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Rainfall, drought, and irrigation in relation to crop patterns in the volcanic topo sequence of Central Java, Indonesia

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ABSTRACT

The uncertainty in precipitation patterns resulting from climate change may contribute to uncertainties in the growing seasons and productivity of rice and other agricultural commodities. This study aimed to examine the changes in precipitation and cropping patterns across various topographic sequences of volcanic regions in Central Java, Indonesia. Precipitation data from 33 rainfall stations across three topographic sequences (0-400 meters, 400-700 meters, and above 700 meters above sea level, categorized as high, mid, and lowlands, respectively) were analyzed to understand cropping patterns using both quantitative and qualitative methods. The findings revealed that farmers' actual cropping patterns were not primarily influenced by precipitation levels but rather by soil suitability. Moreover, the frequency of drought occurrences, as indicated by the Standardized Precipitation Index (SPI), did not significantly impact cropping patterns or crop yields. Instead, agricultural yields were found to be dependent on irrigation infrastructure rather than precipitation levels. This study sheds light on the importance of adaptation and mitigation strategies to address the adverse impacts of climate change on agricultural management across different topographic sequences.

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1. INTRODUCTION

The phenomenon of climate change has resulted in changes and fluctuations in precipitation patterns both spatially and temporally. It is clear that rainfall patterns have shifted globally in Malaysia and several Southeast Asian nations in recent times (Loo et al., 2015). Climate change has already led to major alterations in agricultural output and productivity (Anderson et al., 2020), making uncertainties in precipitation a significant concern as they may lead to uncertainties in the growing periods of crops such as rice and other agricultural commodities. According to Kyei-Mensah et al. (2019), different variations in rainfall have a significant impact on crop production in the West Africa region, where agriculture generally relies on rain. The high fluctuation of rainfall during the minor season is associated with a reduction in crop production yields. Particularly, different areas exhibit distinct characteristics. Central Java, Indonesia, is characterized by seven volcanoes with various topographic sequences, nearly all of which are utilized for farming. Therefore, it is imperative to identify specific precipitation and cropping pattern properties at each topographic sequence to formulate effective adaptation and mitigation measures concerning changes in precipitation and cropping patterns.

Cropping patterns are also influenced by climate trends, necessitating the identification of changes in climate parameters. According to Shaabani et al. (2024), cropping patterns change due to the simultaneous impact of climate change on environmental parameters. Pramudya and Onishi (2018) reported severe drought in Central Java, specifically in Tegal City, in 2015, using the Standardized Precipitation Index. Meanwhile, Komariah et al. (2015) observed an increase in air temperature associated with drier air in parts of Central Java due to land use conversion from rice fields to residential areas. Extreme precipitation events predominantly occur in lowlands and coastal areas in the northern and southern parts of Central Java, making them

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susceptible to floods (Sekaranom et al., 2021). Regional rainfall predictions, rather than global climate indices, have proven to be more reliable in recommending cropping patterns in Banyumas, Central Java (Nugroho & Nuraini, 2016).

Combining statistical analysis and signal processing methods, Fatikhunnada et al. (2020) described 26 cropping patterns on Java Island, covering four types of rice cropping systems. Meanwhile, Kusumo et al. (2019) found that the water requirements for all 13 cropping pattern combinations in Brebes, Central Java, could be met by rainfall. Nugroho and Nuraini (2016) recommended specific cropping patterns: 1) paddy-corn/soybean-paddy; 2) paddy-corn/soybean-corn/soybean; and 3) corn/soybean-corn/soybean-corn/soybean based on the climatic water balance in Central Java.

Decisions regarding cropping patterns, especially crop types, should also consider the suitability of characteristics for specific crops. Each environmental characteristic, especially topographic elevation or topographic sequence, determines specific soil characteristics and consequently, the suitable crop types for establishing cropping patterns. For instance, Kumar et al. (2012) observed an increase in soil organic carbon with decreasing elevation in the Jharkhand plateau, contrasting with increases in soil pH and $CaCO_3$ at higher elevations. Montes and Jose (1995) found that relief in the second topographic sequence prolonged the effects of the wet season on seasonally flooded palm and herbaceous savanna. Additionally, Wang et al. (2008) proposed manipulating the topographic sequence of a sub-catchment in Australia to enhance water harvesting through strategic tree planting. Studies regarding soil characteristic diversity at different topographic elevations or sequences and their impact on cropping patterns are scarce, highlighting a significant research gap to be addressed.

Cropping pattern decisions in a particular region are strongly influenced by the social and economic conditions of surrounding farmers. Although numerous policies have been proposed to mitigate climate uncertainties in crop production, the voluntary adoption of preventive policies by farmers significantly impacts their implementation in the field. Changing crop varieties in cropping patterns (Fahad & Wang, 2020) and reducing the cultivation of water-intensive crops such as rice (Boazar et al., 2020) are among the methods considered. Introducing crop insurance programs to mitigate disaster risks associated with climate change also plays a role in determining cropping patterns (Fahad & Jing, 2018). Farmers' characteristics, knowledge, and perceptions also play a major role in decision-making regarding cropping patterns in Central Java. This research seeks to address the lack of discussion on precipitation and cropping patterns across topographic sequences in Central Java, as highlighted in previous studies, by investigating changes in these factors for each volcanic topographic sequence in Central Java, Indonesia. Are cropping patterns determined by the land characteristics (climate and soil) at each topographic sequence? The findings of this study will be crucial in formulating adaptation and mitigation strategies to minimize the adverse impacts of climate change and maintain agricultural production sustainability.

2. MATERIALS AND METHODS

2.1. Site Characteristics and Period

The research was conducted in the volcanic regions of Central Java Province, Indonesia (see Fig. 1). Central Java is situated between 5° 40' - 8° 30' S; 108° 30' -111° 30' E. Figure 1 illustrates that there are six volcanic mountain ranges in Central Java: Lawu, Merapi, Merbabu, Sindoro, Sumbing, and Slamet Mountains. These areas were categorized into three elevations: low, moderate, and high lands. Low lands refer to areas below 400 meters above sea level (asl), while moderate and high lands are between 400-700 meters asl and above 700 meters asl, respectively.

