

Stoichiometric characteristics of different agroecosystems under the same climatic conditions in the agropastoral ecotone of northern China

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Abstract. Ecological stoichiometry affects the processes and functions of ecosystems, but the similarities and differences of stoichiometric characteristics among diverse agropastoral ecosystems under the same climatic conditions remain unclear. In this study, plant and soil stoichiometric characteristics of different agroecosystems, namely natural grassland (free-grazing and mowed grassland), artificial grassland (oat, Chinese leymus and corn silage), field crops (naked oats, flax and wheat) and commercial crops (cabbage and potatoes), were investigated in Guyuan County, China. Results showed total nitrogen (TN), total phosphorus (TP) and N:P ratios in plant tissue varied significantly among ecosystem types ($P < 0.05$). In general, the mean soil organic carbon, TN and TP content in the 0–0.3 m soil layer in potatoes (8.01, 1.05 and 0.33 g kg⁻¹ respectively) were significantly lower than in other agroecosystems ($P < 0.05$). The mean C:N ratios of the 0–0.3 m soil layer did not differ significantly among the agroecosystems ($P > 0.05$). However, the C:P ratio was lower in potato than cabbage sites (24.64 vs 33.17), and was lower at both these sites than in other agroecosystems ($P < 0.05$). With regard to N:P ratios, only the potato ecosystem had lower values than in other ecosystems ($P < 0.05$), which did not differ significantly ($P > 0.05$). Above all, N is more likely to be limiting than P for biomass production in local agroecosystems. Soil C:P and N:P ratios decreased significantly with an increase in the utilisation intensity (from natural grassland to commercial crop). The findings of this study suggest that restoring, preserving and increasing soil organic carbon (especially for cabbage and potatoes), scientifically adjusting the application of N and P fertiliser and enhancing subsidies for low-loss soil nutrient systems, such as grassland, rather than commercial crops will help improve and sustain agroecosystems.

Additional keywords: ecosystem, farmland, grassland.

Received 4 December 2018, accepted 25 August 2019, published online 19 September 2019

Introduction

Land use has a significant effect on carbon (C), nitrogen (N) and phosphorus (P) balances and cycles by altering land cover, plant community structure, soil fertility, biogeochemical cycles and associated biota (Houghton *et al.* 1999; Guo and Gifford 2002; Zhou *et al.* 2007; Marklein and Houlton 2012). Anthropogenic inputs of N and P have increased from the 1860s to the present time, resulting in stoichiometric imbalances in C, N and P in agricultural lands (Peñuelas *et al.* 2012, 2013). The net exchange of greenhouse gases, including carbon dioxide, methane and nitrous oxide, changes when a grassland is converted into a cropland or forest (Houghton *et al.* 2012; Kim and Kirschbaum 2015). Ecological stoichiometry provides a valuable approach to assess possible changes in element cycles (Hessen *et al.* 2013). Soil and vegetation are the most important components of ecosystem structure and play multiple

functions in terrestrial ecosystems. The primary productivity of plants provides energy for life on Earth; soil is the largest organic carbon pool (Jobbágy and Jackson 2000; Post and Kwon 2000), and soil organic carbon (SOC), N and P content are important indicators for assessing soil fertility and quality (Andrews *et al.* 2004; Lal 2004).

From cool and temperate to tropical ecosystems, terrestrial ecosystems show a general increasing trend in soil and plant N:P ratios, but there is still considerable variation within each climatic area (Sardans *et al.* 2012). However, Wang *et al.* (2008) found the ratio of SOC and total N (TN) did not differ significantly among the soil horizons of grasslands and croplands in Inner Mongolia. Tian *et al.* (2010) analysed the general soil C:N:P ratios in China on a national scale based on inventory data of 2384 soil profiles and found that C:N ratios showed relatively small variation among samples from different

climate zones (10.7–13.6), whereas large spatial heterogeneity (both horizontal and vertical) was found for C:P and N:P ratios (32–78 and 2.6–6.4 respectively). Yang *et al.* (2014) reported the stability of topsoil C:N ratio but variability in the N:P ratio over broad geographical scales, and highlighted that soil C and N are tightly coupled, but N and P tend to be decoupled under a changing environment among grasslands in China. Zhao *et al.* (2015) found that large-scale changes in land use under the Grain-to-Green Program in China significantly affect the C:N, C:P and N:P ratios in soil.

In northern China, the agropastoral ecotone is a transitional zone between grasslands and cultivated land, which was created in the 18th century of the Qing Dynasty immigration, and developed further with China's economic reforms in the 20th century (Ye and Fang 2012). Climatic and soil conditions are categorically marginal for crop production (Zhou *et al.* 2007) and ecosystem types are typically diverse, including natural grazing grassland, artificial grassland, grain field and vegetables among others (Zhai *et al.* 2017). However, the similarities and differences in stoichiometric characteristics of diverse agropastoral ecosystems at the local scale remain unclear. The aims of the present study were to: (1) explore the C:N, C:P and N:P ratios of plant and soil for 10 agroecosystems under the same climatic condition for this region; and (2) determine how these ratios change with different terrestrial agroecosystems.

