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REVIEW

Heterogeneity of Soil Nutrients: A Review of Methodology, Variability and Impact Factors

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ABSTRACT

Soil nutrient heterogeneity highly correlates to plant growth and development of environmental quality. In order to better understand nutrient cycling, heterogeneity of soil nutrients and their driving mechanism in different land use types were summarized from 1945 to 2016. By grouping keywords indexed in the titles of articles from the data base of Web of Science, two hundred and thirty one publications related to our topics were used for analysis. Soil sampling and statistical method were compared, and spatial dependence and the impact factors for soil organic matter (SOM), Nitrogen (N), Phosphorus (P) and Potassium (K). The results showed that soil nutrient heterogeneity was influenced by different factors at different scales. The spatial dependence of SOM, N and P were mainly at the moderate level (48.9-59.0%) and strong level (33.3-42.2%), while for K was at strong level (63.6-84.6%) and moderate level (15.4-36.4%). This was mainly influenced by topography, soil loss, weather condition, parent material, soil type, soil texture, land use, human activities, soil moisture, mineral element, soil structure, animal and plant. These impact factors were summarized separately, and the influence of factors at different spatiotemporal scales was discussed. At the end of the review, the ideas for further research were postulated.

1. Introduction

Ecological flow, e.g. energy flow, material flow, biological flow and information flow are all mainly driven by the spatiotemporal heterogeneity of related factors [1, 2]. Soil nutrients are important environmental factors, especially, nutrient availability as one of the three major drivers of the ongoing global change impacting terrestrial ecosystems worldwide [3, 4]. Nutrient heterogeneity is common in soil at various scales, which highly relates to plant growth, biomass, plant diversity [5, 6], and especially influences fertilization, nutrients loss, ground water eutrophication, and policy decision in agroecosystems [7-9]. This determined the method of nutrient management which are a threat to the development of sustainable agricultural ecosystem and natural ecosystem [10-13].Therefore, in order to better understand nutrient cycling, it is very important to clarify the heterogeneity of soil nutrient in different types of the environment, and to ascertain their driving mechanisms.

With the development of the new theories and technologies, the management method on agricultural fields, forests, grassland and wetland has been changing, which has

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strongly influenced the environment, even at the global scale[14-16]. Chemical fertilizers effectively increase crop yield, and reduce the pressure of food supply in the world [17]. However, excessive fertilization can waste resources, decrease food quality, and increase environmental pollution, while insufficient fertilization decreases crop yield [18,19]. Both excess and insufficient fertilization increase the heterogeneity of nutrients in fields, and enhanced the difficulty of fertilization[13, 20]. Therefore, nutrient heterogeneity at different scales in different kinds of land uses and soil types were studied[21,22], and the techniques of precision fertilization were developed[23]. Accuracy of prediction with a high precision is necessary for the precision fertilization and the study of soil nutrient heterogeneity, which was mainly determined by sampling methods and statistical analysis methods[24-26]. In order to improve the precision of prediction, both sampling methods and statistical analysis method were developed in past years, but the advantage and disadvantage between these sampling, statistical analysis methods is still not clear[25-28]. Fertilizer was used not only for agricultural fields, but also for pasture since livestock farming has developed very quickly and can provide more protein for human consumption[29, 30]. Furthermore, nutrient heterogeneity was not only influenced by the sources of the nutrients, but also influenced by nutrient movement, which was driven by many factors, e.g.by air flow and water flow [31-35]. A great amount of N, P and K released by human activities has been carried by water and wind, which redistributed the nutrients across the farmland, forestland and wetland over a large area [36,37]. Many publications discuss what factors influenced the heterogeneity of nutrients in various kinds of ecosystem, and the mechanisms [12, 26, 31, 32, 38, 39]. However, it is not clear if the heterogeneity and drivers were common between the research areas, and it was even difficult to know the number of factors and their influence [31, 33, 36, 40-44]. Furthermore, it is not clear whether the main factors and driving mechanism are common in the same areas under different spatiotemporal scales [13, 33, 40].

In this review, sampling methods and statistical analysis methods were summarized. The spatial dependence and variability of SOM, N, P and K were discussed, and the manner of operation of how key driver factors were ascertained in various kinds of ecosystems. At the end of summary, ideas for further research were suggested.

2. Scope of Review

N, P and K are three key elements which nourish crop growth, and relate strongly to the environment [4]. SOM releases nutrients after decomposition, and nutrients can be converted into SOM by biological processes [4, 45]. Therefore, the heterogeneity of SOM, N, P and K has been the major focus by previous research work. In this present study, the focus was only on the distribution of SOM, N, P and K and their driving mechanisms in soils under different types of ecosystems.

Table 1. Keywords used to search publication titles

First word	Second word	Third word	Numbers of occurrences
Soil	Heterogeneity	Organic matter	15
		Nitrogen	20
		Phosphorus	6
		Potassium	1
		Nutrient	33
Soil	Spatial distribution	Organic matter	17
		Nitrogen	21
		Phosphorus	17
		Potassium	5
		Nutrient	22
Soil	Spatial pattern	Organic matter	3
		Nitrogen	14
		Phosphorus	3
		Potassium	2
		Nutrient	11
Soil	Variability	Organic matter	32
		Nitrogen	70
		Phosphorus	46
		Potassium	9
		Nutrient	53
Total numbers			400

Note: It was difficult to analyse the data when key words indexed in the topic were used, since over a thousand publications were found in one group of words, e.g. 1222 publications were harvested from the group using the topic words soil-heterogeneity-organic matter.

First, keywords were indexed from topics used to search publications from 1945 to 2016 based on the Web of Science data base (Thomson Reuters). There were 1224 publications found when "soil-heterogeneity-organic matter" was used to define the search, and many of them were not related to heterogeneity of SOM. Therefore, keywords indexed in titles were used to search publications. Heterogeneity, spatial distribution, spatial pattern and variability as the most popular key words, combed with Organic mat-

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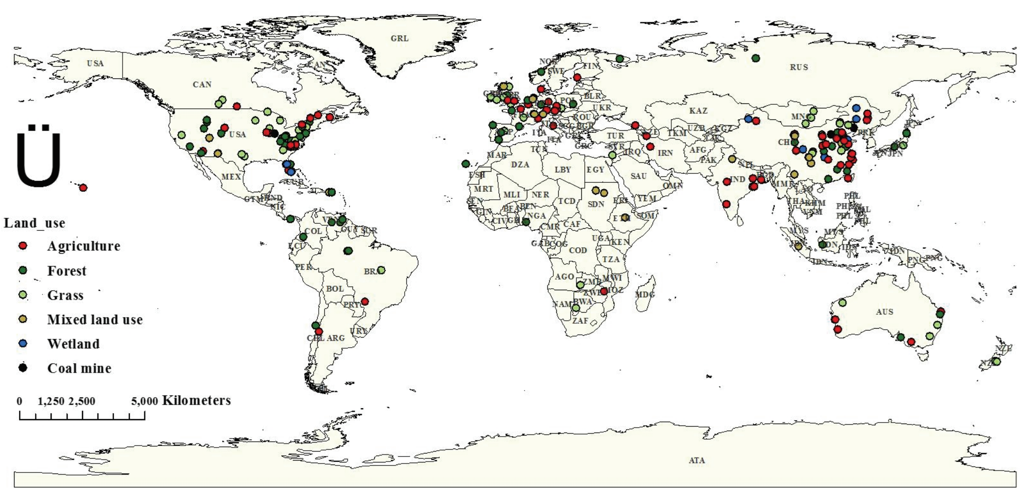

Figure 1. Distribution of research locations under various kinds of land uses from 1945 to 2016 in the global mainland based on the Web of science. Mixed land use means the number of land uses was greater than two. Most of the research locations were concentrated in China, European counties and United States.