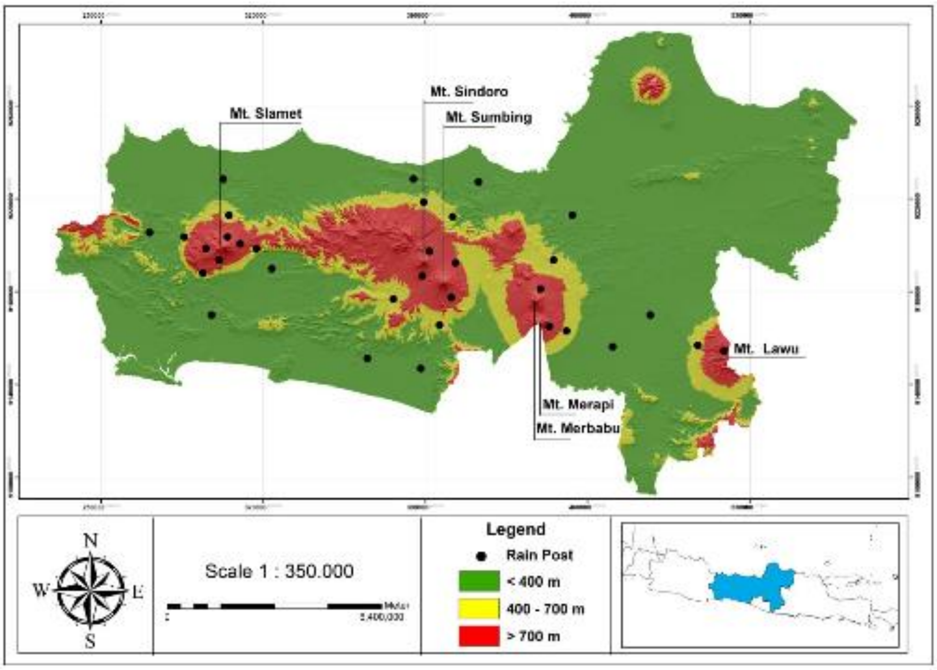


Figure 1. Elevation and rainfall stations at the study site.

Table 1. The land and soil characteristics of the study site.

Parameter	Topo Sequence		
	High Land	Mid Land	Low Land
Maximum air temperature (°C)	28	32	34
Minimum air temperature (°C)	20	23	24
Annual precipitation (mm/year)	5,344	3,903	2,198
Soil Permeability (cm/hour)	8.37	3.44	1.13
pH	6.25	6.1	5.1
Soil Organic Content (%)	3.63	2.88	1.45
Soil porosity (%)	56.85	47.98	35.53
Soil bulk density (g cm^{-3})	0.89	1.14	1.82
Soil particle density (g cm^{-3})	2.063	2.072	2.823
Soil texture			
Clay (%)	12.1	13.2	61.7
Silt (%)	83.8	60.4	21.2
Sand (%)	4.1	26.4	17.1
Class	Medium	Medium	Fine

Source: primary data

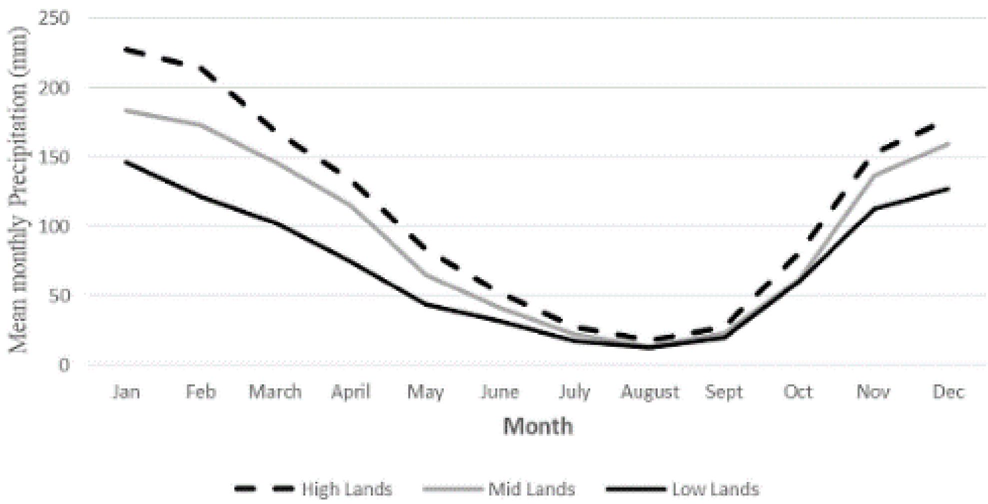


Figure 2. Mean monthly rainfall at topo sequential of the study site (1990-2019).

The land and soil characteristics of the study site are detailed in Table 1. Maximum and minimum air temperatures for high, mid, and low lands are 28°C and 20°C, 32°C and 23°C, and 34°C and 24°C, respectively. Annual precipitation follows the order of high land (5,344 mm/year) > midland (3,903 mm/year) > low land (2,198 mm/year). Soil permeability is notably higher at high land (8.37 cm/hour) compared to midland (3.44 cm/hour) and low land (11.13 cm/hour). Soil pH levels are slightly higher at high land (6.25) and low land (6.1) but lower at midland (5.1). The soil organic content is highest at high land (3.3%), followed by midland (2.88%) and low land (1.45%). Soil porosity, bulk density, and particle density follow the order of low land < mid land < high land. Clay fraction is highest at low land (61.7%) and lowest at high and midlands (12-13%). Silt fraction is highest at high land (83.8%) and lowest at low land (21.2%). Sand fraction is lowest at high land (4.1%), higher at low land (17.1%), and highest at midland (26.4%). The research spanned from January to September 2021 and employed a survey explorative method along with studying existing literature.

2.2. Precipitation Characteristics of Study Site

The precipitation data were obtained as secondary data from precipitation stations belonging to the Watershed Agency in the Central Java Area, Indonesia. These data were collected from 33 rainfall stations spread across the study site, as depicted in Figure 1. The analysis of precipitation data covers the period from 1990 to 2019, divided into three periods: 1990-1999, 2000-2009, and 2010-2019. The characteristics of monthly precipitation in each low, moderate, and highland area from 1990 to 2019 are illustrated in Figure 2.

Figure 2 highlights that the mean monthly precipitation follows the order of highland > midland > lowland. The highest mean monthly precipitation recorded at each highland, midland, and lowland was 227 mm, 183 mm, and 146 mm, respectively, occurring in January. August had the lowest mean monthly precipitation, with less than 15 mm recorded across all areas. Monthly precipitation below 50 mm occurred from late April to October in lowlands, late May to October in midlands, and June to September in highlands.