Materials and methods

Study area

The experimental plots were randomly distributed within 10 km of the National Field Station (41°46'3.79"N, 115°40'45.55"E, elevation 1460 m) for Grassland Ecosystem in Guyuan County, Hebei Province, China. The county has a semi-arid continental monsoon climate with a frost-free period of 80–110 days. The mean annual (1982–2009) precipitation is ~430 mm (range 350–450 mm), with most precipitation occurring from June to September. The mean annual temperature is 1.4°C, with a minimum monthly mean temperature of –18.6°C in January and a maximum of 21.1°C in July (Chen *et al.* 2015). Multiple ecosystem types coexist within the experimental sites (Fig. 1). *Leymus chinensis* is the dominant species in the experimental grassland area. Naked oats (*Avena chinensis*), corn silage (*Zea mays*), flax (*Linum usitatissimum*) and wheat (*Triticum aestivum*) are the main crops on cultivated land. The topography of the sampling area is flat, the soil type in this region according to the US soil classification is Calcic-Orthic Aridisol (Soil Survey Staff 2003) and the soil parent material is mica, feldspar and quartz (Wang *et al.* 2015; Chen *et al.* 2015).

Experimental design

Four land-use types were selected for this study: natural grassland, artificial grassland, field crop and commercial crop. The natural grassland included free-grazing (6 sheep ha⁻¹) and mowed grassland (mowing once a year) ecosystems, both farmed for >10 years. The artificial grassland included three grassland types of oat, *L. chinensis* and corn silage, which had been planted for 5, 8 and >10 years respectively. The field crops were naked oats, flax and wheat, which were cultivated for >10 years, and the commercial crops

were cabbage and potatoes, which had been planted for >6 years. Thus, there was a total of 10 ecosystem types. It should be noted that when the potato field had been planted for 3 years, the field had to be rotated and planted with other crops for 1 year because of substantial soil nutrient depletion due to potato farming. The artificial input amounts of manure, N, P and compound fertiliser are given in Table 1.

Sample collection and measurement

Three study sites were established in every ecosystem type. At each site (1 ha), three randomly arranged replicate plots were installed. At each plot (~10 m × 10 m), a mixed soil sample was obtained by pooling five drilled soil samples (obtained using soil auger; diameter 0.03 m). This study focused on three soil layers: 0–0.1, 0.1–0.2 and 0.2–0.3 m. In addition, we measured the biomass by clipping all living tissues in five replicated 1-m × 1-m quadrats on each site from 10 to 25 August 2015. The potato crop was divided into two parts: (1) the aboveground stems and leaves; and (2) the underground tubers. The clipped plant tissues were oven dried at 65°C to constant weight. All soil samples were air dried in the laboratory, and roots, stones and visible plant remains were carefully removed. Then, all soil samples were sieved through a 2-mm stainless mesh for use in chemical analyses. SOC content was determined using the Walkley–Black method (Nelson and Sommers 1982). The TN of plants and soil was measured using the Kjeldahl digestion procedure (Gallaher *et al.* 1976), and total P (TP) content was determined by the molybdate colourimetric test after perchloric acid digestion (Sommers and Nelson 1972) using a spectrophotometer (Model 723; Jinghua Science and Technology Instruments, Shanghai, China).

Statistical analysis

All statistical analyses were performed using SPSS 19.0 (SPSS Inc., Chicago, IL, USA). Means were compared using analysis of variance (ANOVA) and two-sided $P < 0.05$ was considered significant. The relationships among the stoichiometric characteristics of SOC, nitrogen and phosphorus were examined using Pearson correlation analysis. All figures were generated using SigmaPlot 12.0 (Systat Software Inc., Chicago, IL).

Results

Stoichiometric characteristics of plant tissues in different agroecosystems

Among the 10 land use types, TN, TP and N:P in aboveground plant tissue varied significantly ($P < 0.05$). The mean TN values among land use types ranged from 6.25 g kg⁻¹ (potato tubers) to 25.7 g kg⁻¹ (cabbage; Table 2). The TP content of cabbage was the highest (4.36 g kg⁻¹). The N:P ratios of oats (3.27) and potatoes (tubers; 3.19) were lower than for the other agroecosystems ($P < 0.05$). There was a significant positive correlation between TN and TP ($R^2 = 0.33$, $P < 0.001$; Fig. 2).

