Jurnal
Teknologi

Full Paper

SPATIOTEMPORAL VARIABILITY OF ERODED ORGANIC MATTER, NITROGEN, AND NITRATE IN RESPONSE TO MONSOONAL CHANGES IN A BLACK PEPPER FARM

Article history
Received
14 November 2023
Received in revised form
18 March 2025
Accepted
8 April 2025
Published Online
23 December 2025

Izzah Abd Hamid[a], Wan Asrina Wan Yahaya[a]*, Samsuri Abdul Wahid[b], Wan Mohd Razi Idris[c]

[a]Department of Crop Science, Faculty of Agricultural and Forestry Sciences, Universiti Putra Malaysia Bintulu Sarawak Campus, 97008 Bintulu, Sarawak, Malaysia
[b]Department of Land Management, Faculty of Agriculture, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[c]Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600, Bangi, Selangor, Malaysia

*Corresponding author
asrina@upm.edu.my

Graphical abstract

Abstract

Organic matter (OM), total nitrogen (N) and nitrate (NO3) underpin soil fertility in black pepper farms, yet nutrient redistribution and losses can intensify under alternating monsoonal wet–dry regimes on steep, sandy terrain. This study quantified the spatiotemporal variability and inter-relationships of OM, N and NO3 across four monsoonal phases (Inter-April, Southwest, Inter-October and Northeast) using 264 surface soil samples (0–20 cm) from a 1.5 ha farm. Descriptive statistics, Pearson correlation and geostatistical mapping (semivariograms and Ordinary Kriging) were applied. Monsoonal transitions, compounded by a 26° slope, high sand content (>78.49%) and limited vegetative cover (35.06%), produced marked seasonal contrasts. Relative to Inter-April, OM and N increased by 24.3% and 22.1% during the Southwest monsoon, while NO3 rose by 86.0%, indicating temporary retention under lower rainfall. During the subsequent shift toward the Northeast monsoon, NO3 declined by 53.0, coinciding with high rainfall (1,223 mm) and enhanced leaching/runoff. Spatial dependence also shifted, with OM showing moderate dependence (27.175%) and NO3 consistently weak spatial dependence (<3%), reflecting high mobility and redistribution. Correlations among OM, N and NO3 varied by season, underscoring the sensitivity of nutrient coupling to moisture regime changes. Overall, results demonstrate that monsoonal timing strongly governs nutrient availability and loss pathways in coarse-textured, sloping pepper farms. Improved management particularly aligning fertiliser timing with crop demand and strengthening soil conservation (e.g., cover cropping and terracing) is recommended to mitigate losses and stabilise fertility.

Keywords: Black pepper; Monsoonal climate; Organic matter; Nitrogen; Spatial variability

Abstrak

Bahan organik (OM), jumlah nitrogen (N) dan nitrat (NO3) menyokong kesuburan tanah dalam sistem lada hitam, namun kehilangan serta pengagihan semula nutrien boleh meningkat akibat rejim monsun basah–kering, khususnya pada tanah bertekstur kasar dan cerun curam. Kajian ini mengkuantifikasi variabiliti spatiotemporal dan hubungan antara OM, N dan NO3 merentasi empat fasa monsun (Inter-April, monsun Barat Daya, Inter-Oktober dan monsun Timur Laut) menggunakan 264 sampel tanah permukaan (0–

20 cm) daripada ladang seluas 1.5 ha. Statistik deskriptif, korelasi Pearson dan pemetaan geostatistik (semivariogram dan Kriging Biasa) digunakan. Peralihan monsun, bersama faktor cerun 26°, kandungan pasir tinggi (>78.49%) dan litupan vegetatif terhad (35.06%), menghasilkan perbezaan bermusim yang ketara. Berbanding Inter-April, OM dan N meningkat masing-masing 24.3% dan 22.1% semasa monsun Barat Daya, manakala NO3 meningkat 86.0%, menunjukkan pengekalan sementara apabila hujan lebih rendah. Semasa peralihan berikutnya ke monsun Timur Laut, NO3 menurun 53.0% selari dengan hujan tinggi (1,223 mm) serta peningkatan larut resap dan larian permukaan. Kebergantungan ruang turut berubah, dengan OM menunjukkan kebergantungan sederhana (27.175%) manakala NO3 kekal lemah (<3%) akibat mobiliti yang tinggi. Korelasi antara OM, N dan NO3 juga berubah mengikut musim, menonjolkan sensitiviti ketersediaan nutrien terhadap perubahan kelembapan. Secara keseluruhan, masa monsun mengawal laluan kehilangan nutrien pada ladang lada hitam berpasir dan bercerun. Pengurusan yang lebih baik terutamanya penyelarasan masa pembajaan dengan keperluan tanaman serta amalan pemuliharaan tanah (cth. tanaman tutup bumi dan teres) disyorkan bagi mengurangkan kehilangan dan menstabilkan kesuburan.

Kata kunci: Lada hitam; Iklim monsun; Bahan organik; Nitrogen; Variabiliti spatial

1.0 INTRODUCTION

Agro-climatic factors wield a significant influence on the dynamics of nutrients within the soil system, and their interplay is highly affected by monsoonal transitions, ultimately affecting spatial variability and disrupting the productivity of plants [1]. This condition is particularly prominent on sloping terrains and is subject to the complex interplay of intrinsic and extrinsic factors, ranging from soil classification to human intervention. Soils characterised by finer textures, notably clay-rich composition, have the capacity to store water, which affects nutrient uptake. In conditions where the availability of organic matter (OM), total nitrogen (N), and nitrate (NO_3) take precedence, and the textural classes of the soil assume pivotal importance in preventing nutrient losses. Elevated levels of precipitation or excessive irrigation in sloping landscapes have been observed to cause the leaching of NO_3 from the soil, owing to the formation of a thin saturated layer. This, in turn, results in short-term accumulation and a lag of drainage water discharge, contributing to an increasing loss rate [2], a phenomenon that is highly pronounced in soils with coarser textures. One viable solution to this problem entails the amendment of crop residues onto the soil surface, serving to improve the water retention capacity of sandy soils to store water, thereby curbing the leaching process.

