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RESEARCH ARTICLE

Peanut monoculture-induced decline in fertility of Andosols in Nicaragua

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Abstract

Background: Andosols are generally characterized by strong resilience to degradation and high soil fertility. This may decline during long-term peanut (*Arachis hypogea*) monoculture, as indicated by soil chemical and biological properties.

Aims: The study investigated the monoculture-induced changes in soil chemical environment as driver for the decline in soil fertility.

Methods: In this on-farm study, soils from seven sites cropped with peanut monoculture for different periods between 1 and 20 years were analyzed for soil chemical properties (pH, Al and Fe oxides, soil organic matter) as well as soil microbial biomass and microbial functional diversity, estimated by multiple substrate-induced respiration (MSIR).

Results: Total nitrogen (N), soil organic carbon (SOC), and microbial biomass C (MBC) declined by 57%, 62%, and 73%, respectively, over 20 years of peanut monoculture in comparison with 1 year peanut cultivation. The SOC/total N ratio showed the most consistent decrease during this period. The Shannon diversity index, calculated from the MSIR responses, generally decreased from 2.5 to 2.1 during peanut monoculture, passing a minimum after 10 years. Discriminant function 1 declined with increasing years of peanut monoculture ($r = -0.87$) and explained 74% of the variance, separating nearly all peanut sites from each other. The main predictors were soil pH, exchangeable Al^{3+}, and the SOC/total N ratio, but dithionite extractable Al and Fe as well the ratio of exchangeable Ca^{2+}/Mg^{2+} also made significant contributions.

Conclusion: Twenty years of peanut monoculture led to a strong decline in soil fertility, as strongly indicated by soil microbiological indices.

KEYWORDS
Al and Fe oxides, Andosols, microbial biomass, peanut, respiratory response, soil organic matter

1 | INTRODUCTION

Peanut (*Arachis hypogea* L.) is a crop with considerable economic importance, which is cultivated to produce oil and edible seeds (Daryanto et al., 2015). Peanut can adapt to a wide variety of environmental, growth, and soil conditions in tropical and subtropical climates (Chen et al., 2012). Due to economic pressure, peanut cropping as a monoculture is common in many countries, especially in China (Chen et al., 2012; X.-G. Li et al., 2014), as the main producer, United States, and India (Daryanto et al., 2015) as well as Nicaragua. Peanuts are grown best in sandy loams with a pH between 6 and 7, that is, they have optimum conditions in many Nicaraguan Andosols (Joergensen & Castillo,

2001). In Nicaragua, peanut is mainly cropped in the north-western areas of Leon and Chinandega on approximately 35,000 ha (MAGFOR, 2012). As the pods of geocarpy peanut develop belowground, one of the main problems for soil fertility is the intensive soil disturbance during harvesting, which removes a large part of belowground plant biomass (Jani et al., 2020). However, in crop rotations, peanut cultivation seems to increase soil fertility on a global scale (Daryanto et al., 2015), whereas peanut monoculture most likely leads to a decline (Y. Li et al., 2019).

Andosols (IUSS Working Group WRB, 2015) are widespread in highly volcanic Central America (Herre et al., 2007). They are generally characterized by high soil fertility, due to their strong resilience to long-term degradation by changes in land-use management (Anda & Dahlgren, 2020) as a result of their large nutrient contents (Dahlgren et al., 2004). This is also true for Andosols with sandy textures, as the large soil particles do not consist of quartz but of volcanic glasses (Dahlgren et al., 2004; Hernández Vallecillo et al., 2020). The remaining problem of low water storage capacity in sandy Andosols is small in tropical areas, where rainfall and water for irrigation is not limited. Andosols contain high amounts of Al and Fe oxides, which stabilize the physical soil structure and positively affect carbon (C) sequestration (Batjes, 2014) but reduce phosphorous (P) availability to plants and soil microorganisms (Anda & Dahlgren, 2020; Joergensen & Castillo, 2001). The mean P fixation capacity was 55%, 24 h after adding 25 μg P g^{-1} soil to 25 Nicaraguan Andosols (Joergensen & Castillo, 2001).