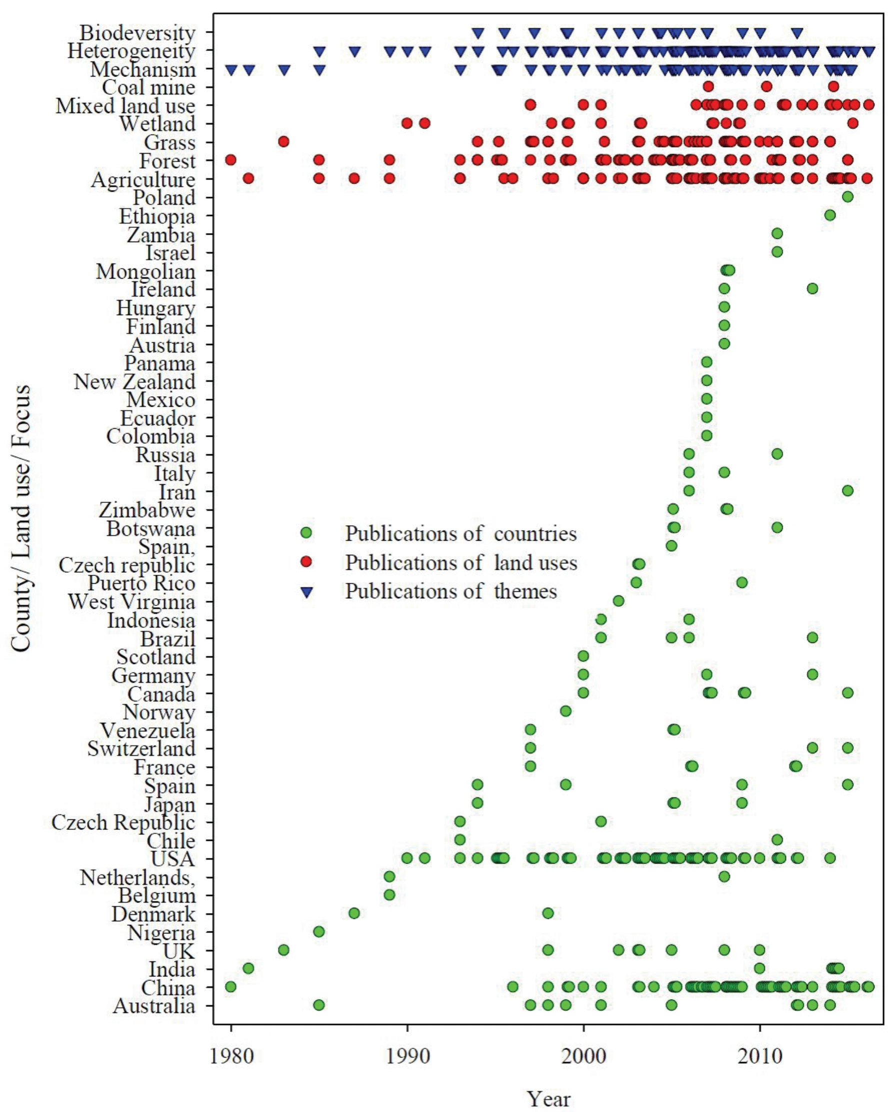

Figure 2. Distribution of publication numbers based on topics, land uses and countries from 1980 to 2016

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ter, Nitrogen, Phosphorus, Potassium and Nutrient were used to search publications from the Web of Science data base. Four hundred publications were harvested when twenty groups of keywords (three consecutive keywords in each group) were used to search the articles (Table 1), and only two hundred and thirty one publications related to our topics were suitable to be used for analysis.

Most of the research locations of the published articles were in China, Americas and European countries (Figure 1). For both USA and European countries, most of the studies were published from 1995 to 2010, while for China the number of publications increased since 2005. Furthermore, there has been a rapid increase in recent years in the themes of heterogeneity and its driving mechanisms, and land use focusing on farmland, forestland and wetland.

3. Sampling Methods and Statistical Analyses

3.1 Soil Sampling Methods

Soil sampling methods are crucial to clarify soil nutrient heterogeneity in space [25-28]. Location, depth and number were typically considered in the sampling methodology. Generally, the design method of sampling locations are one-dimensional (belt sampling)[46], two-dimensional (sampling one soil depth in a whole area or region)[33], and three-dimension (many soil depths in an area)[40]. Two-dimensional sampling typically includes random sampling[36, 47], grid sampling space [43, 48, 49], grid sampling with a nested design space [50, 51], and an irregular design [52]. The belt sampling method was recommend when the study area was large, a relative simple landscape, or in a complicated environment which is not easy to access. The two-dimension method was recommended if cost, labour and time allowed, especially in a complicated landscape where much more information can be captured. The random sampling method was economical, easily controlled and often adopted in a large area, especially for an area with the complicated landscapes and land uses, but the disadvantage is that some important information might be lost when the samples distribute unevenly [36, 40, 47]. Grid sampling with a reasonable resolution can capture more information to accuracy estimate the distribution of soil nutrients, especially for a small area, but the disadvantage is that it is expensive and is labour intensive to find the positions of soil sampling points in a large area [33, 43, 48, 49]. Grid sampling can be done in a number of ways: grid cell method means soil properties are calculated for each grid cell using all the soil samples contained within the grid; grid centre method means soil properties for the soil sample points nearest the centre of the grid are used [53]. Grid cell sampling consistently captures more soil nutrient variability information than the grid centre method [53]. When heterogeneity changes with scale, the nested grid design was always adopted so as to capture more information in short-range spatial variability and to estimate the variogram at short lags [50, 51, 54, 55]. Furthermore, soil sampling methods should be separated when the region includes several soil types and land uses, as this is beneficial for capturing more information for better spatial analysis.

The determination of soil sampling depths is very important in detecting heterogeneity and its driving mechanisms of SOM and soil nutrients, and should be confirmed before collecting the soil samples. Generally, soil layers were clustered into several consecutive layer-groups according to the vertical distribution and the driving mechanism of the soil physio-chemical properties, and then the classification of layer-groups can be used as a guide for soil sampling. For farmland, 0-30 cm, especially in 0-20 cm, were typically focused on due to the plough pan at the 20-30 cm depth (Table 2), since crop growth highly relates to plough layers [33, 56, 57]. Furthermore, the sampling depths could be shallower than 20 cm when a relatively small spatio-temporal scale is the focus [58], and could be deeper than 30 cm soil when vertical heterogeneity, the storage of SOM and nutrients, hydro-logical process, soil erosion, and land degradation were considered [12, 40, 59]. For both forestland and grassland, soil layers in the 0-10 cm depth were mainly focused on since the deep layers were typically not disturbed and were relative stable compared with farmland [60-63]. For wetland, soil sampling was typically designed to study nutrient movement and the hydro-logical process in the deep soil layers [64,65]. Soil sampling depths were influenced by the investigation method, e.g. upper soil layers were always investigated when Gamma ray spectrometry was used to monitor soil properties in a large area [66]. From the view of the publications, soil sampling depths were not obviously different in different years or special periods from 1945 to 2016, and were mainly determined by the aim of the studies and were limited by labors and cost [13, 31, 33, 67-69]. However, soil nutrient distribution and the driving mechanisms in different soil profiles, especially in deep layers were still not clear. This should be studied more in the further research work because soil physio-chemical properties were consecutive in horizontal and vertical and influenced each others [4].