Sandy soils, distinguished by their larger pore size and lower sorption capacity, exhibit a notable deficiency in retaining nutrients effectively, thus imparting a substantial influence on soil variability. It was expected that silty soils would manifest high nutrient uptake compared to sandy soils, as these elements tend to leach to deeper strata and move more freely within the soil system [3, 4]. The influence of monsoonal changes on soil properties and nutrient availability is particularly evident in tropical regions, where alternating dry and wet seasons result in significant shifts in nutrient cycling. High rainfall events, such as those experienced during monsoons, often lead to increased nutrient runoff, soil erosion, and leaching, which can adversely impact crop growth and soil fertility [1, 5]. Conversely, the dry season may induce moisture stress, reducing microbial activity and nutrient mineralisation, thereby affecting plant nutrient availability. Studies conducted in tropical regions have demonstrated that monsoonal rainfall intensifies N and NO_3 losses due to excessive water movement through the soil profile, disrupting the balance of essential nutrients [6].

In regions typified by high rainfall, such as the climatic backdrop of Finland, the consequential large volumes of water and the advent of intense rainy seasons have yielded strong spatiotemporal variations in OM, N, and NO_3 [7]. At the beginning of rainy seasons, elevated levels of N content were observed, especially during periods of peak rainfall. This phenomenon is linked to limited vegetation availability, the use of fertilisers, and continuous rain showers. The presence of N-fixing microbes, which are responsible for increased mineralisation, is a common cause of this condition [8]. Additionally, various exogenous factors specific to the locality also contribute to the uneven distribution and availability of nutrients. In black pepper farms, monsoonal changes impose a critical challenge, as heavy rainfall increases the risk of nutrient depletion due to erosion and runoff, particularly on sloping lands [1, 8]. A study conducted in Bintulu, Sarawak, Malaysia, revealed that different rainfall patterns significantly affected soil chemical properties in black pepper cultivation, highlighting the vulnerability of such farms to monsoonal variations [1].

The hilly and coarse-textured terrains of East Malaysia lack extensive information related to soil fertility, contrasting with Peninsular Malaysia, where studies predominantly focus on sedimentary rock regions. Previous work has primarily centred on the impact of rainfall on nutrient availability, highlighting the occurrence of nutrient depletion in high-rainfall areas due to changes in vegetation practice and hydrologic transport [9]. This is supported by analyses of how rainfall affected tree distribution and fluctuations in soil moisture in forest reserves of Peninsular Malaysia [10]. Despite the well-documented effects of rainfall on nutrient leaching, there remains a gap in understanding how seasonal monsoonal changes distinctly influence the movement and availability of OM, N, and NO_3 in different agricultural settings. Black pepper farms, in particular, are vulnerable to nutrient loss due to the combination of sloping terrain, frequent fertilisation, and exposure to heavy monsoonal rains [1]. Moreover, excessive nitrogen losses, especially in the form of NO_3, can lead to negative environmental consequences, including water contamination and greenhouse gas emissions through denitrification. Studies have highlighted the susceptibility of tropical cash crops, including black pepper, to NO_3 leaching and OM depletion in monsoonal climates, reinforcing the urgency of site-specific soil management strategies [11].

There is a pressing need for more research on the impact of monsoonal changes on nutrient availability in East Malaysia, given its critical role in agriculture, which often takes place in diverse topographies from flat to sloped regions. Moreover, in these topographical structures, precious commodities such as black pepper are cultivated extensively. Access to this information clearly aids the industry by optimising crop growth, boosting outputs, minimising the use of input, and contributing to environmental conservation. A detailed analysis of the spatiotemporal patterns of OM, N, and NO_3 will provide valuable insights into nutrient dynamics, aiding in the development of improved soil management strategies tailored to monsoonal variations. By understanding these inter-relationships, it becomes possible to enhance fertiliser efficiency, reduce nutrient runoff, and ensure the long-term sustainability of black pepper farming systems. Prior studies have indicated that incorporating organic amendments and adjusting fertilisation timing according to monsoonal patterns can mitigate nutrient losses and improve crop resilience, making this study highly relevant for sustainable agriculture in tropical climates. With this in mind, the main objectives of this study are (1) to analyse the spatiotemporal variability of OM, N, and NO_3 in response to monsoonal changes and (2) to explore the inter-relationships between OM, N, and NO_3 in the context of monsoonal changes.

2.0 METHODOLOGY

2.1 Descriptions of the Study Area

This study was conducted on a 1.5-hectare black pepper farm located in the pristine locale of Samarakan, Bintulu, Sarawak (3.0116° N, 113.0260° E), as depicted in Figure 1. The annual precipitation in this area amounts to 4,600 mm. The region experiences two main seasons: the Northeast monsoon (wet season), occurring from November to March, and the Southwest monsoon (dry season), which typically lasts from May to September. The transitions between these seasons take place in April and October, during the inter-monsoon periods. Rainfall data, including volume and the number of rainy days, were acquired from the Malaysian Meteorological Department and are graphically depicted in Figure 2.

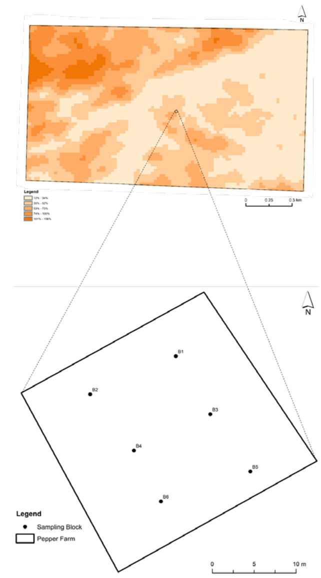

Figure 1 The cartographic representation of the designated study area, located in Samarakan, Bintulu, Sarawak, Malaysia, along with the delineation of the topographical surface using a publicly available Digital Elevation Model (DEM) for visualisation purposes only

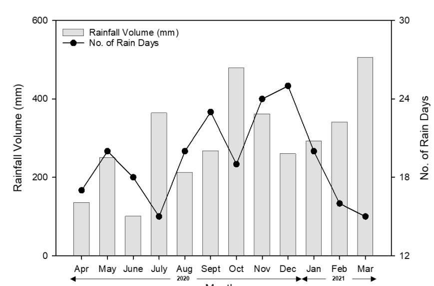

Figure 2 The data comprising records of both rainfall volume and the number of rain days recorded at the meteorological station situated in Bintulu, Sarawak, Malaysia

The land in focus had a steep slope, measuring at a 26°, and it implemented a farming approach that was devoid of terracing and cover crop. The study identified evident signs of poor land management, limited conservation efforts, and restrictions in procuring agricultural supplies. The farm itself had previously been a secondary forest, cleared through slash-and-burn to make way for the cultivation of black pepper. It followed conventional agricultural practices, such as planting during the rainy season and applying fertilisers, either at the onset of flowering emergence or when signs of severe deficiency became apparent. The soil composition in this area had developed over a mixture of sedimentary rocks with a well-draining profile. This soil was characterised as sandy loam, with sand content exceeding 76% according to the USDA soil texture triangle, and it was further designated as the Bekenu Series [12].