Stoichiometric characteristics of soil in different agroecosystems

In the 0–0.1 m soil layer, SOC, TN and TP content did not differ significantly among the 10 agroecosystems ($P > 0.05$). Relatively low SOC, TN and TP values were found in

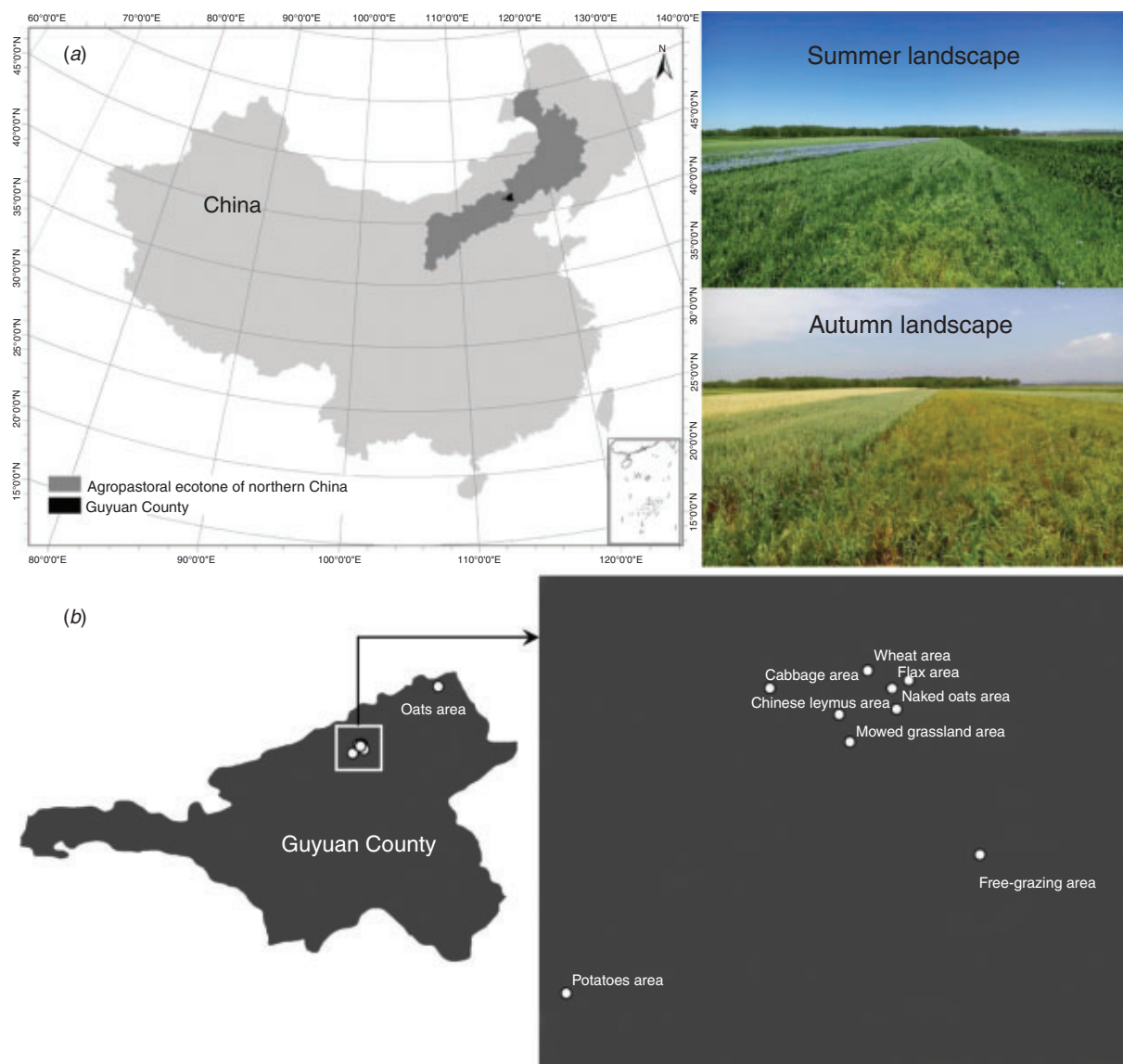


Fig. 1. Site maps. (a) Location of the agropastoral ecotone of northern China. (b) Spatial arrangement of the 10 agroecosystem field sites in Guyuan County, a typical representative county of the agropastoral ecotone (revised from Zhai *et al.* 2017). Multiple agroecosystems coexist under the same environmental conditions.

Table 1. Artificial fertiliser inputs for different agroecosystems in Guyuan County, China

There is livestock excrement in the free-grazing grassland, but no artificial fertiliser is applied; the stocking rate is close to 6 sheep ha⁻¹ from May to October. Potato tubers are treated as aboveground biomass. With the exception of natural and mowed grassland without sowing, other agroecosystems are sowed in May, harvested in September and are fallow from October to April of the following year