Root mean square error (RMSE) can be used to determine the quantity of sampling points for selected soil properties by correcting the data to fitting a normal distribution [70]. Comparison with the mean value and variation between various scales can be used to decide the sampling number and area [71]. Not only the sample numbers, but also the soil sampling density influences the accuracy

Table 2. Sample number size of land use in publications from1945 to 2016

	N	Sample size of publication by soil depth (cm)								
		≤5	≤10	≤15	≤20	≤30	≤40	≤70	≤100	>100
Farmland	72	4	4	8	17	9	5	6	4	1
Forestland	62	5	13	5	5	4	4	4	1	5
Grassland	58	14	11	7	6	3	2	3	1	2
Wetland	15	0	2	0	1	3	1	3	3	1
Coal land	3	0	0	0	0	1	0	1	1	0
Multiplicity	25	1	1	2	8	1	1	1	2	0
Sum	235	24	31	22	38	21	12	18	12	9

Notes: N sample size, parts of publications

of the prediction, and should be adjusted to suit the spatio-temporal scale [55].

Each soil sample can be mixed with three horizontal cores taken at the same depth (deep soil layers were focused on) [28, 72], five cores (four cores at the ends and one at the centre of the square)[31, 40], or many cores (in a large area, a systematic sampling strategy is better than a random one) [43, 55, 73]. Furthermore, sampling using mixed soil cores could be used to at densities of 1 m^2 [28], 10 m^2 [33], and 100 m^2 or several hectares [25, 26]. Generally, several soil sampling methods were used to predict the heterogeneity of nutrients in an area, and the method was determined by the landscape[28], land use[25, 74], soil type[57, 74], scale and so on[27].

3.2 Statistical Analysis and Software

Traditional descriptive statistics (TS) [59], or both traditional statistics and geostatistics (GS) were used to clarify the heterogeneity of soil nutrients in different ecosystems[13,75]. Coefficient of variation (CV) was always used to reflect the spatial variance of soil nutrient distribution[40, 75], and a high CV value represents high spatial variability[40]. However, CV can't quantitatively describe the spatial variance of soil nutrients, and only can be used to clarify the character of a special area or region when the sample size is sufficient. Soil nutrient data should fit a normal distribution before geostatistical analysis, and log-normal transformation, square-root transformation, scale to 0-1 or box-transformation can be used to adjust the data [76, 77]. r^2 (square of the correlation coefficient) and RSS (Residual Sums of Squares) can be used to reflect how well the model fits the variogram data. The higher r^2 and lower the RSS, the better the model fits. RSS is more sensitive than r^2 and should be used first to judge the suitability of the models [76]. Spatial dependence, or spatial autocorrelation, is typically used to reflect the spatial heterogeneity influenced by structural and random factors, and the nugget to sill ratio (NSR) is used to define distinct classes of spatial dependence. NSR <25%, 25%-75% and >75%, represented strong, moderate, and weak spatial dependence, respectively [70, 78, 79]. The spatial correlation distance (A, effective range) indicated that properties were auto-related each other in space (spatial dependence) when the distance between sampling points was less than A, and A typically increases as the research area increases [57, 80]. Moran's I analysis can be used to quantify the spatial autocorrelation. The variable is considered to have negative or positive spatial autocorrelation if Moran's I is less than or greater than 0, respectively, while the variable is not spatially correlated if the value is equal to 0. Positive spatial autocorrelation means that similar values (either high or low) of the variables are spatially clustered. Negative spatial autocorrelation means that neighbouring values are dissimilar [43, 81, 82]. Anisotropic analysis (single-direction) should be done before prediction if the data was collected from a complicated landscape, because isotropic (all-direction) analysis may hide much of the autocorrelation that in fact is present [76]. However, very few publications carried the anisotropic analysis [33, 74].

Geostatistical methods primarily include Ordinary Kriging (OK), Inverse Distance Weighting (IDW), Cokriging (CK), Conditional sequential Gaussian simulation (CSGS), Simple Kriging (SK), Universal Kriging (UK), Regression Kriging (RK), Multiple Linear Stepwise Regression (MLSR), Geographically weighted regression (GWR), and so on [25, 83-86]. TS with a belt sampling method could be used in preliminary analysis due to the ease of calculation, relative small data requirements, acceptable accuracy and precision [46, 68, 87]. TS combed with GS were always used to clarify nutrient heterogeneity. From the statistics of 231 publications, studies with the OK+TS method accounted for 88.2% of total GS methods, followed by CK+TS, SK+TS, UK+TS, RK+TS, GWR+TS and IDW+TS (Table 3). The spatial heterogeneity or pat-

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tern of soil nutrients by OK prediction could be similar to other methods, especially for IDW, but the content and gradient could be relative exaggerated or minimized[86,88]. Owing to the influence of the complicated natural of environment factors, the OK method is relatively limited, and the vegetation index, terrain attributes and other factors were always used as the co-variate to predict SOM and nutrient distribution [25, 84]. CK can be used to predict the distribution of soil nutrients when the number of co-variate data is greater than the main-variate data, and the co-variate significantly correlates to the main-variate [83]. For example, compared with OK, CK with pH can better evaluate nitrate (NO_3-N), and reduced sampling numbers and curtailed the analytical cost [83]. CK with elevation can better predict SOM distribution, and had a lower RMSE (root mean square error) than SK. Elevation data (DEM) can be used to reduce the spatial uncertainty of SOM by sequential Gaussian co-simulation compared with the sequential Gaussian simulation algorithm [89]. In order to improve the accuracy and precision, new methods of GS, especially UK, RK, GWR have been developed since from 2010 (Table 3). RK and GWR were recognized as the most accurate methods to predict soil nutrient distribution compared with OK [84], and the accuracy of a map interpolated by GWR can be higher than that using RK [85]. DEM and NDVI as common covariables were always grouped with RK and GWR, and can significantly improve the accuracy for soil nutrient prediction [89, 90]. However, the analysis process were complicated and the co-variate was difficult to find, and thus this method is not generally used now [85]. In a sloping area, soil erosion was the major causal factor of nutrient depletion, but high accuracy of soil erosion was difficult to simulate and the ability to better predict nutrient distribution in a large area was lost [12, 31, 40, 91]. Furthermore, remote sensing using three dimensional fluorescence spectra, Micro-X-ray fluorescence (μ-XRF), near-infrared reflectance spectroscopy (NiRS) and so on can improve the accuracy of prediction, but only the surface soil layer and limited area could be studied [27, 66, 92-94].

Many types of software can be used to analyse nutrient spatial distribution, e.g. GS+, ArcGIS, Super map, Surfer v.6, Matlab, Origen, Sigmaplot, gstat package, geoRpackage, VESPER and so on [95-100]. GS+ was widely used for spatial analysis, and ArcGIS was tend to be used for map interpolation[12, 26, 31, 40, 42, 95].

3.3 Indicators Used to Evaluate the Prediction Accuracy

The validation method of spatial interpolation was not consistence among the studies[42,75,101,102]. It is uncertain whether all the validation methods can be accepted, and the theory should be tested. Root mean square error (RMSE), mean error (ME), coefficient of determination (R^2), standard deviation (STD), mean sum error (MSE, 0-1), reduced kriging variance (RKV, 0-1, values close to 1), mean sum square error (MSSE), mean kriging variance (MKV), correlation between estimated data and error(CEE c), correlation between estimated and measured data (CEM) can be used to evaluate the performance of prediction accuracy [25, 70, 89, 94, 103]. Jackknife analyses [12, 75], Cross-validation [22, 101, 104, 105], cross-validation combined with RMSE and ME[42, 84, 102], ME and R^2 were usually used to estimate the prediction accuracy [51, 83, 84, 88]. Interpolation is hypothesized to be the most accurate when the RMSE is at a minimum and stable [70, 106]. RMSE was also used to determine the number of sampling points for soil

Table 3. Statistical methods in publications from1945 to 2016

		Percent of publications during the period to total publications				
	N	<2000	2000≤yr<2005	2005≤yr<2010	2010≤yr<2015	2015≤yr≤2016
TS	110	18.2%	13.6%	20.0%	25.5%	14.5%
OK+ TS	105	5.7%	3.8%	28.6%	45.7%	16.2%
CK+ TS	5	40.0%	0.0%	40.0%	0.0%	20.0%
SK+ TS	2	0.0%	0.0%	33.3%	0.0%	66.7%
UK+ TS	2	0.0%	0.0%	0.0%	50.0%	50.0%
RK+ TS	2	0.0%	0.0%	0.0%	100.0%	0.0%
GWR+ TS	2	0.0%	0.0%	0.0%	100.0%	0.0%
IDW+ TS	1	0.0%	0.0%	0.0%	0.0%	100.0%

Notes: N: sample size; TS represents that only "Traditional analysis" was uses. GS methods always are combining with TS to analyse nutrient heterogeneity. OK, IDW, SK, UK, CK, RK and GWR represent Ordinary kriging, Inverse Distance Weighting, Simple kriging, Universal kriging, Cokriging, Regression kriging, and Geographically weighted regression, respectively.

properties [70, 101], but the assessment of the best geostatistical methods could be different depending on whether RMSE or ME is used [84].