The research focused on a plot containing 264 black pepper vines, all of which were 16 months old and belonged to the Uthirancotta cultivar (Indian cultivar). These vines were trained to climb on the non-living trunks of *Commersonia bartramia* trees, with a planting distance of 2.1 m × 1.8 m. In terms of fertilisation, the farmers adhered to a regimen of NPK green (15:15:15), administering 100 g/vine each month for vines under the age of 24 months. Upon surpassing 24 months, the vines were treated with NPK blue (12:12:17) and applied at the same rate. Preventative measures against potential threats were also in place; the farmers regularly applied fungicides and insecticides to stave off fungal diseases and protect against insect infestations.

2.2 Data Collection and Analysis

Approximately 1 kg of soil was systematically collected (0-20 cm depth) on a weekly basis over a span of three weeks, starting during the transitional inter-monsoon period from the Northeast to the Southwest monsoon in April 2020. The sampling regimen for the October inter-monsoon mirrored that of the April inter-monsoon (Inter-Apr.). However, during the main seasons, soil collection was performed bi-weekly.

All procured soil samples were pulverised and sifted through a 2 mm mesh. Subsequent soil analysis adhered to established protocols, with pH and soil texture following the methodology outlined by Tan [13], and N and NO_3 evaluations conforming to standards set by the Food and Agriculture Organization [14]. To lay the groundwork for this study, basic soil characterisation was performed using soil samples collected a month prior to the initiation of the research, the details of which are presented in Table 1. The estimation of crop coverage percentages was facilitated by Google Earth Pro, supplemented by on-site ground-truthing of the black pepper farms using ArcGIS for crop coverage projections and other relevant data. For the analysis phase, a combination of descriptive statistics, geostatistical analysis, and interpolation of a projected model was employed, utilising ArcGIS for the spatial analysis of selected variables, and XLSTAT for correlation assessments. Spatial interpolation of OM, N, and NO_3 was performed using the Ordinary Kriging method in ArcGIS. Ordinary Kriging was selected due to its ability to provide statistically optimal estimates by accounting for spatial autocorrelation, making it suitable for environmental and soil studies where data points exhibit spatial dependence.

While rainfall and topography significantly influence nutrient transport and retention, this study primarily focused on the spatiotemporal variability of OM, N, and NO_3 rather than a direct correlation analysis. However, rainfall data were incorporated to contextualise seasonal variations, and topographical influences were considered through soil texture and slope assessments. Future research should explore the direct impact of rainfall intensity and topographical features on nutrient leaching and retention to provide a more holistic understanding of monsoonal effects.

Table 1 Physical-chemical properties of the study area during the sampling period (April–October 2020)

Soil chemical properties			
Parameter	**Value**	**Parameter**	**Value**
pH	4.46	N (g/kg)	1.37
OM (%)	2.27	NO_3 (g/kg)	0.01

Soil physical properties			
Parameter	**Value**	**Parameter**	**Value**
Granulometric composition			
Clay (%)	15.24	Sand/silt	12.54
Silt (%)	6.26	Silt/clay	0.41
Sand (%)	78.49		
		Crop coverage (%)	35.06
Slope (°)	26		

3.0 RESULTS AND DISCUSSION

3.1 Descriptive Statistical Analysis of OM, N, and NO_3

The dispersion of OM, N, and NO_3 levels, including minimum, maximum, mean variables, CV, skewness, and kurtosis, can be found in Table 2 through descriptive analysis. There was a reduced concentration of OM (0.99-3.23%), N (0.3587-1.2634 g/kg), and NO_3 (0.0037-0.0330 g/kg) during the transition from the wet to the dry season (Inter-Apr). However, these levels showed a proportional increment during the dry period (Southwest) with OM increasing by 24.3%, N by 22.1%, and NO_3 by 86.0% until the transition from the dry to the wet season (Inter-Oct.), where OM further increased by 5.0%, N by 29.3%, and NO_3 decreased by 53.0% compared to the Southwest monsoon. Moreover, nutrient concentrations remained lower during the Northeast monsoon (wet period) compared to the Inter-Oct. period.

In this study, the skewness values ranged from -0.8219 to 1.6064, indicating that the data displayed moderate to highly skewed distributions. Specifically, OM had a skewness of -0.0318, and NO_3 had a skewness of 0.0049 during the Northeast and Southeast monsoons, suggesting a distribution close to normal with values approaching zero. Kurtosis values in this study varied from -0.7758 to 4.5577, signifying differences in tail weight. Notably, N displayed a kurtosis value of 2.6328 during Inter-Oct., and NO_3 had a kurtosis value of 2.6724 during Inter-Apr., both of which are close to three, indicating a normal or mesokurtic distribution. To assess the degree of variability, the coefficient of variation (CV) was employed. CV values in this study ranged from 7.04% to 67.92%. Based on established classification groups, these values fall into the categories of low to moderate variability. Specifically, CV values ≤ 10% are considered low, CV values between 10% and 90% are considered moderate, and CV values ≥ 90% are considered high [7].