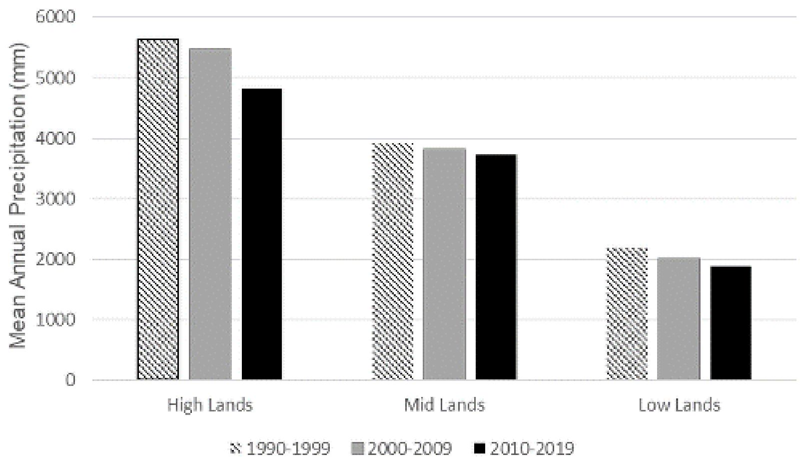


Figure 3. Mean annual precipitation at the study site (1990-2019).

Table 2. Land properties requirement for selected crops.

Commodities	Climate: Air Temperature (°C)	Climate: Precipitation (mm/year)	Soil: pH	Soil: Soil Organic Carbon (SOC) (%)	Soil: Texture
Rice					
Irrigation Rice	24-29	-	5.5-8.2	> 1.5	Fine
Rain-fed Rice	14-29	>1800	5.5-8.2	> 1.5	Fine - Medium
Secondary Crop					
Maize	25-27	400-900	5.5-8.2	> 0.4	Fine - Medium
Groundnut	12-24	350-600	5.6-7.6	> 1.2	Fine - Medium
Cassava	12-23	350-1,250	6.0-8.2	> 0.4	Fine - Medium
Onion	10-25	350-600	6.0-7.8	> 1.2	Fine - Medium
Garlic	20-25	350-600	6.0-7.8	> 1.2	Fine - Medium
Chili	18-26	600-1,200	6.0-7.6	> 0.8	Fine - Medium
Carrot	16-18	>960	5.6-7.0	> 1.2	Fine - Medium
Potato	16-18	250-400	6.0-7.0	> 1.2	Fine - Medium
Soybean	26-30	2,000-3,000	5.0-7.0	> 0.4	Fine - Medium
Mung bean	25-27	400-1,100	6.0-7.0	> 1.2	Fine - Medium
Sweet Potato	25-32	>960	5.5-6.5	> 0.8	Fine - Medium
Horticulture					
Choy sum	18-25	1,000-2,500	5.5-7.8	> 1.2	Fine - Medium
Cabbage	12-24	350-600	5.6-7.6	> 1.2	Fine - Medium
Broccoli	12-24	350-600	5.6-7.6	> 1.2	Fine - Medium
Lettuce	16-22	250-400	6.0-7.0	> 1.2	Fine - Coarse
Melon	22-30	400-700	5.8-7.6	> 1.2	Fine - Medium
Watermelon	22-25	1,000-2,000	5.5-7.8	> 1.2	Fine - Medium

Source: Land Evaluation for Agriculture, in Indonesian (BBSL, 2011).

The average annual decadal precipitation, as shown in Figure 3, reveals a consistent decrease in precipitation across all topographical sequences over the decades. Precipitation decreased by around 30% in each decade across all topographical sequences. Over the span of three decades, the mean annual precipitation decreased by approximately 60%.

2.3. Cropping Pattern Determination

The recommended cropping pattern was established following the guidelines of Oldeman and Frere (1982), which are based on the seasonal water requirement of 150 mm per month for rice cultivation. The initial phase of the rice cropping pattern begins when there is a cumulative precipitation of 50 mm over a 10-day period, occurring consecutively for three such periods. Additionally, approximately 50 mm of precipitation is needed for soil tillage during the initial growing season, making the total precipitation required for the first month a minimum of 200 mm. Subsequently, 50 mm of precipitation every 10 days is sufficient for rice growth. The water requirement for secondary crops is 100 mm per month.

The actual cropping pattern was determined through in-depth interviews with agricultural authorities at the district level and local farmers. There are 180 respondents who were interviewed, consisting of community leaders and farmer groups.

2.4. Determining Land Evaluation for Crops

The assessment of land suitability was conducted in accordance with the guidelines outlined in the handbook issued by the Indonesia Center for Agriculture Land Resources Research and Development (Djaenudin et al., 2011). Table 2 presents the specific requirements for selected crops, including air temperature, precipitation, soil pH, soil organic carbon, and soil texture.

According to Table 2, rainfed rice necessitates annual precipitation exceeding 1800 mm, with a higher tolerance for lower air temperatures ranging from 14 to 29 degrees Celsius. Secondary crops like maize, soybean, mung bean, and sweet potato thrive in hotter temperatures, with annual precipitation ranging from 350 to 1200 mm. Horticultural crops are suitable for moderately warm temperatures and varying annual precipitation levels. The optimal soil pH ranges from 5.5 to 8.2, while the soil organic carbon content should be higher than 1.2 to 1.5 percent. Additionally, the ideal soil texture for major crops falls within the fine to medium range.

2.5. Crop Yield

The temporal crop yield data is sourced from the Indonesian Statistical Agency (https://www.bps.go.id/) as secondary data.

2.6. Standardized Precipitation Index (SPI)

The SPI analyses were performed using the R-studio software, which is an open-access program utilizing the SPI package. The SPI can be computed for various timescales, enabling it to assess different types of droughts due to its flexibility in evaluating precipitation conditions relative to water supply. It was developed to measure the deficit in precipitation across multiple timescales through moving average windows, reflecting the impact of drought on various water resources.

In terms of agricultural drought, meteorological and soil moisture conditions react to precipitation anomalies on relatively short timescales (1–6 months), while streamflow, reservoirs, and groundwater respond to longer-term precipitation anomalies (6–24 months and beyond). For this study, the SPI and SPEI were calculated at 1-, 3-, 6-, and 12-month intervals, using index data from the previous three years (November 2016–October 2019). These values from the SPI and SPEI can be used to classify the severity of drought based on the SPI classifications outlined in Table 3. The most detail was calculated over a one-month period. This will help in making decisions in agriculture, especially in identifying the commodities that are viable.