Ecosystem type	Agroecosystem	Total artificial fertiliser input (kg ha ⁻¹ year ⁻¹)				Aboveground biomass in 2015 (t hm ⁻²)	Irrigation condition
		Manure	N fertiliser	P fertiliser	Compound fertiliser		
Commercial crop	Potatoes	0	0	0	1575	17.9	Groundwater
	Cabbage	0	375	0	750	6.7	Groundwater
Artificial grassland	Corn silage	1500	150	0	150	18.2	None
	Chinese leymus	1500	0	0	0	5.4	None
Field crop	Oats	10 000	0	0	0	11.0	Groundwater
	Naked oats	1500	150	0	150	4.2	None
	Wheat	3000	0	0	0	4.1	None
	Flax	1500	0	0	150	3.5	None
Natural grassland	Mowed grassland	0	0	0	0	1.6	None
	Free grazing	0	0	0	0	0.4	None

Table 2. Plant stoichiometric characteristics of different agroecosystems

Data are the mean $\pm$ s.e.m. Within columns, different letters indicate significant differences ($P < 0.05$). TN, total nitrogen; TP, total phosphorus

Ecosystem type	Agroecosystem	TN (g kg^{-1})	TP (g kg^{-1})	N : P ratio
Commercial crop	Potatoes (aboveground)	$15.47 \pm 0.38\text{bc}$	$1.88 \pm 0.05\text{cde}$	$8.22 \pm 0.09\text{a}$
	Potatoes (tubers)	$6.25 \pm 0.76\text{c}$	$1.96 \pm 0.10\text{cde}$	$3.19 \pm 0.29\text{c}$
	Cabbage	$25.70 \pm 4.33\text{a}$	$4.36 \pm 0.02\text{a}$	$5.90 \pm 0.98\text{abc}$
Artificial grassland	Corn silage	$10.59 \pm 1.45\text{bc}$	$2.13 \pm 0.23\text{cd}$	$4.96 \pm 0.38\text{abc}$
	Chinese leymus	$8.70 \pm 0.61\text{c}$	$1.16 \pm 0.08\text{e}$	$7.58 \pm 0.82\text{ab}$
	Oats	$11.83 \pm 0.78\text{bc}$	$3.66 \pm 0.40\text{b}$	$3.27 \pm 0.16\text{c}$
Field crop	Naked oats	$9.39 \pm 0.46\text{c}$	$1.89 \pm 0.16\text{cde}$	$5.02 \pm 0.22\text{abc}$
	Wheat	$10.37 \pm 0.79\text{bc}$	$2.31 \pm 0.10\text{c}$	$4.49 \pm 0.38\text{bc}$
	Flax	$11.02 \pm 1.32\text{bc}$	$1.89 \pm 0.10\text{cde}$	$5.80 \pm 0.45\text{abc}$
Natural grassland	Mowed grassland	$11.13 \pm 2.45\text{bc}$	$1.41 \pm 0.25\text{de}$	$7.96 \pm 0.84\text{a}$
	Free grazing	$19.56 \pm 1.12\text{b}$	$2.45 \pm 0.10\text{c}$	$8.09 \pm 0.47\text{a}$

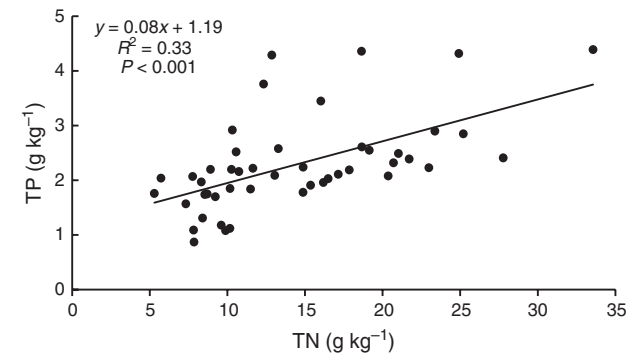


Fig. 2. Relationship between total nitrogen (TN) and total phosphorus (TP) content in the plant tissue of different agroecosystems.

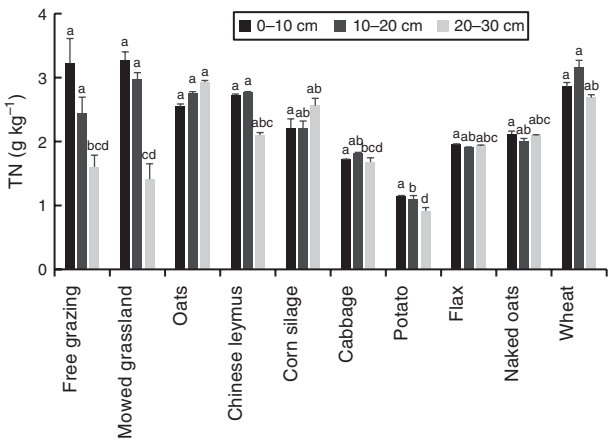


Fig. 4. Soil total nitrogen (TN) content along the gradient of soil layer depths in 10 agroecosystems. Data are the mean $\pm$ s.e.m. Within soil layer depths, different letters above columns indicate significant differences between agroecosystems ($P < 0.05$).

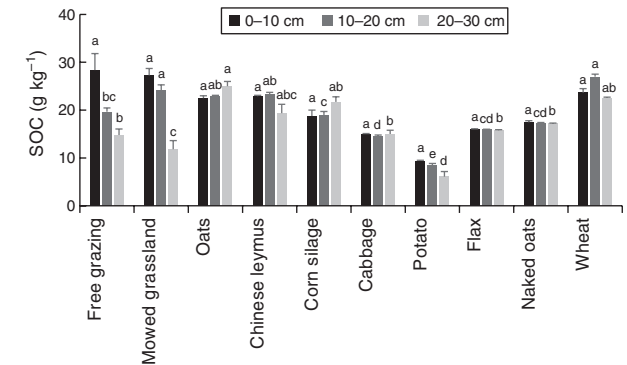


Fig. 3. Soil organic carbon (SOC) content along the gradient of soil layer depths in 10 agroecosystems. Data are the mean $\pm$ s.e.m. Within soil layer depths, different letters above columns indicate significant differences between agroecosystems ($P < 0.05$).

potatoes (9.39, 1.15 and 0.36 g kg^{-1} respectively; Figs 3–5). In the 0.1–0.2 and 0.2–0.3 m soil layers, SOC, TN and TP content differed significantly among the 10 agroecosystems ($P < 0.05$). The lowest SOC content was in potatoes (8.54 and 6.10 g kg^{-1} in the 0.1–0.2 and 0.2–0.3 m soil layers respectively). Similar results were obtained for TN and TP, with lowest values found

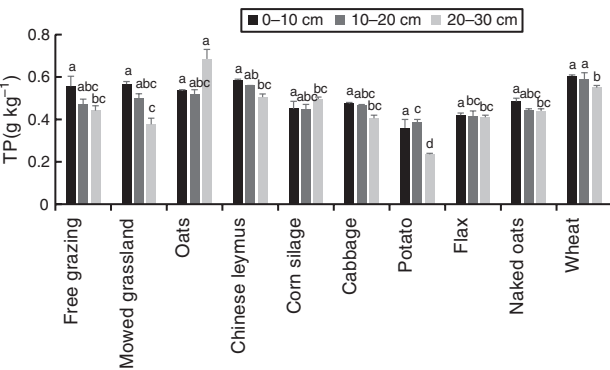


Fig. 5. Soil total phosphorus (TP) content along the gradient of soil layer depths in 10 agroecosystems. Data are the mean $\pm$ s.e.m. Within soil layer depths, different letters above columns indicate significant differences between agroecosystems ($P < 0.05$).

Table 3. Soil stoichiometric characteristics of different agroecosystems at different soil depths
Data are the mean $\pm$ s.e.m. Within columns, different letters indicate significant differences ($P < 0.05$)

Agroecosystem	C:N			C:P			N:P		
	0–0.1 m	0.1–0.2 m	0.2–0.3 m	0–0.1 m	0.1–0.2 m	0.2–0.3 m	0–0.1 m	0.1–0.2 m	0.2–0.3 m
Free grazing	8.84 $\pm$ 0.14a	8.40 $\pm$ 0.53a	9.55 $\pm$ 0.69a	50.49 $\pm$ 2.66a	42.36 $\pm$ 1.92ab	33.46 $\pm$ 2.38ab	5.73 $\pm$ 0.33a	5.19 $\pm$ 0.37a	3.63 $\pm$ 0.38a
Mowed grassland	8.34 $\pm$ 0.10a	8.13 $\pm$ 0.12a	8.46 $\pm$ 0.30a	48.09 $\pm$ 2.10a	48.49 $\pm$ 2.16a	31.06 $\pm$ 2.29ab	5.76 $\pm$ 0.19a	5.96 $\pm$ 0.18a	3.69 $\pm$ 0.36a
Oats	8.86 $\pm$ 0.36a	8.31 $\pm$ 0.14a	8.53 $\pm$ 0.27a	42.05 $\pm$ 0.54ab	44.09 $\pm$ 1.31ab	36.56 $\pm$ 0.94ab	4.75 $\pm$ 0.13ab	5.32 $\pm$ 0.25a	4.30 $\pm$ 0.25a
Chinese leymus	8.40 $\pm$ 0.02a	8.45 $\pm$ 0.07a	9.23 $\pm$ 1.06a	39.15 $\pm$ 0.68ab	41.70 $\pm$ 0.63ab	38.24 $\pm$ 2.53ab	4.66 $\pm$ 0.07ab	4.94 $\pm$ 0.04a	4.17 $\pm$ 0.21a
Corn silage	8.48 $\pm$ 0.14a	8.58 $\pm$ 0.15a	8.47 $\pm$ 0.06a	41.85 $\pm$ 1.58ab	42.60 $\pm$ 2.60ab	43.72 $\pm$ 2.25a	4.93 $\pm$ 0.12ab	4.96 $\pm$ 0.25a	5.16 $\pm$ 0.25a
Cabbage	8.70 $\pm$ 0.05a	8.07 $\pm$ 0.20a	8.93 $\pm$ 0.13a	31.59 $\pm$ 0.55b	31.41 $\pm$ 0.77b	37.16 $\pm$ 3.35ab	3.63 $\pm$ 0.04b	3.89 $\pm$ 0.00ab	4.16 $\pm$ 0.32a
Potatoes	8.19 $\pm$ 0.06a	7.88 $\pm$ 0.75a	6.62 $\pm$ 0.77a	26.36 $\pm$ 2.56b	22.24 $\pm$ 1.66c	25.85 $\pm$ 3.94b	3.23 $\pm$ 0.34b	2.83 $\pm$ 0.06b	3.89 $\pm$ 0.15a
Flax	8.19 $\pm$ 0.04a	8.36 $\pm$ 0.01a	8.18 $\pm$ 0.11a	38.24 $\pm$ 1.03ab	38.70 $\pm$ 2.34ab	38.57 $\pm$ 1.19ab	4.67 $\pm$ 0.10ab	4.63 $\pm$ 0.28ab	4.72 $\pm$ 0.09a
Naked oats	8.24 $\pm$ 0.01a	8.64 $\pm$ 0.15a	8.21 $\pm$ 0.09a	35.99 $\pm$ 0.39ab	38.89 $\pm$ 0.67ab	39.11 $\pm$ 0.67ab	4.37 $\pm$ 0.04ab	4.51 $\pm$ 0.16ab	4.77 $\pm$ 0.13a
Wheat	8.29 $\pm$ 0.10a	8.57 $\pm$ 0.16a	8.40 $\pm$ 0.20a	39.11 $\pm$ 1.73ab	45.93 $\pm$ 3.19a	41.02 $\pm$ 1.02ab	4.72 $\pm$ 0.16ab	5.37 $\pm$ 0.48a	4.89 $\pm$ 0.01a

in potatoes. Overall, in the 0–0.3 m soil layer, the mean SOC content in potatoes was 8.01 g kg⁻¹, which was lower than in cabbage (14.87 g kg⁻¹), and both these values were significantly lower than in other agroecosystems ($P < 0.05$). The mean TN and TP contents in potatoes (1.05 and 0.33 g kg⁻¹ respectively) were significantly lower than in the other agroecosystems.

The C:N ratios of the 10 agroecosystems did not differ significantly among the three sampled soil depths ($P > 0.05$), with values in the range 8.19–8.86, 7.88–8.64 and 6.62–9.55 for the 0–0.1, 0.1–0.2 and 0.2–0.3 m soil depths respectively. Although there appeared to be a slight decreasing trend in C:N with increasing soil depth in potato sites, the differences did not reach statistical significance. The C:P ratios in cabbage (0–0.1 and 0.1–0.2 m soil depths) and potatoes (0–0.1, 0.1–0.2 and 0.2–0.3 m soil depths) were lower than in other agroecosystems. Similarly, N:P ratios in cabbage (0–0.1 m depth) and potatoes (0–0.1 and 0.1–0.2 m depths) were lower than in the other agroecosystems ($P < 0.05$; Table 3). At a depth of 0–0.1 m, C:P ratios in the 10 agroecosystems ranged from 26 (potatoes) to 51 (free grazing), whereas N:P ratios ranged from 3 (potatoes) to 6 (natural grassland). In the 0.1–0.2 m soil layer, C:P ratios ranged from 22 (potatoes) to 49 (mowed grassland), whereas N:P ratios ranged from 3 (potatoes) to 6 (mowed grassland). At a depth of 0.2–0.3 m, C:P ratios ranged from 26 (potatoes) to 44 (corn silage), whereas N:P ratios ranged from 4 (grasslands) to 5 (corn silage). In general, the mean C:N ratios of the 10 agroecosystems over the depth 0–0.3 m did not exhibit any significant differences ($P > 0.05$). However, mean C:P ratios were lower in potatoes than in cabbage (24.64 vs 33.17 respectively), and both these ratios were lower than C:P ratios in other agroecosystems ($P < 0.05$). There were no significant differences in mean N:P ratios among nine agroecosystems ($P > 0.05$), but the N:P ratio was lower in potatoes (3.23) than in the other nine agroecosystems.

The relationship between SOC and TN was stronger than relationships between SOC and TP and between TN and TP. Across the agroecosystems, there was a linear relationship between SOC and TN content ($P < 0.001$; Fig. 6). There were significant positive correlations between SOC and TP ($P < 0.001$), as well as between TN and TP

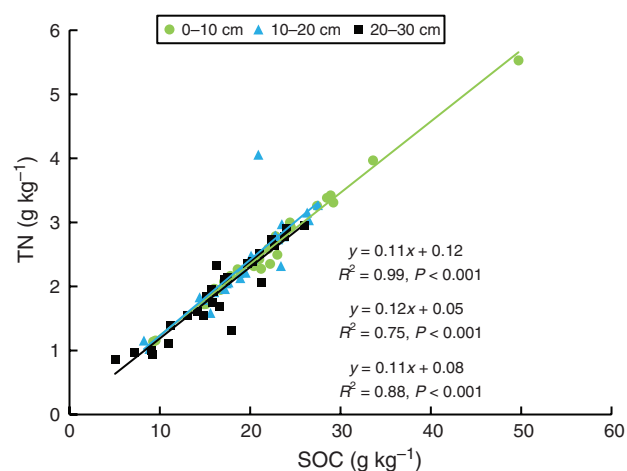


Fig. 6. Relationships between soil organic carbon (SOC) and total nitrogen (TN) content for the three soil layer depths in 10 agroecosystems.

($P < 0.001$; Figs 7, 8). All linear relationships between SOC, TN and TP demonstrated a strong stoichiometric link between C, N and P in the soil.

Discussion

N and P are generally considered the two most limiting elements to terrestrial vegetation primary productivity. Many studies have assessed both N and P content in plant tissues to investigate whether is N or P limiting, or whether they are colimiting (Güsewell 2004; Reich and Oleksyn 2004; Han *et al.* 2005; Niklas *et al.* 2005; Yuan and Chen 2009). In general, leaf N and P decline and the N:P ratio increases towards the Equator as mean temperatures and the length of the growing season increase (Reich and Oleksyn 2004); herbs have lower N:P ratios in photosynthetic tissues than woody plants, and graminoids have higher N:P ratios than forbs (Güsewell 2004; Sardans *et al.* 2012). A meta-analysis of the N:P stoichiometry of different crops found that the N:P ratio was highest in legumes, followed by cereals and lowest in oilseed crops (Sadras 2006). In the present study, we

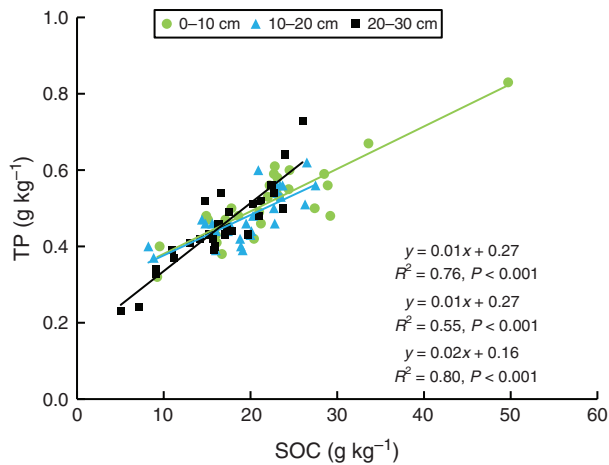


Fig. 7. Relationships between soil organic carbon (SOC) and total phosphorus (TP) content for the three soil layer depths in 10 agroecosystems.

investigated the N and P status of whole herbaceous plants across 10 agroecosystems. The results are consistent with those reported for ecosystems having low soil and plant N:P ratios supporting species with high growth rates (high biomass at the same growing time; e.g. the potatoes and corn silage in the present study), which is in line with the growth rate hypothesis at the ecosystem level (Sterners and Elser 2002; Wang *et al.* 2014). Researchers have proposed critical N:P ratios to indicate N and P limitation for terrestrial ecosystems. Güsewell (2004) suggested N:P ratios <10 and >20 correspond to N- and P-limited biomass production respectively. In the present study, N:P ratios in different agroecosystems ranged from 3.19 to 8.22, suggesting that N limitation was likely an important factor affecting variation in productivity among land use types. Soil and plant N:P ratios exhibit a general increasing trend from cool to temperate and to tropical ecosystems, but vary greatly within each climatic area (Sardans *et al.* 2012).

Human interventions can strongly alter C, N and P by changing nutrient inputs (e.g. fertilisation) and outputs (e.g. crop harvesting), as well as by changing the structure of plant communities. Little research has focused on how humans affect ecosystem stoichiometry via different land uses, especially in terrestrial ecosystems (Sardans *et al.* 2012; Wang *et al.* 2014). For ecosystems within the same climatic conditions, different land use patterns can cause changes in soil stoichiometric characteristics (Yang *et al.* 2014). Spohn *et al.* (2016) found a strong increase in soil total organic carbon (TOC) concentrations after land abandonment, and the TOC:TN ratio increased by a factor of 1.3–1.6 in the south-exposed chronosequence.

Stevenson *et al.* (2016) obtained similar results to those of the present study by measuring spatial distributions of soil organic matter (SOM) concentrations and nutrient ratios across different land uses. Stevenson *et al.* (2016) found that soil C:N followed the same pattern with pasture approximately equal to maize cropping, whereas soil C:P and N:P ratios were higher in pasture than under maize. Globally, 21.8% of land area has already been converted into human-dominated uses (Hoekstra *et al.* 2005). Based on a database from 2004 to

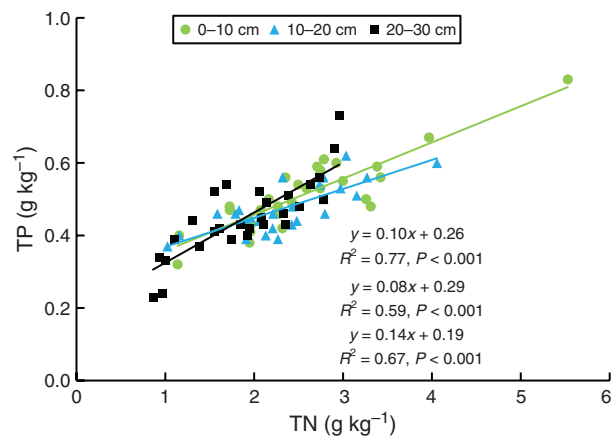


Fig. 8. Relationships between total nitrogen (TN) and total phosphorus (TP) content for the three soil layer depths in 10 agroecosystems.

2013, Chai *et al.* (2015) reported that the stoichiometric ratios of N:P and C:P in grassland ecosystems are greater than in agroecosystems. The results of the present study show the same trend. It is worth mentioning that the changes in N:P ratios are due primarily to changes in soil N concentrations among the different land uses, because soil TP remains almost constant (Wang *et al.* 2014).

Tian *et al.* (2010) reported that generally C:N ratios in the 0–0.3 m soil layer are 12.65 in China; this is higher than the value obtained in the present study (8.39). The C:P and N:P ratios in the present study are similar to and lower than, respectively, the results reported by Tian *et al.* (2010). The reasons for these differences can be summarised as follows. On the one hand, the C:N:P ratios vary significantly among different climate zones and soil bedrock in China and the world (Tian *et al.* 2010; Sardans *et al.* 2012; Zhao *et al.* 2015). The high productivity of tropical and subtropical ecosystems fosters relatively high soil C and N content, which results in high C:P and N:P ratios. In contrast, the dry and cool climates of locations such as Guyuan County generally have low C:N and C:P ratios because aridity and low temperature limit biological production and result in poorly developed soils (Spohn *et al.* 2016; Plaza *et al.* 2018). The C:N:P ratio decreases from 29:2.3:1 for dry subhumid soils to 15:1.5:1 for semi-arid soils, to 9:1.0:1 for arid soils and to 6:0.8:1 for hyperarid soils (Plaza *et al.* 2018). Lower soil C and N contents and higher soil P content with less leaching also lead to lower C:P and N:P ratios (Tian *et al.* 2010). On the other hand, different vegetation types result in different uses of soil nutrients. In the present study, the consumption of soil nutrients by potatoes was high in relation to their high biomass, and the soil C:P and N:P ratios were significantly reduced compared with those in other agroecosystems. Soil C stocks decline during intensification of land use, particularly as natural and seminatural ecosystems are converted to agricultural ecosystems (Don *et al.* 2011), and cabbages and potatoes were clearly very detrimental in the present study; one of the important reasons for this is that multiple tillage practices from sowing to harvesting promote soil respiration (Rong *et al.* 2015) and carbon emissions (Spawn *et al.* 2019). The human-induced

leaching from croplands affects C : N and C : P ratios at the local scale (De Vries *et al.* 2011). Soil health, especially the SOM, is the key component of any terrestrial ecosystem and has a broad effect on ecosystem services, such as food supply, environmental quality and climate regulation (Paul 2016; Haney *et al.* 2018; Pereira *et al.* 2018; Plaza *et al.* 2018). Restoring, preserving and increasing the SOC content (especially for cabbages and potatoes) and scientifically adjusting the application of N and P fertiliser are highly promising strategies to both improve the efficiency, sustainability and profitability of agroecosystems and to reduce eutrophication risk, greenhouse gas emissions while contributing to improved food and water security (Conley *et al.* 2009; Rowe *et al.* 2016; Carlson *et al.* 2017; Plaza *et al.* 2018).

Conclusions

N is more likely a limiting factor than P for biomass production in local areas in the present study. Different material inputs and plant nutrient consumption significantly affected soil stoichiometric characteristics of local agroecosystems, especially in potatoes. Soil C : P and N : P ratios significantly decreased with increased human utilisation intensity (from grasslands with low artificial material inputs to high human inputs, such as the potato ecosystem). Restoring, preserving and increasing the SOC content, scientifically adjusting the application of N and P fertiliser and enhancing subsidies for low-loss soil nutrient systems will help improve and sustain agroecosystems.

Conflicts of interest

The authors declare no conflict of interest

Acknowledgements

The authors are grateful to the anonymous reviewers who contributed to improving the manuscript. In addition, the authors thank the local farmers for their practical support during field data collection. This study was supported by the Agricultural Extension Service Pilot Program of the National Research Institutions – Ecological Function Area of Northern in Hebei Province, China (201604710410126), as well as the China Scholarship Council (Grant no. 201706350067).

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Handling Editor: Nick Dickinson