In tropical soils, microbial biomass C (MBC) is an important quantitative microbial indicator for soil fertility (Joergensen, 2010) because MBC draws a relationship between C input and soil organic C (SOC) storage (Joergensen & Wichern, 2018; Khan et al., 2016). MBC is usually measured by fumigation extraction (Joergensen, 2010; Vance et al., 1987), but in low organic matter tropical soils, this method is sometimes hampered by the decreasing difference in organic C extracted from fumigated minus non-fumigated soil (Joergensen et al., 2011). In such cases, substrate, that is, glucose-induced respiration (J. P. E. Anderson & Domsch, 1978), is an interesting alternative, especially in combination with multiple low-molecular weight organic substrates for estimating functional diversity (Campbell et al., 2003; Creamer et al., 2016). In contrast to genetic diversity (Y. Li et al., 2019), multiple substrate-induced respiration (MSIR) creates a link between functional diversity and soil processes (Struecker & Joergensen, 2015).

Soil properties were studied at seven farm sites, cropped with peanuts between one and up to 20 years. Such on-farm approaches were previously used to evaluate long-term effects of specific land-use management, such as application of biogas slurry (Wentzel et al., 2015), soybean monoculture (Pérez-Brandán et al., 2016), or organic farming in Nicaragua (Castillo & Joergensen, 2001). In contrast to many previous studies, the current research is focussed on the interactions of MBC and microbial activity with exchangeable cations but especially with Al and Fe species in Andosols. Joergensen and Castillo (2001) suggested the importance of Al and Fe oxides for the microbial performance in Nicaraguan Andosols, but they did not provide any experimental evidence for this view.

The central objective of the current study is to close this gap of knowledge by investigating the following three hypotheses: (1) Peanut monoculture leads to a strong decline in soil fertility, as indicated by losses in SOC, MBC, and microbial functional diversity. (2) This decline in soil fertility is specifically related to changes in the soil chemical environment, that is, soil pH, Al und Fe species as well as to the availability of exchangeable nutrients.

2 | MATERIALS AND METHODS

2.1 | Sites and sampling

The soils were sampled at 0–30 cm depth on 29 and 30 January 2015 from seven arable sites in the county Chinandega, Nicaragua. Between 10 and 15 cores were taken per site with a loam auger (7 cm diameter), using a zig-zag sampling scheme, and combined to four separate bulk samples per site, that is, one bulk sample consisted of two to four cores. The samples were shipped in polyethylene bags by air-cargo and train to Witzenhausen, Germany. The soils had a loamy sand texture with on average 73% sand, 18% silt, and 5% clay (Table 1). They were classified as Andosols (IUSS Working Group WRB, 2015), derived from volcanic ash deposits. Soil cropped with peanut (*Arachis hypogaea* L.) monoculture for 1 year (Punta de Plancha 2, 2 ha), 3 years (Lote el Chente, 3 ha), 6 years (Lote la Sandia, 5 ha), 10 years (Lote Chicho, 7 ha), 14 years (Ginizaro A, 39 ha), 18 years (Punta de Planta alta, 43 ha), and 20 years (Lote Papalote a, 48 ha) was sampled from a finca close to Cosigüina (12° 54′ 46″ N, 87° 30′ 07″ W), county Chinandega (see Supplementary Figure 1).

Peanuts were cropped twice a year. The peanut yield varied between 4.5 and 7.7 t ha^{-1}. The mean last harvest yield before soil sampling was 5.6 t ha^{-1}, without strong differences between the sites. They received a full mineral NPK fertilizer (12/30/10) at a rate of approximately 130 kg N ha^{-1}, 325 kg P_2O_5 (= 142 kg P) ha^{-1}, and 108 kg K_2O (= 90 kg K) ha^{-1} at planting in August and early September (wet season) or between January and early February (dry season with irrigation). Peanuts were harvested after 110 and 130 days, depending on the variety. The predominant peanut variety was "Georgia", but "Virginia" and "Espanola y Valencia" were also planted. The soils were tilled once a year with a skimmer plough at 6–8 cm depth in April, followed by harrowing at 3–5 cm depth twice in the dry season and harrowing three times in the wet season for seedbed preparation. Weeds were controlled with pendimethalin (0.5 L ha^{-1}), metolachlor (1.5 L h^{-1}), and trifluralin (1.0–1.5 L ha^{-1}). Insects were controlled with chlopyrifos (7.5–8.0 kg ha^{-1}), ethoprop (8–10 kg ha^{-1}), carbofuran (12 kg ha^{-1}), phorat (8 kg ha^{-1}), and terbuphos (10 kg ha^{-1}). Fungi were controlled with benomyl, carbedazim, chlorothalonil, cyproconazol, mancozeb, tebuconazol, and $Cu_2(OH)_3Cl$, depending on the fungal disease occurring.