4. Spatial Dependence and Variability of Soil Nutrients

Spatial dependency or spatial autocorrelation is the indicator reflecting the degree of heterogeneity influenced by structural factors and random factors. Generally, strongly spatial dependent properties were controlled by intrinsic variations or structural factors (e.g. soil parent material, soil texture, mineralogy, climate, landform and so on), while extrinsic variations or random factors (e.g. fertilizer application, tillage, crop planting, and other soil managements) may be weakly the spatially dependent [38, 78, 107]. Both structural factors and random factors changed the variance of SOM and soil nutrients in soil depths, which was mainly decided by the scale of the study area, soil sampling depth, land uses, and the physiochemical properties of the soils [33, 40, 108].

4.1 Spatial Autocorrelation and Variability of Soil Nitrogen (N)

N typically strongly correlates to SOM (Soil organic matter, soil organic matter was typically 1.724 times of soil organic carbon) in the surface soil layers [40, 109], especially at 0-20 cm [33, 40, 108, 110]. Because SOM was mainly accumulated in surface soils and N is the main component of SOM [111], N and SOM were summarized and discussed together in this study [33, 40, 108, 112]. Spatial dependence of TN and SOM varied [74, 88] and was typical at the moderate level (52.1%), followed by strong level (38.1%) in many kinds of ecosystem (Figure 3), but was not consistence at various soil depths, soil types, scales, and land use. For soil depth, the spatial dependence generally increase with soil depth, and different between soil types [40, 107]. On the other hand, at a small spatial scale, the spatial dependence of soil nutrient was lower, while it became strong at big spatial scales in surface soils [33]. The spatial dependence of TN showed a moderate level for various land uses[43,113], and decreased in this order: farmland >grassland > shrub land [43], while TN was at a strong level in sandy soil (mainly shrub land)[113]. For the available nutrients (AN), the spatial dependence was 36.7%, 33.3% and 30.0% at the strong, moderate and weak level respectively. This was mainly influenced by land use, soil types, soil moisture-temperature (typically determined by latitudes and altitude), and differed according to plant growth stages [13, 113].

The spatial variability (usually represented by CV) of N and SOM was typically at strong levels in farmland, was at the moderate level in forests and wetland, and varied by soil depths. This could be mainly influenced by soil

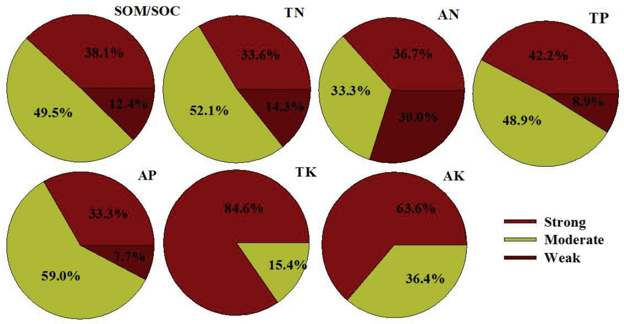

Figure 3. Proportion of spatial dependence degree for SOM/SOC, TN, AN, TP, AP, TK and AK in the studies from 1945 to 2016

types and land use, and this should be quantificationally estimated in further research work [40, 114, 115]. Furthermore, SOM was not consistently correlated to TN in soils, which resulted in a different spatial pattern and variance of SOM and N in different regions, or different in soil depths in the same region [40, 45, 116].

4.2 Spatial Autocorrelation and Variability of Soil Phosphorus (P)

P is not easily moved in the soil and most P is adsorbed by soil particles [4]. P distribution is dominated by a low-concentration diffuse background with a minor contribution from minute hot spots, and no modification of P distribution and speciation is observed close to roots at a microscale in agricultural soil [27]. Spatial dependence was similar between TP and AP, which were typical at the strong (TP 42.2%, AP 59.0%) and moderate level (TP 48.9%, AP 33.3%) in depths of different regions (Figure 3). TP differed from AP, and typically correlates to SOM in surface soil layers [12, 65, 117], and mainly shows moderate spatial dependency, followed by strong dependence under different land use types, while AP typically has a moderate spatial dependency in the surface layer which became stronger in deep soil depths, and was changed with scales [12, 38, 42]. TP at a relatively small scale had a strong spatial dependence, but was at moderate at a large scale [12, 33]. For land use, the nugget ratios of TP decreased in the order: farmland> grassland> shrub land, and showed a strong, moderate, and weak spatial dependence, respectively [43, 113]. The spatial dependence of AP could be at the strong, medium, or weak level in cropped fields [74, 118], and was at the medium level in wetland [115]. The spatial variance of TP typically increased with soil depth, while AP in the surface layer was at the moderate level, and typically increased with depth in the upper soil layers and then decreased in deeper soil layers in both agricultural field and forestland [12].

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4.3 Spatial Autocorrelation and Variability of Soil Potassium (K)

Soil K mainly originated from soil minerals and fertilization [4, 31]. Very few publications focused on the spatial heterogeneity of TK and particularly for AK. The spatial dependency of TK and AK were typically at the strong level (TK 84.6%, AK 63.4%), followed by the medium level (TK 15.4%, AK 36.4%) in both farmland and forestland (Figure 3). This was mainly enhanced by soil parent materials, especially influenced by being released from clay mineralogy (Non-exchangeable K^+ is highly correlated to the proportions of 2:1 layer silicates present in the clay fraction), and weaken by fertilization, plant absorption, and leaching in areas of intensive farming and irrigation [31, 74, 118, 119]. However, it was reported that high quantities of AK were coincident with the size of the tree canopy and had a lower spatial dependence in a forest of Mediterranean Dehesa, which may be attribute to stem flow and residue return [120].

From the review results, the spatial dependence of SOM, TN, TP and AP were mainly at the moderate level (48.9-59.0%), followed by strong level (33.3-42.2%) and weak level (7.7-14.3%), while for TK and AK were mainly at the strong level (63.6-84.6%) and weak level (15.4-36.4%)(Figure 3). The difference may be caused by the sampling area, resolution, sampling time, plants, or human activities, and these results should be validated more in future research work [12, 13, 108, 121]. Furthermore, the degree of spatial dependence judged by NSR can only be used to coarsely describe the proportion of influence by structure factors and random factors, and can't be adapted to clarify what factors and how much these factors influence nutrient distribution [31, 33, 40, 41]. TS was typically used to quantify the influence of these factors [43,74], e.g. principal component analysis (PCA), classification and regression tree analysis (CART), and regression analysis (RS). However, the new methodologies, indicators or parameters should be developed in future research work to more exactly describe their influence. Furthermore, since most previous research on nutrient heterogeneity was carried out only once, it was difficult to accuracy reflect the heterogeneity and driving mechanisms. Long-term monitoring of the spatial distribution of nutrients necessary, and the influence of impact factors should be quantitatively estimated. Most previous studies mainly focused on the whole research area, and neglected the special positions located in the research region (e.g. gully, mini-forest, windbreak in the field). The details of nutrient heterogeneity can't be accuracy reflected, and they were the key intersections influencing nutrient movement.