Table 2 Statistical characteristics of OM, N, and NO_3 across various monsoonal phases

Index	Monsoon	Min. (g/kg)	Max. (g/kg)	Mean (g/kg)	CV*	Skew.	Kurt.
OM*	**Inter-Apr.**	0.99	3.23	2.10	29.25	0.4520	-0.7758
	Southwest	1.75	3.32	2.61	21.03	-0.1820	-1.4202
	Inter-Oct.	1.86	5.35	2.74	28.32	1.6064	4.5577
	Northeast	1.44	3.15	2.37	22.09	-0.0318	-0.9913
N	**Inter-Apr.**	0.3587	1.2634	0.8960	25.94	-0.8219	0.2553
	Southwest	0.4734	0.9785	0.6947	19.63	0.5188	-0.2752
	Inter-Oct.	0.7945	1.0930	0.8984	7.04	1.1905	2.6328
	Northeast	0.5837	1.0133	0.7293	14.07	1.3006	1.7782
NO_3	**Inter-Apr.**	0.0037	0.0330	0.0143	45.26	1.4864	2.6724
	Southwest	0.0171	0.0363	0.0266	16.95	0.0049	0.1485
	Inter-Oct.	$1.2X10^5$	0.0296	0.0125	67.92	-0.2427	-0.5563
	Northeast	0.0115	0.0306	0.0189	23.60	0.6705	0.7251

*The values for OM are expressed as percentages (%)

The observed changes in nutrient concentrations across monsoonal periods were strongly influenced by accumulated rainfall. The total rainfall recorded during the Northeast monsoon was 1,223 mm, while the Southwest monsoon had a significantly lower amount at 387 mm. The transitional periods (Inter-Apr. and Inter-Oct.) experienced moderate rainfall, at 625 mm and 781 mm, respectively (Figure 2). This rainfall pattern explains why OM, N, and NO_3 concentrations showed increased variability during Inter-Apr. and Inter-Oct., as moderate rainfall facilitated nutrient accumulation without excessive leaching.

The study revealed a moderate variability in OM content ranging from 21.03% to 29.25%, as reported in Table 2, and this variability was interpreted as the effect of both intrinsic and extrinsic factors. Notably, the CV values were higher during the Inter-Apr. (29.25%) and Inter-Oct. (28.32%) seasons when compared to the main monsoons, representing the dry and wet periods. Lower CV values (<23%), on the other hand, indicated that OM variability was highly affected by intrinsic factors, with coarse texture accounting for a significant portion (78.49%) of this variability, as highlighted in Table 1. The coarse textural composition tended to inhibit bacterial growth, reducing the population responsible for OM decomposition and resulting in poor aggregate formation [5, 15]. During the Inter-Apr. and Inter-Oct. periods, a slight increase in variability was observed, attributed to the transitional dry-wet and wet-dry phases, which facilitated the accumulation and temporary storage of OM. Conversely, the main monsoons, characterised by extended drought periods followed by heavy rainfall, led to the swift removal of OM, particularly in light of the steep topographic layout (elevation range: 45–85 m, average slope: 26°), which promoted the transportation of this substance through rainfall-induced erosion, which promoted the transportation of this substance through rainfall-induced erosion. This finding aligns with the research of Siswanto and Sule (2019), which indicated that OM movement was influenced by erosion in the Cirandu catchment and Citarum watershed in West Java, Indonesia.

The CV for N exhibited a state of moderate variability in several periods, with values of 25.94% in Inter-Apr., 19.63% in the Southwest, and 14.07% in the Northeast. Conversely, during Inter-Oct., the variability dropped significantly to a mere 7.04%, with the highest recorded value manifesting in Inter-Apr. due to repeated N fertilisation. During periods of excessive moisture, agricultural practitioners tend to curtail fertiliser application or temporarily suspend it to mitigate potential losses arising from excessive water flow. Nonetheless, it is crucial to recognise that CV values below 20% during the Southwest and Northeast monsoons resulted from a complex interplay of intrinsic factors, such as soil parent material and soil mineral composition, as well as extrinsic factors, including practices related to fertiliser application and crop management strategies. For example, the reduction in fertiliser application during the Southwest monsoon was largely due to restricted farm operations caused by the Malaysian government's Movement Control Order (MCO) (March 18–May 3, 2020), which disrupted fertiliser supply chains and labour availability. Notably, the period of the Southwest monsoon witnessed a noticeable reduction in fertiliser application, leading to a substantial reduction in the CV, which reached a low of 7.04% during the Inter-Oct. season.

The investigation unveiled a remarkable spectrum of variability in the concentration of NO_3, ranging from 16.95% to an impressive 67.92%. The peak of this variability was observed during the Inter-Oct. period, as documented in Table 2. This surge in variability during Inter-Oct., coincided with the onset of frequent rainfall during the transition from the monsoonal season to the wet season (Northeast). However, as the Northeast monsoon season settled in, the CV decreased by a factor of three, only to increase two-fold during the Inter-Apr. period. During dry periods, the CV was as low as 16.95%, indicating that both inherent and external factors contributed to the observed variations. For instance, the coarse soil texture (sand content >65%) limited NO_3 retention, resulting in increased mobility and leaching under high rainfall conditions. The mobility of NO_3 in sandy soil primarily followed groundwater tables situated below the root zone, a crucial determinant in these findings. Moreover, the application of fertilisers using the broadcasting technique introduced ionic form N into percolating water, thereby accelerating the mobility of NO_3, resulting in the high variability observed during the Inter-Oct. period, where the CV reached 67.92%. Conversely, during the peak of the wet season, ineffective fertiliser applications aimed at mitigating N deficiency led to a reduced CV of 23.60% in the Northeast monsoon. The area's predominant coarse-textured soil and limited crop coverage (35.06%) contributed to excessive nutrient leaching into the soil profile, ultimately yielding low variability in NO_3 on the soil surface [16, 17].

3.2 Correlations between Selected Soil Properties

Conducting a Pearson correlation analysis allowed the authors to examine the strength and direction of the data presented in Table 3. In the Inter-Apr. period, a substantial negative correlation emerged, indicating that NO_3 (r=-0.618, p=0.05) exhibited a strong inverse connection with N. During both the Southwest and Northeast monsoons, N displayed robust positive correlations with OM (Southwest: r=0.659, p=0.05; Northeast: r=0.781, p=0.05), underlining the influence of these factors in a synergistic manner. In the Southwest monsoon, moderate positive correlations were documented between NO_3 and N (r=0.384, p=0.05), as well as between OM and NO_3 during the Inter-Oct. period. During the Inter-Apr. period, subtle yet meaningful positive correlations were identified, illustrating the delicate relationship between OM and N (r=0.284, p=0.05), as well as between OM and NO_3 in both the Southwest (r=0.228, p=0.05) and Northeast (r=0.287, p=0.05) monsoons. Conversely, a weak negative correlation surfaced between NO_3 and OM in the Inter-Apr. period (r=-0.157, p=0.05), as well as between NO_3 and N in the Inter-Oct. period (r=-0.150, p=0.05). Notably, a higher degree of variation was observed around the line of best fit for NO_3 and OM during the Inter-Oct. period (r=0.040, p=0.05), adding depth to the understanding of these dynamics.

