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Exploration of spatial and temporal variability of rainfall and their impact on rice production in Burma in 1901–1939 during the colonial period

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Abstract

Climate is one of the main factors for rice crop growth. Understanding the relationship between climate variability and rice production during the period from 1901 to 1939 in Burma can give a clear picture of the impact of climate variability on rice yield since there were fewer human interventions on the catchment and almost no use of chemical fertilizer or high-yielding rice varieties at that time. However, the quantitative analysis of climate variability and its impact on rice production has not yet been paid sufficient scientific attention for the historic period. First, the changing trends of rainfall and rice yield between 1901 and 1939 were analyzed, including the effect of rainfall variability on rice production from multiple perspectives regarding rainfall characteristics, such as seasonal rainfall, various rainfall indices, rainfall anomalies, and monthly rainfall variability. Then, the relationship between rice yield and rainfall was investigated using multiple regression analysis to show how rainfall spatial and temporal variabilities have influenced rice yield and production, including essential factors that affected rice yield in each Burma district. The historical development of rice production in Burma during the period was also explored. Our findings indicate that not only the annual variability of rainfall, but also its monthly variability within a particular year likely influenced rice production. Excessive rainfall in the early or middle stage of crop growth or less during the early-middle or latter half of crop growth possibly caused the rice yield reduction in Burma during the colonial period. Furthermore, the results indicated that although rainfall anomalies widely differed from period to period, rice yield anomalies clearly showed the distinction of periods with higher or lower rice yields than average rice yield. Mostly higher than average rice yield was observed before 1910 in the Coastal Zone and before 1918 in the Delta, Dry, and Hilly Zones. The results of this study imply that selected rainfall indices could affect rice yield, positively or negatively, including the varied magnitude of their effects from one district to another, depending on climatic zones and agricultural ecosystems.

Keywords: Rice development, Rice production, Climate variability, Burma, Colonial period, Rainfall

1 Introduction

Rice crop is a major agricultural produce in terms of production and food consumption in many countries (Matsuda 2009; Auffhammer et al. 2012), particularly in Asia and Africa, and it is also a major source of income of people living in many developing countries. Rice production substantially influences global food security as it is a crucial food for the daily life of the people (Ara et al. 2017). It is currently the staple food for over 4.7 billion people globally, and rice demand is expected to continue more in the future (Asada and Matsumoto 2009; Homma et al. 2014; Akinbile et al. 2020). Alternatively, climate variables, such as rainfall and temperature, may largely influence rice production and food security worldwide

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(Homma et al. 2014; Ara et al. 2017; Rokonuzzaman et al. 2018). Moreover, temporal changes in rice crop yield and production are driven by a several environmental variables, such as climate and agricultural practices. Therefore, it is necessary to understand variability of such variables and their impact on rice production that enables us to understand the capacity of agriculture to adapt to climatic changes (Stuecker et al. 2018).

The climate is one of the main factors for rice crop growth and yield. Climatic factors, mainly rainfall and temperature, directly affect rice crop cultivation (Alam et al. 2011; Panda et al. 2019; Abbas and Mayo 2021), and any changes in such climate factors may have a significant impact on rice crop yield and production and economic, social, and environmental sustainability of a country (Alam et al. 2011; Panda et al. 2019). To reveal relationships between climate factors and rice cultivation, numerous studies have been conducted at country or regional level in various locations (e.g., Saseendran et al. 2000; Sarker et al. 2012; Mainuddin et al. 2013; Zakaria et al. 2014; Chung et al. 2015; Le 2016; Pheakdey et al. 2017; Rene et al. 2016; Ara et al. 2017; Rahman et al. 2017; Ali 2018; Baliarsingh et al. 2018; Nath and Mandal 2018; Kingra et al. 2018; Stuecker et al. 2018; Panda et al. 2019; Abbas and Mayo 2021). Some used temperature and rainfall factors in their analyses (Lansigan et al. 2000; Alam et al. 2011; Rowhani et al. 2011; Masud et al. 2014; Bhatt et al. 2019; Ratnasiri et al. 2019; Rayamajhee et al. 2021), and some only used rainfall as a primary climate factor that affects the rice yield (Asada and Matsumoto 2009; Tiamiyu et al. 2015; Kunimitsu and Kudo 2015; Riad and Peter 2017; Ferreira et al. 2018; Rokonuzzaman et al. 2018; Singh et al. 2018; Chandrasiri et al. 2020; Molla et al. 2020). Most of the previous studies found that rainfall is one of the most essential climatic variables that affect the rice production in the tropics, because of its two-sided effects: (i) a lacking resource such as droughts and (ii) a catastrophic driver such as floods (Alam et al. 2011; Koudahe et al. 2017; Rokonuzzaman et al. 2018; Singh et al. 2018; Panda et al. 2019; Chandrasiri et al. 2020; Molla et al. 2020). Particularly, the rainfed rice crop has a direct relationship with seasonal and inter-seasonal rainfall, which makes it the most vulnerable to seasonal climate variability (Molla et al. 2020). The excess rainfall may cause flooding in paddy fields, which can damage the rice crops. Alternatively, little or no rainfall can also lead to dying rice crops. Walishinge et al. (2017) also highlighted that the water availability for crops essentially depends upon the rainfall distribution, and excessive rainfall can damage early crop growth until the grain harvest. Therefore, understanding the features of rainfall variable in a particular area has significant importance in rainfed rice crops (Molla et al. 2020).

Rainfall is the most variable climate parameter in space and time (Mathanraj and Kaleel 2016). The impact of rainfall variables on rice production can be positive or negative in an area of interest depending on the characteristics of rainfall and rice production. For example, a recent study by Chung et al. (2015) found that rainfall positively affected rice yield in Vietnam, while Abbas and Mayo (2021) observed the adverse effects of rainfall on rice production in Pakistan. Chandrasiri et al. (2020) reported that continuous rainfall during the harvesting time caused complete damage on rice crop in Sri Lanka. The study by Singh et al. (2018) shows evidence of significant influences of fewer rain days on crop production and significant positive correlation of moderate rainfall with crop production in India. Molla et al. (2020) reported that the annual rainfall amount and number of rainy days had a strong significant positive correlation with rice yield, while the number of dry spells had a strong negative correlation with rice yield in Ethiopia. In some areas, such as Bangladesh, Nigeria, Suriname, and Sri Lanka, the evidence of a lesser rainfall effect on rice yield or a lesser significant relationship between rainfall and rice yield has also been reported (Zakaria et al. 2014; Tiamiyu et al. 2015; Riad and Peter 2017; Walishinge et al. 2017). This evidence found in previous researches clearly shows that the features of rainfall variable and their impact on rice yield vary from place to place and region to region. The effect of climate variables on agricultural production is related to the variability in the local climate rather than global climate patterns (Kingra et al. 2018). Hence, analyzing climate variability and its impact on agricultural production for each region, and considering local characteristics of climate and crops, is crucial for the agricultural sector to adapt to climate changes.

Even though the impact of rainfall variability on rice yield has been investigated in previous researches, the complete answers are still not clearly understood. Additionally, previous researches mainly focused on the analysis of the effect of climate factors on recent rice production or periods in the latter half of the twentieth century (Lansigan et al. 2000; Chung et al. 2015; Kunimitsu and Kudo 2015; Tiamiyu et al. 2015; Adedeji et al. 2017; Rahman et al. 2017; Kingra et al. 2018; Singh et al. 2018; Stuecker et al. 2018; Bhatt et al. 2019; Chandrasiri et al. 2020; Abbas and Mayo 2021). Few researchers attempted to analyze the changing trend in rainfall and/or temperature for the first half of the twentieth century (Jones and Hulme 1996; Vincent and Mekis 2006; Riad and Peter 2017; Koudahe et al. 2017; Ferreira et al. 2018). Furthermore, the quantitative analysis of climate variability and its impact on rice production has not yet been paid sufficient scientific attention for the early twentieth century or its first half. Moreover, since observed climate data cannot be easily obtained due to the lack of observation stations or systematic recording of climate data, agricultural data on rice production and yield for this period are unreadily available in many countries. In the first half of the twentieth century, there were fewer human interventions on the catchment and almost no use of chemical fertilizer or high-yielding rice variety, particularly in developing countries (Win 1991; Young et al. 1998). Therefore, studies on impact of climate variability on agricultural production for this period can provide useful information to better understand the impact of climate variability on agricultural production. Moreover, the previous studies only used local rainfall over the area to analyze the effect of rainfall on rice production, and the use of local rainfall is mainly appropriate to explore the impact of rainfall shortages on crop reductions. However, in general, excess rainfall in the upstream runoff contributing to catchment areas can damage rice crops in the downstream areas of the river basin. Only the occurrence of rainfall in the upstream catchment of the river basin can cause severe flooding in the downstream areas and can have significant effects on rice production in downstream areas. To analyze crop yield loss due to flooding or excess rainfall, rainfall in the upstream catchment area is also an essential factor that needs to be included in the analysis. Particularly in the case of large upstream contributing catchment areas, the effect of rainfall in the upstream catchment area on crop production cannot be ignored. It is thus also necessary to analyze the relationship between rainfall in the upstream catchment areas and rice yield to clarify the effects of rainfall variability on rice production.

Burma was the main rice exporter in the world during the colonial period. Rice production was mainly dependent on rainfall in most of the districts in Burma during the colonial period. Only some areas in the Dry Zone had irrigation systems, and the irrigation systems in other areas were not well-developed during the study period (Win 1991). No systematic studies have yet been conducted about the trend of rainfall variability and its impact on rice production in Burma during the colonial period. In this context, the main objectives of this study were to demonstrate how the spatial and temporal variability of rainfall impacted rice yield and rice production and to identify the most critical factors that affected rice yield in Burma during the colonial period (1901–1939), by analyzing the spatiotemporal variability of rainfall and rice yield, and exploring the relationship between rainfall and rice yield. The historical development of rice production in Burma during the colonial period was also explored. The novelties of this study were (1) to focus on the effect of rainfall on rice yield for the early twentieth century (1901–1939) and (2) to investigate area-averaged rainfall over the districts, including the whole upstream contributing catchment areas. The nonparametric Mann–Kendall test for detecting the trend and Sen's method for estimating the magnitude of the trend were employed to analyze rainfall and rice yield variability. The relationship between rice yield and rainfall with different rainfall indices was analyzed on the basis of multiple regression analysis. To explore the effects of rainfall on rice yield from the aspects of water shortage and floods, local rainfall at each district and area-averaged rainfall over the district, including the whole upstream contributing catchment areas (average rainfall over the catchment), were used.

2 Background of Burma (Myanmar)

Burma (currently Myanmar) is situated in Southeast Asia, lying between 10°N and 29°N in latitude and between 92°E and 101°E in longitude (Fig. 1). The elevation is highest in the northern part of the country exceeding 5,000 m, and lowest in the Delta areas in the southern part of the country (Fig. 1). The country can be divided into four main agroecological zones: (1) Coastal Zone, (2) Delta Zone, (3) Dry Zone, and (4) Hilly or Mountainous Zone (Fig. 2a). The climate of the country can be divided into three seasons: (1) Summer (mid-February to mid-May), (2) Monsoon (Rainy) season (mid-May to late October), and (3) Winter (late October to mid-February) (DMH and UNEP 2012; Sein et al. 2018). The annual average rainfall in the coastal area is about 5080 mm, while it is about 762 mm in the central Dry Zone of the country (Aung et al. 2017). The mean maximum temperature is about 37.8 °C in the central area during March and April, while the mean minimum temperature is about 4.4 °C–10.0 °C in the northern part of the country during January and February (Aung et al. 2017).