TABLE 1 Soil pH, texture, cation exchange capacity (CEC), exchangeable cations as well as contents of oxalate (OX) and dithionite (DT) extractable aluminum (Al) and iron (Fe) in soils cropped between 1 year and up to 20 years with peanuts.

Years	Soil pH	Sand	Silt	Clay	CEC	Ca^{2+}	Mg^{2+}	K^+	Na^+	Al^{3+}	Al_{OX}	Al_{DT}	Fe_{OX}	Fe_{DT}
			(%)		($\mu mol_C\ g^{-1}$ soil)						($mg\ g^{-1}$ soil)			
01	6.32	72	22	6	97	76.3	12.9	7.9	0.3	0.0	0.69	2.5	0.27	9.7
03	5.95	76	19	5	54	45.1	7.0	1.8	0.3	0.0	0.59	1.9	0.20	8.4
06	6.00	53	38	9	106	86.9	14.5	3.6	0.6	0.0	0.96	2.9	0.37	13.1
10	5.96	86	11	3	50	42.6	4.8	1.2	0.3	1.1	0.78	2.4	0.23	8.0
14	5.91	73	22	5	52	41.2	7.0	2.5	0.5	0.9	0.57	2.4	0.25	10.0
18	6.00	78	18	4	52	43.2	6.3	1.7	0.5	0.5	0.56	2.2	0.22	9.3
20	5.76	71	24	4	52	42.7	6.4	1.6	0.6	0.4	0.52	1.7	0.23	9.6
CV (± %)	0.5	4.6	8.7	15	6.2	5.8	3.9	20	27	41	5.6	14	5.2	4.9

Abbreviation: CV, mean coefficient of variation between replicate samples ($n = 4$).

2.2 | Chemical soil properties

All soils were sieved (<2 mm), homogenized and stored in polyethylene bags at 4°C until the biological analyses started in April 2015. Subsamples of sieved soils were dried and finely ground for chemical analyses. Soil pH was measured in water (ratio 1 to 2.5). Total C and total N in soil and plant material were determined by gas chromatography using a Vario EL (Elementar, Hanau, Germany) analyzer. For soil texture, the sand fraction was determined by wet sieving after destruction of the organic matter with H_2O_2, and dispersion with sodium hexametaphosphate. Clay fraction was quantified by the pipette method. Silt fraction was calculated as the difference of the sum of sand and clay to 100% (Blume et al., 2011). Cation exchange capacity was measured after extraction with 0.1 M $BaCl_2$ solution according to Mehlich (Blume et al., 2011). Concentrations of exchangeable Ca^{2+}, Mg^{2+}, K^+, and Al^{3+} were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES) analysis (Spectro Analytical Instruments, Kleve, Germany). In addition, Al and Fe were also measured by ICP-AES after extraction with ammonium oxalate and dithionite citrate solution (Blume et al., 2011).

2.3 | Microbial biomass, activity, and functional diversity

Community level physiological profiles were determined by the MSIR approach, using the MicroResp method (Campbell et al., 2003). The soils were adjusted to 35% water-holding capacity and pre-incubated for 5 days in the dark at 25°C, prior to adding 300 mg moist soil to each 1.1 mL deep-well of a microtiter plate (Nunc, Thermo Electron, Langenselbold, Germany). Then, aqueous solutions of the different C sources were applied before the wells were sealed with a CO_2 trap.

The physiological profiles were determined by applying distilled water (for basal respiration), five amino acids (L-alanine [Ala], L-asparagine [ASP], γ-aminobutyric acid [GABA], L-glutamine (Glu), L-leucine [Leu]), five carboxylic acids (ascorbic acid [Asc], citric acid [Cit], α-ketoglutaric acid [Ket], malic acid [Mal], and oxalic acid [Oxa]), five neutral sugars (arabinose [Ara], fructose [Fru], galactose [Gal], D-glucose [Glc], and trehalose [Tre]), and two amino sugars (glucosamine [GlcN], N-acetyl-glucosamine [NAG]). These low molecular weight organic substances were chosen to represent a cross section of root exudates (Campbell et al., 2003) as well as microbial metabolites (Struecker & Joergensen, 2015). In addition, most substrates have been used in previous studies (Creamer et al., 2016; Sradnick et al., 2013).