Table 3 Pearson correlation coefficients of OM, N, and NO_3

Monsoon	Index	OM	N
Inter-Apr.	N	0.284	
	NO_3	-0.157	-0.618
Southwest	N	0.659	
	NO_3	0.228	0.384
Inter-Oct.	N	0.398	
	NO_3	-0.040	-0.150
Northeast	N	0.781	
	NO_3	0.287	0.007

The importance of N and OM in relation to nutrient availability was demonstrated by a positive relationship (weak to strong) between these elements. This correlation was particularly pronounced during the Southwest (r=0.659) and Northeast (r=0.781) monsoons, both of which experienced active N mineralisation processes. The presence of sustained moisture in these periods promoted microbial activity, leading to higher OM decomposition and increased NO_3 availability. This trend aligns with the findings of Chen, Mao, Zhang, Zhang, Chang, Gao and Thompson [18], who reported that the combined use of crop residues and chemical fertilisers over six years in China enhanced N availability [18].

During the Inter-Apr. and Inter-Oct. periods, a negative correlation was observed between OM and NO_3 (r=-0.157 and r=-0.040, respectively), contrasting with the positive correlation seen during the Southwest (r=0.228) and Northeast (r=0.287) monsoons. This pattern can be attributed to the consistent use of crop residues and occasional applications of chicken manure during crop replacement, which improved OM levels, subsequently increasing NO_3 availability, particularly during wet and dry periods. However, the negative correlation between NO_3 and OM during monsoonal transitions suggests that erratic weather conditions contributed to NO_3 losses through leaching and surface runoff. This observation is critical for understanding how monsoonal shifts impact NO_3 retention and black pepper growth, as highlighted in previous studies [17, 19]. Additionally, monsoon-driven rainfall intensity influences nutrient leaching, particularly in the case of NO_3, which is highly mobile in the soil. The negative correlation between NO_3 and OM during Inter-Apr. (-0.157) and Inter-Oct. (-0.040) suggests that increased leaching potential during transitional periods reduces NO_3 retention. Conversely, during the wet Northeast monsoon, the stronger positive correlation (r=0.287) between OM and NO_3 suggests enhanced mineralisation due to sustained moisture availability.

The topography characteristics of the black pepper farm also played a significant role in nutrient movement. The study area, characterised by a moderate slope (~26°), directly influenced NO_3 retention and transport. During heavy rainfall in the Northeast monsoon, steeper slopes promoted runoff, leading to NO_3 displacement from higher elevations to flatter zones. This phenomenon explains the lower correlation between NO_3 and N (-0.150) during Inter-Oct., indicating that NO_3 had moved beyond the sampled areas. In contrast, during the drier Southwest monsoon, minimal rainfall facilitated NO_3 accumulation, reinforcing the moderate correlation observed (r=0.384). These findings highlight how monsoonal variations, in combination with topographic influences, govern nutrient cycling within the black pepper farm system.

A similar relationship was observed between NO_3 and N during the Inter-Apr. and Inter-Oct. periods (r=-0.618 and r=-0.150, respectively), indicating the active uptake of inorganic N (NH_4^+ and NO_3^-) by plants. Importantly, the influence of organic amendments was evident, as the positive correlation between NO_3 and OM in the Southwest and Northeast monsoons (r=0.384 and r=0.007, respectively) suggests that organic inputs played a role in replenishing soil NO_3.

3.3 Different Monsoonal Changes on OM, N, and NO_3

Geostatistical analysis was employed to derive best-fit models using semivariograms, yielding spherical, exponential, and Gaussian models (Table 4). The R-squared (R^2) values, ranging from poor to excellent regression model fit, displayed a spread with a range (A) spanning between 4.36 and 27.96. Impressively, the residual sum of squares (RSS) approached zero, signifying a superior model fit. Spatial dependence, a critical aspect of the analysis, was identified within the range of 0.098-27.175%. It is worth noting that only OM in the Southwest monsoon exceeded the 25% threshold. Accordingly, spatial dependence was categorized as strong, moderate, and weak, indicating values of <25%, 25-75%, and >75%, correspondingly [20].

Accuracy estimation of model performance for both predicted and measured values was carried out using Leave-One-Out Cross-Validation (LOOCV), represented by mean error (ME), absolute mean error (AME), and root mean square error (RMSE). All these metrics closely approached zero, except for NO_3, which exhibited a negative value, indicating underestimation, while positive values indicated a close alignment between predicted and measured values. Additionally, the LOOCV results suggest that the models effectively captured the spatial variability of OM and N but underestimated NO_3, possibly due to its high mobility in the soil profile. The tendency of NO_3 to leach during high rainfall periods and accumulate during drier conditions may have introduced challenges in capturing its precise spatial distribution. Cross-validation was performed to uphold the accuracy of the dataset.

Table 4 Theoretical semivariogram models of OM, N, and NO_3

Index	Monsoon	Nugget (Co)	Sill (Co+C)	Range (A)	Ratio (%)	Model	ME	AME	RMSE
OM	IA	0.001000000	0.429000000	19.14	0.233	G	0.021667	0.261667	0.318538
	SW	0.001000000	0.633000000	27.96	0.158	G	0.011667	0.153333	0.188768
	IO	0.228000000	0.839000000	19.47	27.175	G	0.018333	0.414167	0.640104
	NE	0.001000000	0.324000000	20.27	0.309	G	0.012500	0.218333	0.257973
N	IA	0.002800000	0.061500000	22.08	4.553	E	0.006685	0.155805	0.202903
	SW	0.001780000	0.019960000	12.41	8.918	S	0.002579	0.087671	0.105824
	IO	0.000010000	0.003000000	4.36	0.333	S	0.000801	0.043506	0.059086
	NE	0.000010000	0.010220000	9.06	0.098	G	0.003456	0.064067	0.090555
NO_3	IA	0.000000800	0.000037100	6.02	2.156	S	-0.000133	0.004911	0.006827
	SW	0.000007390	0.000029080	19.38	25.413	E	-0.000045	0.003672	0.004522
	IO	0.000000100	0.000068200	4.36	0.147	S	-0.001042	0.007243	0.008653
	NE	0.000000140	0.000016980	5.33	0.824	S	-0.000138	0.003579	0.004330

*Monsoon: IA – Inter-Apr., SW – Southwest, IO – Inter-Oct., and NE – Northeast
**Model: E – Exponential, G – Gaussian, and S – Spherical

