Exploring the relationship between climate change and rice production in Northern Italy

CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD

School of Earth and Environmental Sciences

Ysgol Gwyddorau'r Ddaear a'r Amgylchedd

Environmental Geography Dissertation 2023

Dissertation submitted as part of the BSc Degree of Environmental Geography

Cardiff University

Date: 14/01/2023

Author: Lucas Zazzi Carbone

ABSTRACT

The present study aims to investigate the extent climate variables analysed influence rice production, with an in-depth focus on how future climate change may inadvertently impact the production of rice, in Northern Italy. This project utilised a simple linear regression and correlation analysis model. As well as a Spearman's rank correlation coefficient ($r_{s)}$, to determine the statistical significance between each climate variable and rice, and thus p values. The strength and direction of the correlations were then quantified. The results determined sunshine duration (r_s= 0.46847>0.421, $p<.01$), evapotranspiration (r_s= 0.58328>0.497, $p<.001$) and soil moisture (r_s= 0.46977>0.421, $p<.01$) as statistically significant to rice production over 1985-2021. Respectively, temperature, precipitation and soil temperature were not statistically significant to rice production over 1985-2021. Interpretations highlighted spatiotemporal climate change will pose a threat, potentially shifting the extent climate variables influence the production of rice. Derived from alterations in Po River's discharge level and reoccurrence of natural hazards, through climate-system interactions in the Alps. The study provides valuable information, highlighting the importance of future research on climate change, to manage and maintain rice production in Northern Italy.

ACKNOWLEDGEMENTS

Firstly, I would like to thank my supervisor Henrik Sass, who guided me throughout the process. Without his continued support, this dissertation would not have been possible. Secondly, I would like to thank Meteoblue for allowing me to access their data for the completion of this academic work.

I would also like to acknowledge my peers, Rory Bateson, Robb Baxter, Ollie Bebbington and Piers O’Connor for the continued support, allowing an arduous piece of academic work to become more manageable.

TABLE OF CONTENTS

LIST OF FIGURES, TABLES AND ABBREVIATIONS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

NI – Northern Italy

FAO – Food and Agriculture Organisation of the United Nations

SDG – Sustainable Development Goals

IPCC – Intergovernmental Panel on Climate Change

GHG – Greenhouse gas

CO_2 – Carbon dioxide

NNM – Nonhydrostatic Meso-Scale Modelling

NMS- NOAA Environment Monitoring System

NOAA – National Oceanic and Atmospheric Administration

R^2 – Coefficient of determination

r_s – Spearman's Rank Correlation Coefficient

DF – Degrees of Freedom

ENSO – El Niño Southern Oscillation

GCM – Global Circulation Model

CHAPTER 1.0 INTRODUCTION

1.1 Scientific background

The unprecedented increase in global GHG emissions will inadvertently exacerbate climate change, holding great influence in the agri-food sector. In Italy, rice (Oryza Sativa L.) is the major cereal producer in Europe, responsible for over 13,472 tonnes of exported rice in 2021 (FAOSTAT 2021). According to the FAO, approximately 2.5% of Europe is facing hunger; with the notion that about 50% of the world population is dependent on rice (Giuliana et al. 2022), it is crucial that the impacts of a changing climate on rice production in Northern Italy are well understood.

Rice production in Northern Italy is characterised by continuous flooding through irrigative practices as the main source of water supply, with a smaller influence derived from alpine lakes, as illustrated by Zoli et al. (2021) as well as Arcieri and Ghinassi (2021). However, the authors do not consider the climatic patterns posing an influence on rice production in Northern Italy. Rice is an important food source that contains the nutrients required for survival, thus globally, rice is a staple food for many regions. Most rice is produced in Asia, whereby myriad studies on climate change and rice production are conducted over rice paddy fields that heavily rely on water supply from rainfall (Matthews et al. 1995), unlike Italy.

In Italy, Russo and Callegarin (1997) recognise the main constraint to rice production being climate, specifically colder temperatures (≤5°C) at sowing times in April, causing damage to seedlings as well as increasing the predisposition of rice to blast attacks. Other variables posing risks to rice production include the aforementioned rice blast fungus, increase in weed populations and salinity problems. Although, the author's article can be deemed 'outdated' as improved varieties of rice, with enhanced technology have become more common in NI, combatting these implications. Such as a more profound use of nitrogen fertilizers to prevent rice disease (Titone et al. 2015). It is still important to note the main constraint of a colder climate, has and will likely shift as climate change becomes prevalent. The implications of a changing climate on rice are highlighted by Figueiredo et al. (2015) and Krishna et al. (2011), who demonstrate the phenological stages of rice sensitivity to temperature and photoperiods, highly dependent on plant species and genotype. Especially during vegetative stages, where high temperatures influence the growth duration of rice. These conclusions are similar to Madan et al. (2012), stating high temperature and longer photoperiods to show influence on rice production in NI. Mahmood et al. (2012) also concluded temperature to have a significant statistical relationship with rice in Punjab, Pakistan. Of course, these conclusions are derived from areas with a tropical climate, where rice production is rainfed, rather than irrigated.

According to Jena and Hardy (2012) the summers in temperate regions are characterised by longer sunshine durations, actively improving the photosynthetic ability favourable for rice growth. As opposed to cold and wet winters being characterised by intense precipitation and cloud cover, decreasing the photosynthetic active radiation that is unfavourable for rice growth. The intense and frequent precipitation also raises the water table, allowing for a more simplified extraction of ground water for irrigation. The relationships between precipitation and rice varies between studies. In some European regions, such as Turkey, precipitation increases are shown to have a positive correlation with rice production (Kayam et al. 2000). Whereas other studies show precipitation and rice having an inverse relationship, such as Kerala, India (Mahmood et al. 2012; Saseendran et al. 2000).

When evaporation of water from the soil occurs simultaneously with transpiration in crop canopies, the term evapotranspiration is used by scientists to quantify the relationship of both variables, explicating the transfer of water from vegetative surfaces to the atmosphere (Tomar and O'Toole 1980). The connection between evapotranspiration and rice is established by Qiu et al. (2021), who states evapotranspiration to have a synonymous relationship to rice production, because well-irrigated areas contain high soil moisture availability, increasing the potential for land-atmosphere interactions. The author also connotes warming patterns in Italy to increase the rate of evapotranspiration, enhancing growth of rice. Available literature specific to NI is scarce, however, Facchi et al. (2013) states evapotranspiration is key to maintaining the water fluxes of paddy fields, encouraging an effect on the quality of grains developed in rice. Accordingly, soil moisture content correlates with evapotranspiration rates to promote rice growth, through continuous flooding techniques, permitting the active use of the water table. Even when excess irrigation is prevalent, water as a by-product is not wasted, rather it is recycled into the hydrological cycle (Bocchiola 2015; Chapagain and Hoekstra 2011). Overall, to the author's knowledge, all literature agrees that soil water content induces favourable conditions for rice development and growth (Paiman and Effendy 2020; Xu et al. 2002).

Increased soil temperature has potential to increase the photosynthetic rate of vegetation through roots (Anderson and McNaughton 1973). According to Arai-Sanoh et al. (2010), soil temperature increases of 37°C were shown to strongly influence the growth of rice crops in Japan, on the other hand, soil temperatures below that threshold did not display a significant influence on rice growth. The temperate climate of Northern Italy means soil temperatures never reach the aforesaid threshold of 37°C. Furthermore, literature on the connection between these variables specific to NI is scarce, therefore it will be interesting to examine whether soil temperature and rice display a different relationship in this study.

Certain difficulty arises from comparing the trends of results from the above-mentioned authors on climate variables and rice, as the climate is a complex system filled with land-atmosphere interactions, that greatly differ regionally and temporally. For example, these differences can arise from seasonal-specific changes. From the literature it is evident that no drastic differences have been observed between each variable and rice surrounding the region of NI. There is importance in declaring impacts of certain variables on rice may differ from other research projects, and this study.

The accessibility and availability of scientific literature that promotes understanding of the relationship between rice production and the climate is ubiquitous. However, there is a noticeable gap in the literature related to the climate variables analysed in this study (temperature, precipitation, soil temperature, soil moisture, sunshine duration, and evapotranspiration) and rice, in NI. Thus, conceptualising the influence of climate change on rice production in NI becomes challenging, both in the past and future. Kim et al. (2013) proposed the use of predictive models that are calibrated and validated to infer interactions between the agricultural system and climate change. In fact, most research studies related to rice production in Northern Italy display a vast focus on models to produce rice yield and climate pattern relationships (Stroppiana et al. 2013; Confalonieri and Bocchi 2005; Miao et al. 2004). However, the scope of these models is limited to specific cultivars, as well as not pertaining the inclusion of soil moisture's correlation with rice production. To gain a specialised understanding of the relationship between climate variables and rice, a holistic approach was undertaken, focusing on the entirety of Northern Italy.

In the next 20 years, global temperatures are predicted to reach or exceed 1.5°C warming (IPCC 2021). Paving the way for a multitude of future climate alterations associated with the atmosphere, which in turn, influence the vegetative land in which rice is grown. Bocchiola et al. (2013) inferred under future climate scenarios, an increase in temperature and a decrease in precipitation is likely to occur in the Po Valley region, lowering potential crop yield. This study was primarily focused on maize crops, it does however suggest the scale of this effect may go beyond maize crops, affecting most agronomic systems in Po Valley. Cropping scenarios are expected to change when increased seasonal variability shift, directly influencing the ability of rice cultivation, through reductions in CO_2 fertilisation and increasing temperatures (Lee et al. 2012; Baker et al. 1992; Jagadish et al. 2007). Ultimately the available literature on future climate change indicates negative impacts on the ability of regions to produce rice crops.

The rationale behind this project is to identify the role agrometeorological factors have on rice production, both in the past and future. The findings depict an important step in the advancement of scientific knowledge, correlating the effects of each climate variable analysed with rice production. Combined with vital information needed to understand how a future change in climate may influence rice production in Northern Italy.

Aims, Objectives and a General Hypothesis

AIMS

1) To examine the extent climate variables (temperature, precipitation, sunshine duration, soil temperature, evapotranspiration and soil moisture) influence rice production in Northern Italy.

2) To explore how future climate change may induce potential climatic factors to influence rice production in Northern Italy.

To complete aim 1, aim 2 must be investigated.

OBJECTIVES

- Dataset collation for all variables analysed will be tested for monotonic relationships, utilising linear regression and correlation analysis.

- Quantitative data collected on the climate variables will be synthesised and analysed through Spearman's rank correlation coefficient to determine the strength and direction of the relationship between these variables.

- An investigation (using relevant scientific literature) on the extent other variables influence rice production will be adopted to achieve the aim "*To examine the extent climate variables (temperature, precipitation, sunshine duration, soil temperature, evapotranspiration, soil moisture) influence rice production in Northern Italy*".

- Synthesise and analyse scientific literature to decipher the aim *“To explore how future climate change may induce potential climatic factors to influence rice production in Northern Italy”*.

GENERAL HYPOTHESIS

A generalised hypothesis will be stated regarding the correlation between the variables analysed and rice production, to support scientific research:

“All climate variables analysed in this project will show a significant influence on rice production in Northern Italy”.

METHODOLOGY

This section communicates the methods used to construct this investigation. It includes the study area in which this investigation was conducted, an explication of data collation of these secondary sources, and the thorough data analysis utilised to better comprehend the aims and objectives of this study.

Study Area

Rice cultivation is mainly focused on the Northern Region of Italy, Piedmont and Lombardy, accounting for 93% of rice production in Italy. Rice cultivation manifests along the Po Valley, extending over 240 000 ha (Arcieri and Ghenassi 2020). The extension of rice paddy fields in NI is visually depicted in the figure (1) below.