A substrate concentration of 8 mg g^{-1} dry soil was used for most substrates. Only 2 mg Glu and 1.3 mg Leu g^{-1} soil were used, due to their low solubility at higher concentrations. All substrates were added as 20 μL solution to the soil samples, which were weighed into the cavities of a deep well plate. The colorimetric CO_2 trap was produced according to Campbell et al. (2003). The color of the CO_2 trap was measured immediately before sealing and after 6 h of incubation (25°C) at 572 nm (FLUOstar, BMG, Offenburg, Germany). The calibration of the CO_2 trap is described in Sradnick et al. (2013):

$$\mu L\ CO_2 = 51 \times (0.2 + ABS)^3, \quad (1)$$

where ABS is the difference in absorption of time 6 h and time 0 h.

The Shannon diversity index was calculated using the formula:

$$H = -\Sigma\, pi\, (\ln pi), \quad (2)$$

where pi is the sum of all activities (Zak et al., 1994). Basal respiration was calculated from aqua dest. addition and MBC from Glc addition ($30 \times \mu L\ CO_2\ g^{-1}\ h^{-1}$) according to Kaiser et al. (1992). The metabolic quotient qCO_2 was calculated as the ratio of basal respiration to MBC (T. H. Anderson & Domsch, 1990).

2.4 | Statistical analysis

Data are presented as arithmetic means of four independent replicates on an oven dry weight basis (about 24 h at 105°C). Discriminant function analysis was conducted to investigate the effects of peanut

monoculture years on the substrate utilization patterns with SPSS 16.0 statistical software (SPSS, IBM, Ehningen, Germany). Correlation and multiple linear regression analyses were carried out using SigmaPlot 13.0 (Systat, San José, USA). Multiple regression models were calculated between the Shannon index, discriminant functions 1 (DF1) and 2 (DF2) as dependent variables, and soil chemical properties as independent variables by stepwise forward regression analysis. All regression models were tested for normality (Shapiro–Wilk), constancy of variance, absence of correlation between the residuals (Durban–Watson statistics), and absence of multi-collinearity, calculating the variance inflation factor (VIF). Variables were removed from the model if the VIF value exceeded 4.0.

3 | RESULTS

3.1 | Soil chemical properties

Soil pH was 6.32 at the 1-year peanut cropping site and much lower with 5.76 at the 20-year peanut monoculture site (Table 1). Soil pH was not related to the clay content. Cation exchange capacity (CEC) values formed two groups, the first at a mean of approximately 100 μmol_C g^{-1} soil (1-year and 6-year peanut monoculture) and the second at a mean of 52 μmol_C g^{-1} soil (3-year and 10- to 20-year peanut monoculture). Ca^{2+} contributed on average 81.0% to the CEC of all soils, Mg^{2+} 13.8%, K^+ 3.7%, and Na^+ 0.7%. Al^3+ contributed on average 1.4% to the CEC only in the soils from the 10- to 20-year peanut monoculture sites. Mean Al_{OX} and Al_{DT} contents were 0.7 and 2.3 mg g^{-1} soil, respectively, without significant pH, year, or crop effects. The same was true for the mean Fe_{OX} and Fe_{DT} contents, which varied around means of 0.3 and 11.1 mg g^{-1} soil, respectively. The clay content showed strong positive linear relationships with Fe_{OX} ($r = 0.93$, $n = 32$, $p < 0.01$) and Fe_{DT} ($r = 0.96$, $n = 32$, $p < 0.01$) but not with Al_{DT}.

SOC and total nitrogen (N) contents were 62% and 57%, respectively, lower at the 20-year peanut monoculture site in comparison with the 1-year peanut cropping site, passing a maximum at the 6-year site (Table 2), on a soil with a higher clay content (Table 1). The SOC/total N ratio showed the most consistent decrease with increasing years of peanut monoculture (Figure 1A) with a correlation coefficient of $r = -0.85$ ($n = 28$, $p < 0.01$).