3. RESULTS

Table 4 displays the results of the F-test, indicating significant differences in precipitation across each topographical sequence and period. Specifically, the data reveal that precipitation varies significantly among different topographical sequences ($p<0.001$), with higher precipitation levels observed in highland areas compared to mid and lowlands, as illustrated in Figure 3. Furthermore, precipitation levels vary significantly across different decadal periods, with the period 1990-1999 experiencing notably higher precipitation than both 2000-2009 and 2010-2019. This suggests a significant decrease in precipitation over time, as depicted in Figure 3.

In Table 5, the 10-year average of cumulative precipitation over 10 days is presented for each topographical sequence. Using this data, the recommended cropping pattern according to Oldeman and Frere (1982) has been outlined in Table 6. Additionally, Table 7 showcases the actual cropping pattern adopted by the farmers.

Table 5 indicates that in highland areas during 1990-1999, there was substantial seasonal precipitation from January to March, reaching up to 282 mm. By April and May, the precipitation tended to decrease to a range of 110-171 mm. There was notably no precipitation even in the second mean decade of May. The dry season typically commenced in June and extended until the first or second mean decade of October. However, by the third mean decade of October, precipitation began to increase, continuing into the following months. The third mean decade of December saw a return to higher levels of precipitation. Moving on to the period of 2000-2009, precipitation was limited to January through March. The dry season in this period started earlier in April and lasted until October. The rainy season resumed in November and persisted into the following month. In the years 2010-2019, the peak seasonal precipitation occurred in the third mean decade of January, reaching 202 mm. The dry season once again started in early May, lasting until the second mean decade of November. However, in the third mean decade of November, rainfall resumed with a volume of 126 mm, continuing into the following month.

In Table 5, it's also evident that across midland areas during 1990-1999, the highest seasonal precipitation occurred in the first mean decade of February, peaking at 307 mm. During this period, the rainy season extended until the second mean decade of May. Subsequently, the dry season began in the third mean decade of May and lasted until the first mean decade of November. Precipitation resumed in the second mean decade of November. From 2000 to 2019, the highest precipitation was recorded in the first mean decade of January, with a volume of 310 mm. However, the dry season extended from the second mean decade of May until October. Rainfall returned in the first mean decade of November, continuing into the following months. The third mean decade of January from 2010 to 2019 saw a total seasonal precipitation of 365 mm, with rainfall persisting until the first mean decade of May, followed by the dry season until October.

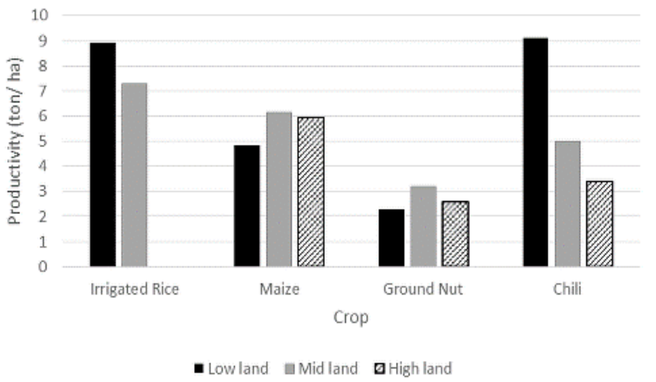
Table 3. Standardized Precipitation (SPI) classifications (McKee et al., 1993).

SPI value	Category
≥ 2.0	extremely wet
1.5 ~ 1.99	very wet
1.0 ~ 1.49	moderately wet
-0.99 ~ 0.99	near normal
-1.0 ~ -1.49	moderately dry
-1.5 ~ -1.99	severely dry
≤ -2.0	extremely dry

Table 4. F-test of topo sequences and period (10 years) on precipitation.

Variable	Coef.	Std. Error	F-stat	Sig.
Topo sequences	-1624.67	72.80	-22.564	<0.001
Period	-219.83	72.80	-3.02	0.023

Notes: α=0.05; topo sequences: 0-400, 400-700, and >700 m asl, respectively; period: 1990-1999; 2000-2009 and 2010-2019.



Source: Indonesian National Statistic Agency (https://www.bps.go.id/).

Figure 4. Average productivity of selected crops in 2019-2021 at each topo sequence.

Moreover, Table 5 illustrates that in lowland areas, precipitation tended to be lower compared to other regions during 1990-1999, with the highest seasonal precipitation reaching only 173 mm. The dry season typically spanned from May to October during this period. However, in November, precipitation began to increase, continuing into the following months. Even in the second mean decade of November, precipitation levels rose. From 2000 to 2009, precipitation was scarce, with no recorded rainfall in the second mean decade of January. The dry season started earlier in this period, from the third mean decade of April to October. Rainfall resumed in November, continuing into the following month. In 2010-2019, the highest precipitation occurred in the third mean decade of December, totaling 227 mm. The dry season started again in early May until the first mean decade of November. However, in the second mean decade of November, rainfall returned with a volume of 176 mm, continuing into the following month.

Based on the recommended rice cropping pattern correlating with precipitation levels, where adequate rice growth requires 70 mm of rain every 10 consecutive days or 200 mm over a 30-day period, Table 6 illustrates the optimal planting times for rice across different terrains. In highland areas from 1990 to 1999, the recommended rice planting window was from the third mean decade of October to the second mean decade of June. From 2000 to 2009, farmers were advised to commence rice planting from the third mean decade of October until the third mean decade of June. Subsequently, between 2010 and 2019, optimal rice planting periods shifted to start from the first mean decade of November to the third mean decade of June, with the land left fallow from July to early October. Similarly, in midland regions from 1990 to 1999, the recommended rice planting period spanned from the second mean decade of October to the second mean decade of June. This pattern continued from 2000 to 2009. From 2010 to 2019, farmers were advised to plant rice from the third mean decade of October to the third mean decade of June, with the land left fallow during the third mean decade of June. In lowland areas from 1990 to 1999, rice planting was recommended from the second mean decade of October to the second mean decade of June. From 2000 to 2009, this shifted to planting rice from the first mean decade of November to the third mean decade of February. Horticultural crops were recommended from the first mean decade of March to the first mean decade of May, after which the land was left fallow. Additionally, between 2010 and 2019, farmers were advised to start planting rice from the second mean decade of November to the first mean decade of March, with horticultural crops planted in the second mean decade of March and the land left fallow until the first mean decade of May.