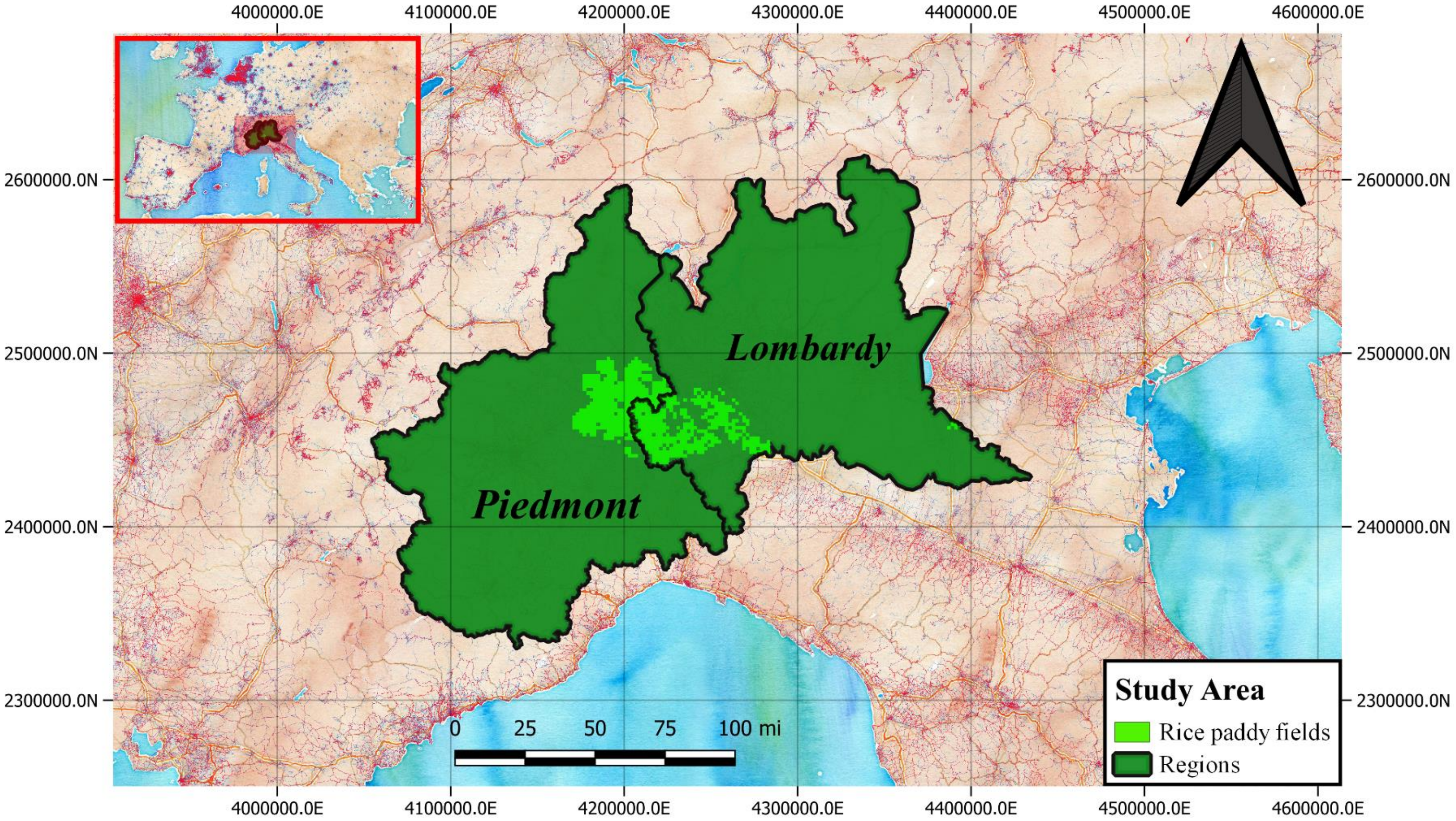


Figure 1. A study area map displaying the location in which this investigation is conducted, produced in QGIS. Source: Original, 2022.

Data Collection

As of 2020 the world faced COVID-19, a deadly pandemic which has seen restrictions at a global scale. To facilitate this study and prevent the spread of the virus, all data collected came from secondary sources. The ancillary climate datasets were produced and distributed by Meteoblue (2021). This Swiss-based company provided high precision simulation data, which arise from stored forecasts, not measurement data. This is often more precise than measurement data from a station more than 10 to 50km away from the desired location, and are 100% complete, which seldom occurs for measurement data. Furthermore, this simulated data is assimilated with measurement data, increasing its accuracy. This data is created with NMM (Nonhydrostatic Meso-Scale Modelling) technology, first developed by NEMS (NOAA Environment Monitoring System) – enabling the inclusion of detailed topographical data, ground and surface cover. Acquiring and manipulating this data was crucial in gaining broader knowledge of climate influences over time on rice production, in Northern Italy.

The annual rice production dataset from 1985-2021 was obtained from the FAO (FAO 2021). The FAO is a specialised agency and part of the United Nations, pursuing to achieve multiple goals by 2030, such as the SDG's, which include 17 different development goals that are aimed at the global, regional and country level. For example, combatting food hunger. The FAO processes, develops and distributes a range of domains which contain a vast quantity of data, such as the data analysed in this study – agriculture. The agriculture domain was chosen and used in this project, as it contains rice production data dating from 1961-2021 – all of which are free-access and available to everyone. This data was manipulated before the rice harvesting period of 2022; hence no data was collected for this period.

Data Manipulation

The Meteoblue dataset was available for download and use in Excel, from 1985-2021. From 2008 onwards, the option for high resolution data was available and chosen to keep the consistency of recent data more accurate. Up to two locations were free of charge, with the desired locations chosen being 'Torazza Piemonte' and 'Romano di Lombardia', which is suitable as the Lombardy and Piedmont region constitute for 93% of Italy's annual rice production (Arcieri and Ghenassi 2020). The variables available and used in this dataset include simulation data for temperature (°C at 2m elevation), sunshine duration (minutes), precipitation amount (mm), evapotranspiration (mm), soil temperature (°C, 0-10 cm down) and soil moisture (mm, 0-10 cm down).

These values originally displayed an hourly timeframe - however the resolution was adjusted for a daily timeframe. This is due to rice production being a yearly value, so these variables were aggregated and adapted to suit the dependent variable that is rice production, keeping this investigation consistent. This daily timeframe displayed values specific to the time-periods in which rice is produced and developed – from the vegetative stage, (to reproductive stage, to ripening stage) all the way to the harvesting period stage, which in Northern Italy, it begins in April and ends approximately in October (Giuliana et al. 2022). Thus, daily values were collected every year from 1985-2021 for the months of April-October.

These daily values presented in Excel, were manipulated with the =AVERAGE function, to produce one annual mean value for temperature, sunshine duration, precipitation amount, evapotranspiration, soil moisture and soil temperature – for both desired locations. Upon having mean values for the two separate locations, this data was manipulated once again to produce an aggregated mean value for both locations in one single year. This was repeated every year from 1985-2021, with the acquired mean values for each year being constructed into an Excel table with annual rice production, to permit the analysis of this data. In this investigation, for the purpose of simplicity, mean daily values are communicated as just the variable. For example, defining the mean daily temperature as simply ‘temperature’.

FAO data required little manipulation with annual data readily accessible and available for use, with all rice production values used (1985-2021) presented in an Excel table.

Data Analysis and Visualisation

A timeseries was created for each climate variable against rice production (y-axis), to track the change of these variables over time (x-axis). This permits visual depictions of how rice production changed over the years 1985-2021, as well as each climate variable. Furthermore, to enhance this graphical relationship, linear regression and correlation analysis was conducted in Excel, to determine whether each variable and rice showed monotonic or non-monotonic correlations. Linear regression analysis produces the R^2 (coefficient of determination) value, which means the variation of the dependent variable (rice production) that can be explained by the variation of the independent (climate) variable. For example, a R^2 value of 0.1, would suggest a 10% variation in rice production is caused by the dependent (climate) variable.

The software PAST was utilised to transform the dataset into parameters of statistical significance, to truly develop and comprehend aim 1 and its objectives in this investigation. Two normality tests were used to strengthen the validity of the normal distribution: Shapiro-Wilk and Anderson-Darling. This suggests whether a parametric or non-parametric statistical test should be used. Although most variables showed normal distribution, sunshine duration and soil moisture did not display normal distribution (As seen in table 1), and considering multiple sets of data are being analysed, a non-parametric test was chosen to keep these comparisons consistent. Accordingly, the non-parametric test most suitable for quantifying the correlation between each climate variable and rice production over time was Spearman's rank correlation coefficient (r_s).

Spearman's rank analysis measures the strength and direction of the association between variables, displaying values from -1 to +1, where +1 measures a perfect positive association, and -1 a perfect negative association. To create this value, rice production data was ranked against each climate variable, utilising the =RANK function. Then, =CORREL function was used to show the correlation between both ranked datasets. As the number of pairs investigated in this project are n=37, an upper critical value table was used to compare r_s values to significance levels (University of York, 2005). If r_s values are above the alpha value at the significance level displayed, then the r_s value is correct to the degree of confidence stated. For example, at n=37, r_s >0.497 is correct with a 99.9% confidence level.

This confidence in correlation is further supported by calculating p (probability) values, determining the likelihood these associations are true. There were 3 requirements to produce p values. Firstly, n (number of pairs), was calculated using the =COUNT function. Secondly, the t statistic was measured, using the function =(ABS(r_s)*SQRT(n-2))/SQRT(1-ABS(r_s)^2)). Thirdly, DF (degrees of freedom) was measured using the equation =n-2. By calculating these 3 requirements, p values were created utilising the equation =TDIST(T statistic, DF, 2). The production of p values in this investigation strengthens the significance of each association between rice and the climate variable.

RESULTS

This section will present a visual depiction of the findings obtained from the data collection – a timeseries, graphically displaying comparisons between rice production and the climate variable for every data point each year. As well as displaying linear regression and correlation analysis for each climate variable and rice, respectively. It will finally include the non-parametric test results for Spearman's rank correlation and p (probability) values. For the purpose of conciseness, 'mean daily' nomenclature will be simplified to the variable investigated, as stated in the methodology.