3.2 | Soil biological properties

MBC was 73% lower at the 20-year peanut monoculture site than at the 1-year peanut cropping site. For this reason, the MBC/SOC ratio decreased from 1.0% at the 1-year site to 0.7% at the 20-year peanut monoculture site. In contrast to other soil properties, maximum basal respiration occurred at the 3-year peanut monoculture site, followed by a rapid decline to mean rates around 4.4 μg CO_2-C d^{-1} g^{-1} soil at the sites with 10- to 20-year peanut monoculture. The metabolic quotient qCO_2 increased with decreasing pH ($r = -0.59$, $n = 28$, $p < 0.01$) and decreasing clay content ($r = -0.58$, $n = 28$, $p < 0.01$) but also with increasing years of peanut monoculture ($r = 0.52$, $n = 28$, $p < 0.01$).

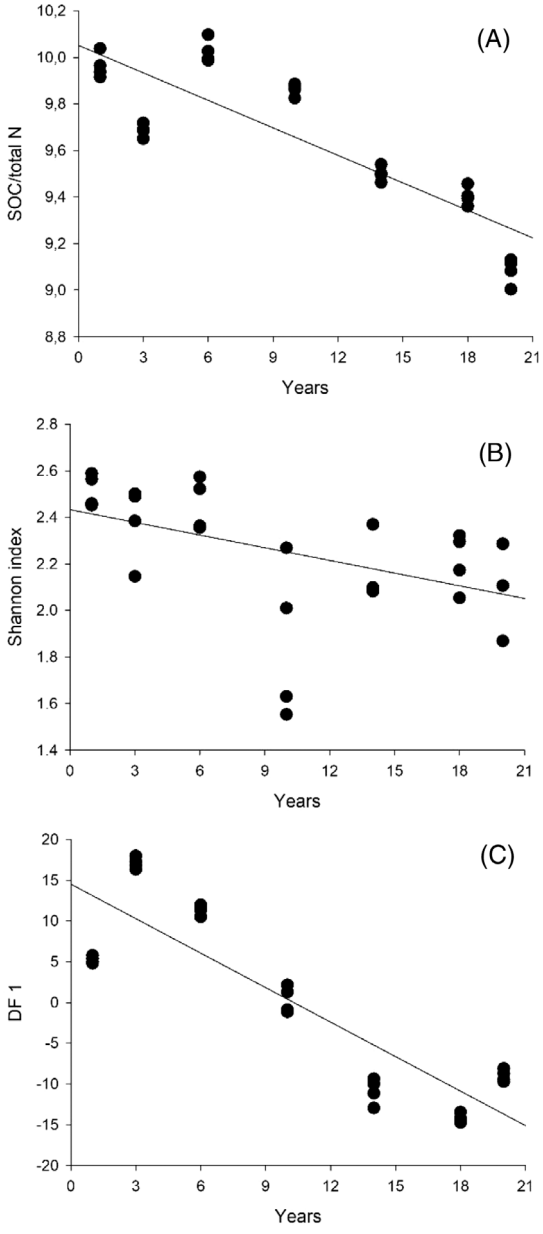

FIGURE 1 Linear relationship between years of peanut monoculture and (A) soil organic carbon (SOC)/total nitrogen (N) ratio for each independent sample, (B) Shannon diversity index as well as (C) discriminant function (DF) 1 for each sample.

The Shannon diversity index generally decreased from 2.5 at the 1-year peanut cropping site to 2.1 at the 20-year peanut monoculture site ($r = -0.48$, $p < 0.01$), passing a minimum at the 10-year peanut monoculture site (Figure 1B). The Shannon index of the seven peanut sites could be predicted by exchangeable Mg^{2+} and Al_{OX}, with a relatively low $r^2 = 0.52$ by multiple linear regression (Table 3).

3.3 | Discrimination analysis

Discrimination analysis created two functions, where DF1 declined with increasing years of peanut monoculture, with $r = -0.87$

TABLE 2 Contents of soil organic C (SOC), total nitrogen (N) and microbial biomass C (MBC), the ratios of SOC/total N and MBC/SOC, basal respiration, and metabolic quotient qCO_2 in soils cropped between 1 year and up to 20 years with peanuts.