Table 7 indicates that farmers' actual cropping patterns did not align with the recommended water availability based on seasonal precipitation. This discrepancy persisted over the last 30 years (1990-2019). In the highlands, farmers consistently planted secondary and horticultural crops from 1990 to 2019. Midland farmers predominantly planted rice during the first growing season, incorporating rice and secondary crops in the second and third growing seasons. Conversely, lowland farmers consistently planted rice across all growing seasons.

Figure 4 presents the average recent productivity (2019-2021) of selected primary and secondary crops across different topographic sequences. Notably, rice productivity was highest in the lowlands (8.91 tons/ha) compared to the midlands (7.27 tons/ha), with the highlands not producing rice. Maize yield was high in midlands (6.15 tons/ha), almost on par with highlands (5.94 tons/ha), and lower in lowlands (4.85 tons/ha). Similarly, groundnut productivity was highest in midlands (3.195 tons/ha), followed by highlands and lowlands (2.605 and 2.28 tons/ha, respectively). Chili productivity was highest in the lowlands (9.13 tons/ha) and lowest in the highlands.

Table 8 provides an analysis of land suitability requirements for selected crops, including irrigated rice, maize, groundnut, and chili. It's evident that the air temperature and soil texture in the highlands do not meet the requirements for irrigated rice. Similarly, the soil texture and soil organic carbon in midlands and lowlands do not meet the specifications for rice cultivation, respectively. The recommended adaptation and improvement measures include refraining from rice cultivation in highlands and enhancing soil properties through organic fertilizer inputs. Conversely, the air temperature is not conducive for maize, groundnut, and chili cultivation in midlands and lowlands. Additionally, the precipitation levels do not meet the requirements for these crops. However, specific soil properties such as pH, soil organic carbon, and soil texture meet the necessary conditions for cultivating maize, groundnut, and chili.

Table 5. Mean decadal (cumulative 10-days) precipitation (mm) 1990-2019 at study site.

Year	Jan.			Feb.			Mar.			Apr.			May			Jun.			Jul.			Aug.			Sep.			Oct.			Nov.			Dec		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
High land																																				
1990-1999	247	237	276	282	256	214	248	158	165	124	171	138	139	87	110	60	64	53	35	12	15	19	22	48	34	21	64	72	65	149	88	125	157	155	153	201
2000-2009	158	161	214	165	184	122	134	146	116	105	97	67	77	69	67	57	30	29	9	15	12	4	2	14	4	4	12	45	66	84	142	190	186	123	124	172
2010-2019	122	136	202	146	141	107	98	116	116	138	179	114	74	75	69	36	47	36	22	17	29	10	12	11	25	29	35	45	62	59	105	101	126	118	169	152
Mid land																																				
1990-1999	228	260	289	307	226	210	236	172	186	132	176	163	136	110	71	98	24	43	33	27	32	18	16	31	23	6	33	46	89	92	91	142	168	139	143	186
2000-2009	144	166	290	310	266	211	221	178	166	148	155	126	117	62	107	19	41	40	27	39	36	5	8	19	16	31	32	47	27	100	166	138	136	145	145	219
2010-2019	188	300	365	321	230	179	181	145	155	165	178	177	114	81	37	42	32	48	35	43	18	14	19	23	26	33	41	45	31	114	128	114	144	141	154	153
Low land																																				
1990-1999	169	169	173	197	159	117	128	138	173	121	114	121	86	65	45	33	24	43	32	23	19	13	16	57	8	6	33	46	48	109	133	210	195	207	157	187
2000-2009	145	95	196	113	66	107	128	127	182	165	148	102	85	19	24	19	25	41	9	19	12	10	8	11	12	14	32	47	27	25	144	154	170	161	138	227
2010-2019	117	118	162	135	149	125	154	128	154	129	189	110	72	13	37	42	32	48	38	36	29	13	11	14	38	40	41	45	31	29	41	176	163	143	209	194

Notes: I (decade 1); II (decade 2); III (decade 3)

Table 6. Recommended cropping pattern for rice based on seasonal precipitation (70 mm per 10-days; ≥200 mm cumulative per 30-days) (Oldeman & Frere, 1982).

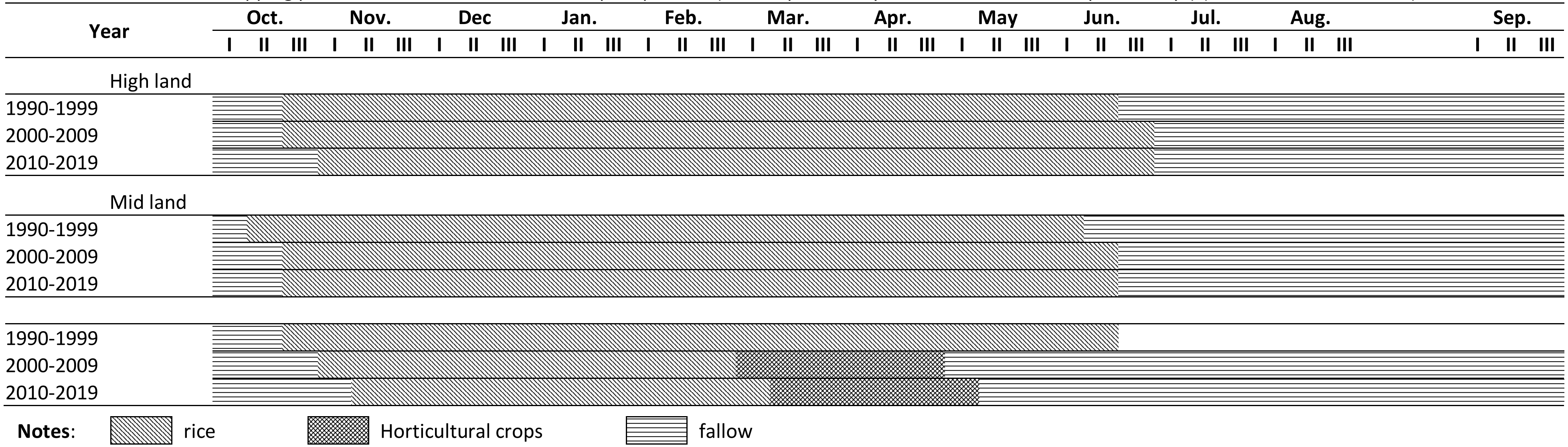


Table 7. Actual cropping pattern at volcano topo sequences in Central Java, Indonesia over 30-year period (1990-2019).

Year	Oct.			Nov.			Dec			Jan.			Feb.			Mar.			Apr.			May			Jun.			Jul.			Aug.			Sep.		
	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
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2000-2009																																				
2010-2019																																				

Notes: rice; Secondary and Horticultural crops; Rice and secondary crops

Table 8. Land requirement suitability with current land properties for selected crops.

