	0	73.92
	40-70	23.19	35.98	40.83	5.59	0.51	0.050	0.068	1.42	9.43	1.07	15.28	0	77.28
PL.6	0-20	57.48	29.01	13.51	5.54	0.73	0.068	0.067	0.67	5.34	1.28	15.37	0	76.16
	20-40	45.16	24.93	29.91	4.48	0.37	0.033	0.061	0.66	3.09	0.59	8.22	1.00	47.04
	40-120	30.09	23.14	46.77	4.23	0.37	0.033	0.163	0.82	1.74	0.37	8.74	2.08	30.24
PL.7	0-15	17.24	44.51	38.25	4.08	3.65	0.252	0.188	0.93	5.15	1.28	20.54	1.80	76.16
	20-40	22.25	41.59	36.16	4.01	1.39	0.117	0.117	1.22	2.43	0.42	15.32	1.60	71.68
	> 70	11.94	45.34	42.72	4.05	0.66	0.056	0.079	1.49	2.22	0.34	12.14	2.32	58.24
PL.11	0-20	32.77	44.52	22.71	4.04	1.68	0.134	0.212	1.02	2.59	0.36	13.44	1.52	81.76
	20-40	22.32	36.91	40.77	3.93	0.51	0.050	0.116	1.28	1.55	0.16	10.08	1.92	54.88

	40-120	22.81	33.33	43.86	4.12	0.37	0.039	0.117	1.64	1.27	0.14	7.72	1.92	35.84
PL.13	0-20	17.48	43.40	39.12	4.22	1.55	0.123	0.216	1.73	3.92	0.81	15.19	1.60	64.96
	20-60	15.35	46.69	37.96	4.17	1.10	0.106	0.118	1.59	3.82	0.88	14.27	1.84	73.92
	60-120	10.32	40.17	49.51	4.06	0.51	0.050	0.084	1.62	2.35	0.38	9.10	2.68	52.64
PL.15	0-15	19.02	35.62	45.36	3.98	1.83	0.128	0.092	1.63	1.17	0.25	16.33	3.60	86.64
	15-35	18.25	34.88	46.87	3.97	0.95	0.089	0.068	1.68	0.94	0.19	16.11	3.52	77.28
	35-70	19.76	33.65	46.59	4.02	0.47	0.044	0.054	1.76	0.90	0.13	17.03	3.28	38.08

Table 17. Description of indices by Agriclim model

Name	Definition	Inputs parameters	output format
SRAD_LGPt5 (winter, spring, fodder)	Effective global radiation sum calculated for winter and summer cereal as well as fodder crop, respectively	Tmean, AET, ET0, SRAD	MJ/m2/day
DryI_AJ (winter, spring, fodder)	Number of days with intensive water deficit for April-June calculated for winter and summer cereal as well as fodder crop, respectively	AET, ET0	number of days in defined period when AET/ET0 < 0.4
DryI_AS* (winter, spring, fodder)	Number of days with intensive water deficit for April to September calculated for winter and summer cereal as well as fodder crop, respectively	AET, ET0	number of days in defined period when AET/ET0 < 0.4
Harvest_July	Number of days suitable for harvest_July	Soil moisture in top 20 cm; Rain	number of days
Harvest_June	Number of days suitable for harvest_June	Rain	number of days
Heat Stress_Early	Heat stress days >28°C	TMAX	number of days
SumEf_10	Sum of effective temperatures above 10°C	Tmean, TMIN, TMAX, Tbase = 0	sum of temperatures per year
TotalDuration of HeatW3	sum of days per year fitting to HeatW3 conditions	TMAX, TMIN	number of days
WatBal_AJ	potential water balance April-June	ET0, RainC	sum (mm)
WatBal_AS	potential water balance April-September	ET0, RainC	sum (mm)

Table 18. Number of the day in the year (J)

Day	January	February	March*	April*	May*	June*	July*	August*	September*	October*	November*	December*
1	1	32	60	91	121	152	182	213	244	274	305	335
2	2	33	61	92	122	153	183	214	245	275	306	336
3	3	34	62	93	123	154	184	215	246	276	307	337
4	4	35	63	94	124	155	185	216	247	277	308	338
5	5	36	64	95	125	156	186	217	248	278	309	339
6	6	37	65	96	126	157	187	218	249	279	310	340
7	7	38	66	97	127	158	188	219	250	280	311	341
8	8	39	67	98	128	159	189	220	251	281	312	342
9	9	40	68	99	129	160	190	221	252	282	313	343
10	10	41	69	100	130	161	191	222	253	283	314	344
11	11	42	70	101	131	162	192	223	254	284	315	345
12	12	43	71	102	132	163	193	224	255	285	316	346
13	13	44	72	103	133	164	194	225	256	286	317	347
14	14	45	73	104	134	165	195	226	257	287	318	348
15	15	46	74	105	135	166	196	227	258	288	319	349
16	16	47	75	106	136	167	197	228	259	289	320	350
17	17	48	76	107	137	168	198	229	260	290	321	351
18	18	49	77	108	138	169	199	230	261	291	322	352
19	19	50	78	109	139	170	200	231	262	292	323	353
20	20	51	79	110	140	171	201	232	263	293	324	354
21	21	52	80	111	141	172	202	233	264	294	325	355

22	22	53	81	112	142	173	203	234	265	295	326	356
23	23	54	82	113	143	174	204	235	266	296	327	357
24	24	55	83	114	144	175	205	236	267	297	328	358
25	25	56	84	115	145	176	206	237	268	298	329	359
26	26	57	85	116	146	177,	207	238	269	299	330	360
27	27	58	86	117	147	178	208	239	270	300	331	361
28	28	59	87	118	148	179	209	240	271	301	332	362
29	29	(60)	88	119	149	180	210	241	272	302	333	363
30	30	-	89	120	150	181	211	242	273	303	334	364
31	31	-	90	-	151	-	212	243	-	304	-	365

* add 1 if leap year

J can be determined for each day (D) of month (M) by

J = **INTEGER** (275 M/9 - 30 + D) - 2

IF (M < 3) **THEN J = J + 2**

also, **IF** (leap year and (M > 2)) **THEN** J = J + 1

For ten-day calculations, compute J for day D = 5, 15 and 25 For monthly calculations, J at the middle of the month is approximately given by

J = **INTEGER** (30.4 M - 15)

Fig. 49. Laboratory, Thai Nguyen university of Agriculture and Forestry, 2016

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