Years	SOC (mg g^{-1} soil)	Total N	MBC (μg g^{-1} soil)	MBC/SOC (%)	CO_2-C (μg d^{-1} g^{-1} soil)	qCO_2 (mg CO_2-C d^{-1} g^{-1} MBC)
01	15.4	1.54	160	1.0	5.9	38
03	8.8	0.91	91	1.0	8.0	87
06	18.9	1.89	156	0.8	6.3	41
10	8.8	0.89	50	0.6	4.1	85
14	7.4	0.76	54	0.7	4.8	97
18	6.7	0.71	53	0.8	4.1	80
20	5.9	0.66	44	0.7	4.4	102
CV (±%)	2.6	2.3	21	21	18	27

Abbreviation: CV, mean coefficient of variation between replicate samples ($n = 4$).

TABLE 3 Multiple linear regression models between different soil chemical properties and the Shannon diversity index as well as discriminant functions 1 (DF1) and 2 (DF2); oxalate (OX) and dithionite (DT) extractable fraction ($n = 28$).

	Coefficient	Standard error	Probability value
Shannon index (adjusted $R^2 = 0.52$)			
Constant	2.14	0.16	<0.01
Mg^{2+} (μmol_C g^{-1} soil)	0.07	0.01	<0.01
Al_{OX} (μg g^{-1} soil)	−0.72	0.29	0.02
DF1 (adjusted $R^2 = 0.85$)			
Constant	−101.1	43.6	0.03
Soil pH	−46.9	8.8	<0.01
Exchangeable Ca^{2+}/Mg^{2+}	−3.0	1.3	0.03
Al^{3+} (μmol_C g^{-1} soil)	−10.9	2.3	<0.01
Al_{DT} (μg g^{-1} soil)	−7.1	2.6	0.01
Fe_{DT} (μg g^{-1} soil)	−2.6	0.8	0.01
SOC/total N	46.4	4.8	<0.01
DF2 (adjusted $R^2 = 0.89$)			
Constant	138.3	15.4	<0.01
pH	−41.9	3.4	<0.01
Fe_{OX} (μg g^{-1} soil)	−70.6	9.1	<0.01
SOC/total N	13.5	2.0	<0.01

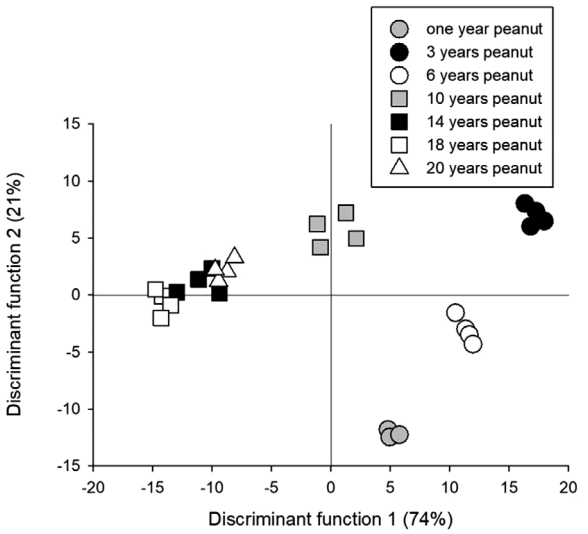

FIGURE 2 Discriminant function analysis of catabolic response of 17 substrates plus H_2O for each sample.

(Figure 1C). DF1 explained 74% of the variance and separated nearly all peanut sites from each other (Figure 2). The only exception was that the 14-year site did not differ from the 18- and 20-year sites. However, the peanut sites were generally not strictly ordered according to the years of monoculture. DF1 of the seven peanut sites could be predicted by six soil properties, with $r^2 = 0.85$ by multiple linear regression (Table 3). The main predictors were soil pH, exchangeable Al^{3+}, and the SOC/total N ratio, but Al_{DT}, Fe_{DT}, and the exchangeable Ca^{2+}/Mg^{2+} ratio also made significant contributions to DF1. In contrast, DF2 was not related to increasing years of peanut monoculture. DF2 explained 21% of the variance and mainly separated the 1-year site from the other peanut monoculture sites (Figure 2), although the 6-year site was also clearly separated from the 3- and 10-year sites. DF2 of the seven peanut sites could be predicted by Fe_{OX} and the SOC/total N ratio, with $r^2 = 0.89$ by multiple linear regression (Table 3).

