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Variability of sequences of days with precipitation in the eastern part of the Mazowian Lowland

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Abstract: This study aimed to examine the frequency and variability of sequences of days with atmospheric precipitation across the Mazovian Lowland during the growing season (April–October) over the period 1971–2020. The research was based on daily precipitation totals recorded at meteorological stations in Legionowo, Pułtusk, and Siedlce. A precipitation sequence was defined as a series of consecutive days with rainfall ≥0.1 mm, and classification was conducted following the methodology proposed by Zawora (1995). The structure and variability of these sequences were assessed in both spatial and temporal dimensions, and trends in their number were analysed using the Mann–Kendall test. During the study period, a total of 1,787 precipitation events at least three days long were recorded. The majority (approximately 64%) comprised sequences of 4–9 days. Shorter, 3-day events represented 19% of observations, while sequences exceeding 9 days were considerably less frequent. Exceptionally long sequences (≥23 days) occurred sporadically. The highest number of short and medium-length events was observed in Legionowo, whereas Siedlce experienced a greater frequency of extended sequences exceeding 10 days. The structure of sequences in Pułtusk was the most stable, with a predominance of medium-length series. Seasonally, 4–9 day sequences were most common in spring, while in the latter half of the growing season, both short events and those exceeding 10 days became increasingly prominent.

Keywords: central Poland, frequency, long-term trends, Mazovian Lowland, precipitation

INTRODUCTION

The analysis of sequences of days with atmospheric precipitation forms a fundamental component of the study of landscape and hydrological processes within the Mazovian Lowland. These sequences, defined as consecutive days when daily precipitation exceeds a specified threshold (typically 0.1 mm or 1 mm), are critical for assessing moisture conditions, identifying drought periods, and planning water and spatial management strategies, as well as evaluating flood risk (Ustrnul and Czekierda, 2001; Chattopadhyay, Edwards and Yu, 2017; Labonté and Merlis, 2023; Sun *et al.*, 2023). Ustrnul and Czekierda (2001) presented a comprehensive analysis of the length and number of precipitation sequences in Poland, highlighting regional differences. Unlike those in mountainous regions, the shortest sequences predominated in the Mazovian Lowland and central Poland. Their study showed that while prolonged sequences characterised mountainous areas, shorter series prevailed in lower, flatter terrains such as Mazovia. In her study encompassing the period of 1951–2007, Łupikasza (2010) found no unequivocal trends in sequence length but observed increased variability and a higher incidence of extreme precipitation events. These findings align with projections of climate change impacts, particularly the growing risk of extreme droughts and floods. Such observations underscore the need for localised research accounting for geographical and seasonal specificity. Szyga-Pluta (2018) and Walkowska, Bąk and Szyga-Pluta (2022) also examined precipitation days in Greater Poland, reinforcing the value of regional studies. The issue of sequences of days with precipitation is also widely studied in the international literature, with indicators developed by the Expert Team on Climate Change Detection and Indices (ETCCDI) commonly employed – most notably consecutive wet days (*CWD* = precipitation ≥1 mm on successive days) and consecutive dry days (*CDD* = successive days without

precipitation) (Frich *et al*., 2002; Sillmann *et al*., 2013). Research conducted in Greece revealed regional disparities in sequence length and variability, with a marked decline in *CWD*s in western areas (Nastos and Zerefos, 2009). In China, Zhang *et al*. (2011) analysed maximum consecutive wet days, noting the predominance of short, several-day series and their contribution to seasonal totals. Zong (2023) reported an increase in the frequency and intensity of consecutive extreme wet days (*CEWD*s) from 1980 to 2020, indicating a rising prevalence of climate-linked extremes. In South America, Iacovone, Pántano and Penalba (2020) demonstrated significant correlations between *CWD* and *CDD* duration and the El Niño-Southern Oscillation (ENSO) – a cyclical climate phenomenon involving sea surface temperature fluctuations in the tropical Pacific and associated atmospheric pressure changes. This body of research establishes sequences of days with precipitation as a universal indicator of climate variability, enabling interregional and long-term comparisons. However, local climatic differences are pronounced, necessitating detailed regional analyses, particularly in regions like the Mazovian Lowland, where low precipitation totals and marked seasonal variability are critical to water management and agriculture.