Figure 2b shows the spatial distribution of soil types in Burma based on the FAO/UNESCO soil map. We observed that Acrisols, which are the most widespread soil type in Burma (covering 51.44% of the total land area), were widely distributed in the Hilly Zone or higher elevated lands. However, Gleysols (also known as paddy soils) were widely distributed in the river plains, Delta Zone, lowland areas of the Coastal Zone, and valleys of the Hilly or Mountainous Zone (covering approximately 14.82% of the total land area). Interestingly, the Gleysols were saturated with groundwater for long periods during the year, making them suitable for paddy cultivation. Alternatively, while Cambisols were only dominant in districts located in the western part of Burma (covering 13.85% of the total land area), Fluvisols were found in the Delta and Coastal Zones (covering 0.94% of the total land area). In contrast, Luvisols were mainly found in central areas of the Dry Zone (covering 6.44% of the

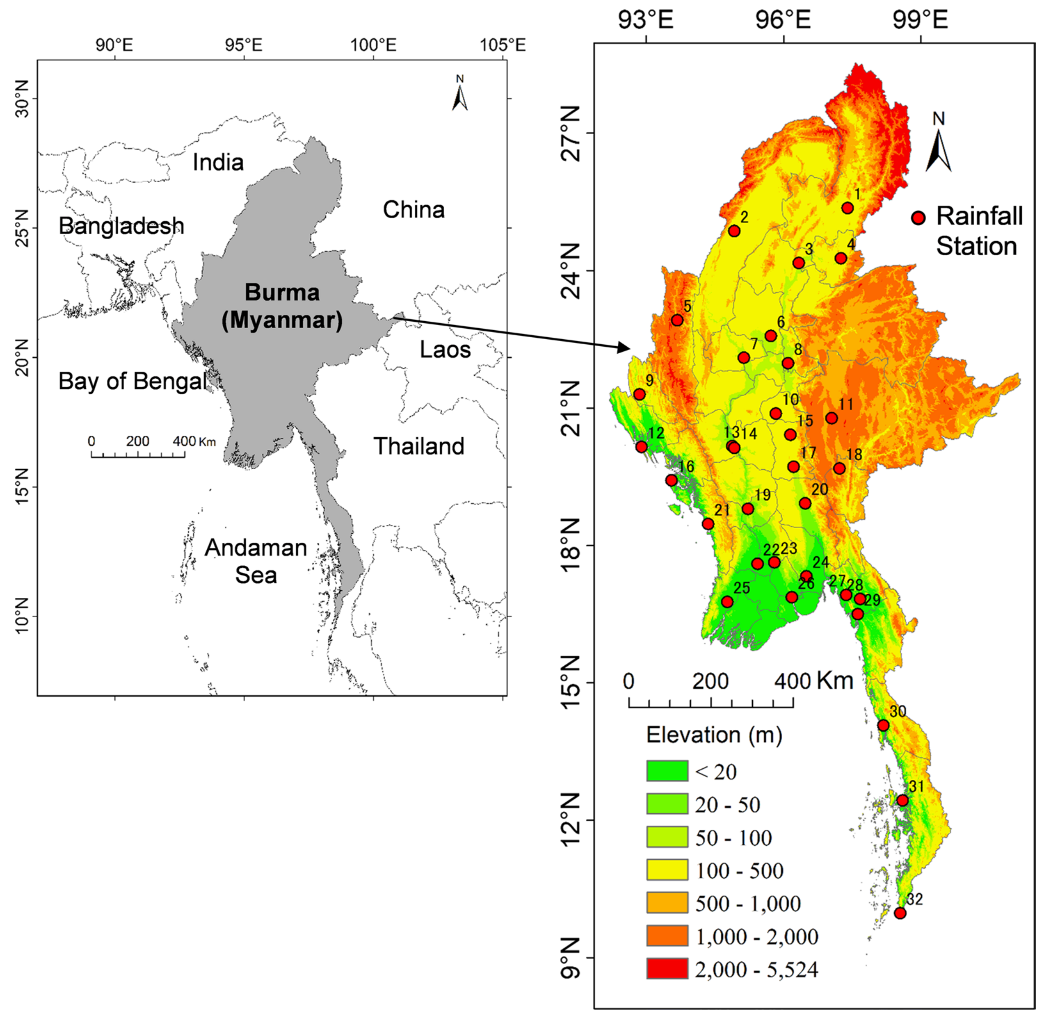

Fig. 1 The geographical location of Burma (Myanmar), topographical distribution in Burma based on HydroSHEDS digital elevation model, and location of rainfall stations (name and latitude and longitude coordinates of the stations are indicated in Additional file 1: Table S1)

total land area). They are the most important agricultural soils in the central areas of the Dry Zone. Furthermore, Vertisols, which are rich in clay, and the best soils for irrigated agricultural cultivation, were also identified. They are mainly distributed within the districts located in the Dry Zone (covering 1% of the total land area). Furthermore, they are the second most important soil for agriculture in the central areas of the Dry Zone (IFDC 2018). However, Nitosols cover 8.12% of the total land area and are mainly distributed in the inland valley of the Dry and Delta Zones. They are found in some parts of the Coastal and Hilly Zones. Other soil types discovered in Burma are Lithosols (covering 2.57%), Planosols (covering only 0.06%), and Solonchaks (covering 0.76%). Soils that are heavy and almost impervious in nature, such as heavy clay, through which water cannot seep easily, are suitable for rice cultivation (Siok-Hwa 2012). Thus, while the Gleysols, Vertisols, Luvisols, Cambisols, and Fluvisols are naturally good fertile, the Acrisols and Nitosols are considered naturally low fertile soils (Win 1991; ICEM 2016; Htwe 2016; Elstner 2017; IFDC 2018). Nevertheless, although the Fluvisols, Gleysols, Luvisols, and Vertisols are the primary rice cultivation soils in these areas (Htwe 2016), upland rice is still grown in large areas with Acrisols in hilly or mountainous areas.

The British colonized the country in three stages. The colonization of Burma began in 1826 with parts of Lower Burma by occupying the Arakan and Tenasserim coastal strips. Pegu and Martaban were colonized in 1852 and the rest of the country in 1885 (Hlaining 1964; Win 1991). Burma politically remained a province of India until 1937 when Burma

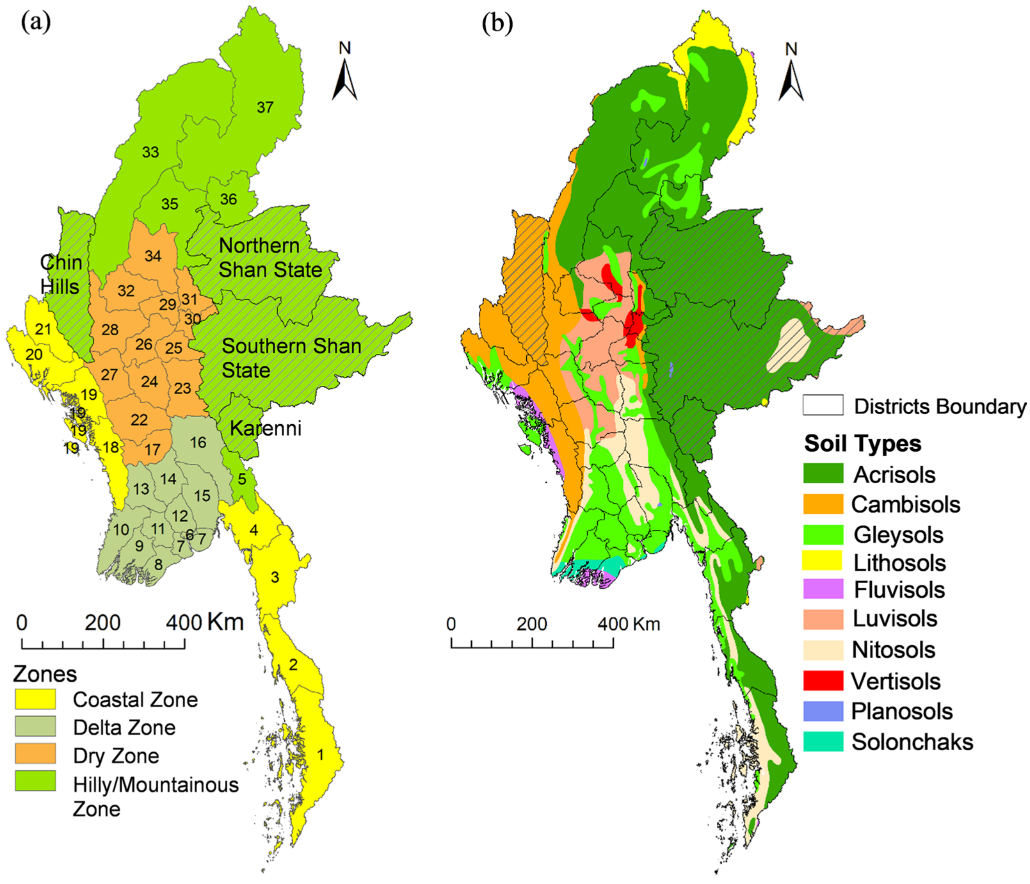

Fig. 2 **a** Agroecological zones and district boundary during the Colonial Burma period (1925/26–1946/47) (Bennison 1933; Zaw and Than 2017; Okamoto 1998) and **b** soil types in Burma based on digital soil map of FAO/UNESCO (https://data.apps.fao.org/). The district names are indicated in Additional file 1: Table S5. The states with hatched lines (Northern Shan, Southern Shan, Chin Hill, and Karenni) were excluded from the study because the rice crop data were unavailable for these states

was separated from India. Then, the Japanese occupied Burma in early 1942, and it was re-occupied by the British in 1945. Finally, it was granted independence in 1948. The regions of Burma, which were under the direct control of the British, were also commonly called Burma Proper (Okamoto 1998). The administrative divisional boundaries of Colonial Burma were changed many times. However, there were seven divisions with 37 districts from 1925/26 to 1946/47 that were directly under British rule. The administrative district boundaries of Colonial Burma are indicated in Fig. 2a. The Chin Hills, Northern Shan, Southern Shan, and Karenni states indicated in Fig. 2a were not under the direct control of British rule (Okamoto 1998). The population in the country was about 10.49, 14.53, and 16.82 million people in 1901, 1931, and 1941, respectively (Bennison 1933; Aye 2019). The increase in population from 1901 to 1931 was about 38.5%.

3 Data

Table 1 indicates the list of obtained climate and crop data for the study. The available climate data for Burma during the colonial period were only precipitation, and other climate data, such as temperature, were readily unavailable. In this study, only precipitation data were thus used to analyze climate variability and its impact on rice production. The daily precipitation data were obtained for the period 1891–1939 at 32 stations. The locations of precipitation stations are indicated in Fig. 1 (also see Additional file 1: Table S1 for the latitude and longitude coordinates of each station). During World War II, the precipitation data were completely unavailable for December 1940 and from August 1941 to December 1946 at all 32 stations. There are no available data at some stations before 1900. The data from 1891 to 1939 were digitized by some authors from the data books listed in Table 1.

Table 1 List of data available for study and their sources

Data	Spatial resolution	Temporal resolution	Period	Sources
Climate data				
Precipitation* (rainfall)	Point data	Daily (32 stations)	1891–1937	"Rainfall of India (1891–1914) and Daily Rainfall of India (1915–1937)" available on the web page of the NOAA Central Library, National Oceanic and Atmospheric Administration, USA https://library.noaa.gov/Collections/Digital-Docs/Foreign-Climate-Data/India-Climate-Data Data were checked by the original books at the Library of the Indian Institute of Tropical Meteorology (IITM)
			1938–1939	"Daily Rainfall Recorded in Burma" stored in the Library of The Royal Netherlands Meteorological Institute (KNMI; 1938–1939)
Rice crop data				
Rice-cultivated area	District-level data	Yearly (37 districts)	1901/02–1946/47**	Okamoto (1998) http://hdl.handle.net/10086/14672
	Country level data (whole Burma)	5-Yearly (from 1830 to 1900), Yearly (from 1900 to 1985)	1830–1985	Win (1991): 1830–1985 Okamoto (1998): 1901–1946
Rice-harvested area	District-level data	Yearly (37 districts)	1912/13–1946/47	Okamoto (1998) http://hdl.handle.net/10086/14672
Rice yield	District-level data	Yearly (37 districts)	1901/02–1946/47**	Okamoto (1998)
Rice production	District-level data	Yearly (37 districts)	1901/02–1946/47 (not available for 1941/42–1944/45) **	Okamoto (1998)
	Country level data (whole Burma)	5-Yearly (from 1830 to 1900), Yearly (from 1900 to 1985)	1830–1985	Win (1991): 1830–1985 Okamoto (1998): 1901–1946
Rice export	Country level data (whole Burma)	10-Yearly (from 1860 to 1900), Yearly (from 1900 to 1985)	1860–1985	Win (1991): 1860–1985
Digital elevation data (DEM, flow direction, flow accumulation)	30-arcsecond	–	–	HydroSHEDS (provided by the United States Geological Survey) https://www.hydrosheds.org/downloads
Administrative boundary map and data	District, country	–	–	Okamoto (1998), Myanmar Information Management Unit (http://themimu.info/)
Soil Types (Digital Soil Map)				FAO/UNESCO https://data.apps.fao.org/map/catalog/srv/eng/catalog.search?id=14116#/metadata/446ed430-8383-11db-b9b2-000d939bc5d8

*The precipitation data from December 1940 and August 1941 to December 1946 were unavailable (missing or unreadable) at all 32 stations. The precipitation data are unavailable at some stations before 1900

**Rice crop, yield, and production data for Maubin and Paypon district are available from 1903/04, and for Insein district from 1912/13

Rice crop data such as rice-cultivated areas, harvested areas, rice yield, and rice production were obtained from the report published in Okamoto (1998). The rice crop data at the district level were available for the period 1901/02–1946/47. However, the district-level data were completely unavailable at all districts during World War II for 1941/42–1944/45. Since the crop data are available from 1901 to 1939/40, this study focused on the analysis of rainfall impact on rice production over the period from 1901 to 1939. Additionally, the crop data were unavailable for the Northern Shan, Southern Shan, Chin Hill, and Karenni states because these areas were under the indirect control of the British government rather than the direct British control (Okamoto 1998). Therefore, these areas were also excluded from the study. The rice crop area and production data for the whole Burma over 1830–1985 and rice export data over 1860–1985 were also obtained for the study from previous reports (Win 1991; Okamoto 1998).

The digital elevation model (DEM), flow direction data, and flow accumulation data were obtained from HydroSHEDS (https://www.hydrosheds.org/) (provided by the United States Geological Survey) to extract watershed boundaries to calculate the basin average rainfall for the districts. The administrative boundary maps and data were obtained from Okamoto (1998) and Myanmar Information Management Unit (http://themimu.info/) to digitize the district map for the Colonial Burma period. Additionally, while the digital soil map was obtained from the FAO/UNESCO (https://data.apps.fao.org/), other secondary information (paddy land areas for Upper and Lower Burma, use of rice varieties, fertilizers, rice policy, and rice development for the Colonial Burma period) was obtained from previous studies.

The annual and seasonal rainfall data at each station for the study period (1901–1939) are presented in Additional file 1: Tables S2 and S3, respectively. The average monthly rainfall during 1901–1939 is presented in Additional file 1: Table S4. The average rice yield during 1901–1939 at each district in Burma is also presented in Additional file 1: Table S5.