In this study, the spatial dependence of OM, N, and NO_3 during the Inter-Apr. (0.233-4.553%) and Inter-Oct. (0.147-27.175%) demonstrated strong to moderate patterns of dependence, respectively. During the Inter-Apr., a strong spatial dependence (0.233-4.553%) was governed by endogenous variations arising from soil characteristics, such as coarse texture, soil mineralogy, and farm topography. The lower spatial dependence values in this period suggest a relatively uniform distribution of OM and N, likely due to slower decomposition rates under drier conditions. These variations are influenced by non-human structural elements and significantly affect the availability of OM, N, and NO_3 [1, 21]. Conversely, during the Inter-Oct. season, spatial dependence exhibited both strong and moderate variability, encompassing both endogenous and exogenous factors. The onset of wetter conditions likely accelerated OM decomposition, increasing NO_3 availability, yet also introduced greater spatial heterogeneity due to differential rates of leaching and plant uptake. Exogenous factors included factors such as limited return of black pepper crop residues to the soil, sub-optimal farm management practices (e.g., absence of terracing and exposed soil surfaces), and inadequate nutrient availability, particularly for N and potassium (K). Furthermore, the accelerated decomposition of OM during the monsoonal transition from dry to wet conditions released inorganic N for uptake by black pepper, contributing to smaller spatial dependence values due to increased variability [22, 23].

The spatial dependence patterns in the Southwest monsoon (0.158-25.413%) exhibited strong to moderate levels, whereas the Northeast monsoon (0.098-0.824%) had a strong spatial dependence. The lower values observed during the Northeast monsoon suggest that high rainfall-induced leaching played a significant role in NO_3 redistribution, making it less spatially structured. Additionally, despite the high rainfall, the steep terrain (~26°) and low vegetative cover (~35.06%) facilitated surface runoff, which contributed to greater spatial variability. During the wet season, any crop cultivated on the farm could dissipate rainfall and help control variability, resulting in lower spatial dependence. However, even though the Northeast monsoon displayed lower spatial dependence, the ability of crops to dissipate raindrops was limited due to sparse crop coverage. This supports the idea that plant coverage influences the degree of NO_3 retention and redistribution, highlighting the importance of ground cover in mitigating nutrient loss [24, 25].

In contrast, the spatial variability value was notably higher during the Southwest monsoon, closely associated with the farmers' irrigation activities aimed at supporting crop growth. The water input from irrigation may have led to non-uniform soil moisture conditions, exacerbating spatial heterogeneity in NO_3 distribution. The extended dry period during this monsoon adversely affected black pepper growth, resulting in wilted and dying crops.

3.4 Spatiotemporal Distributions of OM, N, and NO_3

Ordinary Kriging was employed for the spatial interpolation of OM, N, and NO_3, as depicted in Figure 3. The spatial patterns observed closely corresponded to the topography of the study area. For OM concentrations (Figures 3a, b, c, and d), the highest levels were found in the West-North West (WNW) region, reaching 26.77% and gradually reduced towards the East (E), East-South East (ESE), and South East (SE) directions. The movement of N and NO_3 displayed similar patterns, as shown in Figures 3e, f, g, and h for N and Figures 3i, j, k, and l for NO_3. These nutrients tended to move from upper to lower steep areas, with N ranging from 0.4210 to 0.8953 g/kg and NO_3 from 0.0128 to 0.0243 g/kg, respectively. A patchy distribution was noticeable during the Inter-Apr., particularly for NO_3, as well as for N and NO_3 during the Southwest monsoon. These trends indicated higher concentrations in the North or the upper areas spanning from the North West (NW) to the North East (NE). During the Inter-Apr. season, N movement was observed from the upper hills toward lower areas (Figure 3e). The distinct movement of nutrients during this season could be attributed to the combined effects of topographic control and rainfall-driven surface runoff, influencing the redistribution of soil nutrients.

A similar pattern in the spatial distribution of OM, as depicted in Figures 3a, b, c, and d, is evident across the Inter-Apr., Southwest, and Inter-Oct. seasons, with slight variations during the Northeast monsoon. A notable decline in OM content, ranging from 3.65% to 0.63%, was observed from the WNW to E, ESE, and SE directions. This occurrence is linked to the soil morphology of the area, which was actively transported with the help of erosion processes accelerated by monsoonal rainfall and slope-driven water movement, particularly as a result of intense farming practices adopted by the farmers. Factors such as slope length, poorly aggregated soil, and low vegetative coverage contributed to the accelerated loss of OM, a trend further corroborated by continuous seasonal changes (Table 5). During the Northeast monsoon, a broad range of spatial distribution (-8.78–28.77%) was observed, primarily driven by frequent and high-intensity rainfall events that facilitated the translocation of OM towards the nearest gentle slopes. Additionally, higher OM concentrations were observed in the West (W) and South-South West (SSW) directions due to the application of banana leaf residues on the black pepper crop during routine farming maintenance, affecting the area's spatial distribution patterns [26].

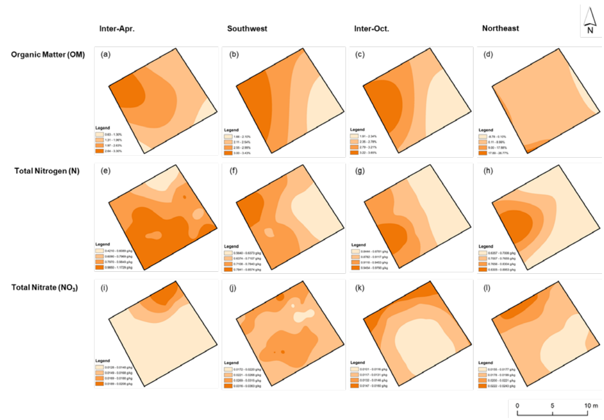

Figure 3 The spatiotemporal distribution patterns of OM, N, and NO_3 across the periods of Inter-Apr., the Southwest monsoon, Inter-Oct., and the Northeast monsoon

Table 5 Changes in nutrient levels in response to monsoonal changes

	OM	N	NO_3
Inter-Apr.	-7.33	-34.60	43.70
Southwest	15.03	-49.30	165.54
Inter-Oct.	20.63	-34.43	24.93
Northeast	4.56	-46.77	88.79