This study aims to determine the frequency and variability of sequences of days with precipitation in the Mazovian Lowland during 1971–2020.

MATERIALS AND METHODS

The Mazovian Lowland, part of the Central Polish Lowlands, is located in east-central Poland. It is bordered to the north by the Masurian Lake District, to the south by the Lesser Poland Upland, to the west by the Greater Poland Lowland, and to the east by the Podlasie Lowland. One of Poland's largest lowland areas, it comprises a vast, flat basin with the Warsaw Basin at its centre. The terrain is predominantly flat and characterised by a radial river network. Major rivers, including the Vistula, Narew, Bug, Pilica, Bzura, and Wieprz Rivers, traverse the region, converging near Warsaw, the hydrographic centre. The climate is temperate continental, with warm summers and cold winters. Mean summer temperatures range from 18.0 to 18.5°C, while January means reach –3.7°C in some subregions. The Mazovian Lowland is among Poland's driest regions, with annual precipitation of less than 500 mm in central areas, rising to 500–600 mm peripherally (Kondracki, 2002).

The analysis used daily precipitation totals recorded during the growing season (April–October) at three IMGW-PIB (Institute of Meteorology and Water Management – National Research Institute) meteorological stations in the Mazovian Lowland over 1971–2020. Sequences of days with precipitation were defined as consecutive days with rainfall of over 0.1 mm. Sequence length was classified following Zawora (1995):

- 3 days – three consecutive days with precipitation,
- 4–9 days – one dry day permitted,
- 10–16 days – two dry days permitted,
- 17–22 days – three dry days permitted,
- 23–28 days – four dry days permitted,
- ≥29 days – five dry days permitted.

The mean, minimum, and maximum sequence lengths and their number per growing season were calculated. Spatial and seasonal variability among stations was evaluated. To obtain a more comprehensive picture of the temporal structure of rainfall sequences during the vegetation months, an analysis was conducted of changes in the number of days with rainfall sequences lasting 4–9 days (as only for sequences of this length was the number of cases sufficient). Trends in the frequency of each sequence type were assessed using the non-parametric Mann–Kendall test (MK) (Li *et al*., 2012; Hu *et al*., 2020). This widely used method analyses hydrological and meteorological time series, detecting monotonic trends without assuming normality or linearity. Significance was evaluated at the level of $\alpha = 0.05$.

Principal component analysis (PCA) based on the correlation matrix was applied to identify dominant patterns of covariation (Ringnér, 2008; Abdi and Williams, 2010). All analyses were conducted using Statistica 13.0, with results visualised via biplots (Yan and Tinker, 2006).

RESULTS AND DISCUSSION

Between 1971 and 2020, a total of 1,787 precipitation sequences lasting at least 3 days were recorded during the growing season (April–October) at meteorological stations in Legionowo, Pułtusk, and Siedlce. Sequences of 4–9 days were most frequent, with 1,142 occurrences accounting for approximately 67% of all observations. They were followed by 3-day sequences (336 cases, 19%). In the study period, longer sequences were considerably less common, comprising 251 events of 10–16 days, 43 of 17–22 days, 12 of 23–28 days, and only 3 sequences of at least 29 days (Tab. 1).

Table 1. Number of precipitation sequences per growing season by length and station (1971–2020)

Station	Length of sequence (days)					
	3	4–9	10–16	17–22	23–28	≥29
Legionowo	113	383	78	17	4	1
Pułtusk	100	385	73	10	3	1
Siedlce	123	374	100	16	5	1
Total	**336**	**1142**	**251**	**43**	**12**	**3**

Source: own study.

A comparison of the individual stations reveals discernible spatial differences. It was recorded in Legionowo the most 4–9-day (383) and 17–22-day (17) sequences, while Pułtusk had 385 and 10, respectively. Siedlce had the highest number of extended sequences (100 of 10–16 days; 5 of 23–28 days), with each station recording one 29-day event. These results confirm the dominance of 4–9-day sequences in the Mazovian Lowland in 1971–2020, which constituted about two-thirds of all the sequences. This finding is consistent with earlier studies reporting central Poland's prevalence of short and medium-length events compared to prolonged sequences in mountainous regions (Ustrnul and Czekierda, 2001).