4 Overview of rice ecosystems and historical development of rice production in Burma

4.1 Rice cultivation and ecosystems

The traditional rice cultivation methods in Burma can be divided into lowland (wetland, i.e., practiced in lowland or plain areas) and upland (dryland, i.e., practiced in hilly areas or wooded hillsides) methods (Kyaw et al. 1977; Mochizuki et al. 1993; Mackill et al. 1996; Young et al. 1998; Siok-Hwa 2012). The upland cultivation methods practiced on wooded hillsides were typical slash-and-burn methods, also called shifting cultivations (*taungya*) or fire farming (Siok-Hwa 2012; Denning et al. 2013). The main differences between these two rice cultivation methods are that (i) in lowland rice cultivation, rice seeds are first sown in the nursery beds, and transplanting of seedlings is done in the paddy field, except in some areas where the soil is poor, labor is scarce, or in situation when seedlings cannot be uprooted due to deep watering (where broadcasting or direct seeding was practiced), while direct seeding of rice in the paddy field is practiced in upland rice cultivation. (ii) The lowland rice is grown on wet paddy fields or fields flooded either following rainfall or irrigation, while upland rice is grown on dry paddy fields without flooding. Additionally, most lowland rice fields have a bund, except in some areas that are subject to flooding. The rice plant is kept partially submerged from transplanting to harvesting in these areas. In comparison, upland rice cultivation is practiced without bunding (Win 1991; Young et al. 1998; Siok-Hwa 2012). Finally, since upland rice depends on rainfall greatly, the rice yield of upland rice is lower than lowland rice.

Rice ecosystems of Burma during the twentieth century were referred to as rainfed-lowland, deep-water, irrigated-lowland, and upland rice (Kyaw et al. 1977; Win 1991; Young et al. 1998; Denning et al. 2013). The rainfed-lowland rice was the primary dominant rice production system in Burma during the colonial period, concentrated mainly in the Delta and Coastal Zones because the rainfall amount in these areas during monsoon was sufficient for rice cultivation without irrigation. However, the deep-water rice production was primarily concentrated in lower delta areas and coastal strips, usually cultivated under deep submerged water. Contrastively, the irrigated-lowland and upland rice productions were concentrated mainly in the Dry and Hilly Zones, respectively (Win 1991; Young et al. 1998; Denning et al. 2013). The major production constraint in poorly drained rainfed-lowland and deep-water areas is the excessive floodwater during the monsoon (Young et al. 1998; Denning et al. 2013). Furthermore, while annual rainfall is inadequate to produce a rainfed rice crop in the Dry Zone except in low-lying areas with a high-water table, rice cultivation in the Dry Zone can only be productive when rice is grown under irrigation conditions because of the increased number of sunshine hours (Denning et al. 2013).

4.2 Historical development of rice production

During the colonial period, Burma was the largest rice producer and major rice exporter country in the world. Figure 3 indicates the expansion trend of planted paddy areas, rice production, and rice exports from 1830 to 1985. The rice crop area in 1830 was only about 27,000 ha, and it was increased to 3.46 million ha in 1900 and 5.0 million ha in 1930. Such rapid expansion of rice crop area

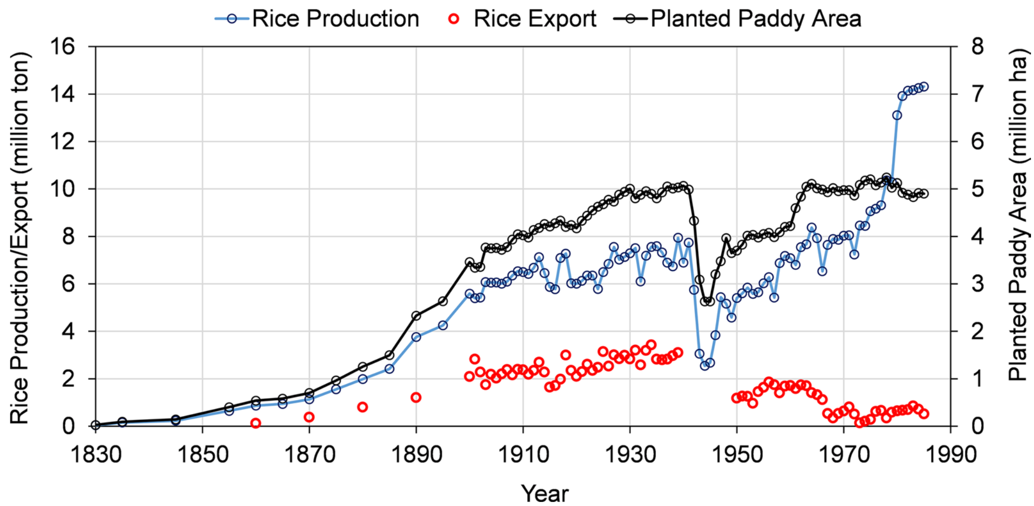

Fig. 3 The historical development of rice production and planted paddy area and rice export in Burma (Data Source: Win 1991)

was attributed to several reasons: (1) availability of vast areas of deltaic land favorable for rice cultivation, (2) rising demand for rice in Europe and Asian countries such as Malaya, India, and Sri Lanka, (3) provision of different incentives and rice development policy, (4) improvement in transport and shipping facilities, and (5) the removal of previous prohibitions on rice exports by the British government (Jayasuriya 1984; Win 1991; Young et al. 1998). The expansion of the rice crop area was then relatively stable from 1930 to 1940 (Win 1991; Young et al. 1998). The annual rice production increased from 44,000 tons in 1830 to 5.5 million tons in 1900 and 7.2 million tons in 1930, and it ranged from 5.39 to 7.9 million tons for 1900–1939. The rice production in Burma has continued to increase, except for a considerable decline in the 1940s during World War II period (Young et al. 1998; Matsuda 2009).

British administration mainly focused on the development of rice crops in the Ayeyarwady Delta in Lower Burma with rapid expansion of rice crop areas between 1885 and 1910 (see Additional file 1: Figure S1) because the delta area was a favorable rice environment in terms of soil and climatic conditions. Figure 4 indicates the spatial development of rice crop area and rice production for the studied period (for the beginning: 5-year average from 1901 to 1905, and for the end: 5-year average from 1935 to 1939) and their variations. The 5-year average rice crop area for 1901–1905 was about 0.74, 2.16, 0.75, and 0.14 million ha, respectively, in the Coastal, Delta, Dry, and Hilly Zones. For 1935–1939, it was increased to 0.97, 2.86, 0.94, and 0.20 million ha, respectively, in the Coastal, Delta, Dry, and Hilly Zones. Similarly, the 5-year average rice production for 1901–1905 was about 1.50, 4.18, 1.05, and 0.24 million tons, respectively, in the Coastal, Delta, Dry, and Hilly Zones, while it was about 1.34, 4.60, 1.16, and 0.27 million tons, respectively, in the Coastal, Delta, Dry, and Hilly Zones for 1935–1939. The rice crop areas were vastly expanded in the districts where Gleysols or Gleysols and Vertisols or Gleysols and Luvisols, or Gleysols and Cambisols, or Gleysols and Fluvisols were widely distributed. However, in some districts of the central Dry Zone, the rice crop areas were decreased, even with the wide distribution of naturally good and fertile soil types, such as Luvisols and Cambisols in the Lower Chindwin District; Gleysols, Vertisols, and Luvisols in the Meiktila and Sagaing Districts; Luvisols in the Myingyan District; and Gleysols and Vertisols in the Magwe District. This contrasting observation was possibly due to the insufficient water supply during rice cultivation in the central Dry Zone. Furthermore, we observed that the widely distributed soil types in the districts with an increased tendency of rice production (red/orange colored in Fig. 4) were Acrisols and Gleysols in the Myitkyina District; Gleysols, Vertisols, and Luvisols in the Shwebo District; Gleysols, Cambisols, and Luvisols in the Minbu and Yamethin Districts; Gleysols and Nitosols in the Prome and Pegu Districts; Gleysols in the Maubin District; Gleysols and Fluvisols in the Pyapon and Myaungmya Districts; and Gleysols and Cambisols in the Bassein District. In addition, it was observed that the rice production was primarily reduced in the districts where Acrisols (Katha and Upper Chindwin Districts) or Acrisols and Nitosols (Mergui District) or Cambisols (Sandoway and Kyaukpyu Districts) were widely distributed.

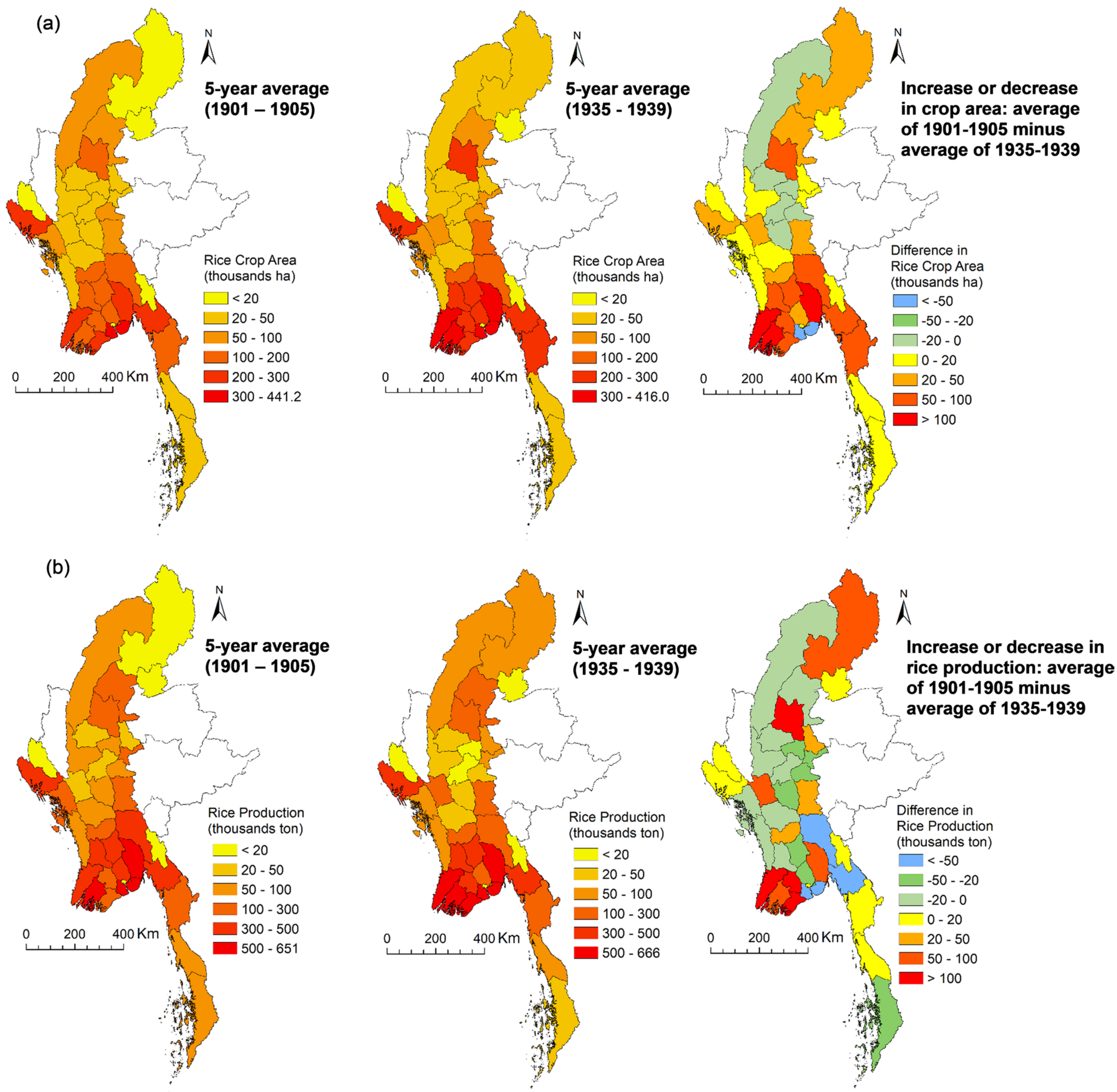

Fig. 4 **a** 5-year average planted rice crop areas in the beginning (average of 1901–1905) and end (average of 1935–1939) of the study period and their differences and **b** 5-year rice production in the beginning (average of 1901–1905) and end (average of 1935–1939) of the study period and their differences. The states with white colored (Northern Shan, Southern Shan, Chin Hill, and Karenni) were excluded from the study because the rice crop data were unavailable for these states. (Note: Since data on crop area and rice production for Insein district are available only from 1912, average data for years 1912–1916 were used for the 5-year average for the beginning of study areas in the case of Insein district)

Burma rapidly became the major world rice exporter during the colonial period, contributing 47% of world exports in 1938/39, and it exported 2–3 million tons of rice annually (up to 70% of national production) between 1900 and 1940 (Win 1991). Additionally, while Lower Burma produced the quality of rice for external trade, the upland rice produced in Upper Burma was mainly used for internal consumption because it was barely sufficient for internal consumption in that region (Siok-Hwa 2012).