The distribution of N exhibited a consistent pattern during the Southwest, Inter-Oct., and Northeast monsoons, as shown in Figures 3e, f, g, and h. There was a decline in N concentration from the WNW toward E, ESE, and SE directions. Nonetheless, during the Inter-Apr. season, a distinct pattern emerged with N concentrations increasing towards the South (S). The shift in concentration can be attributed to the transition from dry to wet periods, impacting the movement of N in response to the topography and loosely packed soil aggregates. As indicated in Table 5, this condition led to N levels exceeding 36% throughout our study. This seasonal variation in N concentration was influenced by both climate and farm management, including fertilisation timing, rainfall, and crop uptake. In Inter-Apr. seasons, extensive fertilisation practices have resulted in elevated N concentrations, ranging from 0.4210 to 1.1729 g/kg. A surge in fertilisation activity during this period, often as a pre-monsoonal measure to enhance soil fertility, contributed to the observed peak N values. The highest N concentration was observed during Inter-Apr., due to variable nutrient retention and potential gaseous losses through volatilisation, which subsequently reduced nutrient concentrations in soil and significantly altered spatial distribution. However, N concentrations slowly recovered after reaching the Inter-Oct. and Northeast seasons. The spatial distribution of N was subject to the influence of monsoon patterns and the application of N-based fertilisers to crops, subsequently compounded by natural factors such as topographical variations and soil aggregate dynamics.

In the context of the Southwest monsoon (as illustrated in Figures 3i, j, k, and l), a patchy distribution was observed for NO_3, setting it apart from the more uniform distributions observed in other monsoons. In the latter, a consistent pattern extended from the WNW to E, ESE, and SE directions. However, during the Inter-Apr. season, a decline trend in NO_3 became evident, with the levels decreasing from the West (W) to the East (E). This decline was expected, given the high mobility of NO_3, which allowed for rapid movement, particularly influenced by the steep topography (26°), low vegetative coverage (35.06%), and leaching processes. Steeper slopes enhanced overland flow, expediting NO_3 displacement, while reduced vegetative interception further facilitated downward percolation. In dry seasons, the temporary moisture limitations led to NO_3 accumulating on the soil surface, resulting in the observed patchy distribution during the Southwest monsoon. This phenomenon is further supported by significant nutrient fluctuations (as detailed in Table 5). The application of fertilisers using broadcasting techniques can contribute to leaching due to deep percolation [27]. Additionally, improper timing of fertiliser applications during heavy rainfall periods may have exacerbated NO_3 leaching losses, reducing nutrient retention in the soil profile. Besides, limited root growth during the early stages of crop establishment exacerbated nutrient losses and contributed to the broader spatial distribution of NO_3. This shows the need to align fertiliser application with crop uptake to improve efficiency and reduce environmental losses.

4.0 CONCLUSION

Monsoonal changes, affected by a combination of soil characteristics, topography orientation, vegetative coverage, and agricultural management practices (i.e., inconsistent fertiliser application and limited crop residue retention) exert a noticeable influence on the availability of OM, N, and NO_3. This influence became evident through the amplified availability of these nutrients during the Southwest monsoon (dry period), compared to the Northeast monsoon (wet period). The highest OM, N, and NO_3 concentrations were recorded during the dry period due to reduced leaching, whereas NO_3 losses intensified during the Northeast monsoon due to increased rainfall-driven runoff and infiltration. The recurrent episodes of rainfall coupled with limited nutrient supply have resulted in reduced spatial dependence, particularly for NO_3, and increased temporal fluctuations in nutrient distribution. Proper soil conservation strategies, including optimised fertilisation timing, terracing, and cover cropping, are recommended to mitigate nutrient losses, stabilise soil fertility, and improve crop productivity in monsoonal agroecosystems.

Acknowledgement

This research received partial financial support through a grant provided by Universiti Putra Malaysia (UPM), under project number GP-IPB/2018/9557605. We would also like to express our gratitude to the owners of the black pepper farm, Mr. Jambai anak Ango and Mrs. Ingan anak Ampi and Mr. Dusil ak Madui from the Malaysian Pepper Board.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

[1] Izzah, A. H., W. Y. Wan Asrina, A. W. Samsuri, I. Wan Mohd Razi, and V. Jeyanny. 2022. Effects of Three Rainfall Patterns on Soil Chemical Properties in Black Pepper Cultivation in a Hilly Topography. *Pertanika Journal of Tropical Agricultural Science*. 45: 103–14. https://doi.org/10.47836/pjtas.45.1.06.

[2] Xu, L., H. Niu, J. Xu, and X. Wang. 2013. Nitrate-Nitrogen Leaching and Modeling in Intensive Agriculture Farmland in China. *The Scientific World Journal.* 2013: 1–11. https://doi.org/10.1155/2013/353086.

[3] Izzah, A. H., and W. Y. Wan Asrina. 2018. Spatial Variability of Nitrogen, Phosphorus, and Potassium Using Geospatial Techniques on Black Pepper Farms. *Azarian Journal of Agriculture*. 5: 76–85.

[4] Podlasek, A., E. Koda, and M. D. Vaverková. 2021. The Variability of Nitrogen Forms in Soils Due to Traditional and Precision Agriculture: Case Studies in Poland. *International Journal of Environmental Research and Public Health.* 18: 1–28. https://doi.org/10.3390/ijerph18020465.

[5] Izzah, A. H., W. Y. Wan Asrina, and I. Wan Mohd Razi. 2023. Effect of Different Black Pepper Crop Ages on the Availability of Nitrogen, Phosphorus, and Potassium. *AGRIVITA Journal of Agricultural Science*. 45: 1–10. https://doi.org/10.17503/agrivita.v45i1.2618.

[6] Seleiman, M. F., N. Al Suhaibani, N. Ali, M. Akmal, M. Alotaibi, Y. Refay, T. Dindaroglu, H. H. Abdul-Wajid, and M. L. Battaglia. 2021. Drought Stress Impacts on Plants and Different Approaches to Alleviate Its Adverse Effects. *Plants.* 10: 1–25. https://doi.org/10.3390/plants10020259.

[7] Zhang, M. K., L. P. Wang, and Z. L. He. 2007. Spatial and Temporal Variation of Nitrogen Exported by Runoff from Sandy Agricultural Soils. *Journal of Environmental Sciences.* 19: 1086–92. https://doi.org/10.1016/S1001-0742(07)60177-6.