Decadal variability of the frequency and structure of precipitation sequences was marked, yet 4–9-day sequences remained dominant at all the stations (Fig. 1). In Pułtusk, their frequency was high and quite stable (from 71 in 2011–2020 to 82 in 1981–1990); shorter, 3-day sequences were relatively rare and ranged from 12 (1971–1980) to 28 (2001–2010); 10–16-day sequences were quite regular but declined from 20 in the first decade to 11 in 1991–2000 and 2001–2010. Longer episodes (≥17 days) were sporadic with the maximum number of three cases in 1991–2000 and individual cases in the remaining decades. In Legionowo, 4–9-day sequences were the most frequent with a peak in 1971–1980 and 2001–2010 and the lowest number in 1981–1990; 3-day sequences were relatively frequent, peaking in 1981–1990 (28) and 1991–2000 (25). Sequences of 10–16 days occurred 14–20 times per decade, whereas the longest (17–22 days) appeared sporadically, with a maximum of seven cases in 2001–2010. In Siedlce, distributions were more balanced, with 4–9-day sequences stable, ranging from 72 to 79 per decade. The frequency of 3-day sequences was quite high for this station, ranging from 21 in 2001–2010 to 31 in 1971–1980. There was also quite a high number of 10–16-day sequences (16–26). The sequences ≥17 days occurred more often than elsewhere, up to four per decade.

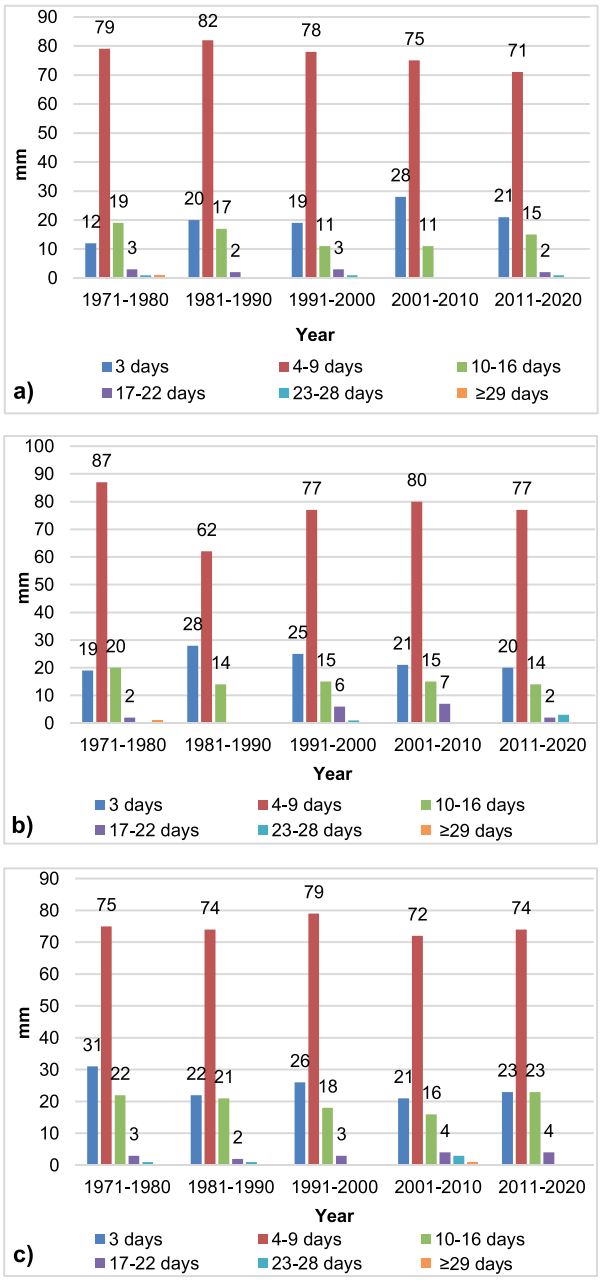

Fig. 1. Decadal frequency of sequences of days with precipitation in 1971–2020 in: a) Pułtusk, b) Legionowo, c) Siedlce; source: own study

Sequences ≥23 days were rare, aligning with Łupikasza (2010), who reported increased variability with more extremes but no clear trend toward longer sequences. International comparisons support these patterns. Short sequences dominated in China but contributed significantly to seasonal totals (Zhang *et al.*, 2011). More recently, Zong (2023) identified an increase in the frequency of extremely long and intense sequences of consecutive extreme wet days (*CEWDs*) over recent decades, which has been linked to climate change. Regional differences were noticeable in the study area, with longer sequences dominant in Siedlce, and medium-length in Legionowo and Pułtusk. This spatial differentiation is consistent with findings from Greece, where pronounced regional variability in the length of consecutive wet days (*CWDs*) was observed (Nastos and Zerefos, 2009). In South America, studies have documented correlations between the duration of *CWDs* and consecutive dry days (*CDDs*), and the El Niño–Southern Oscillation (ENSO), a global climate phenomenon that influences local precipitation regimes (Iacovone, Pántano and Penalba, 2020).

From a seasonal perspective, medium-length sequences were most prevalent in spring across the Mazovian Lowland, while the frequency of both shorter and longer episodes increased during summer and autumn. Comparable conclusions have been drawn in other regions of Poland (Szyga-Pluta, 2018; Walkowska, Bąk and Szyga-Pluta, 2022), where an elevated risk of extreme precipitation events was noted in the latter part of the growing season.

In 1971–2000, monthly distributions of precipitation sequence length in individual months of the growing season (April–October) showed strong inter-station similarity, despite minor local differences (Tab. 2). Medium-length sequences (4–9 days) predominated across all the locations, accounting for over 60% of events in most months, with peak frequencies observed in spring (April and May). Short, 3-days sequences increased in summer and autumn. In Siedlce, their frequency rose steadily from 16% (April) to 25% (August). In Pułtusk and Legionowo, they peaked in August (26% and 27%, respectively) and remained high in October (20–22%). Sequences of 10–16 days were most common in June and September, reaching 30% (June) and 19% (September) in Siedlce, and 23% (September) in Legionowo; whereas in Pułtusk, peaks occurred in July (16%) and October (14%). Sequences of 17–22 days occurred sporadically, notably in August (6% Siedlce, 4% Legionowo) and June (5% Pułtusk). Sequences ≥23 days were rare: 1–2% (July–October) in Siedlce, 2% (August) in Pułtusk, and 1% (August, October) in Legionowo.

The trend analysis of the number of days with rainfall sequences lasting 4–9 days (the dominant category) revealed no statistically significant monotonic trends in any of the examined cases (Tab. 3). All calculated *p*-values (ranging from 0.139 to 0.887) were considerably higher than the standard significance threshold, indicating that the observed fluctuations in the frequency of these rainfall sequences result from natural variability rather than long-term climatic change. At the Siedlce station, the strongest (though still statistically insignificant)

Table 2. Frequency of precipitation sequence classes (%) by month during the growing season (1971–2020)

Month	Frequency of precipitation sequences classes (%)					
	3 days	4–9 days	10–16 days	17–22 days	23–28 days	≥29 days
Siedlce						
April	16	68	13	2	0	0
May	17	64	16	3	0	0
June	19	48	30	3	0	0
July	23	61	14	0	1	1
August	25	58	9	6	2	0
September	19	56	19	4	1	0
October	20	66	12	0	1	0
Pułtusk						
April	14	71	14	1	0	0
May	14	71	14	1	0	0
June	15	67	13	5	0	0
July	16	65	16	2	0	0
August	26	62	8	1	2	1
September	17	70	10	1	1	0
October	21	65	14	0	0	0
Legionowo						
April	16	72	9	3	0	0
May	14	70	12	4	0	0
June	14	69	13	2	1	0
July	16	66	15	2	0	0
August	27	58	8	4	2	1
September	24	52	23	1	0	0
October	22	62	12	3	1	0

Source: own study.

Table 3. Values of the Mann–Kendall test assessing the relationship between month and the number of precipitation sequences of each type during the growing season (1971–2020) for rainfall sequences lasting 4–9 consecutive days

Parameter	April	May	June	July	August	September	October	Growing season
Siedlce								
Z	−0.887	0.586	0.234	−0.820	−0.552	1.071	1.455	−0.410
p-value	0.375	0.558	0.815	0.412	0.581	0.284	0.146	0.682
Legionowo								
Z	−1.129	−0.151	0.142	−0.485	0.251	−1.104	0.402	−1.096
p-value	0.259	0.880	0.887	0.628	0.802	0.270	0.688	0.273
Pułtusk								
Z	−0.836	1.037	−0.853	1.046	1.213	0.217	1.481	−0.694
p-value	0.403	0.300	0.394	0.296	0.225	0.828	0.139	0.488

Explanations: Z = standardised value of the test statistic, p-value = probability value.
Source: own study.

increasing tendencies were recorded in October (Z = 1.455, p = 0.146) and in April (Z = –0.887, p = 0.375). For the entire growing season, the trend was slightly decreasing (Z = –0.410, p = 0.682). Similar tendencies were observed in Legionowo, where the strongest increasing trend also occurred in October (Z = 1.481, p = 0.139), while the trend closest to the significance threshold was a slight increase in August (Z = 1.213, p = 0.225). When considering the growing season as a whole, a slight decreasing trend was recorded in Legionowo (Z = –0.694, p = 0.488). The Pułtusk station, in turn, exhibited the strongest, albeit still insignificant, decreasing trend over the entire growing season (Z = –1.096, p = 0.273). The strongest monthly decreasing tendency at this location occurred in April (Z = –1.129, p = 0.259).

The results Mann–Kendall test, used to assess the direction and significance of trends in the number of precipitation sequences by type during the growing season (April–October) and by location over the period 1971–2020, are presented in

Table 4. In Legionowo, the *Z*-statistic values were non-significant for all sequence types (3, 4–9, and 10–16 days), indicating no significant temporal trends. In Pułtusk, only 3-day sequences showed a significant increasing trend ($Z = 2.48$, $p = 0.013$). For Siedlce, in contrast, it was found a significant decline in the number of 10–16-day sequences ($Z = -3.50$, $p < 0.001$), indicating reduced frequency of medium-length precipitation episodes. No significant trends were found for shorter sequences (3 and 4–9 days) at this station. Mann–Kendall test analysis revealed no consistent trends across stations, except in Pułtusk (an increasing number of short sequences) and Siedlce (a declining number of 10–16-day episodes). This may reflect considerable local variability and the need for detailed regional studies, as frequently highlighted in the literature on climate change in Poland and Central Europe (Łupikasza, 2010; Wibig, 2024).

Principal component analysis revealed clear spatial and temporal differentiation in precipitation sequence distribution across stations and decades. The first principal component (PC1) separated high-frequency 3-day sequences in Siedlce and Legionowo from lower frequencies in Pułtusk and from longer sequences (≥10 days) across all stations. The PC1 thus reflected higher 3-day sequence frequency in Siedlce and Legionowo than in Pułtusk, where such events were consistently rarer compared with Siedlce (Fig. 2). The second principal component (PC2) distinguished Legionowo (dominated by 3-day sequences) from Siedlce (dominated by 4–9-day sequences). Medium-length sequences (4–9 days) were dominant in Legionowo. The PC2 captured structural differences in sequence length distribution between stations.

Table 4. Values of the Mann–Kendall test assessing the relationship between years and the number of precipitation sequences of each type during the growing season (1971–2020)

Parameter	Value in sequence		
	3-days	4–9-days	10–16-days
Legionowo			
n	50	50	50
S	−57	−84	−84
Z	−0.46843	−0.69428	−0.69428
p-value	0.639476	0.487505	0.487505
Pułtusk			
n	50	50	50
S	298	−132	−127
Z	2.484363	−1.0958	−1.05397
p-value	0.012978	0.273168	0.291896
Siedlce			
n	50	50	50
S	−178	−50	−420
Z	−1.48058	−0.40988	−3.50488
p-value	0.138719	0.681895	0.000457

Explanations: *n* = number of cases, *S* = Mann–Kendall test statistic; *Z* = standardised value of the test statistic, *p*-value = probability value; trend significant at $p \leq 0.05$.
Source: own study.

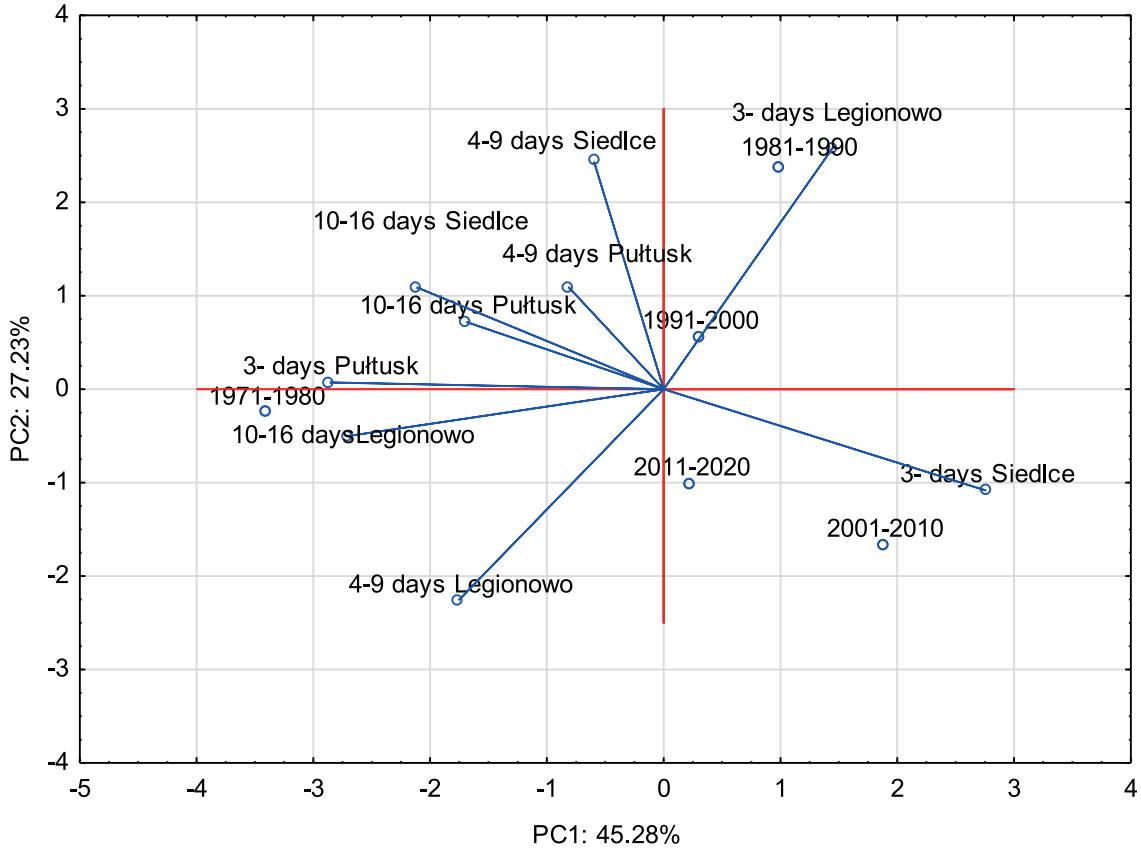

Fig. 2. Biplot illustrating the results of the principal component analysis (PCA) for the number of days with rainfall sequences occurring during the growing period, analysed by decades, at the Siedlce, Pułtusk and Legionowo stations; source: own study

CONCLUSIONS

During the study period, a total of 1,787 precipitation events lasting at least three days were recorded, the majority of which were sequences of 4–9 days, accounting for approximately two-thirds of all cases. Short events (3-day sequences) represented around 19% of observations, while sequences exceeding nine days were much less frequent. The longest sequences, lasting 29 days, occurred only three times. Spatial analysis revealed that short and medium-length events were more frequent in Legionowo, whereas Siedlce experienced the highest number of long sequences (exceeding 10 days). In contrast, Pułtusk exhibited the most stable precipitation structure, with a predominance of medium-length sequences. From a seasonal perspective, 4–9-day sequences were most common in spring, while the proportion of both short (3-day) and longer (over 10-day) episodes increased during summer and early autumn. The number of 4–9-day rainfall sequences (the most common in the region) remained stable over the analysed period and did not exhibit any significant trend-related evolution. The greatest structural variability in sequence length was observed in August and September. Trend analyses indicated no clear tendencies in the length or number of sequences at most stations. However, a statistically significant decline in the number of 10–16-day episodes was observed in Siedlce. Overall, medium-length precipitation sequences dominate in the Mazovian Lowland, while extremely long episodes remain marginal phenomena. These findings are of particular relevance for assessing drought and flood risk, as well as for informing water management strategies under conditions of increasing climate variability.

CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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