Temperature and Rice Production

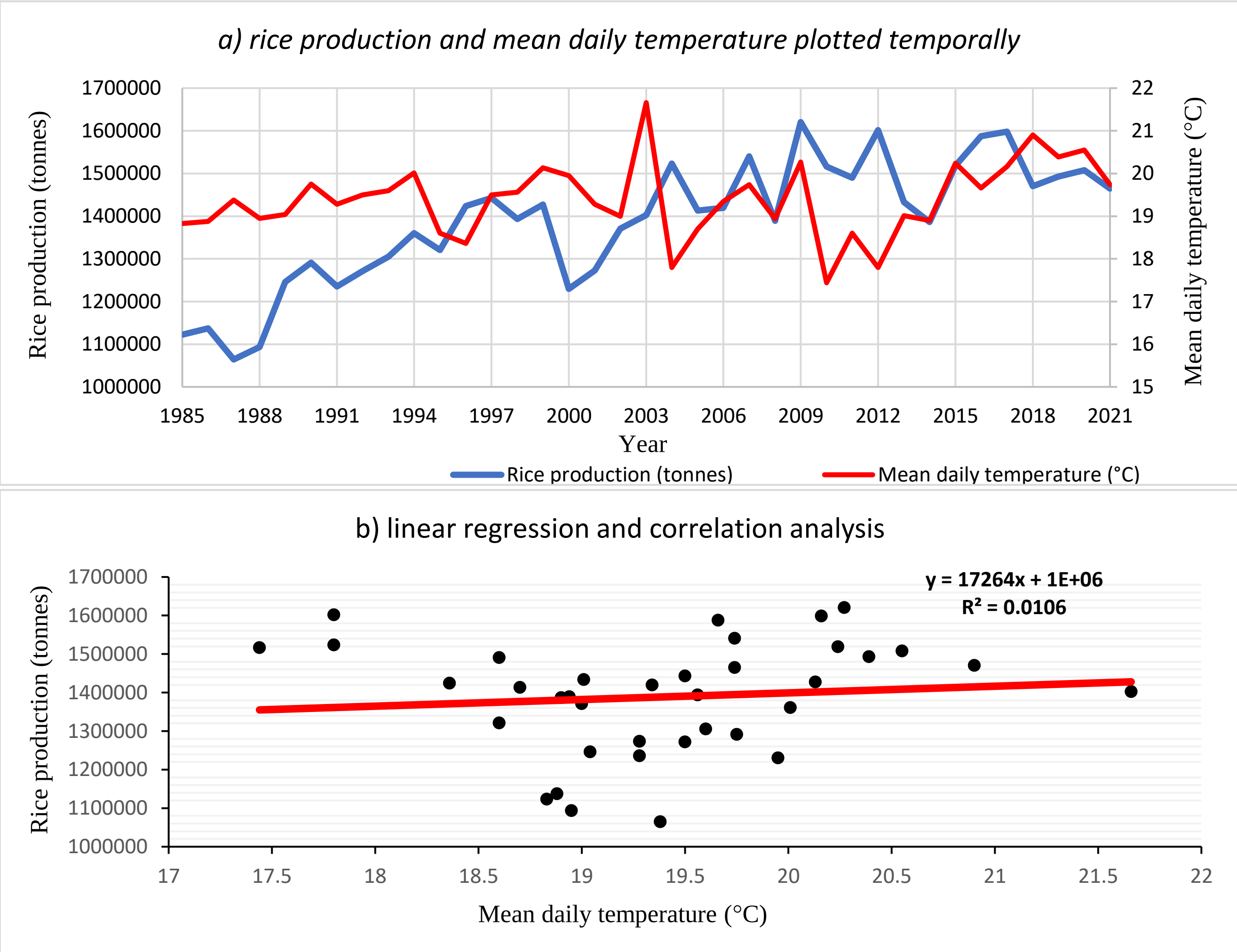


Figure 2. *Two original graphs created in excel, a) a timeseries graph displaying the temporal relationship of rice production (tonnes) and daily mean temperature (°C) in Northern Italy, b) a linear regression and correlation analysis model, quantifying this relationship.*

In figure 2, part a visually depicts both variables displaying similarities in their fluctuation over time. Earlier in the period, temperature seems to fluctuate inadvertently to rice production - although they show similar fluctuations, rice production generally does not increase following daily mean temperature increases. However, from 2003-2021 daily mean temperature increases, tend to be followed by rice production increases. The linear regression and correlation analysis (part b) display a slight increase in the trendline, showing some relationship between the variables over time, even if insignificant. The R^2 value highlights that there is a small-scale statistical association between the variation of the two variables. The R^2 value of 0.0106 signifies that 99% of variation in rice production values is derived from other factors.

Precipitation and Rice Production

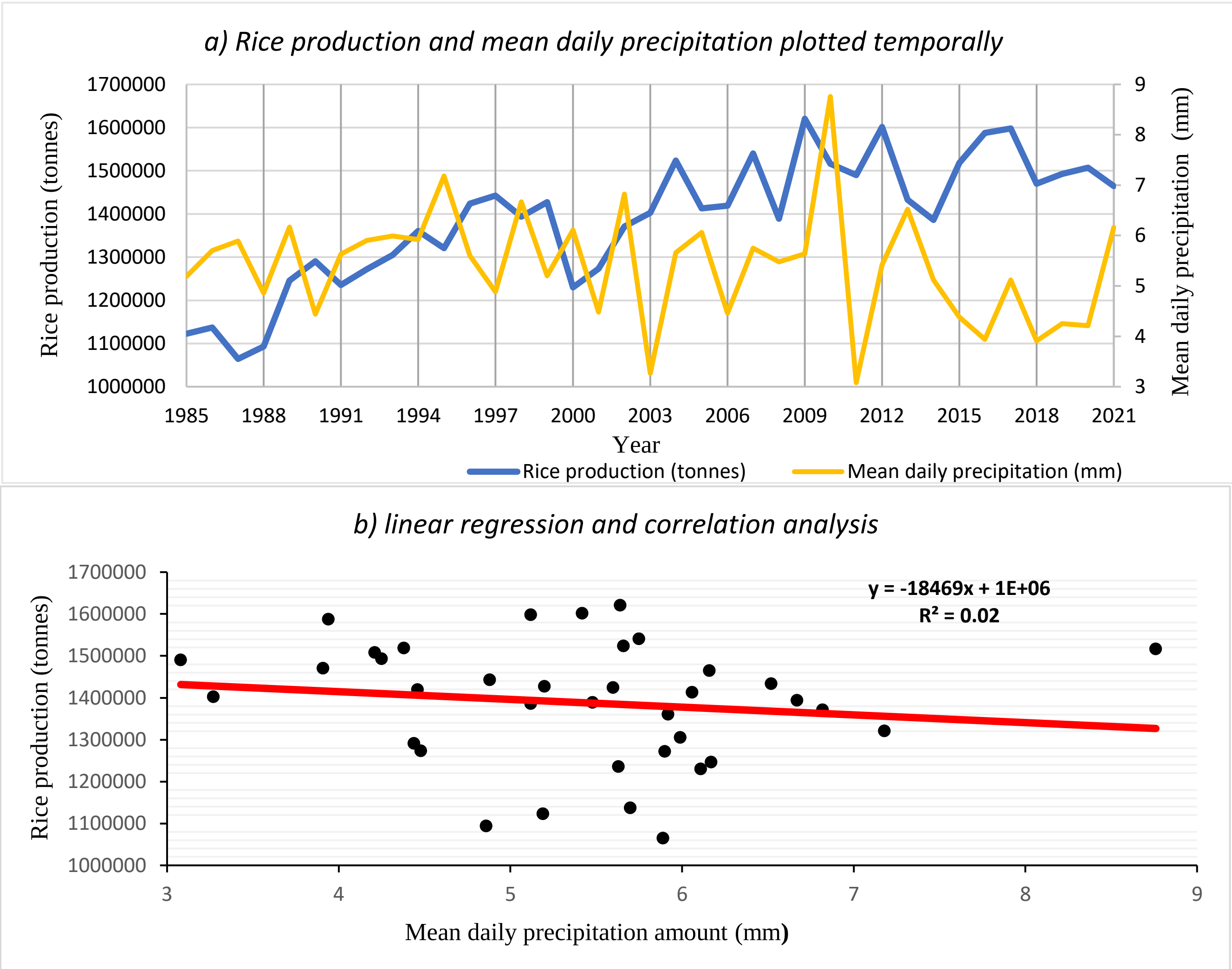
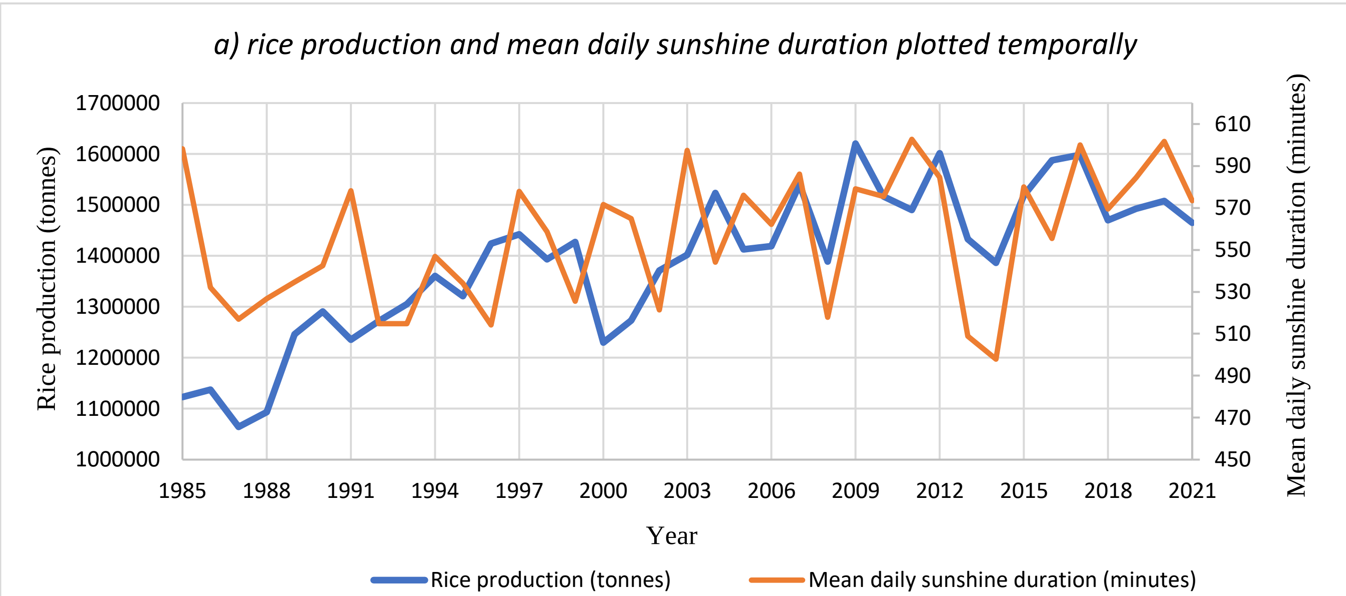


Figure 3. *Two original graphs created in excel. Part a) is a timeseries graph displaying the temporal relationship between rice production (tonnes) and daily mean daily precipitation amount (mm) in Northern Italy. Whereas graph b) is a linear regression and correlation analysis model, quantifying this relationship.*

As shown above, figure 3 presents a trend between the data points each year. In part a, rice production and daily mean precipitation show some similarities in peak, albeit it is not enough to determine whether there is a significant relationship. The declines in precipitation are shown to have some effect on rice production after a few years, for example, the decline in precipitation from 8.76mm in 2010 to 3mm in 2011 is followed by an increase in rice production through the years 2011-2012. This is supported by part b, whereby the linear regression model displays a slight negative correlation between the two variables. The coefficient of determination (R^2) gives a value of 0.02, which means that 98% of variation in rice production is determined by other factors, signifying 2% of this variation being due to alterations in precipitation amount.