The main classes of rice produced in Burma during the British Colonial period were Emata, Letywezin, Ngasein, Meedon, and Byat rice varieties (Win 1991; Young et al. 1998). No modern rice varieties were used during this period in Burma as the high-yielding variety of rice

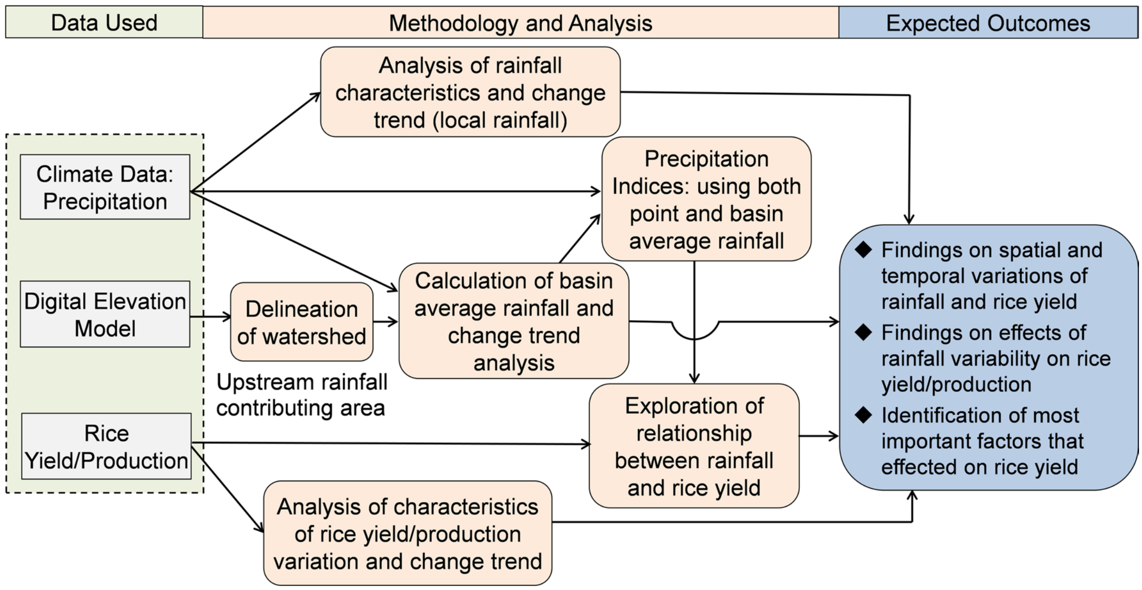

Fig. 5 Overview of the research methodology

(IR-8) was first introduced in Burma in 1967 (Win 1991; Young et al. 1998) (see Additional file 1: Figure S2). During the colonial period, fertilizer use was only limited to an experimental stage, and farmers mainly used domestic fertilizer such as cattle dung, fish waste, bat guano, rice bran, cotton cakes, and bone meal (Win 1991). The rice yield mainly depended on the fertility of the land and the distribution of rainfall amount in a particular area. The delta areas in Lower Burma had these favorable conditions for agriculture cultivation, and the highest rice yield could be obtained. The rice yield in the Upper Burma highly varied because some areas had irrigation, while others received insufficient rainfall (Win 1991). According to Siok-Hwa (2012), approximately half of the crops grown in the Upper Burma were cultivated under irrigated systems from canals, storage tanks, and lakes. For example, most crops were cultivated under canal irrigation in Mandalay, Kyaukse, Minbu, and Meiktila Districts. However, in Shwebo and Yamethin Districts, about half of the crops were cultivated under irrigation. Finally, while about two-thirds of the crops were rainfed in Pakokku, Sagaing, Bhamo, Katha, and Upper Chindwin Districts, crop cultivation was almost entirely rainfed in Thayetmyo, Lower Chindwin, and Myitkyina Districts (Siok-Hwa 2012).

5 Method

The rainfall variability and their impact on rice yield were analyzed for 1901–1939 based on the methodology (Fig. 5). First, spatial and temporal variability of rainfall and rice yield and variation in rice production were analyzed. Then, the relationship between different rainfall indices and rice yield was analyzed on the basis of multiple regression analysis. Finally, the effects of rainfall on rice yield and factors that affected the rice production in Burma during the colonial period were explored. In this study, the analyses were conducted at the district level. To explore the effects of rainfall on rice yield from the aspects of water shortage and floods, local rainfall at each district and area-averaged rainfall over the district, including the whole upstream contributing catchment areas (basin average rainfall over the catchment), were used. The details of the methodology are described in Sects. 5.1, 5.2 and 5.3.

5.1 Rainfall characteristics and variability analysis

Daily rainfall data were used to calculate the annual, seasonal, and monthly rainfall. First, annual rainfall and monthly average rainfall features in each zone (Coastal, Delta, Dry, and Hilly Zones) were calculated using rainfall data at stations located in each zone. Then, the changing trend in local seasonal rainfall (local point rainfall) and basin average rainfall during the crop growing season for each district was analyzed.

The rice crop could be affected by excessively low or high rainfall at any particular time within the crop growing season. To analyze the effect of rainfall shortage (low rainfall) on the rice crop production, daily rainfall at the station located in each district was used to calculate the local seasonal rainfall for each district. If there were more than one station in the district, rainfall at the station with no missing data or less missing data during monsoon was used. If there is no station in the district, rainfall data at the nearest station located in a neighboring district in the same zone were used. In Burma, the monsoon is from mid-May to late October (Matsumoto 1997), during which rice crop was cultivated, and rainfall amount during this period is essential for rice crop growing. Furthermore, the soil moisture in cropland areas before rice transplanting is an essential factor for rice crop cultivation. Therefore, local seasonal rainfall was calculated from May to October.

To analyze the effect of extremely high rainfall or flooding on rice crop yield, the rainfall distribution in the upstream drainage basin is necessary to be included in the analysis. Therefore, the basin average rainfall was calculated by delineating the upstream drainage basin for each district case. By using DEM, flow direction, and flow accumulation (30-arcsec spatial resolution) obtained from HydroSHEDS, the upstream drainage basin of the river, which passes through the district, was delineated in ArcGIS for each district. Then, daily basin average rainfall for each district was calculated using observed daily rainfall at the stations based on the Thiessen Polygon method. In Burma, rice crop was planted in July and harvested in October, and rice crop was affected by flooding during this period. Therefore, seasonal basin average rainfall was calculated from July to October.

The trend of local seasonal rainfall and seasonal basin average rainfall for each district case was calculated using MAKESENS 1.0 (Mann–Kendall test for trend and Sen's slope estimates) excel-based tool (Salmi et al. 2002) (https://en.ilmatieteenlaitos.fi/makesens). The MAKESENS tool calculates the changing trend based on the nonparametric Mann–Kendall test and the nonparametric Sen's method for the magnitude of the trend. The Mann–Kendall test (Mann 1945; Kendall 1975) is a nonparametric test and does not need the data to be normally distributed, and the test has low sensitivity to sudden breaks due to inhomogeneous time series and outliers (Koudahe et al. 2017; Ali and Abubaker 2019). The Mann–Kendall test is applicable to detecting a monotonic trend of a time series with no seasonal or other cycles (Salmi et al. 2002). The Sen's method (Sen 1968) uses a linear model for the trend and estimates the magnitude of trends in the time series. The spatial variability of rainfall was analyzed using a geographical information system (GIS) tool (ArcGIS). The variability in seasonal rainfall was also analyzed using the standardized rainfall anomaly which was calculated as follows.

$$\mathrm{RA}_i = (R_i - R_{\mathrm{mean}})/R_{\mathrm{SD}} \quad (1)$$

where RA_i is the standardized rainfall anomaly for year i, R_i is the annual or seasonal rainfall for year i, R_{mean} is the mean rainfall of time series, and R_{SD} is the standard deviation of time series.

5.2 Rice yield and production variation analysis

To understand variations in rice yield, first, average rice yield and its change trend in each zone were calculated for the period 1901–1939. Then, variations in rice crop area, rice-harvested area, rice yield, and rice production in each district were analyzed for the period 1901–1939 using district-level data. Based on this, the extremely low- and high-yield years were identified, and the rainfall variability in those years was analyzed to explore the effect of rainfall on rice yield. The spatial variations of rice yield/production were analyzed using GIS tools (ArcGIS). Further, the standardized rice yield anomaly was calculated in the same way as for rainfall (Eq. 1), and the correlation between the rice yield and rainfall anomalies was estimated for each district.

5.3 Analysis of relationship between rainfall and rice yield

The relationship between rainfall and rice yield for each district was explored using seasonal rainfall and other various rainfall indices (Table 2). To analyze the effect of rainfall shortage on rice crop, rainfall-related indices, such as seasonal local rainfall (SLR), the number of dry days (NDD), the maximum number of consecutive dry days (CDD), and maximum number of consecutive wet days (CWD) during monsoon, which was calculated using daily local rainfall, were used. Similarly, to analyze the effect of flooding on rice crops, seasonal basin average rainfall (SBR), number of heavy rainfall days (HRD), and 5-day maximum rainfall (5DR), which were calculated using basin average daily rainfall data, were used. The definition of each rainfall index is also indicated in Table 2. The seasonal rainfall provides information on the variability of interannual rainfall during the monsoon. The NDD provides data on total dry days during the monsoon. The maximum number of consecutive dry or wet days was used to characterize the length of dry or wet periods (Vincent and Mekis 2006; Wu et al. 2016). By referring to a previous research (Vinnarasi and Dhanya 2016), the dry day was defined as a day with rainfall less than 2.5 mm, while the wet day was defined as a day with rainfall of 2.5 mm or more rainfall. The number of HRD and 5-day maximum rainfall describe the features of extreme rainfall. The threshold for heavy rainfall day was used as the day with rainfall $\geq$ 20 mm (Wu et al. 2016; Pińskwar et al. 2019).

Regression analysis is a useful approach to analyze the relationship between dependent and independent variables. In this study, multiple regression analyses were conducted to determine the relationship between rice yield and features of the rainfall indices indicated in Table 2,

Table 2 Various rainfall indices and their definition

Rainfall Index	Definition	Unit	Remarks
For rainfall shortage effect: extracted using local rainfall			
Seasonal local rainfall (SLR)	Total amount of rainfall during monsoon season (May to October)	mm	
Number of dry days (NDD)	Number of days with daily rainfall < 2.5 mm during monsoon season (May to October)	day	Vinnarasi and Dhanya (2016)
Maximum consecutive dry days (CDD)	Maximum number of consecutive dry days during monsoon season (May to October). The dry day is defined as the day with rainfall < 2.5 mm	day	
Maximum consecutive wet days (CWD)	Maximum number of consecutive wet days during monsoon season (May to October). The wet day is defined as the day with rainfall ≥ 2.5 mm	day	
For flooding effect: extracted using basin average rainfall			
Seasonal Basin average rainfall (SBR)	Total amount of basin average rainfall during crop growing period (July to October)	mm	
Number of heavy rainfall days (HRD)	Number of days with daily basin average rainfall ≥ 20 mm during crop growing period (July to October)	day	Wu et al. (2016), Pińskwar et al. (2019)
5-day maximum rainfall (5DR)	Maximum 5-day basin average rainfall (during July to October)	mm	

which is widely used in previous researches for analyzing the relationship between crop yield and climate variables (e.g., Jayakumar et al. 2016; Pheakdey et al. 2017; Sitienei et al. 2017; Panda et al. 2019). Multiple regression analysis is useful to determine the relationship between the dependent variable and many independent variables and the importance of each independent variable to the relationship.

6 Results

6.1 Characteristics and variability of rainfall

Figure 6a indicates the variability of annual rainfall at the stations located in each zone of Burma from 1901 to 1939. The annual rainfall in the Coastal Zone was comparatively higher (more than 4000 mm at most of the stations) than in other areas. The annual rainfall amount mostly ranges from 2000 to 3000 mm in the Delta Zone, from 700 to 1300 mm in the Dry Zone, and from 1500 to 2200 mm in the Hilly Zone. Figure 6b indicates the average monthly rainfall from 1901 to 1939 for each zone. The monthly rainfall amount was also comparatively high in the Coastal Zone than in other areas, and less in the Dry Zone. The monthly average rainfall in Dry Zone was below 200 mm in the months. Figure 6b indicates that the rainfall mainly occurred from May to October in all zones.

Figure 7 indicates spatial pattern of change trend of seasonal local and basin average rainfall. The changing trends in seasonal local and basin average rainfall for the selected districts in the period from 1901 to 1939 are presented in Additional file 1: Figs. S3 and S4, respectively. The detailed statistics summary of change trend analysis of rainfall for all districts is presented in Additional file 1: Table S6. There was a clear interannual variation in the rainfall in each district. SLR positively varies over time at 25 districts out of 37 districts, while the SBR positively varies over time at 32 districts out of 37 districts, i.e., most of the districts experienced an increase in seasonal rainfall for the period 1901–1939. However, the increasing trend of local rainfall over time was statistically significant with a significant level of 5% (two-tailed test) only in six districts, while the increasing trend of basin average rainfall was statistically significant with a significance level of 5% or 10% (two-tailed test) in 14 districts (Additional file 1: Table S6), which were located in the Delta and Dry Zones.

6.2 Variations in rice yield and production

Figure 8a indicates the spatial pattern of the average value of rice yield from 1901 to 1939. The rice yield was highest in the Delta Zone than in other zones because this zone had favorable soil and rainfall conditions for rice crop cultivation than in other areas. As expected, this zone had an average rice yield that was > 1500 kg/ha in all the districts where Gleysols were widely distributed, except in Insein, and > 1800 kg/ha rice yields in Myaungmya (2000 kg/ha), Henzada (1869 kg/ha), and Tharrawaddy (1889 kg/ha) Districts. The lowest rice yield was obtained in Insein District (1424 kg/ha). Furthermore, while the average value of district-level rice yield in the Coastal Zone varied from 1360 kg/ha in the Arakan District to 1710 kg/ha in the Sandoway District, the rice yield was > 1500 kg/ha in the Sandoway (areas with Cambisols and Fluvisols), Akyab (areas with Gleysols and Cambisols), and Mergui (areas with Acrisols and Nitosols) Districts. It was also observed that although the

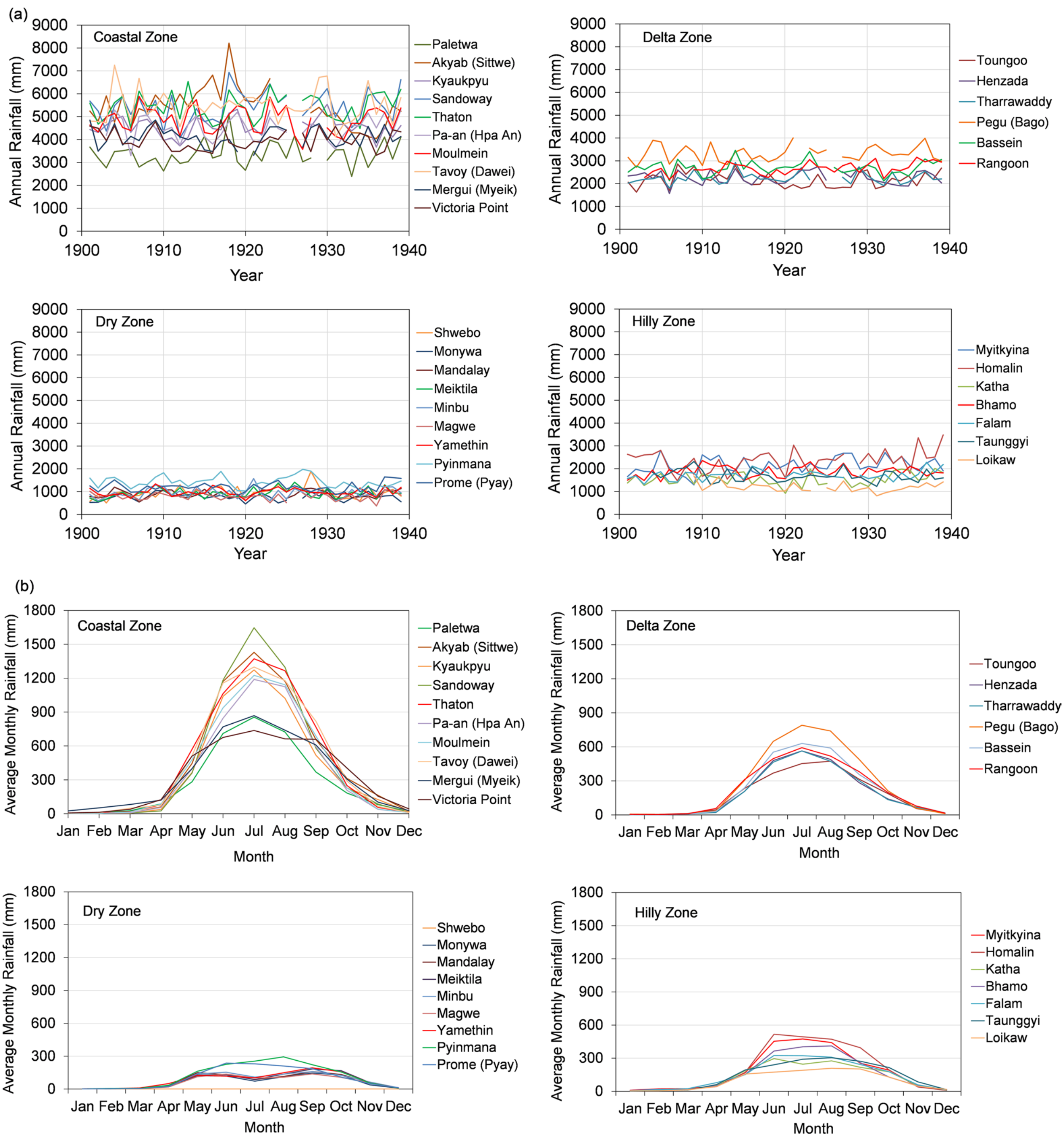

Fig. 6 Rainfall characteristics in the Coastal, Delta, Dry, and Hilly Zones of Burma from 1901 to 1939: **a** annual rainfall and **b** average monthly rainfall

average rice yield was much higher in the Mergui District, low fertile soils (Acrisols and Nitosols) are widely distributed in the district. Along the seacoast in the Amherst and Thaton Districts of the Coastal Zone were high-yielding areas; however, crop damage from flooding of the Salween River led to low yields in many of the inland areas, reducing the average value of rice yield for these districts (Siok-Hwa 2012). Alternatively, rice yield was lowest in the Dry Zone. A study observed that while there were high variations in rice yield of the Dry Zone because some areas in this zone had irrigation systems (large-scale irrigation systems developed by the Burmese King and small-scale irrigation systems constructed by local people, such as small diversions, wells, and ponds),

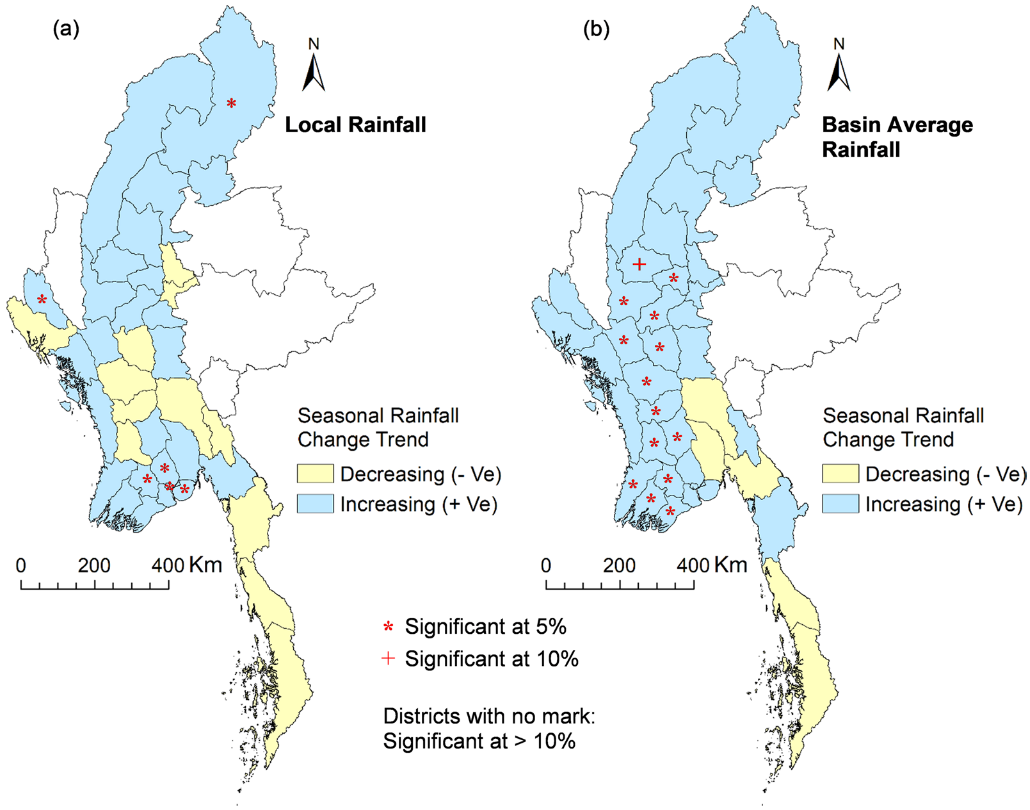

Fig. 7 Spatial pattern of the change trend of seasonal **a** local rainfall and **b** basin average rainfall from 1901 to 1939 (with significance level of two-tailed test)

other areas received little rainfall (Win 1991). The district-level rice yield in the Dry Zone varied from 702 kg/ha in the Myingyan District to 1828 kg/ha in the Minbu District. Additionally, the highest yield in the Dry Zone was obtained in the Minbu District, where the soil types were Cambisols, Gleysols, and Luvisols, and most of the crops were cultivated under an irrigation system. Moreover, the average value of rice yield in the Dry Zone was higher in Mandalay (1608 kg/ha) and Kyaukse (1726 kg/ha) Districts, where Vertisols, Luvisols, and Acrisols were distributed, and most of the crops were cultivated under an irrigation system. In contrast, the average value of rice yield was 950 kg/ha in the Meiktila District, even though the crops were cultivated under irrigation and in good-fertile soils (Gleysols, Luvisols, and Vertisols). One possible reason for such lower rice yield in the Meiktila District was crop damage due to flooding in the areas. We also observed that the average values of rice yield in Shwebo (areas with mostly Vertisols, Gleysols, and Luvisols) and Yamethin (areas with Gleysols, Luvisols, and Nitosols), where half of the crops were cultivated under irrigation, were 1258 and 1313 kg/ha, respectively. In contrast, the average value of rice yield in the Hilly Zone varied from 1243 kg/ha in the Salween District (areas with Acrisols) to 1758 kg/ha in the Myitkyina District (areas with Gleysols and Acrisols). Nevertheless, the rice yields in Upper Burma were considerably lower than that in Lower Burma, mainly due to insufficient water supply in Upper Burma (Siok-Hwa 2012).

Figure 8b indicates the changing trend of average rice yield over the period from 1901 to 1939 for each zone, and rice yields in all zones show the long-term reducing trend during the study period. The long-term reducing trend of rice yield in all areas was statistically significant at 0.1% significance level of two-tailed test.

Figure 9 indicates the variation of the rice crop planted area, rice-harvested area, and rice yield for selected districts from each zone for the study period. The crop areas were rapidly expanded in the Delta and Coastal Zones in the Lower Burma than in other areas where the annual or seasonal rainfall amount was sufficiently higher than the water requirement for the rice crop cultivation. Rice production and yield fluctuated depending on the behavior of monsoon rainfall and its distribution pattern. Particularly in the years 1919 and 1923, there was a large reduction in rice yield in some districts located in the

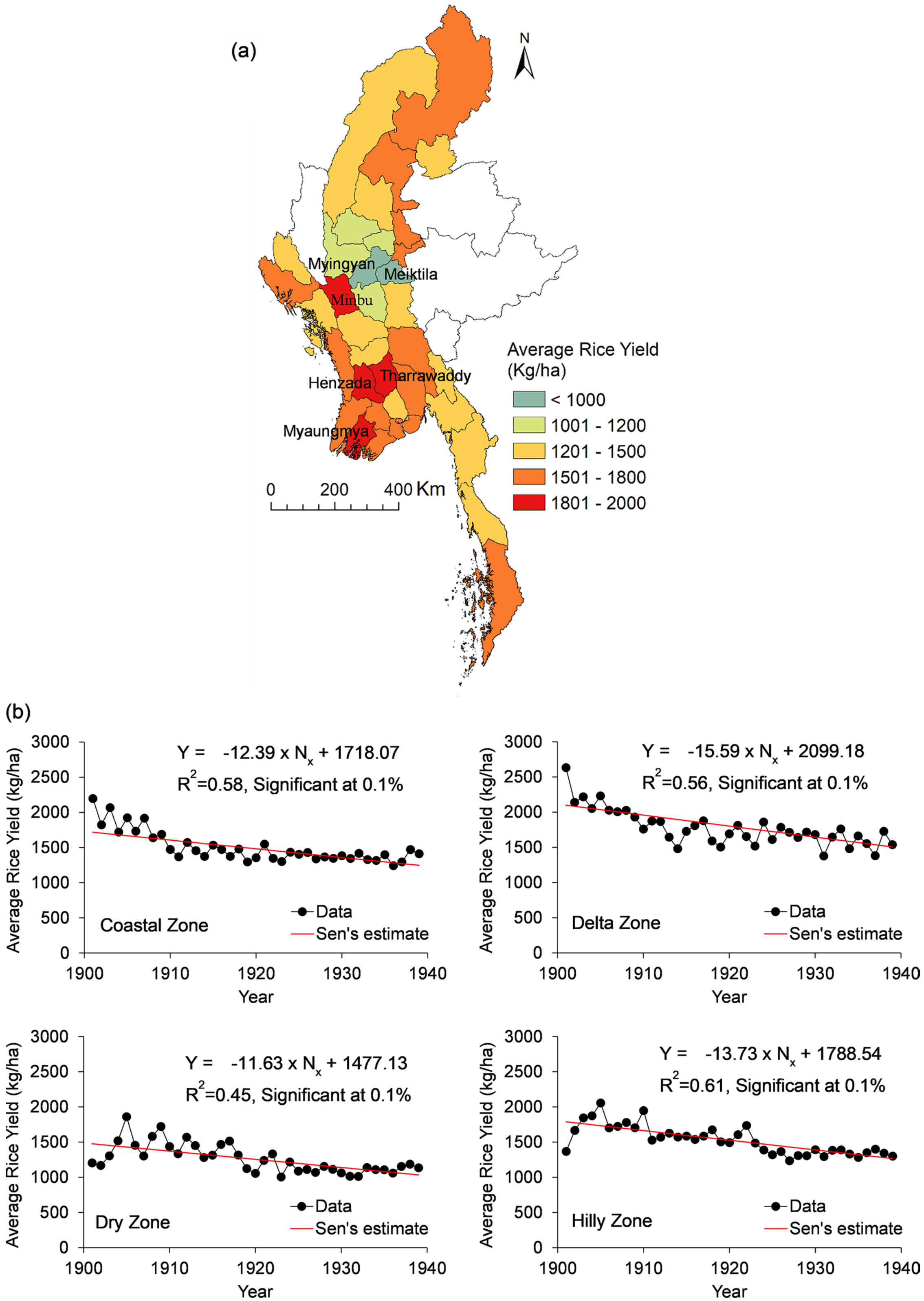

Fig. 8 **a** Spatial pattern of the average value of rice yield from 1901 to 1939 and **b** change trend of average rice yield over the time during the period for 1901–1939 for the Coastal, Delta, Dry, and Hilly Zones (Nx = Year—First Data Year) (with significance level of two-tailed test)

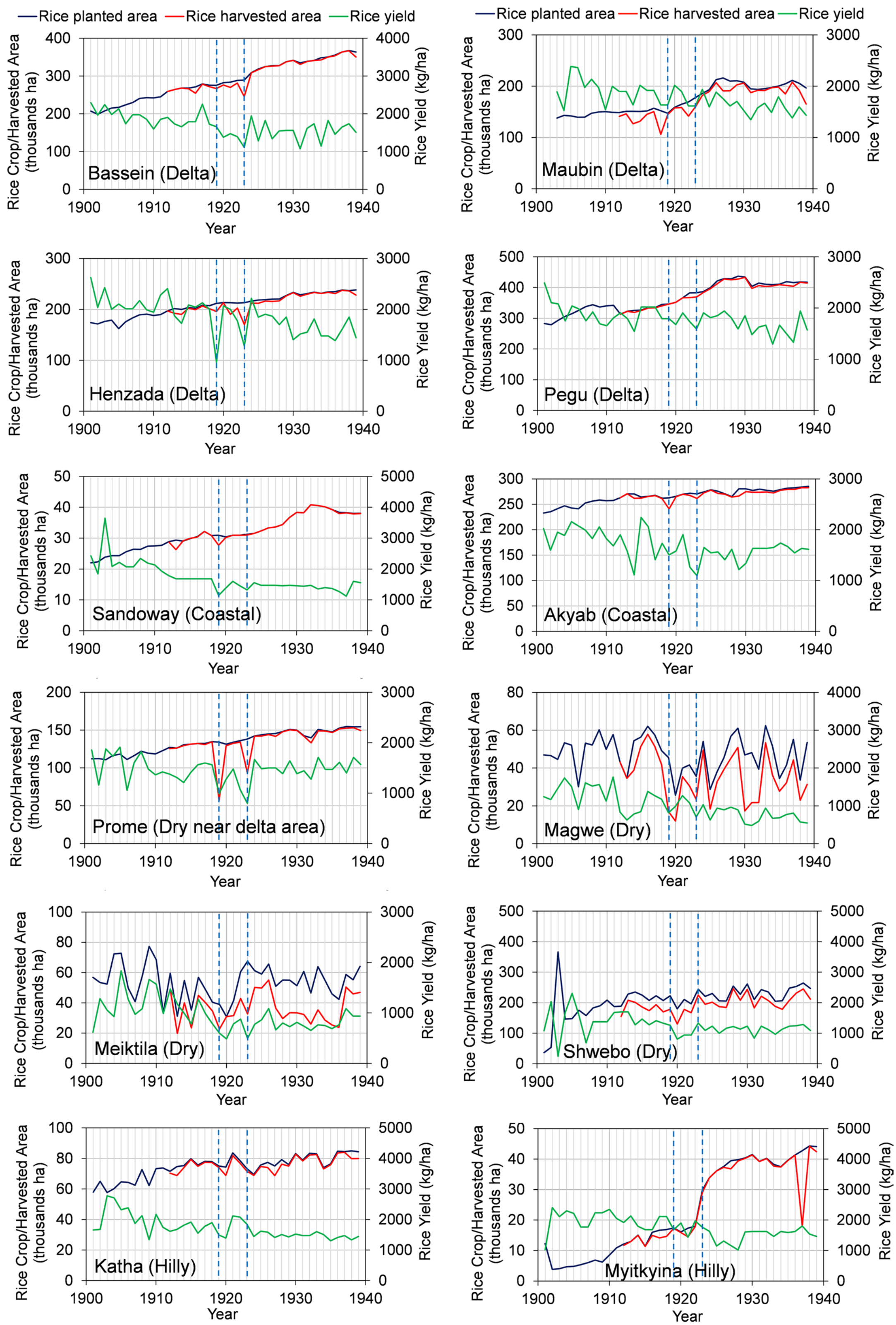

Fig. 9 Variation of planted and harvested cropland areas and rice yield for selected districts (blue vertical dashed line: years (1919 and 1923) in which there was a large reduction in rice yield at some districts located in Coastal, Delta, and Dry Zones)

Coastal, Delta, and Dry Zones. The rice-harvested areas were also lower than the rice crop planted areas in the years 1919 and 1923 in the zones. The difference between planted and harvested rice areas likely depends on the zone. In the districts located in the Dry Zone except for Prome District and some districts of the Hilly Zone, the rice-harvested area was usually lower than the rice crop planted area, and a reason for such lowering in rice-harvested area was insufficient amount of rainfall in the zone for rice cultivation. The occurrence of continuous rainfall during the early growth period of the rice plant often caused floods in the areas, which reduced rice yield and production (Win 1991). In some years, the reduction in rice yield was caused by the occurrence of less rainfall in a particular area.

Figure 10 indicates the interannual variations and trends of rice yield over the period from 1901 to 1939 for the selected districts, and summary statistics of the trend analysis are indicated in Additional file 1: Table S7. Figure 11 indicates the spatial pattern of change trend of rice yield with a statistically significant level (0.1% or 1% or 5% or 10%) (two-tailed test). The

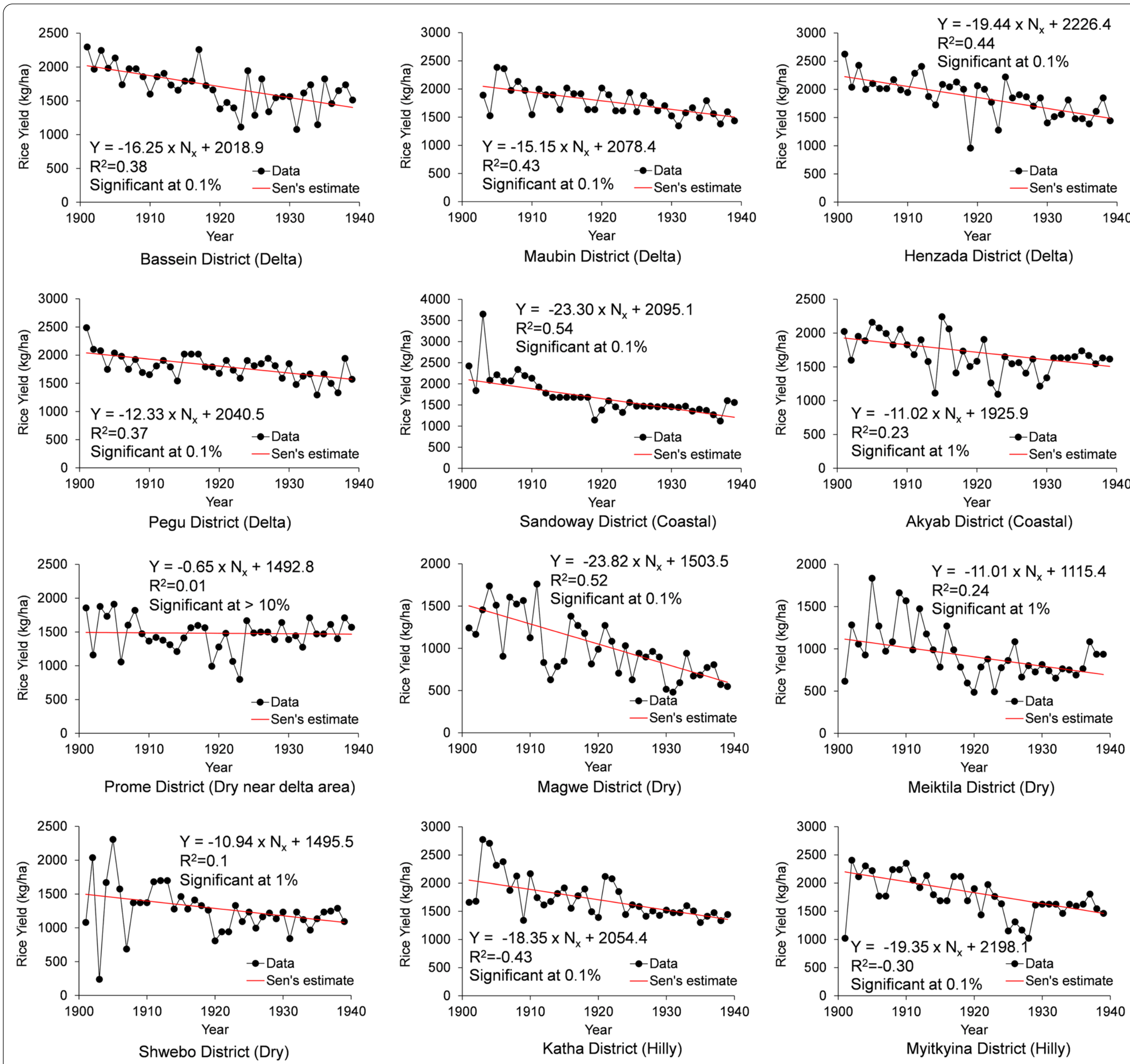

Fig. 10 Interannual changes and change trend of rice yield over the period for 1901–1939 for selected districts (Nx = Year – First Data Year) (with significance level of two-tailed test)

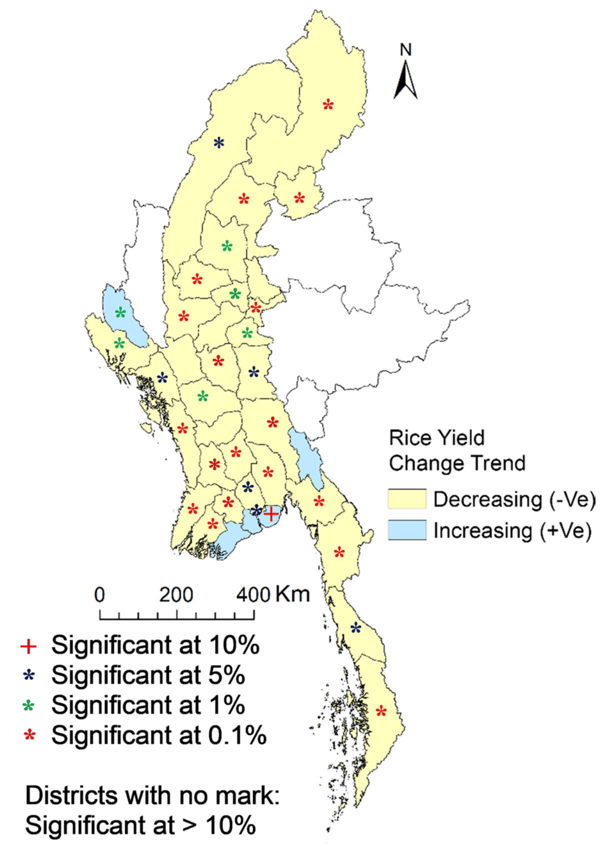

Fig. 11 Spatial pattern of change trend of rice yield during the period for 1901–1939 (with significance level of two-tailed test)

changing trend was statistically significant with a significance level of 0.1% or 1% or 5% or 10% at 31 districts. The results of trend analysis indicate that 33 districts out of 37 districts experienced a decrease in rice yield for 1901–1939. The rice yield increased in trend only in four districts (Arakan, Hanthawaddy, Pyapon, and Salween). The rice yield mainly depended on the fertility of the land and the amount and distribution of rainfall in a particular area. The reducing trend of rice yield over the years in Burma during the colonial period was attributed to several reasons, such as variability of seasonal and monthly rainfall and other environmental factors during the crop growth period, the estimation of rice yield covering wider areas representing various types of soil and climate with the years, and reaching the minimum fertility rate of the land after several years of rice cultivation. During this period, cropland areas for rice cultivation were expanded by clearing swamps, grasslands, and forest areas, and the fertility of such lands possibly became the minimum level after many years of cultivation. Even though rice yield tended to decrease during the study period, rice production remarkably increased due to the rapid expansion of cropland areas for rice cultivation.

Figure 12 shows the cross-plot between rainfall and rice yield anomalies with their linear tendency. The linear regression analysis statistics are also indicated in Additional file 1: Table S8. The results showed that rice yield anomaly positively varied with rainfall anomaly in all dry and hilly zone districts, except Salween District in the Hilly Zone. We also observed that rice yield anomaly negatively varied with rainfall anomaly in four (Amherst, Thaton, Sandoway, and Akyab) of eight districts in the Coastal Zone and seven (Rangoon, Pyapon, Myaungmya, Bassein, Maubin, Insein, and Pegu) of 11 districts in the Delta Zone. There were also some rice yield variation tendencies due to rainfall deviation, such as a reduction in rice yield when rainfall is lower than the average rainfall, particularly in most dry and hilly zone districts or higher than the average rainfall in more than half of the districts located in the Delta and Coastal Zones. However, the linear relationship between rice yield and rainfall anomalies was statistically significant, with a significance level (p-value using two-tailed test) of 5% or 10% only in the Sandoway District (areas with mostly Cambisols) in the Coastal Zone; Insein District (areas with Gleysols and Nitosols) in the Delta Zone; Prome (areas with Gleysols and Nitosols), Thayetmyo (areas with mostly Luvisols and Cambisols), Meiktila (areas with Gleysols, Luvisols, and Vertisols), and Myingyan (areas with Luvisols) Districts in the Dry Zone; and Bhamo District (areas with Gleysols and Acrisols) in the Hilly Zone. The annual variation in rainfall and rice yield anomalies with their 5-year moving average values is presented in Additional file 1: Figure S5. The characteristics of rainfall and rice yield anomalies were completely different. The rainfall anomaly widely differs from period to period; however, results of rice yield anomaly clearly show the distinction of the period with higher or lower rice yield than average rice yield. Rice yield tended to decline after 1910 in most districts (Win 1991; Okamoto 1998). Mostly higher than average rice yield was observed before 1910 in the Coastal Zone and before 1918 in other zones, while mostly lower than average rice yield was observed after 1910 in the Coastal Zone and after 1918 in other zones. Moreover, during the latter part of the study period, the reduction in rice yield was possibly due to the variability of various environmental factors and the expansion of cropland areas with less favorable environments.

6.3 Exploration of relationship between rainfall and rice yield

The summary results of multiple regression analysis with slope coefficient, constant, significance level, and t-stat values of each rainfall index are indicated in Additional

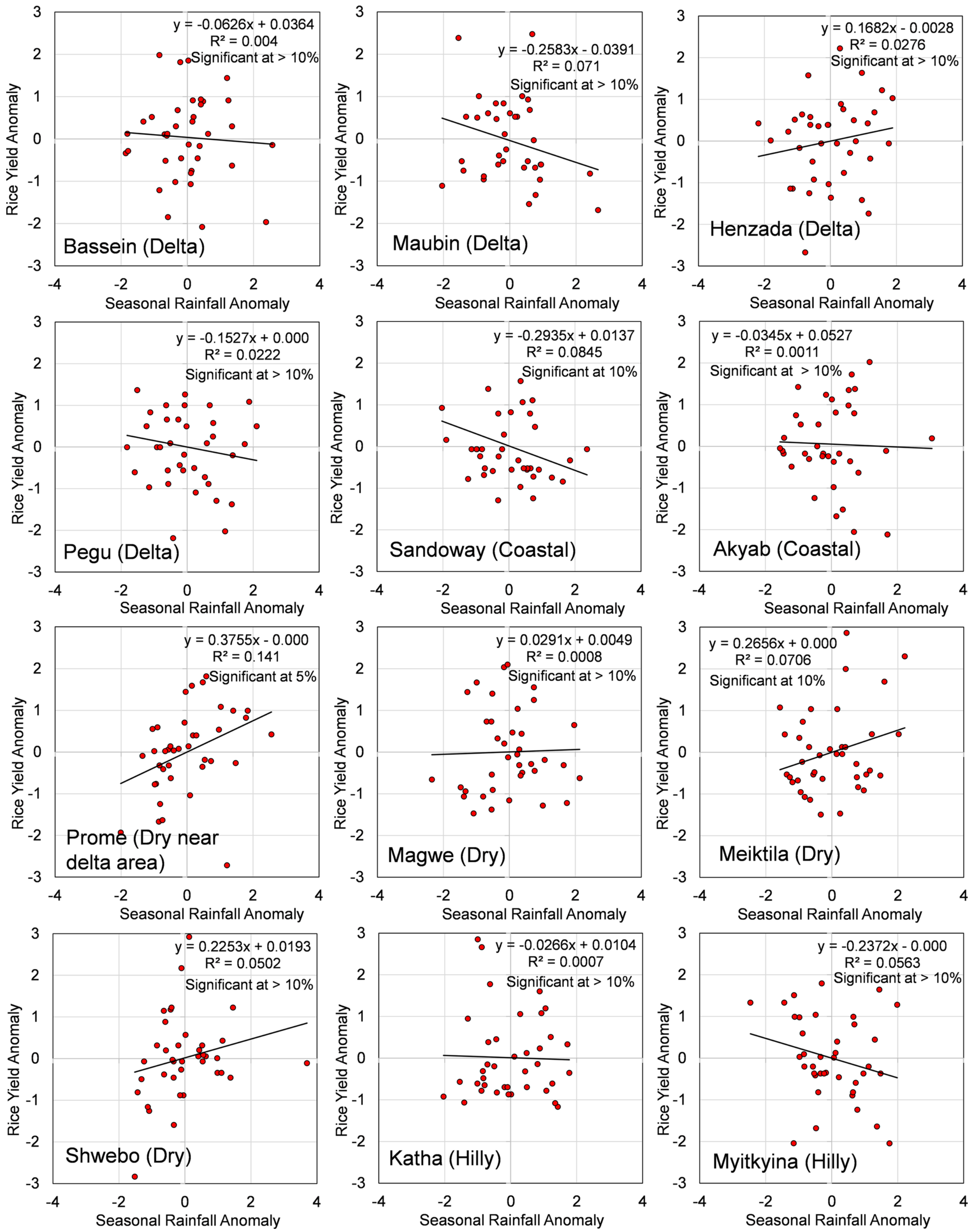

Fig. 12 Cross-plots between rice yield and seasonal local rainfall anomalies with their linear regression trend for selected districts (with significance level of two-tailed test)

file 1: Table S9 for all districts. The *t*-stat values with bold in Additional file 1: Table S9 are statistically significant variables (at 10% or 5% or 1% or 0.1% significance level of two-tailed test). The results of multiple regression analysis indicate that the rice yield varied negatively with SLR, NDD, CDD, CWD, and SBR at most of the districts located in the Coastal Zone. In contrast, rice yield varied positively with HRD and 5DR. In Delta and Hilly Zones, rice yield varied negatively with all rainfall indices at most of the districts. In the Dry Zone, rice yield correlated positively with SLR and SBR and negatively with NDD, CDD, CWD, HRD, and 5DR at most of the districts, respectively. The results show that the flood-related indices, such as SBR, HRD, and 5DR, had both positive and negative effects on rice production, i.e., rice yield varied negatively with those indices at some districts and positively varied in some other districts. The rice yield negatively or positively varied with rainfall indices. We observed that the relationship between rice yield and each rainfall index was statistically significant, with a significance level of 0.1% or 1% or 5% or 10% (two-tailed test) in the districts presented in Table 3. The SLR was statistically significant, with a significance level of 10% only in the Bhamo District in the Hilly Zone. Similarly, the NDD was statistically significant, with a significance level of 5% or 10% in the Tavoy District of the Coastal Zone; Hanthawaddy, Tharrawaddy, and Toungoo Districts of the Delta Zone; Meiktila and Mandalay Districts of the Dry Zone; and the Katha District of the Hilly Zone. Furthermore, while CDD was statistically significant, with a significance level of 1% or 10% in the Pegu and Toungoo Districts of the Delta Zone and the Bhamo District of the Hilly Zone, the CWD was statistically significant, with a significance level of 10% only in the Rangoon District in the Delta Zone. Results also showed that the HRD was statistically significant, with a significance level of 5% or 10% in Sandoway and Kyaukpyu Districts of the Coastal Zone; Magwe District of the Dry Zone; and then Salween and Katha Districts of the Hilly Zone. Likewise, 5DR was also statistically significant, with a significance level of 5% or 10% in Amherst and Kyaukpyu Districts of the Coastal Zone; Bassein District in the Delta Zone; and Bhamo District in the Hilly Zone (see Table 3 and Additional file 1: Table S9).

The relationship between rice yield and annual rainfall variability with various rainfall indices was analyzed using multiple regression analysis, and the effect of annual rainfall variability on rice production was explored. However, the monthly variability of rainfall during the crop growth period in the years may significantly impact on rice yield because the amount and distribution of rainfall in a particular year determine the success or failure of rice crop production. Rice crop yields will boost significantly if the precipitation occurs at the right times and in the right amounts. To explore the monthly variability of rainfall in the years, the monthly rainfall during monsoon for rice yield failure or success years was analyzed. Figure 13 indicates the variation of monthly rainfall for crop failure years for the selected districts. (Blue bar diagram in the figure is the average of the period 1901–1939.) From the results, we observed that the monthly rainfall that resulted in years of crop failure was usually either comparatively higher during the crop growth period (particularly in July and August) than the average monthly rainfall of period 1901–1939 or less during the early or latter half of crop growth (Fig. 13). For example, there was a higher rainfall between July and August in most districts of the Coastal and Delta Zones in 1923 (e.g., Bassein, Maubin, Henzada, Pegu, Sandoway, Akyab, and Prome (near delta area) Districts in Fig. 13). Contrastively, in 1919, less rainfall was observed during the latter growth stage of rice crops in most districts. Investigations also showed that some districts experienced rice crop failure due to less rainfall during the early or middle stage of crop growth in some years (e.g., Maubin, Pegu, Meiktila, Shwebo, and Katha Districts in

Table 3 District with a statistically significant relationship between rice yield and rainfall indices

Rainfall indices	District with statistically significant relationship between rice yield and rainfall indices (significance level of two-tailed test)
Seasonal local rainfall (SLR)	Bhamo (10%)
Number of dry days (NDD)	Tavoy (10%), Hanthawaddy (10%). Tharrawaddy (5%), Toungoo (10%), Meiktila (10%), Mandalay (10%), Katha (5%)
Maximum consecutive dry days (CDD)	Pegu (1%), Toungoo (10%), Bhamo (10%)
Maximum consecutive wet days (CWD)	Rangoon (10%)
Seasonal Basin average rainfall (SBR)	–
Number of heavy rainfall days (HRD)	Sandoway (5%), Kyaukpyu (10%), Magwe (5%), Salween (5%), Katha (10%)
5-day maximum rainfall (5DR)	Amherst (5%), Kyaukpyu (10%), Bassein (5%), Bhamo (5%)

Details of summary results of multiple regression analysis are presented in Additional file 1: Table S9

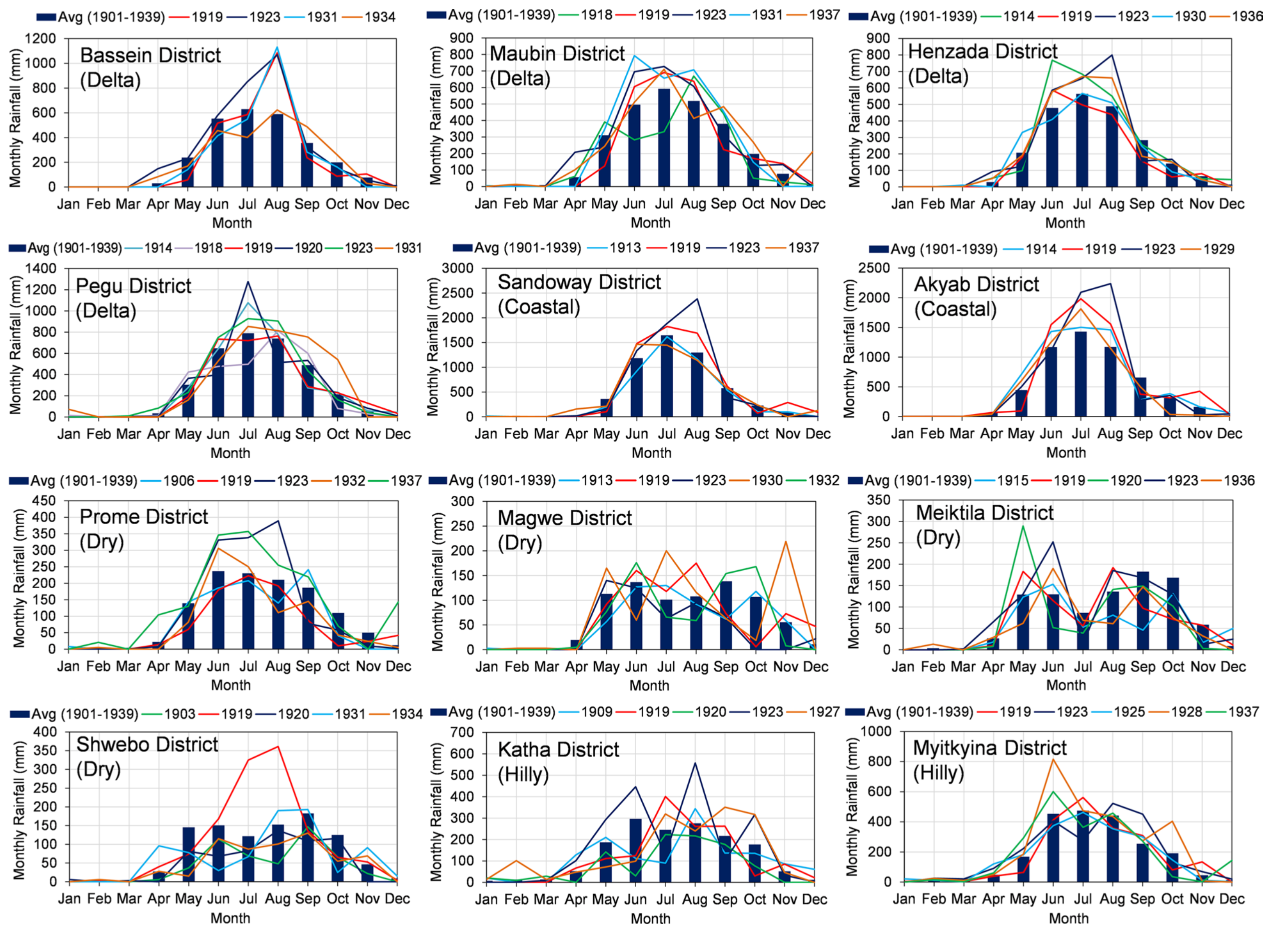

Fig. 13 Monthly variability of rainfall in crop failure years

1918 or 1920). However, other districts had higher rainfall during the early growth stage and less rainfall during the latter growth stage of the rice crop in 1919 (e.g., Bassein, Maubin, Sandoway, Akyab, and Shwebo Districts in Fig. 13). Additionally, while higher rainfall during crop growth often triggered flooding, which reduced production as a result, lesser rainfall during crop growth also reduced rice production. The monthly distribution of rainfall for crop success years (years with higher yields than the average value of rice yield from 1901 to 1939) is indicated in Additional file 1: Figure S6. Furthermore, we observed that the amount of monthly rainfall during the crop growth period for crop success years was usually closer to the average value of 1901–1939 in most districts located in the Delta and Coastal Zones and some districts in the Hilly Zone. These results confirmed that the monthly distribution of rainfall within a particular year determines the influence of rainfall on rice production. Thus, it is vital to analyze the impact of monthly rainfall on rice yield and production. Previous researches reported that continuous rain during the early growth period of the rice plant often caused floods, reducing rice production in Burma (Win 1991). The reduction in rainfall amount could cause negative consequences on rice production, particularly in the Dry and Hilly Zones of Burma.