5. Factors Related to the Heterogeneity of Soil Nutrients

It is well known that soil nutrients were influenced by many factors, but the influence of these key factors on soil nutrient distribution was different, and may be different in varying land use types. From the 231 publications, the factors can be concluded as topography, soil loss, parent material, soil type, soil texture, weather condition, land use, human activities, soil moisture, mineral element, soil structure, and animal and plant, which deeply influence the nutrient distribution in the soil. In this study, N, P and K influenced by these factors were summarized individually.

5.1 Influence of Topography and Soil Loss

In the fertile sloping field, the content of TN, AN, TP, AP and SOM were typically high in the surface layers [38, 45, 65, 112, 122-124]. Furthermore, the surface layers with high nutrients were easily eroded from steep and long slopes, especially on the back slope [28, 125]. Slope steepness and slope length typically positive correlated to soil loss, and changed the distribution of soil nutrients, especially in regions with complicated landscapes, high amounts of precipitation, high rainfall intensity, strong winds and a long period of freeze-thaw cycles [126-128].

Slope steepness and slope length were the key factors influencing soil loss, and both slope position and altitude can coarsely reflect slope length [127, 128]. Thus, slope steepness, slope position, and altitude were always considered as the crucial factors changing the process of soil and water loss, and resulted in changing the spatial heterogeneity of soil nutrients in a sloped area [33-35]. TP, AP and AK typically negatively correlated to slope steepness in many kind of soil types and soil depths [31, 32, 129]. However, there reported that steepness did not significantly correlated to TP, and may be influenced by fertilization [38, 43]. For slope altitude and slope positions, in agricultural fields, TN, TP and SOM typically decreased with deceasing altitude, or decreased to back slope position and then increased (got lowest on the back slope), which was mainly determined by soil loss and deposition [12, 130]. However, the correlation was not consistent throughout nutrient types, soil depths, or in land uses [40, 130]. In the dune land of the subtropical region, where TN and SOC decreased from the crest to the bottom slope, which was associated closely with geomorphic positions [131]. In pasture, P accumulation significantly positively correlated to slope positions (top to middle slope) [132], while TP concentration increased with decreasing altitude [32, 38, 129]. For available nutrients, in agricultural field, AP and AK deceased with altitude, and were lower at the bottom of the slope [31, 40]; NO_3-N dynamics shows a consistent trends related to slope position, and was typically opposite to NH_4-N [13]. However, in pasture, AP increased with decreasing altitude [32, 38, 129]. It is reported that the dynamics of nutrient content and nutrient types were not always consistence on the various slope positions or the altitudes due to the complicated factors [8, 13, 43, 46, 133].

Slope steepness, elevation and slope position highly correlated to nutrient content in a region [45, 134, 135], and were always used in models to predict soil nutrient distribution, particularly, elevation was widely used as the co-variance or regression-variance in a region with a large scale [33, 40, 45]. Generally, slope steepness could be used to build the model only when the number of soil samples was sufficient [33, 40]. Despite the fact that the variability of soil nutrients was mainly influenced by soil loss and deposition, which highly correlated to topographical factors, it was nearly impossible to accurately predict the distribution of SOM, TN and TP when only the soil loss by water was considered [40, 45]. Because soil loss includes wind erosion, water erosion, freezing-thawing erosion and tillage erosion, it was difficult to be accurately simulated by most models.

Slope aspects influence the distribution of solar radiation, precipitation and soil moisture, and changed the process of crop growth, soil erosion and deposition, and thus changed the spatial heterogeneity of soil nutrients [33, 38, 123, 134, 136]. In farmland, SOM and TN were higher in north facing slopes, while the available nutrients were higher in south facing slopes [12, 31, 33, 40, 75]. This was mainly due to the high soil moisture content and the low soil temperature in north facing slopes, which was not beneficial to the release of available nutrient, while they were helpful to the accumulation of nutrients and SOM. In forested land, SOC and soil nutrients had higher values on northern facing slopes than southern facing slopes due to the higher input and lower decomposition rate of organic matter, and the lower temperature and the higher moisture on the northern slopes [137, 138]. In restoring sand dune ecosystems, due to the influence of wind erosion and deposition, soil moisture and plant species, SOC, TN and TP were typically higher on the windward slope, while TK was higher on the leeward slopes [123]. In the alpine sandy land, more soil nutrients were distributed on windward slopes [124]. However, it was reported that TP was high on leeward slope perhaps due to soil particles enriched in P being carried by the wind, and relatively fewer coarse particles being deposited on the windward slopes. Coarse soil particles typically had less P firmly bonded, while more fine particles were deposited on the leeward slopes [129]. Due to most previous reports just focused on nutrients influenced by slope position, elevation, slope steepness, and soil loss, and neglected the influence of slope aspect, thus many results were different for the same land use type, even in the same region. Furthermore, the influence of topography and soil loss on soil nutrient distribution on the slope could change with the time, and the results could be different between two periods. Therefore, nutrient spatial heterogeneity should be monitored in a long-term study.

5.2 Influence of the Weather Condition

The heterogeneity of SOM and soil nutrients was influenced by weather conditions. Higher precipitation and temperatures tended to increase P values in agricultural field[42]. This may be due to climate change, which influenced the water and heat balances, plant growth, land use policy, and soil management, especially P fertilization. Also, P can be more readily weathered and released from rocks under high precipitation and temperature conditions [41, 42]. High temperature and precipitation tended to decrease the SOC due to SOM mineralization and lose, and low temperature and high soil moisture tended to decease SOM decomposition and increase SOC storage [33, 112]. However, the effects of precipitation and temperature on TN and TP were not consistent under different land use types, and it was important to take land use type into account when considering the effects of climate change on TN and TP [42]. Wind can homogenize the distribution of soil components without the presence of grasses, while it increased the heterogeneity of soil variables in various kinds of vegetation and landscapes after erosion and deposition [106]. Furthermore, enhanced wind erosion appears to increase the spatial autocorrelation distance and decrease the spatial dependence of these variables[106]. In desert grassland ecosystems, wind blow reduced both mean soil nutrient concentrations and coefficients of variation over a two-year period (2004–2006), and soil particles deposited in the downwind area maybe form a "nutrient-imbalance"[139]. Despite reports that nutrients heterogeneity was influenced by precipitation, temperature and wind, still some issues need to be better understood. For example, freezing-thawing at high latitude and altitude [140, 141], and the influence of individual precipitation events and other casual weather changes on nutrient cycling [142-144]. It was well known that climate change influences the global biogeochemical cycle and changes nutrient heterogeneity over at a large scale [108]. Only limited study disclosed nutrient heterogeneity influenced global climate change in grass land [145], and it was still not clear that the nutrient heterogeneity influenced climate change in farmland, wetland, forestland at differ-

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ent scales, although there many reports indicated that (1) spatiotemporal variance of nutrient and soil erosion influenced each other [12, 40], and soil erosion highly correlates to global warming[146]; (2) soil nutrient heterogeneity modulates plant responses to elevated atmospheric CO_2 and N enrichment[147].