Sunshine Duration and Rice Production



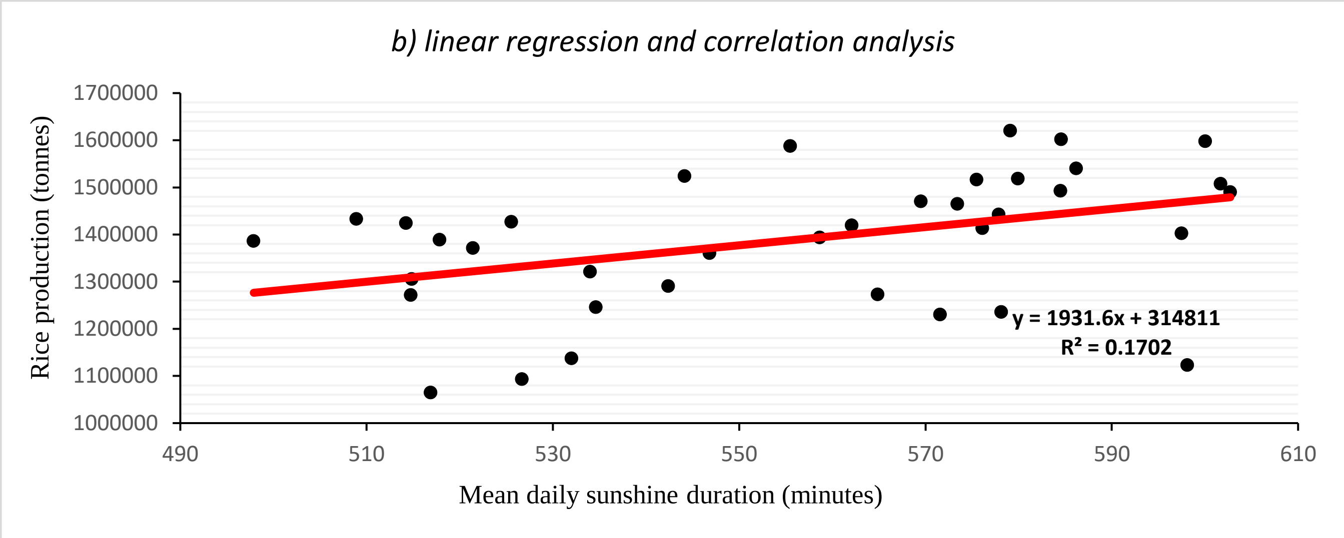


Figure 4. *Two original graphs created in Excel. Part a) is a timeseries graph displaying the temporal relationship between rice production (tonnes) and mean daily sunshine duration (minutes) in Northern Italy. Part b) is a linear regression and correlation analysis model, quantifying this relationship.*

As shown in the figure (4) above, changes in sunshine duration are generally accompanied by similar changes in annual rice production. This is especially evident in the 2012-2014, whereby a sharp decline in the duration of daily sunshine is followed by a sharp decline in the production of rice. The association between these variables is visually depicted with more detail in part b of figure 4, where there is a clear positive correlation between rice production and sunshine duration over time. The R^2 value of 0.1702 accentuates only 83% of variation in rice production being a causal effect of other variables, thus the linear regression analysis implies sunshine duration had a 17% influence on the variation of rice production during the period studied.

Evapotranspiration and Rice Production

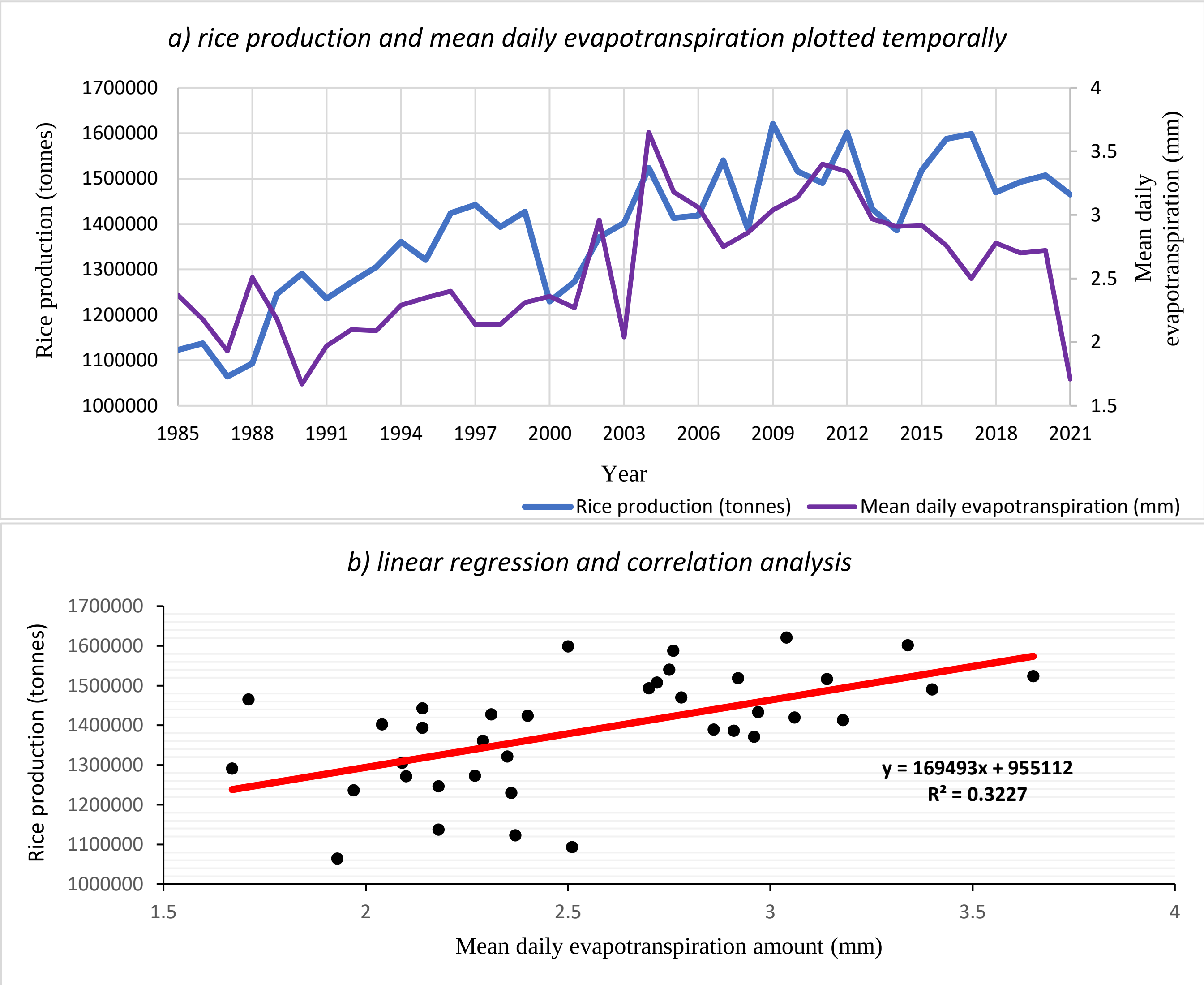


Figure 5. *Two original graphs created in Excel. Part a) is a timeseries graph displaying the temporal relationship between rice production (tonnes) and mean daily evapotranspiration (mm) in Northern Italy. Part b) is a linear regression and correlation analysis model, quantifying this relationship.*

From the figure (4) above, evapotranspiration and rice production display a monotonic correlation to each other. From 1985-2021, only three visible periods are clearly not displaying a graphical correlation – 2007-2008, 2009-2010 and 2014-2018. Figure 4 part b, supports this strong monotonic correlation by linear regression and correlation. Based on these data points, 32% of variation in rice production in Northern Italy has been attributed to evapotranspiration, as opposed to approximately 68% of variation between the data points being linked to other factors (as shown by R^2=0.3227), proving a significant correlation between evapotranspiration and rice production over time.

Soil Temperature and Rice Production

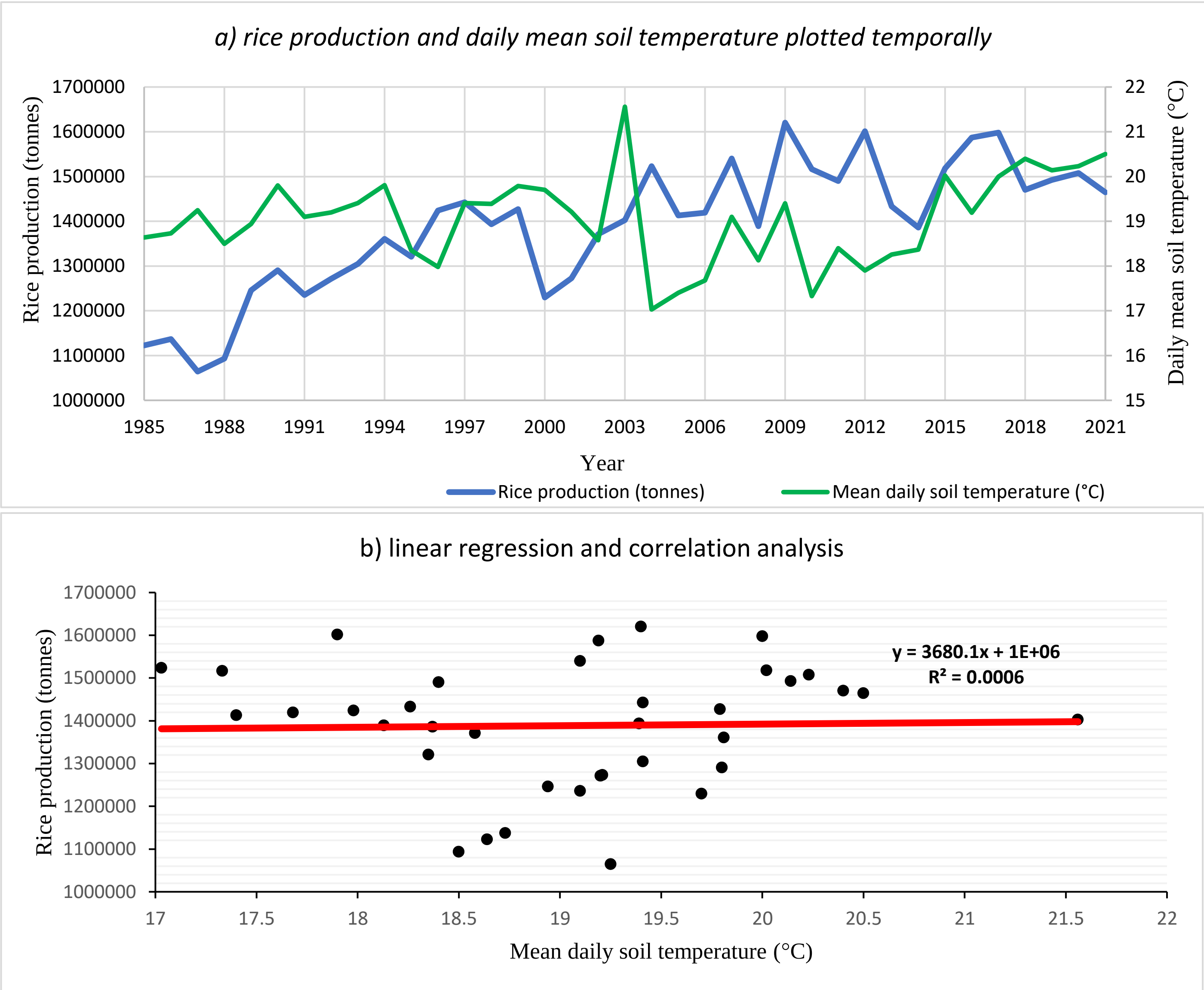


***Figure 6**. Two original graphs created in Excel. Part a) is a timeseries graph displaying the temporal relationship between rice production (tonnes) and mean daily soil temperature (°C) in Northern Italy. Part b) is a linear regression and correlation analysis model, quantifying this relationship.*

From figure 6, part a) at the beginning of the period investigated (1985-1994) increases in both the dependent (rice production) and independent (soil temperature) variable show increases proportionate to each other (1985-1995), although peaks/troughs in rice production appear before changes in soil temperature, on occasion. This relation fluctuates through the periods and do not show enough consistency to prove a strong relationship. For example, rice production inclines are followed by soil temperature inclines in some years (such as, 1995-1997), whereas most of the period shows sporadic patterns. The linear correlation graph (part b) reflects this as the sporadic pattern of data points display a near no correlation between the variables. Furthermore, this is accentuated by the coefficient of determination (R^2=0.0006) signifying this relationship to have been predominantly influenced by other variables, with a variation of rice over the time scale by soil temperature being below 0.001%.