7 Discussion and conclusions

This study evaluated the spatial and temporal variabilities of rainfall and their effects on rice production in Burma during the colonial period, considering the differences in soil types and fertility depending on region, the differences in cultivation methods such as planting and irrigation, and the differences in rice varieties. Furthermore, it analyzed the effects of rainfall variability on rice production from multiple rainfall characteristics perspectives, such as seasonal rainfall, various rainfall indices, rainfall anomalies, and monthly rainfall variability. Our findings showed that the expansion of crop land areas or rice production in Burma was largely dependent on climatic zones and soil-type distribution (e.g., districts with Gleysols or Gleysols and Fluvisols in the Delta Zone; Gleysols and Cambisols in the Coastal Zone; and Gleysols, Vertisols, and Luvisols in the Dry Zone) (Figs. 2b and 4).

Additionally, we observed that while annual and monthly rainfall in the Coastal Zone was comparatively higher than in other zones where rainfed-lowland and deep-water rice were cultivated (Fig. 6), the Dry Zone received less rainfall where rainfed-lowland, irrigated-lowland, and upland rice productions were concentrated (Fig. 6). Moreover, during the study period (1901–1939), increased seasonal rainfall trends in most Burma districts were observed (Fig. 7 and Additional file 1: Table S6); precisely, strong increasing trend of seasonal local and basin average rainfall with a significance level of 10% or less (using the two-tailed test) was observed in six and 14 districts, respectively (Fig. 7 and Additional file 1: Table S6), mostly located in the Dry and Delta Zones. Furthermore, we observed that rice yield was decreasing in trend during the study period in most districts (Figs. 10 and 11; and Additional file 1: Table S7), which started to decline after 1910 in most districts (Fig. 9 and Additional file 1: Fig. S5). The decreasing trend in rice yield was statistically significant, with a significance level of 0.1% or 1% or 5% or 10% (with a two-tailed test) in most districts (Fig. 11 and Additional file 1: Table S7). Nevertheless, higher rice yield was usually observed in most districts when the rice crop was widely cultivated in recently or newly cleared lands, particularly before 1910 (Fig. 9 and Additional file 1: S5). Therefore, the higher yield was possibly due to higher land fertility on recently or newly cleared lands. However, the decrease in rice yield may be due to the variability of monthly rainfall during crop growing period such as excessively low or high rainfall during the crop growing period and the variability of other environmental factors. Based on these findings, we establish that although rice production increased rapidly because of the expansion of rice crop areas, there was a declining trend in rice yield.

Investigations also revealed that although the annual or seasonal rainfall in the Coastal and Delta Zones was comparatively higher than the water requirement for rice crop cultivation, excessive continuous rainfall during the rice growth period may cause frequent flooding in paddy areas and damage to rice crops. The reduction in rice yield was observed in most districts located in the Coastal and Delta Zones when monthly rainfall between July and August was comparatively higher than the average rainfall (e.g., in 1923) (Fig. 13). However, less rainfall during the early-middle or latter half periods of crop growth reduced the rice yield (Fig. 13). Specifically, while the lack of rainfall during the latter stage of crop growth possibly caused the rice yield reduction of most districts in 1919, the rice yield reduction of some other years (e.g., in 1918, 1920) in some districts was possibly due to less rainfall during the early or middle stage of crop growth (Fig. 13). Furthermore, we observed variability in spatial rainfall distribution patterns over the affected rice production areas. Accordingly, recent studies highlighted that rice production depended on rainfall patterns in the Ganges–Brahmaputra–Meghna River basin (Asada and Matsumoto 2009; Matsumoto and Asada 2020) and the Odisha region, India (Panda et al. 2019).

Our investigation showed that the rice yield anomaly varied positively with rainfall anomaly in all the dry and hilly zone districts, except the Salween District in the Hilly Zone (Fig. 12 and Additional file 1: Table S8). This finding indicated higher yield when rainfall amount was higher in the Dry and Hilly Zones. Contrastively, while rice yield varied negatively with rainfall anomalies in most districts of the Delta and Coastal Zones (Fig. 12 and Additional file 1: Table S8), the linear relationship between rice yield and rainfall anomalies was statistically significant, with a significance level of 5% or 10% (with a two-tailed test) in only seven districts (Additional file 1: Table S8), primarily located in the Dry Zone.

Multiple regression analysis results showed that while the effect of selected rainfall indices affected the rice yield positively or negatively, depending on climatic zones, the magnitude of their effect varied immensely from one district to another. These results indicate that relationship between rice yield and rainfall index used in this study was statistically significant, with a 1% or 5% or 10% significance level of two-tailed test in 16 of 37 districts (at least one or more significant rainfall indices) (Tables 3 and Additional file 1: S9). We also observed that while the SLR affecting the rice yield was statistically significant, with a significance level of 10% only in the Bhamo District of the Hilly Zone, the NDD affecting the rice yield was statistically significant, with a significance level of 5% or 10% in the Tavoy District of the Coastal Zone; Hanthawaddy, Tharrawaddy, and Toungoo Districts of the Delta Zone; Meiktila and Mandalay Districts of the Dry Zone; and the Katha District of the Hilly Zone. Furthermore, although the CDD affecting the rice yield was statistically significant, with a significance level of 1% or 10% in the Pegu and Toungoo Districts of the Delta Zone and the Bhamo District of the Hilly Zone, the CWD affecting rice yield was statistically significant, with a significance level of 10% only in the Rangoon District of the Delta Zone. Moreover, while the HRD affecting rice yield was statistically significant, with a significance level of 5% or 10% in the Sandoway and Kyaukpyu Districts of the Coastal Zone; the Magwe District of the Dry Zone; and the Salween and Katha Districts of the Hilly Zone, 5DR that affects rice yield was statistically significant, with a significance level of 5% or 10% in the Amherst and

Kyaukpyu Districts of the Coastal Zone; Bassein District of the Delta Zone; and the Bhamo District of the Hilly Zone. In comparison, researches during recent periods reported that the relationship between rainfall and rice production was not statistically significant in Mali (Dembélé 2015), Assam in India (Nath and Mandal 2018), Nigeria (Tiamiyu et al. 2015), and Benin (Agnontcheme 2018). However, some other studies discovered a significant relationship between rainfall and rice crop production in the Punjab Province of Pakistan (Mohmood et al. 2012), India (Farook and Kannan 2015; Panda et al. 2019), Northwest Ethiopia (Molla et al. 2020), and other parts of Nigeria (Adedeji et al. 2017).

Our findings also revealed that rainfed rice yield in Burma depended greatly on rainfall amount and fertile soil distribution. Specifically, a higher rice yield was observed in the Delta Zone where Gleysols (good-fertile soils) were widely distributed, and rainfall amount was sufficiently higher than the water requirement for crop cultivation. However, the rice yield in the Dry Zone varied greatly, depending on the amount of rainfall, availability of irrigation system, and soil-type distribution. Some districts with Vertisols and partially or mostly irrigated areas also produced higher rice yields in the Dry Zone. This study confirmed that it is vital to examine not only the interannual variability of rainfall and their related rainfall indices, but also the impact of variability of monthly rainfall on rice yield and production. Furthermore, we observed that monthly distribution of rainfall within a particular year determined the influence of rainfall on rice production. Particularly, monthly rainfall during crop failure years was either significantly higher (in the early-middle stage of crop growth) or less (in the early-middle or latter part of crop growth), indicating the variability of monthly rainfall during the crop growing period as one of the factors that significantly affect the rice yield. Riad and Peter (2017) highlighted that short-term climate variability (extreme climate events) was more likely to reduce rice production in Suriname. Based on our findings, some of the possible reasons for the decline in rice yield during the study period (1901–1939) could be variability in seasonal rainfall, variability in monthly rainfall during the crop growth period, and crop cultivation under different soil and climate conditions in the same district.

This study focused on analyzing rainfall effects on rice production for the historical period from 1901 to 1939. There were fewer human interventions on the catchment and almost no use of chemical fertilizers or high-yielding rice varieties in the study area. Therefore, the impact of rainfall variation on rice production may be better understood from this historical period, enabling us to clearly understand the relationship between rainfall and rice yield. Our findings can also be useful to understand the capacity of agriculture to adapt to rainfall variability.

Other climatic factors, such as temperature and relative humidity, which may also influence rice yield, including effects of socioeconomic (e.g., land tenancy/ownership, availability of labor, capital, accessibility to markets) and political (e.g., rice policies of the government, policies on marketing and international trade, subsidies, loan policy, tax policy) factors were not considered in this study, which needs to be explored in the future. Furthermore, although the average rice yield for each district was used in the analysis because of limited data availability for the study period, we observed that rice crop was cultivated under different rice ecosystems or rice varieties in some districts (e.g., rainfed-lowland and deep-water rice cultivation in some delta and coastal zone districts, including rainfed-lowland and irrigated-lowland rice cultivation in some dry zone districts). Therefore, rice yield may vary depending on rice cultivation systems or rice varieties, which needs to be considered, particularly in the districts where rice crops were cultivated under different rice cultivation ecosystems. Furthermore, because soil fertility is an important factor in enhancing crop productivity, more detail analyses considering impact of soil fertility on rice productivity can further enhance our understanding of the factors that affect rice productivity.

Abbreviations

DMH: Department of Meteorology and Hydrology ; UNEP: United Nations Environment Programme; IFDC: International Fertilizer Development Center; ICEM: International Centre for Environmental Management; NOAA: National Oceanic and Atmospheric Administration, USA; IITM: Indian Institute of Tropical Meteorology; KNMI: Royal Netherlands Meteorological Institute; FAO/UNESCO: Food and Agriculture Organization/United Nations Educational, Scientific and Cultural Organization; DEM: Digital elevation model; GIS: Geographical information system; SLR: Seasonal local rainfall; NDD: The number of dry days; CDD: The maximum number of consecutive dry days; CWD: Maximum number of consecutive wet days during monsoon; SBR: Seasonal basin average rainfall; HRD: Number of heavy rainfall days; 5DR: 5-Day maximum rainfall.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40645-022-00506-2.

Additional file 1. Table S1. Coordinates of rainfall stations. **Table S2.** Annual rainfall data at the stations (in mm). **Table S3.** Seasonal rainfall data at the stations (from May to October) (in mm). **Table S4.** Average monthly rainfall during 1901–1939 at the stations (in mm). **Table S5.** Average rice yield during 1901–1939 at each district in Burma. **Figure S1.** Development of paddy areas in the Lower and Upper Burma from 1880 to 1940 (Data Source: Siok-Hwa 2012). **Figure S2.** Use of high yield rice varieties and NPK fertilizer in Burma (Data Source: Young et al. 1998). **Figure S3.** Interannual changes and change trend of seasonal local rainfall for the selected districts from 1901 to 1939 (Nx = Year – First Data Year) (with significance level of two-tailed test). **Figure S4.** Same as in Fig. S3 but for the basin average rainfall for selected districts (with significance level of two-tailed test). **Table S6.** Statistics summary result of trend analysis of rainfall. **Table S7.** Statistics summary result of trend analysis of rice yield. **Table S8.** Statistics summary of linear regression analysis between rice yield and rainfall anomalies. **Figure S5.** Anomaly of seasonal local rainfall and rice yield with a 5-year moving average value for selected districts from 1901 to 1939. **Table S9.** Statistics summary of multiple regression analysis. **Figure S6.** Monthly variability of rainfall in crop success years (the years with rice yield higher than average value of rice yield from 1901-1939).

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Author contributions
BBS and AK proposed the topic and conceived and designed the study. TI and JM collected and digitized the rainfall data; BBS performed research and analyzed the data. AK, TI, JM, and TS collaborated with the corresponding author in the development of the manuscript. All authors read and approved the final manuscript.

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Availability of data and material
"Rainfall of India (1891–1914)" and "Daily Rainfall of India (1915–1937)" are available on the web page of the NOAA Central Library, National Oceanic and Atmospheric Administration, USA (https://library.noaa.gov/Collections/Digital-Docs/Foreign-Climate-Data/India-Climate-Data). Rainfall data were also checked by the original books at the Library of the Indian Institute of Tropical Meteorology (IITM). "Daily Rainfall Recorded in Burma" for 1938–1939 is available in the Library of The Royal Netherlands Meteorological Institute. The annual and seasonal rainfall data at each station for 1901–1939 are presented in Additional file 1: Tables S2 and S3, and the average monthly rainfall during 1901–1939 is also presented in Additional file 1: Table S4. Data on rice yield, rice production, and area of rice crop cultivated and harvested are available in Okamoto (1998) (http://hdl.handle.net/10086/14672). Other secondary data used in this study are available in the sources mentioned in the manuscript.

Declarations

Competing interests
The authors declare that they have no competing interest.

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