Crop	Topo sequence	Air temperature	Annual precipitation	Soil: pH	Soil: Soil Organic Carbon	Soil: Texture	Adaptation/ Improvement Measures
Irrigated Rice	High land	×	O	O	O	×	No rice is planted at highlands; Organic matters input at mid and lowlands
	Mid land	O	O	O	O	×	
	Low land	O	O	O	×	O	
Maize	High land	O	×	O	O	O	Improving drainage technology; using high-temperature tolerance varieties at mid and lowlands
	Mid land	×	×	O	O	O	
	Low land	×	×	O	O	O	
Ground nut	High land	O	×	O	O	O	
	Mid land	×	×	O	O	O	
	Low land	×	×	O	O	O	
Chili	High land	O	×	O	O	O	
	Mid land	×	×	O	O	O	
	Low land	×	×	O	O	O	

Notes: O = current condition of the variable meets the requirement; × = current condition of the variable does not meet the requirement; High land > 700 m asl; Mid land= 400- 700 m asl; Low land < 400 m asl.

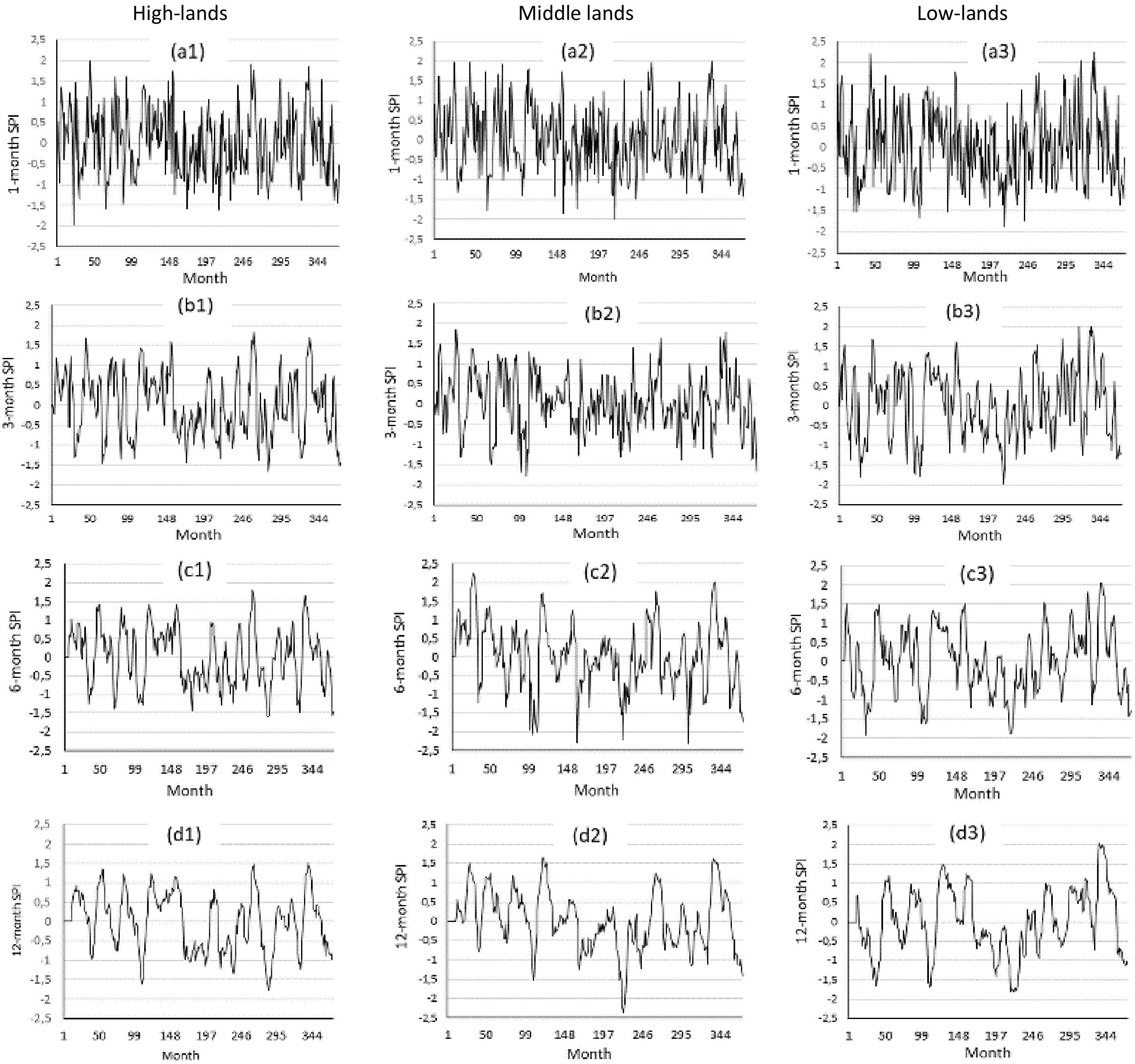
Table 9. Drought frequency according to Standardized Precipitation Index (SPI) at each topo sequence at study site 1990-2019.

Topo-sequences	SPI values		Frequency in 30 years: 1-month SPI	3-month SPI	6-month SPI	12-month SPI	Annual Frequency: 1-month SPI	3-month SPI	6-month SPI	12-month SPI
Low-lands	-1.00 ~ -1.49	moderately dry	36	39	36	30	1.2	1.3	1.2	1
	-1.5 ~ -1.99	severely dry	6	9	9	15	0.2	0.3	0.3	0.5
	< -2.0	extremely dry	0	0	0	0	0	0	0	0
Middle lands	-1.00 ~ -1.49	moderately dry	30	30	30	21	1	1	1	0.7
	-1.5 ~ -1.99	severely dry	3.9	3	10.5	3.9	0.13	0.1	0.3	0.13
	< -2.0	extremely dry	0	0	3.93	6	0	0	0.13	0.2
High-lands	-1.00 ~ -1.49	moderately dry	69	33	33	21	2.3	1.1	1.1	0.7
	-1.5 ~ -1.99	severely dry	6	3	3	6	0.2	0.1	0,13	0.2
	< -2.0	extremely dry	0	0	0	0	0	0	0	0

Figure 5 (a1-d3) illustrates the 1-, 3-, 6-, and 12-month Standardized Precipitation Index (SPI) for each topographic sequence. Table 9 provides the frequency of drought based on the SPI for each topographic sequence.

Figure 5 illustrates notable fluctuations in the 1-month SPI, particularly with greater variability observed in the lowlands (a3) compared to the high (a1) and middlelands (a2). The highest and lowest 1-month SPI values were 2.2 and -1.88, occurring in the 44th and 217th month, respectively. Monthly precipitation data indicates that middle and low lands (a2 and a3) were generally wetter than high lands, as evidenced by more frequent occurrences of 1-month SPI values exceeding 1.5 compared to high lands (a1). In terms of monthly drought, middle lands experienced more instances of drought compared to high and low lands, with more occurrences of SPI below 1.5 (a2). Examining the 3-month SPI in Figure 5 reveals larger fluctuations in lowlands (b3), where extreme wetness was observed at the 317th month, and severe drought occurred at the 217th month. Extreme dryness and wetness of the 3-month SPI did not occur in high and middle lands (b1 and b2). However, the 6-month SPI in middle lands exhibited the highest fluctuation between extreme dry and wet conditions (c2), which were not observed in high and low lands (c1 and c3).

Further analysis of the 3-month SPI indicates severe drought (SPI = -2 at week 217th) and extreme wetness (SPI = +2 at week 316th and 335th) in lowlands (b3). In contrast, the 6-month SPI in middle lands (c2) shows extreme wetness and dryness compared to high (c1) and low (c3) lands. Additionally, Figure 8 depicts severe drought (-2.37 at week 222nd) at the 12-month SPI in middle lands (d2), while extreme wetness was observed in low lands (d3) compared to high lands (d1). Overall, Figure 5 indicates that climate fluctuations were more pronounced in middle lands compared to low lands, with high lands exhibiting greater stability in extreme drought and wet conditions.



Notes: a= 1-month SPI; b= 3-month SPI; c= 6-month SPI; d= 12-month SPI; 1= high lands; 2= middle lands; 3= low-lands.

Figure 5. Standardized Precipitation Index (SPI) graph of 1-, 3-, 6- and 12-months at each topo-sequence from 1990-2019.

Table 9 details the frequency of drought occurrences at the study site from 1990 to 2019 across each topographic sequence. Notably, within this 30-year period, only middle lands experienced extremely dry conditions, with SPI values <-2.0 for 6-month and 12-month periods occurring 3.9 and 6 times, respectively. Annual frequency data reveals that overall, lowlands experienced more dry periods (6 times per year, ranging from moderately to extremely dry) compared to middle and highlands. Middle lands experienced fewer dry periods (4.42 times per year) than high lands (5.83 times per year).

4. DISCUSSION

Table 10 provides a summary of the correlation between parameters and the actual and recommended cropping patterns, respectively. Overall, Table 10 reveals the correlation between the actual cropping pattern, topographic sequences, and annual precipitation, while also highlighting the correlation of both cropping patterns with crop suitability concerning climate and soil properties. Interestingly, the drought index (SPI 1, 3, 6, and 12) does not correlate significantly with either cropping pattern. It's notable that the crop suitability concerning climate and soil shows a stronger correlation with the actual cropping pattern, as indicated by the higher correlation coefficient (0.866) compared to the recommended cropping pattern (0.305). This underscores the intuitive adjustment of the actual cropping pattern by local farmers over the years to align with the local environment. In general, this study reveals that the actual cropping pattern followed by local farmers may not align perfectly with seasonal precipitation levels across each topographic sequence. However, it does align well with the climate and soil characteristics required for the crops predominantly cultivated in the area.

The consistent cropping pattern observed in the actual data appears to be unaffected by the decrease in annual precipitation across all topographic sequences (Fig. 3 and Table 4) or the shifts in season onset (Table 5). Instead, it seems to have been adjusted based on soil characteristics, which farmers have learned from their experiences over the years (Table 8). This suggests that meteorological parameters alone may not be sufficient to determine the most suitable cropping pattern. Although Ejigu and Nigatu (2022) claimed to have produced an optimized cropping pattern using fuzzy logic with precipitation input, the validity of this approach in relation to other crop parameters remains unclear.

The minor changes in season onset observed in the high and midlands (Table 5) have not led to alterations in the local cropping pattern. This could be due to the suitability of the soil for the crops (Table 8) and the support provided by irrigation from either farmers or local government initiatives (Fig. 6, 7, 8). This indicates that the cropping pattern followed by farmers in the volcanic topographic sequences of Central Java, Indonesia, over the past 30 years has not been directly influenced by specific precipitation patterns or variations across different topographic areas. However, changes in precipitation may indeed impact crop yield (Fig. 4), as climate change is closely linked to crop productivity (Batool et al., 2019). This finding is in line with Kogo et al. (2021), whose results indicate that climate change will persist in adversely impacting crop production and food security for communities that are already vulnerable in arid and semi-arid regions. Based on precipitation data, it is advisable to plant rice during growing seasons 1 and 2 in high and midlands (altitude > 400 m above sea level) due to adequate water availability (Table 6). Middle topographic sequence lands also appear to be less susceptible to extreme climate events, particularly drought (Fig. 5 and Table 9). However, the hypothesis that the drought index may correlate with crop yield is not supported by the findings of this study, as indicated in Table 11.

Table 11 reveals that the frequencies of drought indices indicated by SPI 1, 3, 6, and 12 did not show a correlation with yield, possibly due to soil suitability and irrigation support. This finding contrasts with a study by Labudová et al. (2017), which found that the drought index impacted the yield of sugar beet plantations. This suggests that the type of crop may also influence how climate change affects yield. In the context of rice cultivation, particular attention should be given to the 3-month SPI, as it serves as a fundamental indicator for drought monitoring according to the World Meteorological Organization (WMO). Rice cultivation heavily relies on water availability during its 3-month life cycle (Datta et al., 2017). Consequently, the low fluctuation in the drought index in middle lands provides better protection against drought. However, the unsuitable air temperature in the highlands (as indicated in Table 1 and Table 8), which is not conducive to rice cultivation, has resulted in zero productivity of rice in the highlands (Fig. 4).

Table 10. Pearson correlation (r) and significance (p) of actual and recommended cropping pattern on observed parameters.