Soil Moisture and Rice Production

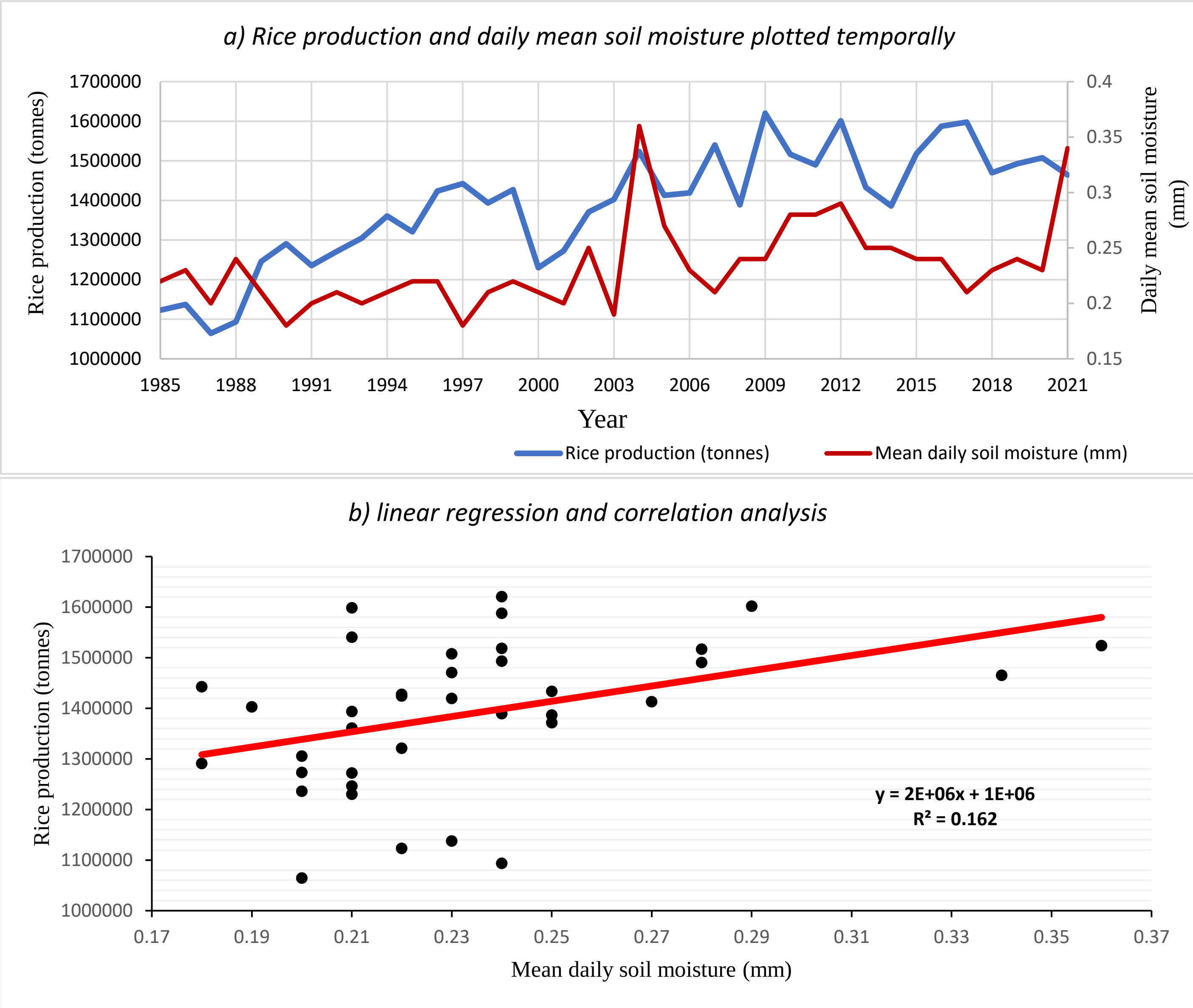


Figure 7. *Two original graphs created in Excel. Part a) is a timeseries graph displaying the temporal relationship between rice production (tonnes) and mean daily soil moisture (mm) in Northern Italy. Part b) is a linear regression and correlation analysis model, quantifying this relationship.*

Figure 7 part a, highlights the graphical relationship between both the independent (soil moisture) and the dependent (rice production) variable. Both displayed a direct correlation between peaks and troughs throughout the years. With the highest peak of soil moisture occurring in 2004, followed by its largest decline from 2004-2007 – although this peak was accompanied by an increase in rice production, the large decline in soil moisture did not have a major influence in the production of rice. This can be observed from 2006-2007, whereby soil moisture continued decreasing in contrast to rice production. A monotonic correlation is demonstrated in part b), with the linear regression and correlation analysis model. The R^2 value of 0.162 numerically quantifies this relationship by suggesting 16.2% of variations in rice production being attributed to the variance of soil moisture content.

Normality Tests

Table 1. Normality tests Shapiro-Wilk and Anderson-Darling to determine whether the datasets demonstrate normal distribution, for an adequate statistical test to be chosen for detailed analysis. As shown, mean daily sunshine duration and mean daily soil moisture were the only climate variables that did not demonstrate normal distribution.

Climate variables analysed	Shapiro-Wilk Test	Anderson-Darling Test	Normal distribution	
			Yes	No
Rice production (tonnes)	0.197	0.283	✓	
Mean daily temperature (°C)	0.907	0.819	✓	
Mean daily precipitation amount (mm)	0.382	0.403	✓	
Mean daily sunshine duration (minutes)	0.037	0.033		✕
Mean daily evapotranspiration amount (mm)	0.611	0.430	✓	
Mean daily soil temperature (°C)	0.955	0.923	✓	
Mean daily soil moisture (mm)	0.004	0.008		✕

Spearman's Rank Correlation Coefficient

As demonstrated in table 2, three climatic variables exhibit an insignificant correlation to rice production over the time measured (temperature, precipitation, soil temperature). Although precipitation has a negative correlation value of -0.25440, when measured against alpha critical values, it did not show significant statistical correlation of its influence on rice production over the years. On the other hand, sunshine duration, evapotranspiration and soil moisture all showed a strong statistical significance. For a sample size of 37, r_s values were assessed against alpha values of confidence, in the upper critical value table for Spearman's rank correlation coefficient. Sunshine duration (r_s = 0.46847>0.421, p<0.01) and soil moisture (r_s = 0.46977>0.421, p<0.01) r_s demonstrated a 99.5% confidence level that there is in fact a correlation between these variables and rice production. In addition, evapotranspiration produced a r_s value of 0.58328>0.497, which demonstrated a 99.9% confidence level that rice production and evapotranspiration are highly interconnected in Northern Italy. This is further supported by its p value p<0.001, accentuating the probability of this significance is extremely high (99.9%).

Table 2. Summarises the Spearman's rank correlation coefficient values and p values of the different climate variables analysed to statistically determine whether a significant correlation is present. (*p < .05; **p < .01; ***p < .001).

Climate variables analysed	Significant correlation between rice production and the climate variable from 1985-2021		Coefficient (r_s)	P value
	Yes	No		
Mean daily temperature (°C)		✕	0.19257	0.25535
Mean daily precipitation amount (mm)		✕	-0.25440	0.12864
Mean daily sunshine duration (minutes)	✓		0.46847	0.00345**
Mean daily evapotranspiration amount (mm)	✓		0.58328	0.00015***
Mean daily soil temperature (°C)		✕	0.05074	0.76552

Mean daily soil moisture (mm)	✓		0.46977	0.00335**

DISCUSSION

From our results, temperature, soil temperature and precipitation unexpectedly had relatively low influences on rice production over time, especially soil temperature showing near no significant correlations with rice production. Conversely, sunshine duration, evapotranspiration and soil moisture demonstrated significant monotonic correlations to rice production over the temporal scale studied. This section will focus on interpreting these results to gauge the aim 1. Utilising relevant scientific literature, it will decipher the relationship of the analysed climate variables and rice production in Northern Italy, as well as whether other factors come into play in the variation of rice production each year. Furthermore, based on the interpretations, it will try to comprehend the future of rice production under a changing climate, unravelling aim 2. Finally, it will look at the limitations encountered in this project.

Climate Variables Analysed and Rice Production

Although the findings showed temperature to have some monotonic relation to rice production, it was not as much as expected. In addition, from the statistical analyses performed, there was no significance in the variation of rice production being caused by temperature. Research suggests temperature can affect rice production both indirectly and directly. For example, through alterations in soil condition and outbreak of diseases (Nishyiama 1976), which may have played a role in the similar declines by both temperature and rice production observed. This declining trait may also be due to colder temperatures leading to thermal retardation (delay in panicle initiation), disrupting the development of spikelets, which minimises the growth of rice, thereafter, leading to a reduction in annual rice production (Jacobs 1999). Much like temperature, most scientific literature suggests soil temperature to concurrently influence soil conditions in which rice is grown. Lower soil temperatures and air temperature differences may have adverse effects on seedling growth, through different growth rates of both the coleoptile and radicle (Stanley 1975) – leading to deformed rice to be discarded, thus disregarded in the rice production census. To a large scale, this relation did not conform with the findings of this study. The reliance of rice production in NI to irrigation practices is the reason fluctuations in temperature and soil temperature had little to no influence on rice production (Blengini and Busto 2009). Furthermore, these studies explicating the influence of soil temperature on rice paddy fields are limited on a spatial scale, specifically to regions with tropical climates. Albeit more research needs to be done on soil temperature influence and rice production; to the author's knowledge no previous investigations have been conducted signifying the relationship between these variables in NI. On the other hand, the positive correlations between temperature and rice production are generally believed to be as a result of increased photosynthetic rates – however this does not play a crucial role in the growth of rice as oxygenation rates reduce the opportunity of temperature influences on rice, by a reduction in the rate of photosynthesis (Ehleringer and Monson 1993). Additionally, whilst the expectation that increasing temperatures should also influence photosynthetic rates and thus rice production, a study by Chen et al. (2016) found that temperature impacts on the growth of Japonica varieties of rice is not influential; considering Japonica varieties account for approximately 84% of all rice varieties produced in Italy (Bettini 2017), it makes sense why there was no statistical significance between temperature and rice production in the findings of this study.

Although visually, a non-monotonic correlation can be observed between precipitation and rice production, significance was not present between both variables. The main reason for the non-monotonic correlation is extensive rainfall and cloud cover limit growth of rice crops, as photosynthetically active radiation is reduced (Jena and Hardy 2012), leading to an inverse relationship between rice and precipitation. In other words, this proves a direct correlation between sunshine duration and rice production, as displayed by the strong statistical significance in this study. Another reason is due to extreme weather events in NI, leading to flooding of crucial rivers for rice production, such as the Po River leading to inundation of rice paddy fields, causing the environmental degradation of rice productivity (Vezzoli et al. 2015). Overall, temperature, soil temperature and precipitation showed a near, statistically insignificant influence on the production of rice in Northern Italy. This is predominantly related to rice production needing to meet a demand as a main source of food for the majority of Europe (Kraehmer et al. 2017). The inconsistent precipitation is managed through maintained flooding practices to irrigate rice paddy fields, therefore still producing large quantities of rice per year (Blengini and Busto 2009). There is a possibility that extensive and prolonged precipitation 'drowns' already inundated rice crops, which would further explain the non-monotonic correlation between precipitation and rice production in NI. In addition, controlled flooding methods by farmers, can also be a reason why extreme climatic events in NI, such as droughts, can have a smaller effect on the productivity of rice; opposed to areas where rice productivity is rainfed, such as South Asia (Li et al. 2015). Contrastingly, although the results of this finding do not suggest strong influence of precipitation over rice, precipitation plays a critical role in maintaining water table and river discharge levels in which irrigation water is obtained from (Nikolopolous et al. 2011), indirectly influencing rice production.

Regardless of rice paddy fields being predominantly inundated by irrigative methods, evapotranspiration and rice yield are highly interconnected variables, resulting in statistically significant values as observed in table 2 (Spearman's rank correlation coefficient and p values). Moreover, this co-dependency arises from plant roots intaking water from the soil to produce rice, by water flux, which occur in tandem, enhancing both transpiration and evaporation from the vegetative surface (Bouman 2009). Consequently, the monotonic correlation between these variables was likely, as variations in evapotranspiration impact rice yield, and thus annual rice production. As aforementioned, most rice production comes from irrigated practices in NI, hence, large troughs in evapotranspiration did not lead to prominent declines in rice production (as shown in figure 5) despite the interrelation between these variables. A study by Haefele et al. (2009) recognised when the rate of evaporation is higher than the rate of transpiration, transpiration efficiency is substantial. Therefore, the rice plant uptakes more water from the soil, through their roots; enabling enhanced photosynthesis and thus growth. There is a likelihood this transpiration efficiency is present in this study through the period 1985-2021.