4 | DISCUSSIONS

4.1 | Peanut monoculture effects on soil fertility

Long-term peanut monoculture has negative effects on most soil biological and chemical properties. These negative effects were obvious at least after 10 years of monoculture. The reasons are most likely the low amounts of plant residues added to soil by peanuts during growth and after harvest, which is accompanied by strong mechanical disturbance

and removal of large parts of the belowground peanut biomass. In contrast, the introduction of peanuts into crop rotations has been shown to improve soil fertility (Daryanto et al., 2015).

The loss in soil fertility was most consistently indicated by DF1, which was largely explained by chemical soil properties, especially by the soil pH, despite its relatively small range from 5.76 to 6.32 at the peanut sites. At the 10-year site, exchangeable Al^{3+} occurred at relatively high pH values of between 5.9 and 6.0 and was only weakly related to the contents of amorphous Al_{OX} and crystalline Al_{DT}. The origin of Al^{3+} might be decaying soil minerals, as indicated by the decreasing Fe_{DT} contents over the years of peanut monoculture. Another possibility might be the release of Al^{3+} from decaying soil organic matter (Zhu et al., 2004). However, no information is available about whether this process may occur in Andosols. Conversely, there is a wealth of information about the detoxification of Al^{3+} by the formation of organic Al chelates (Barceló & Poschenrieder, 2002).

The data from sites of up to 6 years of peanut monoculture are characterized by strong fluctuations of soil chemical and soil biological properties, most likely due to spatial variation. The current on-farm approach requires that the seven experimental sites had initially similar soil properties, as they were not measured before the farmer changed the cropping system to peanut monoculture (Wentzel et al., 2015). However, many long-term experiments also suffer from the problem that the original baseline data were not appropriately determined (Faust et al., 2017), for example, by measuring the initial soil properties from a single "representative" bulk sample. Another problem is that each year of peanut monoculture is represented by solely one field, so that the current research is based on pseudo-replicates from a statistical viewpoint (Gartzia-Bengoetxea et al., 2020).

Inverse time series like the current study, investigating desertification (Liu et al., 2016) or glacier retreat (Insam et al., 2017), are commonly not based on replicate representative sites. Three of four fields would be more appropriate, but it is difficult to find such a high number of sites with similar soil properties. Urgent, current questions on maintaining soil fertility must be answered without waiting for the results after many years of running a costly field experiment. In the current study, over the long-term, at least after 10 years of peanut monoculture, all of the initial differences have disappeared and have been replaced by a small, presumably slow further decline in soil fertility.

4.2 | Peanut monoculture effects on soil organic matter

The consistent decrease in the SOC/total N ratio at sites with increasing years of peanut monoculture indicates the microbial decomposition of soil organic matter. The lower the SOC/total N ratio, the higher is the degree of microbial processing of plant residues (Jenkinson et al., 2008). For this reason, DF1 and DF2 are positively affected by the SOC/total N ratio, that is, the higher this ratio, the better is the organic matter availability to soil microorganisms under the specific conditions of Nicaraguan Andosols. They are characterized by a contribution of 60% fungi and 40% bacteria to the microbial community and a contribution of 40% microbial residues to SOC (Khan et al., 2016). Nicaraguan arable Andosols contain less fungi and more non-decomposed plant residues than arable soils from temperate humid climate (Joergensen & Wichern, 2008; Khan et al., 2016). The high contribution of plant residues to SOC might be the reason for the strong decline in SOC with increasing years of peanut monoculture. Plant residues are most likely more easily mineralized by soil microorganisms than microbial residues (Hobara et al., 2020; Khan et al., 2016).

The quality of legume plant residues is better than that of cereals, that is, the protein is higher and the lignin content is lower (Faust et al., 2018). This is also true for peanut residues (Formowitz et al., 2009). However, the total amount of root and harvest residues is low, so that the starving soil microbial community must survive by decomposing SOC, despite the strong bonding of organic matter to Al and Fe in Andosols (Imaya et al., 2010). This led to the observed strong decline in SOC contents, despite the relatively low SOC contents of Nicaraguan Andosols in comparison with Japanese Andosols (Dahlgren et al., 2004; Fujii et al., 2019). Not only microbial decomposition but also wind erosion might have contributed to the SOC loss (Dubroeucq et al., 1998; Santra et al., 2017). Large amounts of dust, containing especially large amounts of light SOC–clay complexes, are created during peanut harvest in dry periods. However, this process should have been accompanied by a reduction in fine soil particles (J. Li et al., 2009) and, thus, CEC.

A certain part of the SOC decline could also be attributed to a dilution effect caused by an increased bulk density. According to the data of Joergensen and Castillo (2001), bulk density (y in g cm^{-3}) followed the SOC content (x in mg g^{-1} soil) in Nicaraguan Andosols, according to the following relationship: $y = 1.458 - 0.0167x$ ($n = 300$, $p < 0.0001$). The texture had no additional significant effect on this relationship. Assuming that this relationship is also valid for the current data, the SOC stocks (0–30 cm depth) were 55.4 t ha^{-1} at the 1-year peanut cropping site in comparison with 25.8 t ha^{-1} at the 20-year peanut monoculture site, that is, the SOC decline was "only" −54% and not 62% as calculated for the SOC content. For this reason, bulk density should not be neglected when estimating land use effects on soil properties. However, in the current study, the majority of effects were observed for soil properties that were not affected by bulk density, that is, soil pH, exchangeable Al^{3+}, the SOC/total N ratio, dithionite extractable Al and Fe, as well the ratio of exchangeable Ca^{2+}/Mg^{2+}.

4.3 | Peanut monoculture effects on soil microorganisms

The MBC contents estimated by Glc-induced respiration are in the range reported by Joergensen and Castillo (2001) and Khan et al. (2012, 2016), estimated by fumigation extraction. The same is true for the MBC/SOC ratios, which were all below 1, indicating severely restricted SOC availability to soil microorganisms (T. H. Anderson and Domsch, 1989). This low availability is caused by the strong covalent boding of organic matter to Al and Fe oxides (Fujii et al., 2019). The MicroResp approach (Campbell et al., 2003) is apparently able to

estimate low MBC contents with sufficient precision. Also, the basal respiration rates measured by the MicroResp approach and, consequently, also the metabolic quotients qCO_2 calculated were in the range provided by Joergensen and Castillo (2001).

The Shannon diversity index declined with increasing years of peanut monoculture, despite considerable variation, and responded most positively to exchangeable Mg^{2+} as a predictor. Mg^{2+} is a nutrient not supplied as fertilizer by the farmers, that is, not only plants but also soil microorganisms fully rely on the natural presence of this nutrient through the mineral components of Andosols. The relative depletion of mobile elements such as Mg^{2+} is a well-known general weathering trend in aging of perhumid Central American Andosols (Meijer & Buurman, 2003). Close relationships of soil microorganisms and Mg^{2+} have not been described in the literature until now. However, Mg^{2+} effects on the Shannon index are in line with the negative effects of the exchangeable Ca^{2+}/Mg_{2+} ratio on DF1, indicating that a pronounced absence of Mg^{2+} has negative effects on the respiratory response of the soil microbial community to soluble low molecular weight substances. It should be noted that the importance of the Ca^{2+}/Mg^{2+} ratio has been a matter of considerable debate in plant nutrition (Gransee & Führs, 2013), but never in respect to soil microbial communities. This points to the need for intensifying research on the relationships between soil microorganisms and inorganic nutrients such as Ca^{2+}, Mg^{2+}, and K^+ (Hemkemeyer et al., 2021; Yamashita et al., 2014).

5 | CONCLUSIONS

Twenty years of peanut monoculture led to a strong decline in soil fertility, as indicated by soil organic C, microbial biomass C, and microbial functional diversity, using the multiple substrate-induced respiration approach. Peanut monoculture affected soil biological properties more negatively than soil chemical properties. However, the Shannon index and microbial functional diversity could be explained solely by soil chemical properties, especially by aluminum fractions, but partly also by iron fractions and exchangeable Mg^{2+}. A reason for the negative effects of peanut monoculture is most likely the harsh harvest conditions, which needs, however, experimental evidence.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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