Parameters	Actual cropping pattern	Recommended cropping pattern
Topo sequences	1.00 **	0.396^{ns}
Annual precipitation	-0.985**	-0.454^{ns}
Crop suitability with climate requirement	0.866**	0.305**
Crop suitability with soil requirement	0.866**	0.305**
Drought index – SPI 1	0.117^{ns}	-0.565^{ns}
Drought index – SPI 3	0.436^{ns}	-0.086^{ns}
Drought index – SPI 6	0.204^{ns}	0.135^{ns}
Drought index – SPI 12	0.497^{ns}	-0.297^{ns}

Note: **= cropping pattern significantly correlated with parameter; ns= cropping pattern does not significantly correlate with parameter; α=0.05.

(a)

(b)

Figure 6. Small farm reservoirs from runoff water harvesting at lowlands (a) and Farm reservoirs at midlands (b).

Table 11. Pearson correlation (r) and significance (p) of drought index (SPI) and crop yield.

Parameters	Rice yield	Maize yield	Ground Nut yield	Chili yield
Drought index – SPI 1	0.085^{ns}	-0.683^{ns}	-0.174^{ns}	-0.106^{ns}
Drought index – SPI 3	0.0409^{ns}	-0.347^{ns}	-0.236^{ns}	-0.409^{ns}
Drought index – SPI 6	0.312^{ns}	0.090^{ns}	0.197^{ns}	0.098^{ns}
Drought index – SPI 12	0.327^{ns}	-0.664^{ns}	-0.619^{ns}	0.563^{ns}

Notes: ns = crop yield does not significantly correlate with SPI; α = 0.05.

(a) (b)

Figure 7. Groundwater withdrawal for agriculture with diesel power from the surface reservoir (a) and with electrical power from groundwater (b).

(a) (b)

Figure 8. Gravitation pipes irrigation method in high lands (a), the water source, is from spring at the mountain (b).

Beyond climatic factors, advancements in rice breeding technology, genetic engineering, soil properties, and innovative nutrient technologies have encouraged farmers to cultivate crops without strict reliance on rainfall for water availability. The warmer air temperatures in mid and lowlands do not hinder the cultivation of maize, thanks to the discovery of climate-resilient maize varieties such as *Lamuru* and *Arjuna* (Musa & Farid, 2018; Sutresna et al., 2018). These climate-resilient maize varieties have been reported to increase maize productivity by up to 20-25% in South Africa (Setimela et al., 2017). Similarly, certain groundnut cultivars like *Hypoma 1* and *Katana 1* have gained prominence for their superior traits, including resistance to extreme climates (Purnomo & Rahmianna, 2020), enabling groundnut cultivation in mid and lowlands despite the air temperature requirements outlined in Table 8. Additionally, climate-resilient chili (*Capsicum Annuum*) cultivars, such as *Prima, Pilar,* and *Kastilo*, are highly resistant and popular among Indonesian farmers (Basuki et al., 2022). However, Song et al. (2015) reported that chili yield decreases under a 2°C temperature rise. Therefore, global initiatives to evaluate Capsicum genetic materials for biotic and abiotic stress to enhance resilience mechanisms would greatly contribute to sustainable chili production (Chhapekar et al., 2018).

Technology in soil and water management plays a significant role in adapting to and measuring crop production under unfavorable environmental conditions. Amending soil with proper organic fertilizer in rice fields, particularly in low and midlands, can improve soil organic content and texture (Table 8). Effective nutrient supply, ameliorative tools, irrigation techniques, and the use of organic manures are essential to enhance crop resilience against the adverse impacts of climate change (Khaitov et al., 2019). Excess rainfall's impact can be minimized by implementing drainage techniques, such as surface or subsurface drainage, with a preference for subsurface drainage in sloping areas and regions with high precipitation to reduce soil erosion risks (Gramlich et al., 2018). Terracing rice fields in high and midlands also contributes to erosion control (Abasi-Obot et al., 2018).

The high rice yield productivity in the mid and lowlands, despite receiving less precipitation than in the highlands, is supported by intensive irrigation measures. Figure 6 illustrates artificial surface water resources on farms. Figure 6a depicts an earth wall farm reservoir collecting water from surface runoff for irrigation in lowlands, while Figure 6b shows a rainwater-collected reservoir for agricultural irrigation in midlands. The former is typically created by farmers and used for rice fields and secondary crops, while the government funds the latter to irrigate surrounding secondary and horticultural crops. Farm reservoirs offer a solution to water supply challenges, promoting more efficient water management in the face of future climate change (Carvalho-Santos et al., 2017).

Figure 7 illustrates the power resources utilized for irrigating farmlands, namely diesel power with fuel (a) and electrical power (b). The diesel water pump is employed to distribute water from surface water reservoirs, while the electric-powered water pump extracts groundwater from depths of approximately 80 meters. Groundwater can provide more water than surface water, but its invisibility necessitates farmers to assess its availability and efficiency for future use. Pinto et al. (2020) suggest an adaptation measure to enhance water management in lowlands by utilizing sprinklers at specific phenological stages of rice. Additionally, Abasi-Obot et al. (2018) proposed alternative energy sources for water pumps, such as solar energy.

Figure 8 depicts the irrigation system in the highlands, where water resources rely on spring water from the mountains. The volcanoes in Central Java are rich with continuous spring waters, making them a potential source for gravitational irrigation systems in farmlands. Gravitational force pipes are utilized to irrigate secondary and horticultural crops in the highlands, aiming to increase water efficiency.

Regarding water management across all topographic sequences, the cropping pattern does not solely depend on precipitation. Instead, the start of the growing season has historically been determined by season onset, deeply ingrained as a cultural practice and heritage among local farmers. Despite slight changes in season onset, this practice has been maintained. The decrease in precipitation volume has not significantly impacted farming activities or agricultural yield, as similarly observed by Batool et al. (2019).

However, there is a need to reduce groundwater resource exploitation in farmlands to ensure sustainable water resources. Efforts to promote an appropriate cropping calendar aligned with precipitation trends and volume are crucial as adaptation and mitigation strategies. Apriyana et al. (2021) propose the Integrated Cropping Calendar Information System (ICCIS) to enhance farmers' knowledge and facilitate a better understanding of climate hazards in agriculture.

5. CONCLUSIONS

Between 2009 and 2019, rainfall in the Central Java volcanic area has declined. While the onset of the rainy season has been delayed, it has not changed the cropping patterns, which are determined by soil characteristics. Agricultural productivity in this region relies not only on rainfall or drought conditions but also on effective water and soil management, along with careful selection of crop varieties. It's crucial to educate farmers about climate risks to promote agriculture that can withstand climate challenges.

Declaration of Competing Interest

The authors declare that no competing financial or personal interests may appear to influence the work reported in this paper.

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