Unlike rainfed rice systems such as the in the Philippines, where atmospheric phenomena, such as El Niño Southern Oscillation (ENSO), greatly impact soil moisture content (Stuecker et al. 2018), in NI the variations in soil moisture are primarily related to irrigated paddy rice. Similarly, evapotranspiration and soil moisture content increases as the inundation of rice fields is prevalent. The permeability of rice paddy soils is enhanced through vertical percolation due to agricultural flooding practices, by creating compact layers beneath the ploughing zone, increasing soil moisture retention (Mayer et al. 2019). By contrast, soil moisture data collated in this investigation was at 0-10cm depths, but rice roots penetrate deeper than 20cm, so variations in soil moisture and rice production can be ambiguous, as groundwater levels below 10cm play a major influence in the productivity of rice (Kruger et al. 2005).

Sunshine duration is vital for the development of rice crops. It plays a significant role as light intensity allows for photosynthetic rates in rice leaves to thrive, due to longer photoperiods (Hundal et al. 2005). Chen et al. (2016), concluded that sunshine duration has little impact on the vegetative stage of rice production, with strong influence on the ripening stage, which can effectively lead to greater development during harvesting periods (Yoshida 1981). The significant correlation between sunshine duration and rice can be attributed to these interpretations, whereas the reasoning behind the strength of the correlation can be attributed to other variables, that play a factor in the production of rice in NI.

Other Variables and Rice Production

The agroclimate is a complex system filled with microclimate interactions and physiological processes between a multitude of variables and rice. These include variables not examined in this investigation, that potentially play more of a factor in alterations of annual rice production. For example, the interaction between soil-borne microorganisms and rice plants can prove beneficial in yielding more growth during harvest. Research by Wu et al. (2018) found that the rhizospheric microbial community influence rice production more than physiochemical properties (such as, nutrients) – through the enhancement of soil fertility and promotion to rice plant health. To support this, Xiong et al. (2021) states that this microbiological contribution to plant health occurs as a direct effect of soil enzymes stimulating root-soil interactions. This is dictated by the utilisation of nitrogen fertilizers, which, for rice production in NI, accounts for 130kg per hectare of cultivated land (Gazzani 2021). In contrast, the excessive and iterative use of nitrogen fertilizers can be one of the major reasons soil quality and soil enzyme activity deteriorates within the soils over time – by influencing the nutrient cycle in agricultural land, such as in paddy fields (Chaudhry et al. 2009). Consequently, this can play a larger role in the declines and inclines of rice production, than some climate variables analysed in this study, such as temperature, soil temperature and precipitation.

Another variable which may influence the rice agro-ecosystem in NI is potential pathogens that damage rice, locally and regionally (Gianessi and Williams 2011). Rice blast disease is derived from the fungus Pyricularia grisea and is prominent in rice-irrigated regions with a temperate climate. Droughts, soil stress and extensive use of fertilizers can act as a predisposition of rice to this fungus attack (Piotti et al. 2005). Although presently, it is estimated that 75% of rice in Italy is treated with fungicides, to prevent the proliferation of this fungal disease (Titone et al. 2015).

To fully comprehend the extent in which the climate variables analysed influence rice production in NI, it is important to go beyond its microclimate, and investigate the source responsible for the water used in the production of rice. A study by Montanari (2012) indicates the Po Valley as the main geographical feature in NI responsible for changes in annual rice production, through influencing the total accumulated discharge from rivers that is available for irrigation. Furthermore, the researcher explicates the fluvial system's vulnerability to changes in interannual variability, directly impacting how climate variables, such as temperature, sunshine duration and precipitation influence the discharge of rivers running through paddy fields. For example, periods where sunshine duration is high, cloud cover is likely low, which leads to an interrelated inverse effect, whereby the amount of precipitation flux into river systems can be low (Jena and Hardy 2012). The argument is further supported by Zampieri et al. (2017), where it is stated net river discharge has decreased drastically in the past 40 years during rice seasons. In the long term, this positive feedback loop significantly influences the availability of water for irrigation.

In addition, irrigative methods utilised by agronomists rely heavily on aquifers, with 47% of groundwater extraction being used for irrigation in NI (Ribeiro 2007). This process becomes more complex as saltwater intrusion into the Po basin has become more prevalent over the years because of groundwater overexploitation. As temperatures increase with climate change, salt intrusion is likely to worsen as saltwater replaces freshwater due to more evaporation – which over time will flow more readily into irrigation stations that extract groundwater (Sappa and Vitali 2001). It is plausible that if this process exacerbates, temperature will have an inverse relationship with rice production.

Evidently, hydrological systems hold great influence over the availability of water by rivers. Marchina et al. (2015) studied the isotopic compositions of the water within the Po River and determined the Alpine region to have great influence in runoff; mainly the Dora Baltea, Ticino, Tanaro and Adda rivers, all of which are characterised by their contribution to irrigate paddy fields in NI (Petrini et al. 2014). This contribution suggests the Alps plays a critical role in maintaining freshwater levels for use in rice flooding mechanisms. This coincides with a study by Blöschl et al. (2017) who explored the frequency, magnitude, and intensity of river floods in Europe (1960-2010). Within this study, summer floods from the Alps are displayed to flow into the Po River, near Turin. It can de deduced that total discharge flowing in the Po River increases, which could also explain the peaks of evapotranspiration and soil moisture content along rice paddy fields. Although the study does not cover how fluvial systems affect the Po River and rice production, this effect is a probable explanation as to why these variables displayed strong positive correlations to rice production.

Future of Rice Production in Northern Italy

Based on thorough investigations of the available literature, it has been deduced that the future of rice production in NI will be highly dependent on alterations in water levels of the Po River, consequently influencing extraction of groundwater levels utilised for irrigation. Zhongming et al. (2009) infers deglaciation of the Alps will play a gigantic role in shaping Po River's discharge level, and therefore water availability.

Alpine rivers flowing into the Po are sensitive to climate change because of their dependency on snow and glacial meltwater in spring and summer. A decline of either can cause a shift in precipitation patterns, leading to spatial and temporal changes in water flow towards the Po. There is a strong possibility that this shift in precipitation pattern causes a recurrence of extreme flooding events that damage agricultural rice paddy fields. Furthermore, the most important variable in the Alps that controls river discharge levels into the Po is snowfall and cover, both of which can be considerably affected by changes in temperature and precipitation (Beniston et al. 2011); as a result, patterns in snow quantity and duration will change. To elaborate, future trends in heatwaves will become more prominent with increasing GHG emissions, occurring at a higher frequency, intensity, and magnitude within the Alps (Zampieri et al. 2016), which is likely to shift precipitation, and therefore river discharge levels in the Po.

There is an interconnection between increasing temperatures, evapotranspiration, and soil moisture. Regionally, heatwave patterns in rice paddy fields will also lead to increased evapotranspiration and therefore a decrease in soil moisture content. This soil moisture deficit can further amplify heatwaves, creating a positive feedback loop (Zampieri et al. 2016; Seneviratne et al. 2010; van den Hurk et al. 2011). Assuming soil moisture will be present due to irrigation, increasing evapotranspiration from heatwaves in the future could turn out beneficial to rice production, considering the positive correlation between evapotranspiration and rice production in the findings of this study.

Contrastingly, an increase in local sunshine duration and temperature, in addition to decreased precipitation amount due to global warming, could increase the levels of droughts along rice crops and rivers in NI (Carrera et al. 2013). This would cause a general subsidence of the water table, meaning groundwater extraction for irrigation becomes challenging. Soil moisture content, which displayed a strong correlation to rice production in this study, would decrease directly because of this subsidence. It is important to note the prevalence of extreme events can also be attributed to air quality. Bo et al. (2020), proposed climate change robustly influences air particles which in turn lead to more wildfire events in Northern Italy. There is a likelihood that future spatial shifts in these wildfire events damage not only the surface of rice crops, but also infiltrate and damage soils, posing prolonged influence on evapotranspiration and soil moisture content. Bregaglio et al. (2017) utilised a GCM (global circulation model) to prove that with no adaptation to future climate change, rice production would decrease by 8% by 2030 and 12% by 2070, accentuating the importance of future adaptation of rice varieties to the climate.

Limitations

While the gathered information was beneficial, there were some limitations which may have hindered the reliability of results in this study. The paucity of scientific literature on the relevant climate variables and rice production, that is specific to Northern Italy, makes the understanding of these interrelations questionable. Italian rice paddy fields differ from well-researched countries such as Bangladesh, India and China, in terms of microclimatic behaviour between the variables and rice. Nevertheless, assumptions are made utilising previous literature from different case studies in relation to this investigation.

In addition, iterative analysis using projection models could be a better way of gauging future influences these variables may have on rice systems in Northern Italy. This could be achieved through simulating climate-system interactions in the Alps, with fluxes in its fluvial systems that have potential to reach rivers, such as the Po, that affect rice production.

As aforementioned, to the author’s knowledge, little to no research has been produced on soil temperature impacts on rice production in Northern Italy, more research is required to reconcile the interconnection between these variables.

On the contrary, as produced through the workings of Geethalakshmi et al. (2009), this investigation did not consider the effect different rice cultivation practices have on water usage and allocation. A cross-disciplinary approach focusing on different farming practices would be a beneficial method, incorporating confronting questions that differ from the traditional approach in this investigation. Especially investigating sustainable flooding practices, that are less GHG emitting, as they will be utilised more in the future. This could prove especially important when looking at the future of rice growth under a changing climate, as availability of water may become scarcer due to population pressure (Citrini et al. 2020), resulting in less water usage being allocated to rice production.

Lastly, rather than limiting this investigation to annual rice production data, an approach focusing on different agricultural scales, such as rice yield, pave the way for the exploration of seasonal variability and its influence on rice, targeting changes in the patterns of rice during different phenological stages, such as vegetative, reproductive, ripening and harvesting stages (Fageria 2007), specialising in detailed understanding of how variables influence rice, on a shorter scale.

CONCLUSION

This project has highlighted how interchangeable and highly complex the agrometeorological system is, vastly influenced by spatiotemporal changes, proving the true understanding of aim 1 to be ambiguous. Furthermore, the hypothesis "*All climate variables analysed in this project will show a significant influence on rice production in Northern Italy*" can be disregarded, as only sunshine duration, evapotranspiration and soil moisture displayed a significant influence on the production of rice throughout the years 1985-2021.

Irrigation of rice paddy fields by continuous flooding practices is the principal method of increasing the productivity of rice by inundation. Based on statistical significance, in the past, fluctuations in temperature ($r_s = 0.19257$, $p>.05$), precipitation ($r_s =-0.25440$, $p>.05$) and especially soil temperature ($r_s = 0.05074$, $p>.05$) had little to no impact on the production of rice. This is because temperature has little influence on Japonica varieties of rice. To expand, temperature still has potential to enhance the photosynthetic ability of rice, but this potential is decreased by oxygenation rates, reducing the influence of temperature on rice. Enhanced precipitation is accompanied by cloud cover, inhibiting the active radiation absorbed by rice plants through sunshine. Though it was found, precipitation has potential to indirectly improve rice production, through maintaining the water table and Po river's discharge level.

On the other hand, sunshine duration (r_s = 0.46847, p<.01), evapotranspiration (r_s = 0.58328, p<.001) and soil moisture (r_s = 0.46977, p<.01) were statistically significant to rice production through the period (1985-2021). Longer photoperiods increase the light intensity on rice, enhancing its ability to photosynthesise. Evapotranspiration and soil moisture are strongly interconnected due to constant inundation of paddy fields coupled with atmosphere-land interactions, concluding that as long as rice is produced in Northern Italy, both variables will ever-presently influence the production of rice.