[8] Yao, Y., Q. Dai, R. Gao, Y. Gan, and X. Yi. 2021. Effects of Rainfall Intensity on Runoff and Nutrient Loss of Gently Sloping Farmland in a Karst Area of Southwest China. *PLOS ONE*. 16: 1–18. https://doi.org/10.1371/journal.pone.0246505.

[9] Wong, M. K., P. Selliah, T. F. Ng, M. H. Amir Hassan, E. Van Ranst, and K. Inubushi. 2020. Impact of Agricultural Land Use on Physicochemical Properties of Soils Derived from Sedimentary Rocks in Malaysia. *Soil Science and Plant Nutrition*. 66: 214–24. https://doi.org/10.1080/00380768.2019.1705180.

[10] Lion, M., A. R. Kassim, S. A. Shamsuddin, and M. Mohd. 2013. Association between Soil Moisture Gradient and Tree Distribution in Lowland Dipterocarp Forest at Pasoh, Malaysia. *Malaysian Journal of Soil Science*. 16: 23–42.

[11] Mastrocicco, M., N. Colombani, E. Soana, F. Vincenzi, and G. Castaldelli. 2019. Intense Rainfalls Trigger Nitrite Leaching in Agricultural Soils Depleted in Organic Matter. *Science of the Total Environment*. 665: 80–90. https://doi.org/10.1016/j.scitotenv.2019.01.306.

[12] Department of Agriculture Sarawak. 1968. *Soil Map of Sarawak*. Kuching, Malaysia: Department of Agriculture Sarawak.

[13] Tan, K. H. 2011. *Principles of Soil Chemistry*. Boca Raton, FL: Taylor & Francis.

[14] Food and Agriculture Organization. 2021. *Standard Operating Procedure for Soil Nitrogen—Kjeldahl Method*. Rome: FAO.

[15] Tahir, S., and P. Marschner. 2016. Clay Addition to Sandy Soil: Effect of Clay Concentration and Ped Size on Microbial Biomass and Nutrient Dynamics after Addition of Low C/N Ratio Residue. *Journal of Soil Science and Plant Nutrition* 16: 864–75. https://doi.org/10.4067/S0718-95162016005000061.

[16] Azad, N., J. Behmanesh, V. Rezaverdinejad, F. Abbasi, and M. Navabian. 2020. An Analysis of Optimal Fertigation Implications in Different Soils on Reducing Environmental Impacts of Agricultural Nitrate Leaching. *Scientific Reports.* 10: 1–15. https://doi.org/10.1038/s41598-020-64856-x.

[17] Zhang, J., M. Zhang, S. Huang, and X. Zha. 2020. Assessing Spatial Variability of Soil Organic Carbon and Total Nitrogen in Eroded Hilly Region of Subtropical China. *PLOS ONE.* 15: 1–20. https://doi.org/10.1371/journal.pone.0244322.

[18] Chen, X., A. Mao, Y. Zhang, L. Zhang, J. Chang, H. Gao, and M. L. Thompson. 2017. Carbon and Nitrogen Forms in Soil Organic Matter Influenced by Incorporated Wheat and Corn Residues. *Soil Science and Plant Nutrition.* 63: 377–87. https://doi.org/10.1080/00380768.2017.1359797.

[19] Colombani, N., M. Mastrocicco, F. Vincenzi, and G. Castaldelli. 2020. Modeling Soil Nitrate Accumulation and Leaching in Conventional and Conservation Agriculture Cropping Systems. *Water.* 12: 1–15. https://doi.org/10.3390/w12061571.

[20] Cambardella, C. A., T. B. Moorman, T. B. Parkin, D. L. Karlen, J. M. Novak, R. F. Turco, and A. E. Konopka. 1994. Field-Scale Variability of Soil Properties in Central Iowa Soils." *Soil Science Society of America Journal.* 58: 1501–11. https://doi.org/10.2136/sssaj1994.03615995005800050033x.

[21] Balasundram, S. K., P. C. Robert, D. J. Mulla, and D. L. Allan. 2006. Relationship between Oil Palm Yield and Soil Fertility as Affected by Topography in an Indonesian Plantation. *Communications in Soil Science and Plant Analysis.* 37: 1321–37. https://doi.org/10.1080/00103620600626817.

[22] Awal, R., S. Khan, F. Abbas, S. Fares, S. Deb, A. Ahmad, and A. Fares. 2019. Soil Physical Properties Spatial Variability under Long-Term No-Tillage Corn. *Agronomy.* 9: 1–17. https://doi.org/10.3390/agronomy9110750

[23] Ferreira Rodrigues, A., C. de Mello, M. Terra, V. Silva, G. Pereira, and R. Silva. 2019. Soil Water Content and Net Precipitation Spatial Variability in an Atlantic Forest Remnant. *Acta Scientiarum. Agronomy.* 42: 1–13. https://doi.org/10.4025/actasciagron.v42i1.43518.

[24] Awoonor, J., and F. Dogbey. 2021. An Assessment of Soil Variability along a Toposequence in the Tropical Moist Semi-Deciduous Forest of Ghana. *Open Journal of Soil Science.* 11: 448–77. https://doi.org/10.4236/ojss.2021.119023.

[25] Moundjeu, E., T. Emile, P. Azinwi Tamfuh, J. Vounang Zetekouang, J. P. Kabiwa, A. Wouatong, and D. Bitom. 2021. Characteristics, Fertility Status, and Fertility Capability Classification of Steep Slope Soils of the Dschang Cliff (Cameroon Western Highlands). *Journal of Geoscience and Environment Protection.* 9: 164–79. https://doi.org/10.4236/gep.2021.97011.

[26] Stella, T., I. Mouratiadou, T. Gaiser, M. Berg Mohnicke, E. Wallor, F. Ewert, and C. Nendel. 2019. Estimating the Contribution of Crop Residues to Soil Organic Carbon Conservation. *Environmental Research Letters.* 14: 1–12. https://doi.org/10.1088/1748-9326/ab395c.

[27] Sigler, W. A., S. A. Ewing, C. A. Jones, R. A. Payn, P. Miller, and M. Maneta. 2020. Water and Nitrate Loss from Dryland Agricultural Soils Is Controlled by Management, Soils, and Weather. *Agriculture, Ecosystems & Environment.* 304: 1–14. https://doi.org/10.1016/j.agee.2020.107158.