5.3 Influence of Parent Material and Soil Texture

Spatial variation of SOC, N, P and K was typically influenced by parent material and soil texture at the large-range scale [26, 31, 34, 40, 44, 95, 115]. Parent material was enriched with mineral elements which resulted in increasing the nutrient content in an area [31, 39, 43, 44]. Soil texture differed between soil types and influenced the movement and availability of nutrients. Clay content was typically markedly positively co-relate to nutrients sorption in many kinds of land uses [21, 148], particularly, clay combined with SOM recontributed to N, P and K retention in wetlands [43, 44, 64, 65, 148, 149]. Irrespective of hydromorphic gradient, type and age of forest stands (broadleaved or coniferous) in the hydromorphic zones, nutrient stocks(P, K) in the humus were only influenced by soil type, which may be due to the sorption differing between soil types [150]. Furthermore, the heterogeneity of soil nutrients influenced by soil type could be weakened by human activities such as fertilization, especially for AP [36]. It was reported that poor soil permeability with high water tables decreased the mineralization process of organic matter and influenced soil nutrient distribution [26]. Furthermore, soil texture was changed by plants and environmental gradients, and was highly correlated with nutrient heterogeneity, especially SOC and TN in the surface soil [7]. From the summary above, despite of the fact that soil texture influenced nutrient, heterogeneity was widely reported. However there still some issues are not clear, and needed to be validated, especially quantitative estimates of the influence of soil texture on soil nutrient distribution.

5.4 Influence of Land Use

Farmland, grassland and forestland were the main land use types focused on by previous studies (Table 2). SOM/TN, TP, AN and AP were typically higher in farmland, followed by grassland and forestland or shrub land in the same or nearby areas [7, 32, 38, 52, 59]. However, from the statistics in all of the publications, the value range of SOM content was typically higher in forestland, followed by grassland, farmland and wetland, while the median value of SOM was highest in wetland, followed by forestland, farmland and grassland (Table 4). The value range and median value of TN and AN were typically higher in forestland, followed by farmland, grassland and wetland, but the value range of NO_3-N and NH_4-N content were typically higher in both grassland and forestland. Thus, in order to reasonably analyse the spatiotemporal distribution of SOM, TN and AN in the forest, soil sampling numbers should be relatively large compared with other land use type. The value range of TP was high in farmland, while AP was high in wetland. The median value of TP was high in grassland, while AP was high in farmland. The value range of TK and AK were higher in farmland and grassland respectively, while median value of AK was higher in the forestland. Similarly, in order to better clarify the spatiotemporal distribution of TP, TK and AK in the farmland, soil sampling numbers should be relatively large compared with other land use type. Generally, soil samples from dry farming had significantly higher SOM, TN and AK than soil from paddy fields, while the opposite trend was found for AP [95]. Forestland converted from farmland can effectively hold P, especially in surface soil layers, as the loss of P dissolved in water was not a primary process [12, 38]. In contrast, conversions from cropland to forest or grassland could reduce AP due to the fertilization being reduced [32], or increase AK due the parent material releasing K continuously and crops harvesting removing K from the farmland[31]. Although soil nutrients were determined by the intrinsic character of nutrients, and were changed by ecological flow [1, 2, 4], it is still not clear that the land use influences soil nutrients at different scales, and the heterogeneity of soil nutrients in deep soil layers, especially in farmland, forest and grassland.

Not only farmland, grassland and forestland influenced soil nutrient distribution, but also residential land, roads and hydrology system can indirectly influence soil nutrient distribution. SOM, N and P typically increased when close to industrial land and residential land [37], and AP was more concentrated on the plots closest to the homesteads on wealthy farms, compared with plots farther from homesteads and all plots on poor farms [36]. Furthermore, some hay fields contained large areas with elevated P relative to the rest of the field. The high-P areas occurred mostly near the gate and road, and the area where was most accessible to manure application [151]. Nutrient heterogeneity was influenced by rivers. SOC, TC, TN and TP accumulated more in cropland and woodland in those areas farther from the rivers bank than in those near the river banks [7, 117]. However, soil microbial biomass C, basal soil respiration, and net potential N mineralization were greater nearer shade or water than farther away in the grassland [152]. Thus, in order to better clarify the nutrient heterogeneity influenced by land use types, residential land, road and river system should be fully considered.

5.5 Influence of Human Activities

One of the biggest human influences on soil nutrients

Table 4. SOM and nutrient content in four land uses at 0-30 cm depth, in publications from1945 to 2016

			Farmland			Forestland			Grassland			Wetland	
	N	N	R	M	N	R	M	N	R	M	N	R	M
SOM(g kg^{-1})	152	56	0.1-86.6	14.3	32	0.8-168.9	23.0	51	0.02-116.3	2.16	21	3.6-77.2	32.1
TC(g kg^{-1})	54	-	-	-	24	17-512	-	9	17.5-98.2	29.9	21	11.9-472	-
TN(g kg^{-1})	202	53	0-10.3	0.8	62	0.1-14.3	5	64	0.01-10	0.32	22	0.1-31.3	-
AN(mg kg^{-1})	63	8	6.9-81	20.0	9	6.5-114.6	62.4	39	1.1-41.8	17.2	-	-	-
NO_3-N(mg kg^{-1})	18	7	0.2-5.4	-	7	1.0-8.5	-	4	12.4-26.0	-	-	-	-
NH_4-N(mg kg^{-1})	33	7	0.1-5.4	1.46	5	0.5-29.8	-	6	0.1-25.1		11	1.29-5.4	2.2
TP (g kg^{-1})	115	28	0.001-11.8	0.45	36	0.003-0.8	0.3	34	0.02-3.6	0.7	17	0.1-3.7-	0.5
AP (mg kg^{-1})	133	30	0.5-410	21.6	20	0.2-81.8	20.2	68	0.04-586	14.5	15	4.3-429	67
TK (g kg^{-1})	43	8	2.9-262	-	11	0.06-31.0	-	21	0.3-2.4	2.3	3	0.3-0.3	-
AK (mg kg^{-1})	129	18	45-1300	84.2	39	3.9-545	121.7	69	0.1-988	102	3	0.25-0.31	-

Notes: N sample size. SOM=SOC×1.724. AN was alkali-hydrolyzable nitrogen. N=sample number size, R=range, M=median value. The median value was calculated when fitting the data for a normal distribution.

was farming. In farmland, soil nutrient heterogeneity was mainly determined by fertilization, residue amendment, irrigation and tillage methods [7, 8, 26, 42, 153]. Long-term fertilization and residue return significantly increased the contents of SOM, TN, NO_3-N, NH_4-N, TP, AP, TK and AK in both surface and deep soil layers [40, 48, 101, 114, 154]. Nutrient heterogeneity was changed in a short time after fertilization, especially for the available nutrients. However, it was not clear that the heterogeneity of soil nutrients change in various kinds of landscapes and spatiotemporal scales after fertilization or straw return, a situation which should be monitored continuously in future work at various soil depths [58, 155]. Irrigation significant increased P and K in fields when the water with the high nutrient levels was used [80]. As well, irrigation could decrease nutrient content compared with similar areas, possibly if the content of nutrients in the water was low, and if leaching of soil nutrients by high frequency irrigation rates occurs [39].

Soil tillage method and crop rotation obviously changed the content and distribution of N and SOM in agricultural fields, especially for the surface soil layers [67, 104, 114, 156]. In paddy fields, long term-cultivation increased SOC, and cultivation practices most likely maintained a rather high random spatial variability of approx. 45% [110]. In dry land, the sink and source function of N and SOM were different among the tillage methods; conversation tillage methods effectively increased nutrients and SOM. In Northeast China, cross-slope tillage effectively increased SOM, TN and TP by 33.8, 23.3 and 22.4%, respectively compared to down-slope tillage [33]. Sod cultivation increased SOM, STN and TK by 12.8, 12.7 and 7.3% compared to clean cultivation (bare soil) in the 0-20 cm soil layer in a pear orchard [122]. Also, both no-till cultivation in the surface soil layer and sub soiling in deep layers increased the content of TN, while rotary-tillage reduces N in the whole profile [67].

Mining activities didn't significantly influence the SOM distribution [157], but the drastic disturbance during reclamation of mine soils increased the concentration and stocks of SOM. Reclamation by initially seeding to grasses followed by planting trees was considered as the best management option for speedy accretion of soil C and soil quality enhancement in mine soils [158]. In grazed dairy farms, generic management practices can exacerbate elevated soil nutrient concentrations (P and K), and directly influence the decisions of soil managers [159]. Fire can obviously change N and SOM distribution. High intensity fire can decrease both soil N mineralization and TIN (Soil solution total inorganic N), while low intensely fire can increase TIN in the soils under more xeric landscapes and SOM in intermediate soil moisture areas [160]. In contrast, it was reported that an area with an intense fire 7 years in the past didn't change the C and N contents, but aromaticity was elevated in the soils with the longer fire history[161].

5.6 Influence of Soil Moisture, Mineral Element, Microbiology, and Soil Structure

The spatial distribution of SOM, N and P, and especially SOM, were associated with soil moisture, which was mainly driven by landform, such that the spatial heterogeneous in dry sites was stronger than that in the wet sites on the farmland and grassland [107, 162, 163]. Because watering heterogeneity and nutrients affected plant growth in an interactive manner, watering heterogeneity should be ex-

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amined along with nutrients [164]. SOC and N distribution were influenced by the C:N ratio, pH, temperature, bulk density [38, 42, 65, 152, 165-169], and significantly correlated with exchangeable ions, e.g. K^+,Ca^{2+} and Mg^{2+} content [100, 167, 170]. In wetland, pH values influenced the heterogeneity of SOM, TN, TP and AP [65, 171], and increasing soil moisture may be the most important agent determining P release rate and biological availability [149]. Parts of a study carried out in a wetland indicated that soil moisture was not significantly correlated with N, P and C among all soil samples, and the correlation was not consistence between N, P, SOC and pH [65, 168, 169, 171]. This may be due to wetland being rich in soil moisture and water was not a limiting factor in the influence nutrient cycling and movement. Nutrient heterogeneity was not consistently influenced by soil bulk density in farmland [38], while TP typically correlated to soil bulk density in the wetland [168, 169, 171]. N, P and K distribution were influenced by SOM, especially combined with soil structure and soil texture which influenced the heterogeneity of soil nutrients. This was attributed mainly to the function of sorption [12, 64, 65, 149, 150]. Furthermore, the heterogeneity of N, P and SOM were influenced by microbiology, e.g. nitrification, denitrification, nitrogen fixation, denitrification, and so on [4, 65], and were influenced by the volatilization (NH_3, N_2O and CO_2) [65]. Despite the fact that the influence of trends from soil physiochemical properties was not consistence, but these factors in the special areas could be adopted as covariables to improve the quality of prediction [89, 90].

5.7 Influence of Animal

Clumped defecation and animal carcass strongly influenced the spatial distribution of N, P and SOM in farmland and the natural environment [151, 172]. Generally, grazing processes homogenized the spatial patterns of P, net N mineralization and net nitrification, irrespective of the fact that their original spatial patterns were determined by the differences in the vegetation structure in grasslands [63]. P ‘‘hot spots’’ may be caused by manure deposited by grazing animals [151]. Livestock grazing combined with other anthropogenic activities to remove vegetation also changed the distribution of AN in desert grassland [139]. Furthermore, howler monkey latrines [87, 173], clustered prey carcasses left by wolves [174], seabird breeding sites [175] also increased the N, P concentration in the area. Earthworms mediated plant biomass and responses to nutrient patchiness by affecting N capture [176]. Termite activities also significantly influenced soil properties at the local scale in tropical savannas, and termites movement typically changed the P and C distribution in the micro-environment [102]. Thus, in order to reasonably clarify nutrient heterogeneity in an area, the special contribution from animals should be also considered, especially in the forest, grassland, wetland, and the farmland where animals, e.g. rabbit, wild duck and pheasant reside.

5.8 Influence of Plant

Plant species, population structure, and biomass influenced the content and spatial distribution of N, P and SOM [5, 7, 45, 120, 131, 164, 177-181]. In forestland, farmland, grass land and wetland, the spatial variation of soil nutrients was highly correlated with the distribution and abundance of the dominant plants and soil surface micro-topography, because the N, P, C:N, C:P and N:P of residue returning to the soils were mainly determined by the dominant plants [7, 123, 131, 162, 182-184]. Furthermore, N content can also be influenced by species richness, evenness, and land cover, due to nutrient concentrations and types in both above-ground and below-ground biomass differing between plant species [68, 100, 120, 185], and the residues from plants changing the heterogeneity of N, P and C in ecosystems. Communities of grasses and herbs typically had a lower C/N ratio than communities dominated by heather species, and thus TN was higher in the communities with grasses and herbs than in the heather dominated communities[5]. Spatial variation of leaf litter C:N inputs was the major factor associated with heterogeneity of soil C:N ratios relative to soil physical characteristics, while the spatial variation soil N:P was more strongly associated with spatial variation in topography than heterogeneity in leaf litter inputs [68]. Strong negative correlations between the soil nutrients and altitudes were explained by replacement of vascular plants by low-ash lichens at higher elevations [180]. Similarly in forests, shifting species composition towards red maple and away from pines may alter nutrient cycling by increasing surface soil cation availability and increased TN (not NO_3-N or NH_4-N), although the low lignin concentration in red maple litter and low lignin/N ratio, and the lowest N mineralization rates were found in red maple microsites [186]. The presence of an isolated tree in a herbaceous matrix deferentially affects the spatial distribution of the various nutrients (NH_4, NO_3, SOM and K) which coincided with the tree canopy, depending on their biogeochemical characteristics [120].

Furthermore, plants can capture nutrients from air flow, water flow and soil loss, and can influence the distribution of soil nutrition. Leaves and tree tillers can trap windblown particles with nutrients, and subsequently deposit them in the litter under the canopy, especially for N deposition [40,106]. Spruce-fir plots received the most atmospheric N deposition, and the N deposition rate can explain most of the variation of C and N in the organic horizon in these high-elevation soils [21]. In wetlands, sites were closest to the nutrient inflow areas and typically had the highest soil nutrient concentrations [116]. Regardless of their above- and below-ground biomass, legumes can also increase the distribution of N (TN and AN) in soils and change the spatial heterogeneity of soil nutrients by fixing nitrogen from soils [45, 178].

Soil nutrient distribution was influenced by the position of plants. SOM, TN, TP, AP, K, NH_4-N and soil microbial biomass under shrubs were higher than those in the inter-space between shrubs. Micro-environmental factors (slope, soil depth and microsite) significantly influenced the spatial distribution of soil nutrients and microbiological properties [123, 181, 187, 188]. Some publications indicated that SOC, N, P, and K contents decreased with increasing distance from the main stems of the shrub, and this "fertile island" effect was most pronounced in the surface soil in shrub-dominated communities, was also dependent on canopy size and spatial direction [165, 189]. However, there also reported that P was often greater in the interspace than under the plants, and that soil microbial biomass was always greater under the plant compared to the interspace [120, 188]. The potential variability of P found between rooting zones of different individual plants was greater than that likely to be encountered within the area exploited by any one individual root system in a grazed pasture [190]. Angst et al.(2016) also reported that the distance from the individual trees had no influence on the SOC contents and stocks or the chemical composition of the SOM fraction in the forest[191]. The different results may be mainly caused by spatial direction from focal plants, species structure and other unknown factors and process, and this should be studied in the future research work [184, 189].

5.9 Plant Influenced by the Heterogeneity of Soil Nutrients and SOM

Soil nutrient heterogeneity influenced the biomass in many kinds of ecosystems. In heterogeneous environments, plants produced more roots in the nutrient-rich patches and to accumulate more C, N, P and K in plant tissues, which was associated with higher yield of their above- and below- ground biomass [3, 124, 178, 185, 192-197]. Soil nutrients heterogeneity does not affect intraspecific competition in the absence of genotypic differences in plasticity [194, 195]. Single patch fertilization increased the above-ground biomass of individually grown plants compared with same amount of fertilizer (manure) distributed evenly throughout the soil. In contrast to individually grown plants, and soil nutrient distribution had no effect on final above-ground plant biomass for either species when grown with neighbors, even though roots were still concentrated in high nutrient patches [194]. In a temperate grassland, patch N treatments increased plant production but decreased biomass produced per gram nitrogen (a proxy of N use efficiency) compared with uniform N treatments [6]. However, there was a different result from an experiment with no herbivores present, where plant biomass was smaller in the heterogeneous nutrient treatment than in the homogeneous treatment in *P. lanceolata* (a less precise root foraging species), but not in L. *perenne* (a more precise root foraging species) [198]. Furthermore, additional nutrients can consistently reduce local diversity of grassland through light limitation, and herbivory rescued diversity at sites where it alleviated light limitation [199]. SRLagg (Community-aggregated specific root length) was negatively and significantly associated P and N availability rates in a high nutrient availability and heterogeneous distribution scenario [179]. In wetlands, more effective root foraging behaviour confers a higher competitive ability in heterogeneous environments, and a higher physiological (rather than morphological) plasticity was critical in obtaining a long-term competitive advantage [200]. Competitive interactions were size-symmetric in homogeneous soil and size-asymmetric in the heterogeneous treatments, but in the long term, competition became more size-symmetric in the heterogeneous soils, consistent with the increasing importance of physiological plasticity [200]. However, Blair (2001) reported that soil nutrient heterogeneity does not influence the size-symmetry of below-ground competition [20]. The different results should be validated by more publications in the future. N form was limited to change the plant production, plant responses to patchy N inputs occurred over a larger spatial area than soil microbe responses, consistent with optimal foraging by plant roots irrespective of N form [6].

Soil nutrient heterogeneity influenced the biodiversity in many kinds of ecosystems. Soil nutrient heterogeneity (N/P/K) influenced whether particular individuals were destined to be dominant or subordinate within the population, but had little effect on overall population structure [201]. In the forest, tree communities were ranked along a soil fertility gradient: communities dominated by heather species, mosses and lichens, represent poorer sites than the communities dominated by grasses and herbs [5]. Spatial distributions of 36–51% of tree species show a strong associations to soil nutrient distribution, and below-ground resource availability plays an important role in the assembly of tropical tree communities [202]. Mycorrhizal symbiosis has the potential to strongly influence plant population structure when soil nutrient distribution

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was heterogeneous because it promotes pre-emption of limiting resources [203]. In a burned area, surviving plants or new individuals would find the higher soil resources (AN and AP), and higher heterogeneity of nutrients at the small-scale may have a major impact on the performance of individual plants and on the forest structure and dynamics [50]. Furthermore, in the nutrient-enriched patches (N), the influence of N and P on the grass species and size combinations was amplified [197], and the role of soil nutrient heterogeneity as a modulator of ecosystem responses to the change in functional diversity reached beyond the species level [178]. In most of the above studies, the focus was mainly on the distribution of soil nutrients in wetlands and forests, while few reports disclosed that the spatiotemporal heterogeneity of soil nutrients influenced the biodiversity in agricultural fields. In agricultural ecosystems, isolation strips composed of grass and forest, small area of grassland and wetland were mainly distributed in the cropped fields. Soil nutrients was filtered and deposited in the strip, grassland and wetland and influenced the biomass and biodiversity when the flow of soil and water carrying nutrients from filed pass through it. This highly correlates to the development of agroecosystems, and may deeply influence the development of sustainable agriculture, especially for disease and pest control [204], which should be clarified in the future research work.

5.10 Heterogeneity and Change of Mapping Scale

Geology, soil parent material, and climate typically changed the spatial distribution of nutrients in a big area [33, 40, 44, 80, 108], while fertilization, tillage, plant growth, plant species were the main factors causing the spatial heterogeneity of nutrients in a relative small areas [5, 13, 80, 180, 205]. The influence from topography/terrain attributes was determined by the landscape scale, while soil texture was determined by soil parent material, land cover and land management in many scales [4, 5, 22, 205]. However, it was difficult to define the limits of scale, and the influence of structure factors and random factors were always intermixed [22, 44, 80]. Because the landscape scale can't be defined reasonably in most previous studies, or because the studies were only carried out in a single area, sub-area or sub-sub-area, it was very difficult to accurately reflect the real influence of scale change [22, 33, 75]. From a review of these publications, the regional scale (size difference of areas) could be considered as the standard for classification in plains, while in the hydrological catchments, sub-watershed, watershed, sub-basin and basin, could be used to classify the spatial. In most of the studies above, the focus was mainly on soil nutrient heterogeneity at the regional or median scale, and the heterogeneity at the micro-scale, e.g. single plant, rhizosphere environment, was scarce reported [67], especially for crop systems in the field, and which was very important to fertilization design in the field. Furthermore, soil nutrient analysis should be improved for the high precision detection of soil nutrients using micro-weight soil samples because many mineral elements could be measured with limited soil sample at the micro-scale.

Parent material, climate, landscape typically changed nutrients heterogeneity over a long time scale, while fertilization, tillage, residue return, and other human activities mainly dominated at short time scales [22, 44, 101, 154]. Spatial variation of SOC, N and P at different time periods were mainly determined by the length of time a factor had been acting on the soil; N and P, especially for AN and AP, were influenced by factors at different temporal scales [13, 105, 169]. Long-term cultivation with fertilization increased the N and P, and deceased the spatial dependence, while the effects of soil type and soil texture were weakened [49, 59, 154]. Long-term human activity has increased the mean soil P and variance of soil P, and shifted the scale of variance to larger spatial extents [52]. Long-term vegetation restoration results in a more homogeneous distribution of SOC, and TN in sand dunes [131]. Over a short time scale, the spatial heterogeneity of NO_3-N, NH_4-N and AN was changed during plant growth stages, and differed between farmland and wetland [13, 117, 169, 171]. However, most studies of soil nutrient distribution over the short time scale were mainly focused on the available nutrients in wetlands [64, 84, 109, 149, 171, 183, 206], while few studies focused on cropped fields[13, 58], especially the spatiotemporal heterogeneity of available nutrients in the rhizosphere of crops ecosystem.

6. Conclusions and Research Needs

The heterogeneity of soil nutrients highly relate to plant growth and plant diversity, and directly influence the development of environmental quality. Improving the precision of predictive models, accurately clarifying the driving mechanisms, and quantitatively evaluating the influence of these factors are important and are long-term research work. Despite the fact that these issues were focused on by many previous research works, there are still some aspects of study which need to be improved according the summary above: (1) simplify the methods of spatial interpolation and validation, and increase the accuracy of prediction; (2) clarify the heterogeneity and the main driving mechanism of soil nutrients in deep soil layers (3) focus on both anisotropy and isotropy in complicated landscapes; (4) clarify the heterogeneity and the main driving mechanisms at the microscale, e.g. single plant, rhizosphere environment; (5) clarify the heterogeneity and the main driving mechanisms at consecutive spatial scales; (6) develop long-term monitoring of the heterogeneity of soil nutrients at the regional scale with various kind of landscapes and land uses; (7) quantitatively estimate the influence of driving factors on nutrient distribution; (8) clarify how nutrient heterogeneity and dynamics influence biodiversity in agricultural fields, and influence on climate change; (9) improve equipment and techniques to increase the precision of soil nutrient detection using micro-weight soil samples.

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