Beyond the variables analysed, the presence of soil-borne organisms, such as a rhizospheric microbial community, may increase soil fertility and enhance growth, as opposed to, diseases, such as Pyricularia grisea which may damage and degrade rice yields. On top of these findings, in-depth research of available scientific research revealed changes in the Po Valley exhibiting significant influence on the future of rice production. With two causative drivers of change being saltwater intrusion through the Po River, and the climate interactions within the Alpine region, affecting fluvial systems that contribute to irrigation of rice crops in Northern Italy. Evidently, these factors have potential to exacerbate with future climate change.

This project also insinuated future shifts may change the correlation between rice and these variables. Increased saltwater intrusion and droughts, from heatwaves, may cause temperature to influence rice production inversely, in the future. Precipitation and temperature shifts in the Alps from deglaciation have a strong likelihood to intensify the reoccurrence of natural hazards directly and indirectly, such as river floods. From this project, although temperature and precipitation did not display statistical significance with rice production, it is evident these two variables will play the principal role on the future of rice. In addition, with sufficient available water for irrigation, evapotranspiration and soil moisture will also display prominent influence on the production of rice. Sunshine duration will most likely continue positively influencing the production of rice, although intermittent climate change is unpredictable, leaving ambiguity of its future effect. Lastly, the extent soil temperature will influence rice is also ambiguous, as the predictability of change and paucity of literature give no indication of its future.

Subsequently, the aims of this study have been satisfied, highlighting the value in understanding how future climate change can inadvertently impact rice production in Northern Italy, but also signifying critical areas that offer pathways for future research. This encompasses research towards a more sustainable agronomic sector, focusing on the scale and timing of natural hazards, such as droughts and flooding, the prediction of saltwater intrusion, and the direct influences deglaciation in the Alps have on the flow of river discharge into the Po Valley.

REFERENCE LIST

Anderson, J.E. and McNaughton, S.J. 1973. Effects of low soil temperature on transpiration, photosynthesis, leaf relative water content, and growth among elevationally diverse plant populations. Ecology, 54(6), pp.1220-1233. doi: 10.2307/1934185.

Arai-Sanoh, Y., Ishimaru, T., Ohsumi, A. and Kondo, M. 2010. Effects of soil temperature on growth and root function in rice. Plant Production Science, 13(3), pp.235-242.

Arcieri, M. and Ghinassi, G. 2020. Rice cultivation in Italy under the threat of climatic change: Trends, technologies and research gaps. Irrigation and Drainage, 69(4), pp.517-530. doi: 10.1002/ird.2472.

Baker, J.T., Allen Jr, L.H. and Boote, K.J. 1992. Temperature effects on rice at elevated CO2 concentration. Journal of Experimental Botany, 43(7), pp.959-964. doi: 10.1093/jxb/43.7.959.

Beniston, M., Stoffel, M. and Hill, M. 2011. Impacts of climatic change on water and natural hazards in the Alps: can current water governance cope with future challenges? Examples from the European “ACQWA” project. Environmental Science & Policy, 14(7), pp.734-743. doi: 10.1016/j.envsci.2010.12.009.

Bettini, O. 2023. Italy Rice Overview 2017, USDA Foreign Agricultural Service. Available at: https://apps.fas.usda.gov/ (Accessed: January 9, 2023).

Blengini, G.A. and Busto, M. 2009. The life cycle of rice: LCA of alternative agri-food chain management systems in Vercelli (Italy). Journal of environmental management, 90(3), pp.1512-1522. doi: 10.1016/j.jenvman.2008.10.006.

Blöschl, G., Hall, J., Parajka, J., Perdigão, R.A., Merz, B., Arheimer, B., Aronica, G.T., Bilibashi, A., Bonacci, O., Borga, M. and Čanjevac, I. 2017. Changing climate shifts timing of European floods. Science, 357(6351), pp.588-590. doi: 10.1126/science.aan2506.

Bo, M., Mercalli, L., Pognant, F., Berro, D.C. and Clerico, M. 2020. Urban air pollution, climate change and wildfires: The case study of an extended forest fire episode in northern Italy favoured by drought and warm weather conditions. Energy Reports, 6, pp.781-786. doi: 10.1016/j.egyr.2019.11.002.

Bocchiola, D., Nana, E., and Soncini, A. 2013. Impact of climate change scenarios on crop yield and water footprint of maize in the Po valley of Italy. Agricultural water management, 116, pp.50-61. doi: 10.1016/j.agwat.2012.10.009.

Bocchiola, D. 2015. Impact of potential climate change on crop yield and water footprint of rice in the Po valley of Italy. Agricultural Systems, 139, pp.223-237. doi: 10.1016/j.agsy.2015.07.009.

Bouman, B. 2009. How much water does rice use. Management, 69(2), pp.115-133.

Bregaglio, S., Hossard, L., Cappelli, G., Resmond, R., Bocchi, S., Barbier, J.M., Ruget, F. and Delmotte, S. 2017. Identifying trends and associated uncertainties in potential rice production under climate change in Mediterranean areas. Agricultural and Forest Meteorology, 237, pp.219-232. doi: 10.1016/j.agrformet.2017.02.015.

Carrera, L., Mysiak, J. and Crimi, J. 2013. Droughts in northern Italy: Taken by surprise, again. Review of Environment, Energy and Economics (Re3), Forthcoming.

Citrini, A., Camera, C. and Beretta, G.P. 2020. Nossana spring (northern Italy) under climate change: Projections of future discharge rates and water availability. Water, 12(2), p.387. doi: 10.3390/w12020387.

Chaudhry, A.N., Jilani, G., Khan, M.A. and Iqbal, T. 2009. Improved processing of poultry litter reduces nitrate leaching and enhances its fertilizer quality. Asian journal of Chemistry, 21(7), pp.4997-5003.

Chapagain, A.K. and Hoekstra, A.Y. 2011. The blue, green and grey water footprint of rice from production and consumption perspectives. Ecological Economics, 70(4), pp.749-758. doi: 10.1016/j.ecolecon.2010.11.012.

Chen, S., Chen, X. and Xu, J. 2016. Assessing the impacts of temperature variations on rice yield in China. Climatic Change, 138(1), pp.191-205. doi: 10.1007/s10584-016-1707-0.

Confalonieri, R. and Bocchi, S. 2005. Evaluation of CropSyst for simulating the yield of flooded rice in northern Italy. European journal of agronomy, 23(4), pp.315-326. doi: 10.1016/j.eja.2004.12.002.

Ehleringer, J.R. and Monson, R.K. 1993. Evolutionary and ecological aspects of photosynthetic pathway variation. Annual Review of Ecology and Systematics, pp.411-439.

Facchi, A., Gharsallah, O., Chiaradia, E.A., Bischetti, G.B. and Gandolfi, C. 2013. Monitoring and modelling evapotranspiration in flooded and aerobic rice fields. Procedia Environmental Sciences, 19, pp.794-803. doi: 10.1016/j.proenv.2013.06.088.

Fageria, N.K. 2007. Yield physiology of rice. Journal of plant nutrition, 30(6), pp.843-879. doi: 10.1080/15226510701374831.

Figueiredo, N., Carranca, C., Trindade, H., Pereira, J., Goufo, P., Coutinho, J., Marques, P., Maricato, R. and de Varennes, A., 2015. Elevated carbon dioxide and temperature effects on rice yield, leaf greenness, and phenological stages duration. Paddy and Water Environment, 13(4), pp.313-324. doi: 10.1007/s10333-014-0447-x.

Food and Agriculture Organization of the United Nations (FAO). 2022. The State of Food Security and Nutrition in the World. Available at: https://www.fao.org/interactive/state-of-food-security-nutrition/en/ (Accessed: 07/12/2022).

Food and Agriculture Organization of the United Nations (FAO). 2021. Food and Agriculture Data. Available at: https://www.fao.org/faostat/en/#data/QCL (Accessed: 07/12/2022).

Geethalakshmi, V., Ramesh, T., Palamuthirsolai, A. and Lakshmanan. 2011. Agronomic evaluation of rice cultivation systems for water and grain productivity. Archives of Agronomy and Soil Science, 57(2), pp.159-166. doi: 10.1080/03650340903286422.

Gazzani, F., 2021. Rethinking the mineral fertilizer subsidy scheme to promote environmental protection in Italy. Outlook on Agriculture, 50(3), pp.230-237. doi: 10.1177/00307270211031274.

Gianessi, L. and Williams, A. 2011. Italian rice farmers would lose 125 million euros in annual income without fungicides, CropLife International. Available at: https://croplife.org/case-study/italian-rice-farmers-would-lose-125-million-euros-in-annual-income-without-fungicides/ (Accessed: 12/12/2022).

Giuliana, V., Lucia, M., Marco, R. and Simone, V. 2022. Environmental life cycle assessment of rice production in northern Italy: a case study from Vercelli. The International Journal of Life Cycle Assessment, pp.1-18. Doi: 10.1007/s11367-022-02109-x.

Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J. and Stoffel, M. 2014. 21st century climate change in the European Alps—A review. Science of the total environment, 493, pp.1138-1151. doi: 10.1016/j.scitotenv.2013.07.050.

Haefele, S.M., Siopongco, J.D.L.C., Boling, A.A., Bouman, B.A.M. and Tuong, T.P. 2009. Transpiration efficiency of rice (Oryza sativa L.). Field Crops Research, 111(1-2), pp.1-10. doi: 10.1016/j.fcr.2008.09.008.

Hundal, S.S., Kaur, P. and Dhaliwal, L.K. 2005. Growth and yield response of rice (Oryza sativa) in relation to temperature, photoperiod and sunshine duration in Punjab. Journal of Agrometeorology, 7(2), pp.255-261. doi: 10.54386/jam.v7i2.853.

Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and Zhou B. 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Matthews, R.B., Horie, T., Kropff, M.J., Bachelet, D., Centeno, H.G., Shin, J.C., Mohandass, S., Singh, S., Defeng, Z. and Lee, M.H. 1995. A regional evaluation of the effect of future climate change on rice production in Asia. Modeling the Impact of Climate Change on Rice Production in Asia (eds. Matthews, RB, Kropff, MJ, Bachelet, D. and van Laar, HH). CAB International, Oxon, UK, pp.95-139.

Jacobs, B.C. and Pearson, C.J., 1999. Growth, development and yield of rice in response to cold temperature. Journal of Agronomy and Crop Science, 182(2), pp.79-88. doi: 10.1046/j.1439-037x.1999.00259.x.

Jagadish, S.K., Craufurd, P.Q. and Wheeler, T. 2007. High temperature stress and spikelet fertility in rice (Oryza sativa L.). Journal of experimental botany, 58(7), pp.1627-1635. doi: 10.1093/jxb/erm003.

Jena, K.K. and Hardy, B. 2012. Advances in temperate rice research. Los Baños (Philippines): International Rice Research Institute.

Kayam, Y., Ozsoy, U., Lomas, J., Oden, O., Mandel, M. and Gurbuz, M. 2000. The impact of climatic change on wheat production of Aegean region in Turkey: The effect of a reduction of rainfall and the increase of temperature on wheat yields. Menemen Research Institute, Izmir, Turkey.

Kim, H.Y., Ko, J., Kang, S. and Tenhunen, J. 2013. Impacts of climate change on paddy rice yield in a temperate climate. Global change biology, 19(2), pp.548-562. doi: 10.1111/gcb.12047.

Kraehmer, H., Thomas, C. and Vidotto, F. 2017. Rice production in Europe. In Rice production worldwide. pp. 93-116.

Krishnan, P., Ramakrishnan, B., Reddy, K.R. and Reddy, V.R. 2011. High-temperature effects on rice growth, yield, and grain quality. Advances in agronomy, 111, pp.87-206. doi: 10.1016/B978-0-12-387689-8.00004-7.

Krüger, M., Frenzel, P., Kemnitz, D. and Conrad, R. 2005. Activity, structure and dynamics of the methanogenic archaeal community in a flooded Italian rice field. FEMS Microbiology Ecology, 51(3), pp.323-331. doi: 10.1016/j.femsec.2004.09.004.

Lee, C.K., Kim, J., Shon, J., Yang, W.H., Yoon, Y.H., Choi, K.J. and Kim, K.S. 2012. Impacts of climate change on rice production and adaptation method in Korea as evaluated by simulation study. Korean Journal of Agricultural and Forest Meteorology, 14(4), pp.207-221. doi: 10.5532/KJAFM.2012.14.4.207.

Li, T., Angeles, O., Radanielson, A., Marcaida, M. and Manalo, E. 2015. Drought stress impacts of climate change on rainfed rice in South Asia. Climatic Change, 133(4), pp.709-720.

Madan, P., Jagadish, S.V.K., Craufurd, P.Q., Fitzgerald, M., Lafarge, T. and Wheeler, T.R. 2012. Effect of elevated CO2 and high temperature on seed-set and grain quality of rice. Journal of experimental botany, 63(10), pp.3843-3852. doi: 10.1093/jxb/ers077.

Mahmood, N., Ahmad, B., Hassan, S. and Bakhsh, K. 2012. Impact of temperature ADN precipitation on rice productivity in rice-wheat cropping system of Punjab province. J. Anim. Plant Sci, 22, pp.993-997.

Marchina, C., Bianchini, G., Natali, C., Pennisi, M., Colombani, N., Tassinari, R. and Knoeller, K. 2015. The Po river water from the Alps to the Adriatic Sea (Italy): new insights from geochemical and isotopic (δ18O-δD) data. Environmental Science and Pollution Research, 22(7), pp.5184-5203.

Mayer, A., Rienzner, M., Cesari de Maria, S., Romani, M., Lasagna, A. and Facchi, A. 2019. A comprehensive modelling approach to assess water use efficiencies of different irrigation management options in rice irrigation districts of northern Italy. Water, 11(9), p.1833. doi: 10.3390/w11091833.

Miao, Z., Trevisan, M., Capri, E., Padovani, L. and Del Re, A.A. 2004. Uncertainty assessment of the model RICEWQ in northern Italy. Journal of environmental quality, 33(6), pp.2217-2228. doi: 10.2134/jeq2004.2217.

Nikolopoulos, E.I., Anagnostou, E.N., Borga, M., Vivoni, E.R. and Papadopoulos, A. 2011. Sensitivity of a mountain basin flash flood to initial wetness condition and rainfall variability. Journal of Hydrology, 402(3-4), pp.165-178. doi: 10.1016/j.jhydrol.2010.12.020.

Nishiyama, I. 1976. Effects of temperature on the vegetative growth of rice plants. Climate and rice, pp.159-185.

Effendy, I. 2020. The effect of soil water content and biochar on rice cultivation in polybag. Open Agriculture, 5(1), pp.117-125. doi: 10.1515/opag-2020-0012.

Petrini, R., Pennisi, M., Vittori Antisari, L., Cidu, R., Vianello, G. and Aviani, U. 2014. Geochemistry and stable isotope composition of surface waters from the Ravenna plain (Italy): implications for the management of water resources in agricultural lands. Environmental earth sciences, 71(12), pp.5099-5111. doi: 10.1007/s12665-013-2913-y.

Piotti, E., Rigano, M.M., Rodino, D., Rodolfi, M., Castiglione, S., Picco, A.M. and Sala, F. 2005. Genetic structure of Pyricularia grisea (Cooke) Sacc. isolates from Italian paddy fields. Journal of Phytopathology, 153(2), pp.80-86. doi: 10.1111/j.1439-0434.2005.00932.x.

Ribeiro, L. 2007. Groundwater in the Southern Member States of the European Union: an assessment of current knowledge and future prospects. doi: 20.500.12592/5bnjzv.

Qiu, R., Katul, G.G., Wang, J., Xu, J., Kang, S., Liu, C., Zhang, B., Li, L. and Cajucom, E.P. 2021. Differential response of rice evapotranspiration to varying patterns of warming. Agricultural and Forest Meteorology, 298, p.108293. doi: 10.1016/j.agrformet.2020.108293.

Russo, S. and Callegarin, A.M. 2007. Rice production and research potential in Italy. Cahiers Opt. Méditerr, 24, pp.139-46.

Sappa, G. and Vitale, S. 2001. Groundwater protection: contribution from Italian experience. Department of Hydraulics. Transportations and Roads–University “La Sapienza” of Rome.

Saseendran, S.A., Singh, K.K., Rathore, L.S., Singh, S.V. and Sinha, S.K. 2000. Effects of climate change on rice production in the tropical humid climate of Kerala, India. Climatic Change, 44(4), pp.495-514.

Seneviratne, S.I., Corti, T., Davin, E.L., Hirschi, M., Jaeger, E.B., Lehner, I., Orlowsky, B. and Teuling, A.J. 2010. Investigating soil moisture–climate interactions in a changing climate: A review. Earth-Science Reviews, 99(3-4), pp.125-161. doi: 10.1016/j.earscirev.2010.02.004.

Stansel, J.W., 1975. Rice plant--its development and yield. Research monograph-Texas Agricultural Experiment Station.

Stroppiana, D., Migliazzi, M., Chiarabini, V., Crema, A., Musanti, M., Franchino, C. and Villa, P. 2015. Rice yield estimation using multispectral data from UAV: A preliminary experiment in northern Italy. In 2015 IEEE International Geoscience and Remote Sensing Symposium (IGARSS) pp. 4664-4667. doi: 10.1109/IGARSS.2015.7326869.

Stuecker, M.F., Tigchelaar, M. and Kantar, M.B. 2018. Climate variability impacts on rice production in the Philippines. PloS one, 13(8), p.e0201426. doi: 10.1371/journal.pone.0201426.

Titone, P., Mongiano, G. and Tamborini, L. 2015. Resistance to neck blast caused by Pyricularia oryzae in Italian rice cultivars. European journal of plant pathology, 142(1), pp.49-59.

Tomar, V.S. and O'Toole, J.C. 1980. Water use in lowland rice cultivation in Asia: A review of evapotranspiration. Agricultural Water Management, 3(2), pp.83-106. doi: 10.1016/0378-3774(80)90017-7.

University of York. 2005. Department of Mathematics. Upper Critical Values for Spearman’s Rank Correlation Coefficient. Available at: https://www.york.ac.uk/depts/maths/tables/spearman.pdf (Accessed:13/12/2022).

van den Hurk, B., Best, M., Dirmeyer, P., Pitman, A., Polcher, J. and Santanello, J. 2011. Acceleration of land surface model development over a decade of GLASS. Bulletin of the American Meteorological Society, 92(12), pp.1593-1600.

Vezzoli, R., Mercogliano, P., Pecora, S., Zollo, A.L. and Cacciamani, C. 2015. Hydrological simulation of Po River (North Italy) discharge under climate change scenarios using the RCM COSMO-CLM. Science of the Total Environment, 521, pp.346-358.

Wu, Z et al. 2018. Environmental factors shaping the diversity of bacterial communities that promote rice production. BMC microbiology, 18(1), pp.1-11.

Yoshida, S., 1981. Fundamentals of rice crop science. Los Baños (Philippines): International Rice Research Institute.

Xiong, Q., Hu, J., Wei, H., Zhang, H. and Zhu, J. 2021. Relationship between plant roots, rhizosphere microorganisms, and nitrogen and its special focus on rice. Agriculture, 11(3), p.234.

Xu, H., Cai, Z. and Jia, Z. 2002. Effect of soil water contents in the non-rice growth season on CH4 emission during the following rice-growing period. Nutrient Cycling in Agroecosystems, 64(1), pp.101-110.

Zampieri, M., Ceglar, A., Dentener, F. and Toreti, A. 2017. Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. Environmental Research Letters, 12(6), p.064008. doi: 10.1088/1748-9326/aa723b.

Zampieri, M., Russo, S., di Sabatino, S., Michetti, M., Scoccimarro, E. and Gualdi, S. 2016. Global assessment of heat wave magnitudes from 1901 to 2010 and implications for the river discharge of the Alps. Science of the Total Environment, 571, pp.1330-1339. doi: 10.1016/j.scitotenv.2016.07.008.

Zhongming, Z., Linong, L., Xiaona, Y., Wangqiang, Z. and Wei, L. 2009. Regional climate change and adaptation—The Alps facing the challenge of changing water resources. doi: 119.78.100.173/C666/handle/2XK7JSWQ/2921.

Zoli, M., Paleari, L., Confalonieri, R. and Bacenetti, J. 2021. Setting-up of different water managements as mitigation strategy of the environmental impact of paddy rice. Science of The Total Environment, 799, p.149365. doi: 10.1016/j.scitotenv.2021.149365.

APPENDIX

Code created on Google Earth Engine, with the aim of exporting rice paddy fields in the regions of Lombardy and Piedmont for use in QGIS. Source: Original, 2022. Available at: https://code.earthengine.google.com/0f312046b0041927759bb07ceea0b6ce

```
Diss_Rice *                                   Get Link   Save   Run   Reset   Apps
Imports (1 entry)
  var Regions: Table FAO/GAUL/2015/level1

//As part of the Environmental Geography (Bc) degree
//For use in Dissertation
//Lucas Zazzi Carbone

//Upload satellite observation data
var img = ee.Image('COPERNICUS/CORINE/V20/100m/2018');

//Select regions
var Lombardia = Regions.filter(ee.Filter.eq('ADM1_CODE',1624));
print(Lombardia)
Map.addLayer(Lombardia, ['green'],'Lombardia')

var Piemonte = Regions.filter(ee.Filter.eq('ADM1_CODE', 1627));
print(Piemonte)
Map.addLayer(Piemonte,['green'],'Piemonte')

//Merge both regions
var LOMPIE = Lombardia.merge(Piemonte)
print(LOMPIE)
Map.addLayer(LOMPIE, ['green'],'LOMPIE')


Map.setCenter(8.1736, 45.325, 8);


var fromlist = [111,112,121,122,123,124,131,132,133,141,142,211,212,213,
    221,222,223,231,241,242,243,244,311,312,313,321,322,323,324,331,
    332,333,334,335,411,412,421,422,423,511,512,521,522,523];

//Mask artificial surfaces, forest, wetlands and waterbody, display only rice paddy fields
var tolist = [0,0,0,0,0,0,0,0,0,0,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,
          0,0,0,0,0,0,0,0,0,0,0,0,0,0,0];

//Original classification masked to display new classification
var imgRemap = img.remap({
  from: fromlist,
  to: tolist,
  defaultValue: 0,
  bandName: 'landcover'
});
var imgRemap = imgRemap.clip(LOMPIE)

//Add layers to the map
Map.addLayer(img, null, 'Original image');
Map.addLayer(imgRemap, {
  min: 0, max:4,
  palette: 'darkgreen, lightgreen, red, white, blue'
}, 'Remapped image');

var rice = imgRemap.eq(1);
rice = rice.updateMask(rice);
Map.addLayer(rice, {palette: 'white, brown'},'rice');

//Export image for use in QGIS
Export.image.toDrive({
  image:rice,
  description:"rice",
  folder: "GEE export",
  scale:2000,
  region: LOMPIE,
  maxPixels: 100000000
});
```

Subsequent use permit

If you think you may leave your project with us for subsequent use as an example of good practice, please complete the following form and include it in your submitted copy of your dissertation.

Public use permit

Please tick the following as appropriate

☒ I agree to the use of this dissertation as an example for future students. I am free to request its return should I need it at any time.

☐ I do not want my dissertation used in the future and wish it destroyed if I do not collect it within 1 year of graduation.

Type name: Lucas Gabriel Zazzi Carbone

Signature: