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Precipitation Controls Topsoil Nutrient Buildup in Arid and Semiarid Ecosystems

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Abstract: Soil nutrient buildup is a key process in nutrient-poor arid and semiarid regions. However, our knowledge of the factors that control soil nutrient buildup in these systems is still limited. An experiment was set up and carried out for five and a half years in order to investigate how precipitation and other site factors control soil nutrient buildup. Topsoil carbon (C), nitrogen (N), phosphorus (P), and potassium (K) derived from litter (soil nutrient buildup) were tracked twice a year at two sites differing in terms of climate and soils (Urat: arid and Naiman: semiarid, both in Inner Mongolia). Precipitation was manipulated at both sites to include seven precipitation levels: three reduced levels (−20, −40, and −60% with respect to the background), background (control), and three enhanced levels (+20, +40, and +60% with respect to the background). The dynamic buildup (i.e., amount of nutrients released among consecutive samplings) for all nutrients was controlled by precipitation (nonlinearly), site effects (lower buildup at the site dominated by aeolian pedogenesis), and seasonality (higher under warm conditions). However, the considered nutrients differed in the factor that most determined their buildup. Through studying the concurrent dynamics of litter decomposition and soil nutrient buildup, we can foresee that changes in precipitation and land degradation are most likely to affect the soil nutrient pools in these ecosystems.

Keywords: arid regions; semiarid regions; soil nutrients accrual; litter mass loss; soil nutrients availability; precipitation thresholds

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1. Introduction

Soils in arid and semiarid regions are among those with the lowest contents of organic carbon (SOC) and macronutrients (nitrogen, phosphorus, and potassium) [1–3]. In the case of SOC, its controlled buildup across arid gradients has been explained mainly in terms of the low plant litter inputs in these systems [4–6]. In this way, changes in water availability across aridity gradients (i.e., gradients in moisture availability and moisture deficit) affect soil C buildup mainly through their effects on plant productivity/vegetation composition, this being the main mechanism through which changes in precipitation as a result of climate change might affect soil C accrual in the long term [7]. In relatively shorter terms (without large changes in vegetation), however, the key factor that controls the accrual of C and other macronutrients in soils in response to variations in precipitation regimes is how precipitation affects the balance between soil input (from litter decomposition) and soil losses (leaching) through plant litter/microbial decomposition/plant uptake feedback.

The accumulation of other nutrients in soil (e.g., nitrogen (N) or phosphorus (P)) has attracted much less attention than that of SOC, yet similar mechanisms for their buildup have been proposed (i.e., limitation due to low input of plant material associated with low plant abundance), together with nutrient-specific mechanisms such as accumulation through the biological fixation of N [8]. For instance, in the arid and semiarid grasslands of Central and Western Asia, the authors of [9] observed that the main factor explaining the variation in soil N pools was the mean annual precipitation, probably through its effects on vegetation composition and plant biomass; however, the authors of [9] also observed that, on the eastern side of the grasslands they studied, the main factor affecting total soil N was not precipitation but, instead, solar radiation, having negative effects on the soil N pools. In general, several studies have focused on the variation in soil nutrient pools (mainly C and N) across aridity gradients and have concluded that their reductions with increasing aridity are mainly controlled by changes in vegetation and reductions in primary productivity [10,11]. On the other hand, the role of the decomposition of plant material (litter) and its subsequent incorporation into soil, as well as how such soil accumulation is controlled by water availability in arid and semiarid areas, remains poorly known. Understanding such controls in soil nutrient accumulation is particularly relevant in view of the changes in precipitation patterns and the predicted higher variability in precipitation in many areas of the world [12–14].

The accrual of nutrients in soil is affected by both biotic and abiotic factors, which co-interact to determine the levels of soil nutrient contents [15]. For instance, large-scale climatic patterns that determine the degree of soil development can interact with more local parent material to determine the kind and levels of mineral nutrient contents in the soil, as well as the mechanisms through which they are retained in soil [16]. Whereas it is now well known that water availability is a major controller of litter decomposition in arid and semiarid ecosystems, through its effects on soil microbial activity and nutrient leaching from litter [17–21], how water availability controls nutrient accumulation has been relatively unexplored. Although higher precipitation can lead to the higher incorporation of nutrients in the soil as a result of their higher release through decomposition [21] and subsequent absorption in the soil matrix, it may also lead to their translocation to deeper soil layers or to losses through leaching [22–24]. Thus, the final effect of variation in precipitation on soil nutrient accrual depends on the balance between these two mechanisms, with potential differences for particular macronutrients.

In this manuscript, the changes in topsoil nutrient accrual derived from litter decomposition in a nearly six-year-long experiment involving the manipulation of rainfall levels are reported. The effects of such rainfall manipulation at two sites with different climates and soil properties were also compared, serving as a proxy for soil-type effects. Our research questions were as follows: (1) Is precipitation is a limiting factor controlling the rate of litter-derived soil nutrient buildup in semiarid ecosystems (i.e., precipitation control of soil nutrients)? (2) Does nutrient buildup vary depending on the soil type and other site-specific factors? (3) Do the responses of soil nutrients to precipitation and site effects depend on the soil nutrient in question? The objective of this research was to use a manipulative field experiment conducted at two locations in Inner Mongolia, northern China, which differ in terms of climate and soils, in order to answer these questions.

2. Materials and Methods

2.1. Site Description

Our study sites were located in Inner Mongolia, northern People's Republic of China. We carried out our study at the research stations of Naiman and Urat, both affiliated to the Chinese Academy of Sciences. The Naiman Desertification Research Station is located in a temperate, semiarid continental climate on Horqin Sandy Land (42°55′ N, 120°42′ E), with an average annual precipitation of 360 mm, mean annual temperature of 6.4 °C, and annual pan evaporation of 1935 mm [25]. The Urat Desert Steppe Research Station (41°25′ N, 106°58′ E) has a temperate continental monsoon arid climate, with an average annual precipitation of 180 mm and average annual temperature of 5.3 °C. Both sites present typically fragile ecosystems, with plant communities dominated by *Agriophyllum squarrosum*, *Salix gordejevii*, *Caragana microphylla*, and *Artemisia halodendron* in Naiman [26]. Meanwhile, Urat is dominated by desert steppe plant communities, with *Stipa klemenzii*, *Peganum harmala*, *Achnatherum splendens*, and *Caragana microphylla* as the dominant species [27].

2.2. Experimental Design

We followed the soil nutrient buildup dynamics by measuring the soil nutrient concentrations in a long-term litter decomposition experiment [21]. Briefly, the experiment involved manipulating the precipitation amount with a platform that could either increase (rainfall redistribution) or reduce (rainfall exclusion) precipitation on selected areas of 6 × 6 m experimental plots. Seven levels were included in the precipitation treatment in order to determine whether precipitation limited litter-derived soil nutrient buildup: a level representing background normal precipitation (control), three levels where precipitation was enhanced (by +20%, +40%, and +60% with respect to the control), and three levels where precipitation was decreased (by −20%, −40%, and −60% with respect to the control). A randomized complete block design consisting of 6 blocks was used where, in each block, the aforementioned 7 precipitation levels were applied on 6 × 6 m experimental plots (Figure A1). This design was set up at both study sites, such that there were 7 precipitation levels × 6 repetitions × 2 sites = 84 plots in total, with 42 plots at each study site. We used a single-cohort litter bag experiment to follow the dynamics of *C. microphylla* leaf litter (20 g per litter bag), which was placed on the surface of each plot starting in May 2015. The litter bag experiment had a time span of around 2000 days (with two litter bag retrievals per year). Soil samples were collected from a layer of topsoil (0–5 cm) close to the litter bag. A pooled sample was derived from three random cores at a depth of 0–5 cm under each litter bag using a 3 cm diameter soil auger. Soil samples were sieved through a 2 mm mesh to remove rocks and plant materials. As for the litter bag retrievals, soil samples were taken twice a year in May and November, for a total of 11 sampling times plus base time values (84 plots × 12 samplings = 1008 pooled samples). The soil surface temperature at each site was automatically recorded using a HOBO temperature data logger (Onset Company, Bourne, MA, USA) with a recording interval of 10 min. Air temperature and precipitation data were obtained from standard weather stations at both experimental sites. The rainfall data for each plot were corrected according to the precipitation treatment (enhanced or reduced).

2.3. Laboratory Analysis

The total carbon (C) and total nitrogen (N) contents of the soil were measured using an elemental analyzer (vario MACRO cube; Elementar, Langenselbol, Germany). The soil phosphorus (P) and potassium (K) contents were determined with an inductively coupled plasma emission spectrometer after the digestion of the samples in concentrated nitric acid [28].

2.4. Statistical Analysis

We used a simple mass balance to determine the possible amount of nutrients derived from litter that could have been incorporated into the soils over the duration of our experiment. For this, we first calculated the difference in the nutrient mass in the litter (litter Δi) lost at each consecutive sampling date (litter Δi = nutrient masst + 1 − nutrient masst) for each site, precipitation treatment, and sampling date, for each nutrient. The mass of each nutrient in the litter was defined as the nutrient content (%) on a date multiplied by the litter mass remaining on that date. Second, the dynamic soil nutrient buildup (soil Δi) was calculated for each nutrient by subtracting the soil nutrient content (g kg^{-1} of dry soil) on each consecutive sampling date (soil Δi = soil nutrient masst + 1 − soil nutrient masst). The dynamic soil nutrient buildup represents the amount of soil nutrient accumulation. The integration of the soil Δi and litter Δi values over the duration of the experiment corresponded to the total amount of each nutrient's buildup in the soil (i.e., either soil or litter ΣΔi), such that a mass balance between litter-derived nutrient input and soil final total accumulation could be determined. We analyzed the effects of precipitation manipulation and the differences between our two experimental sites on the dynamics of soil nutrient content (soil Δi) using mixed linear models (similar to a single-variable repeated measures ANOVA) [29]. Site, precipitation treatment, time (days since the beginning of the experiment), and average soil monthly temperature (5 months before sampling + sampling month) were considered as fixed effects (with days since the beginning of the experiment and average soil monthly temperature as covariates). The plot at each sampling time was considered a random effect. The total soil nutrient buildup (soil ΣΔi) was also analyzed using mixed linear models, with site and precipitation treatment as fixed effects (as a single-variable two-way ANOVA) and plot (block) as the random effect. All data analyses were carried out with R [30], using transformed data when appropriate, and plots were created using Veuzs for Linux [31]. If interactions among fixed effects were significant, we did not perform post hoc comparison tests of such effects (which was always the case for all analyses).

3. Results

3.1. Dynamic Soil Nutrient Buildup and Mass Balance

There was a steady buildup in soil nutrients over the duration of our study (i.e., an increase in soil nutrient content, in g nutrient per kg dry soil, with respect to the base values at the beginning of the experiment; Figure A2), from May 2015 to November 2020. The increases in soil C and N were nearly twofold with respect to the base values, whereas for P and K, the increases at the end of the experiment were more moderate (Figure A2). Despite being more arid, Urat had higher base and final contents of C and N in comparison to Naiman; however, the latter had higher base and final contents of P and K (Figure A2). The soil type at Urat is gray desert soil with a high silt proportion, while Naiman has mostly been degraded to sandy soil with a high sand content, wind erosion, and an unequal distribution of vegetation coverage, resulting in a relatively high proportion of rock fragments. The difference in the final C, N, P, and K contents could be partly explained by the influence of soil texture and the proportion of rock fragments. Thus, the final contents of C and N at Urat were higher, as it had a higher silt proportion. Due to the influence of the organic matter content, plant decomposition in more barren aeolian sand soil can significantly improve the availability of soil P.

The dynamics of Δi (on a per mass basis) for the nutrients released from the litter and accumulated in the soils are shown in Figures 1–4. In general, the mass of the nutrients released by the litter was always higher than the contents in the soils for all nutrients, except for K. The litter ΔC (C released from litter) always exceeded the soil ΔC by 1.5 to 5 times (Figure 1). The relationship for N was tighter, with litter ΔN values being 0.7 to 1.3 times those observed for soil ΔN (Figure 2). The litter ΔP was 0.8 to 2 times those values observed for the soil ΔP (Figure 3). As mentioned before, the K dynamics showed a very different behavior from that of the other nutrients, with K released via litter decomposition (litter ΔK) being 60 to 120 times lower than the soil ΔK (Figure 4).

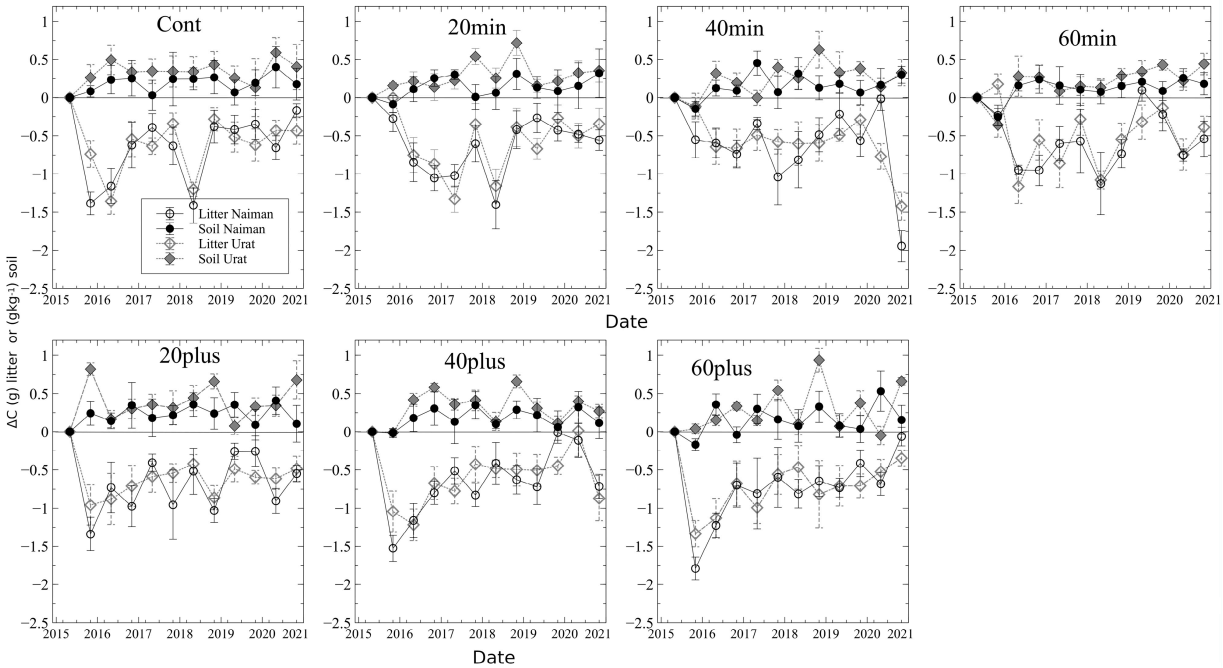

Figure 1. Litter (ΔC litter) and dynamic soil C buildup (ΔC soil) along a five and a half year decomposition experiment that manipulated precipitation inputs at two sites (arid Urat and semiarid Naiman) in Inner Mongolia, China. The dynamic soil C buildup was calculated by subtracting the soil C content (gC $^{-1}$ of dry soil) on each consecutive sampling date (soil ΔC = soil C masst + 1 − soil C masst). Litter C release was calculated similarly, taking into account litter C content and litter mass. Precipitation treatments included precipitation background (cont); precipitation decreases by 20, 40, and 60%; and precipitation surpluses of 20, 40, and 60%.

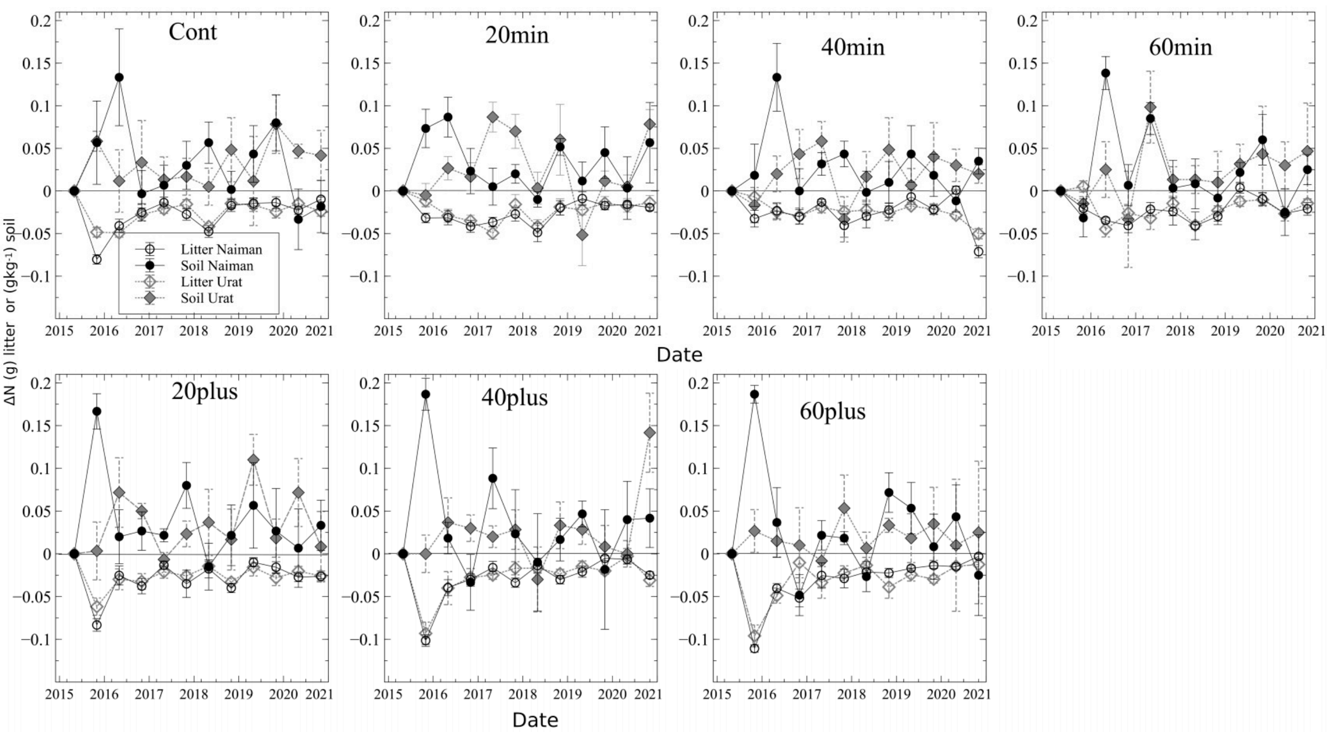

Figure 2. Litter (ΔN litter) and dynamic soil N buildup (ΔN soil) over a five and a half year decomposition experiment that manipulated precipitation inputs at two sites (arid Urat and semiarid Naiman) in Inner Mongolia, China. Explanations of calculations and precipitation treatment labels are provided in Figure 1 caption.

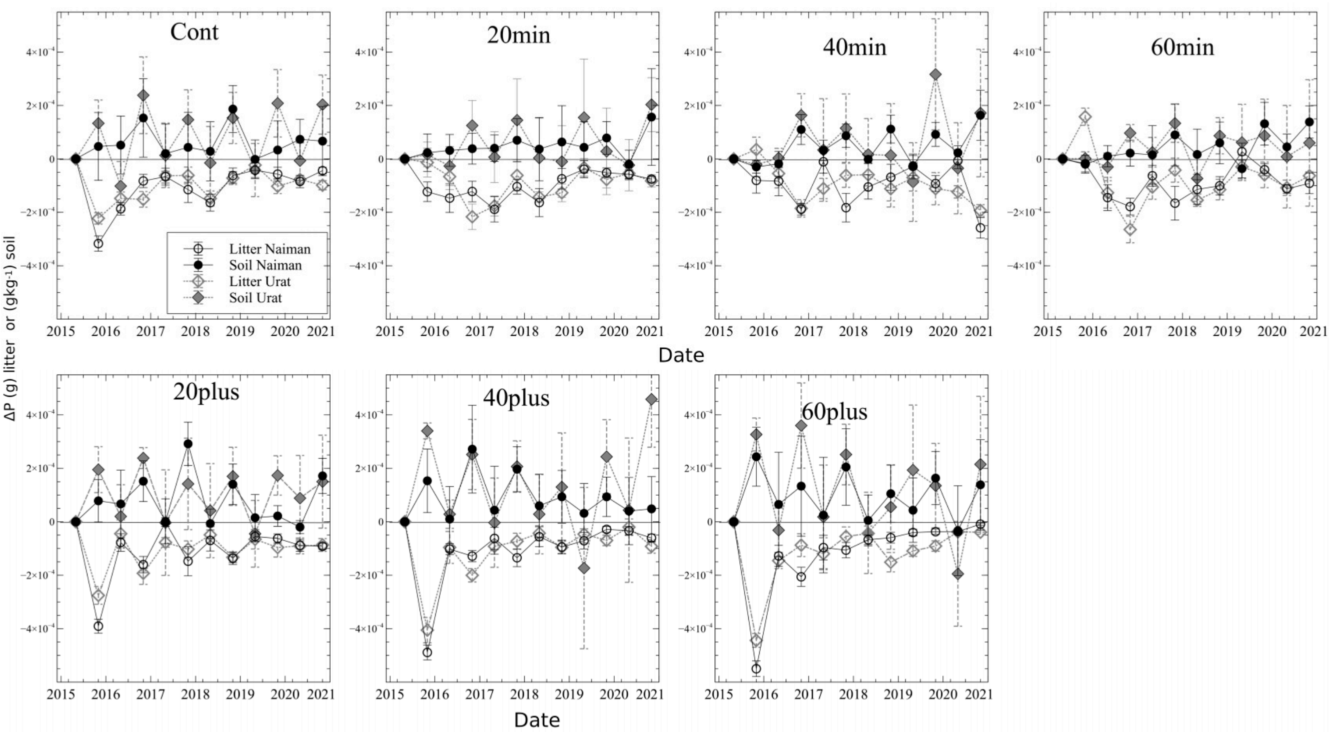

Figure 3. Litter (ΔP litter) and dynamic soil P buildup (ΔP soil) over a five and a half year decomposition experiment that manipulated precipitation inputs at two sites (arid Urat and semiarid Naiman) in Inner Mongolia, China. Explanations of calculations and precipitation treatment labels are provided in Figure 1 caption.

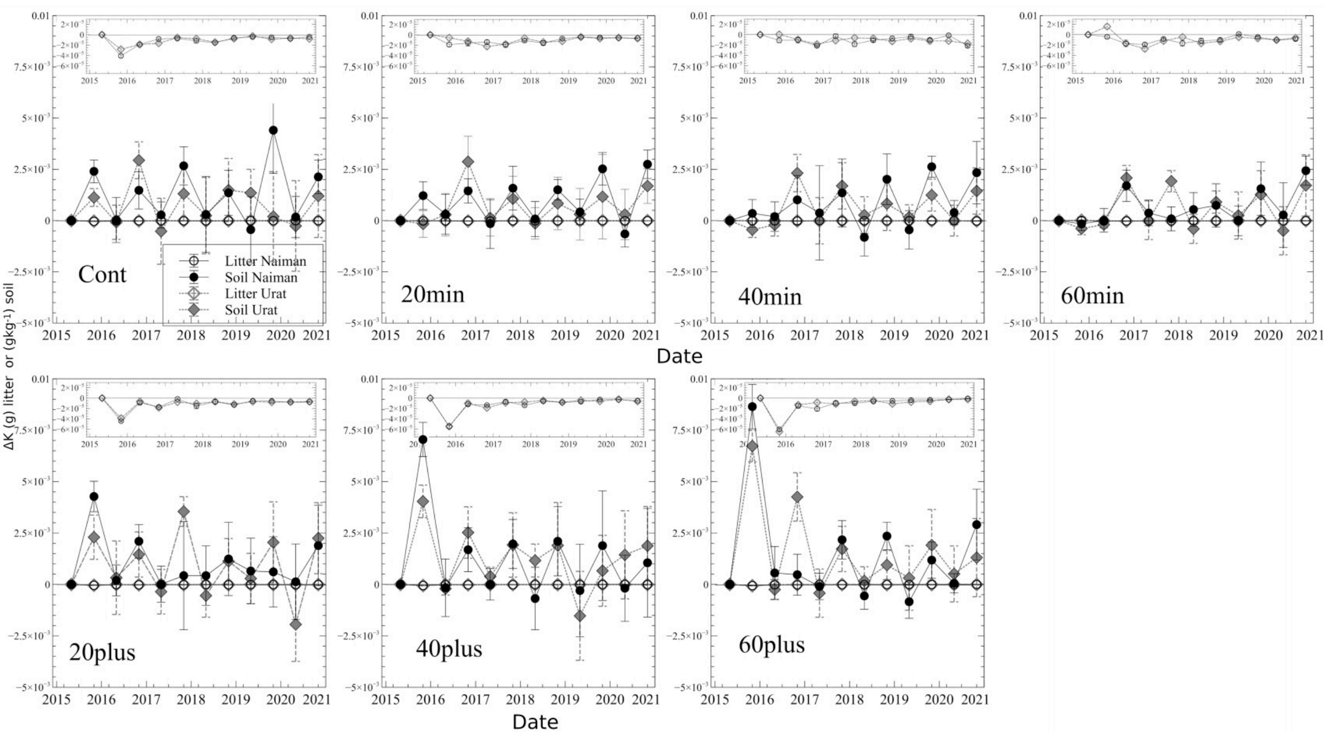

Figure 4. Litter (ΔK litter) and dynamic soil K buildup (ΔK soil) over a five and a half year decomposition experiment that manipulated precipitation inputs at two sites (arid Urat and semiarid Naiman) in Inner Mongolia, China. Explanations of calculations and precipitation treatment labels are provided in Figure 1 caption. Note the difference in the orders of magnitude of the K mass values between the main and insert panels.

3.2. Controls of Dynamic Soil Nutrient Buildup and Total Soil Nutrient Buildup

Controls (i.e., factors we either manipulated or measured) of the dynamic nutrient buildup (Δi) varied depending on the nutrient in question (Table 1). In general, time did not have a significant effect on any nutrient, indicating that the average amount of nutrients incorporated into the soil did not show a strong diminishing trend (Figures 1–4). Yet, there were quite a few significant interactions involving time (see below). Most of the variation in dynamic C buildup was accounted for by between-site differences, with a higher mean dynamic buildup in Urat. *Precipitation* also had a significant effect on the dynamic C buildup (with particularly slower accumulation under the −60% treatment). The interaction of *precipitation* × *time* indicated the fact that the level of dynamic C buildup per treatment varied widely among the sampling dates. Sites differed only marginally for dynamic N buildup, with Naiman having a higher overall dynamic buildup. However, most of the variation was in the interaction of *site* × *time* as, for Naiman, the highest dynamic N buildup occurred early in this study, particularly in *the precipitation* surplus treatments. This coincided with the high N released from the litter (Figure 2). For dynamic P buildup, the sites differed marginally (Urat showed a higher overall dynamic buildup), and the effect of *precipitation* was significant (+40% higher and −60% lower). However, the significant *precipitation* × *time* interaction revealed a wide variation in dynamic P buildup among *the precipitation* treatments over the duration of this study. Most of the variation in dynamic P buildup was accounted for by soil temperature (it increased with temperature). High P contents in the soil occurred early in the litter decomposition stage (Figure 3), coinciding with high P releases from the litter. Finally, for dynamic K buildup, sites also differed marginally, with Naiman having higher overall values. The significant *precipitation* × *time* interaction indicated that the buildup varied widely among treatments over the duration of this experiment. As with P, most variation in the dynamic K buildup was related to soil temperature (it increased with soil temperature).

Table 1. Single-variable ANOVA results (main effects, covariates, and interactions) of mixed models for dynamic soil nutrient build-up (soil Δi). Symbols correspond to probabilities under the null hypothesis being true.

Factor	**Site (*S*)**	**Precipitation (*P*)**	**Time (*t*) (cov)**	**Soil Temp (cov)**	***S* × *P***	***S* × *t***	***P* × *t***	***S* × *P* × *t***
F values	$F_{1,886}$	$F_{6,886}$	$F_{1,9}$	$F_{1,886}$	$F_{6,886}$	$F_{1,886}$	$F_{6,886}$	$F_{6,886}$
Variable								
Soil ΔC	92.1 ****	7.8 ****	2.4	0.5	0.7	0.7	4.3 ***	0.8
Soil ΔN	3.1 *	1.5	0.9	<0.1	0.2	56.5 ****	0.8	0.9
Soil ΔP	4.1 **	6.2 ****	0.1	77.3 ****	0.4	0.1	4.0 ***	0.8
Soil ΔK	2.7 *	5.5 ****	2.6	103.2 ****	0.4	<0.1	12.3 ****	1.0

* <0.1; ** <0.05; *** <0.001; **** <0.0001.

Regarding total soil nutrient buildup ($\Sigma\Delta i$), the interaction of s*ite* × *precipitation* was significant for all nutrients (Table 2); however, the underlying phenomena slightly differed depending on the nutrient in question. In the case of ΣΔC, the interaction revealed that total C buildup was higher in Urat under all *precipitation* treatments, but the site-specific differences were slightly lower under the −40% treatment (Figure 5). The total C buildup was not linear along the *precipitation* treatment gradient: the highest buildup occurred under the +20% treatment while the lowest one was observed under the −60% treatment with respect to the control (Figure 5). For the total N buildup, the *site* × *precipitation* interaction indicated that the higher buildup in Naiman was particularly marked at the top of the high precipitation gradient (−40% and −60%) but not under the other *precipitation* treatments (Figure 5). The *precipitation's* effect was more erratic than that of total C buildup but, as with C, the highest total N buildup occurred at +20% (Figure 5). For the total P buildup, between-site differences (higher in Urat) were more marked at the high end of the gradient as well (significant *site* × *precipitation* interaction; Figure 5). For Naiman, there was a linear increase in the total P buildup along the *precipitation* gradient; however, for Urat, the maximum occurred at +40%, while the minimum occurred at −60% (Figure 5). Finally, for total K buildup, the significant *site* × *precipitation* interaction indicated that the between-site differences (higher buildup in Naiman) were more marked toward the low end of the *precipitation* gradient (Figure 5). There was a linear increase in the total K buildup along the *precipitation* gradient (in Naiman, the amount in the control was higher than in the +20% and +40% treatments; Figure 5).

Table 2. Single-variable ANOVA results (main effects and interactions) of mixed models for total soil nutrient build-up (soil $\Sigma\Delta i$). Symbols correspond to probabilities under the null hypothesis being true.

Factor	**Site (S)**	**Precipitation (Pr)**	**S × Pr**
F values	$F_{1,70}$	$F_{6,70}$	$F_{6,70}$
Variable			
Soil ΣΔC	1956 ****	166 ****	14 ****
Soil ΣΔN	65 ****	31 ****	5 ****
Soil ΣΔP	74 ****	112 ****	7 ****
Soil ΣΔK	59 ****	120 ****	10 ****

**** <0.0001.

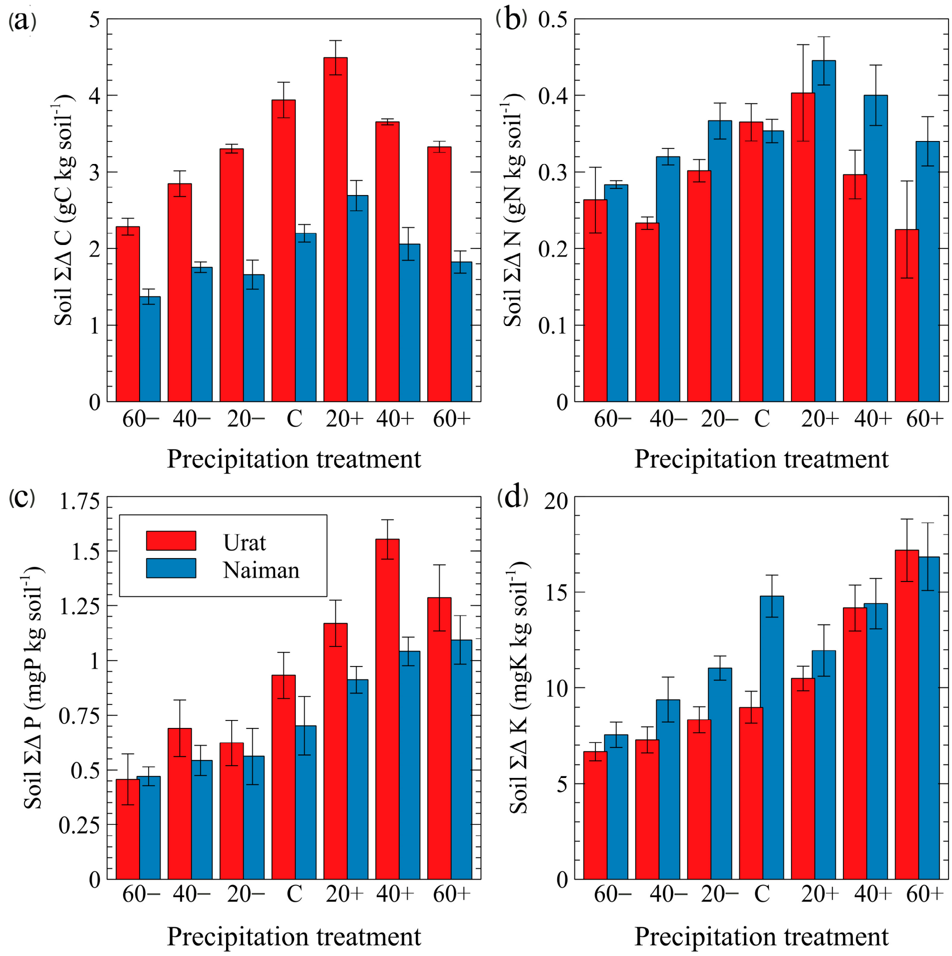

Figure 5. Total soil C (**a**), N (**b**), P (**c**) and K (**d**) buildup (soil ΣΔi) at the end of a five and a half year decomposition experiment that manipulated precipitation inputs at two sites (arid Urat and semi-arid Naiman) in Inner Mongolia, China. ΣΔi calculated as the overall sum of Δi. Precipitation treatment labels are the same as in Figure 1. Note the difference in units for the different nutrients.

4. Discussion

We used a manipulative experiment to determine the effects of precipitation changes on the accumulation dynamics of several soil nutrients in the topsoil between an arid site and a semiarid site. We did so with the purpose of elucidating the limiting effects of precipitation on soil nutrient buildup, whether such effects differed across a gradient of aridity and site-specific conditions, and the differences among the different soil macronutrients. We summarize our main findings in the three subsections below, followed by the implications of our study.

4.1. Controls of the Dynamic Buildup of Soil Nutrients: Three Kinds of Soil Nutrients

With respect to the research questions, precipitation was indeed found to be a factor controlling the rate of litter-derived nutrient buildup in the soil; however, the response depended on the type of nutrient. Our mixed models (which included precipitation, soil temperature, and site as proxies for the inherent soil properties) allowed us to establish differences in the types of nutrients with respect to the main controls of their dynamic litter-derived buildup in soil. In this way, we classified the nutrients into three main groups with respect to their main controlling factors.

First, dynamic derived-litter soil C buildup was controlled mainly by differences in soil properties (as most variation was associated with the site effect) and secondarily by the variation in precipitation (Table 1). The driest site, Urat, had the largest soil C baseline and dynamic buildup derived from litter (Figures 1 and A2). This is because the soil type in Naiman is classified as sandy soil [32] (equivalent to aeolian sandy soils, according to the Chinese Genetic Classification [33]) while that in Urat is classified as gray desert soil [34]. A key difference between these soils is the poorer soil development and higher proportion of sand in the Naiman aeolian soils and the higher clay/silt proportion in the type of soils in Urat. Thus, it seems that the higher dynamic C buildup in Urat was mainly controlled by the differences in soil texture and soil development. Lu compared a number of different soils in arid and semiarid areas in Inner Mongolia and found that, on average, the top soils of the gray desert soils had higher C and N contents than those of the aeolian soils, and such differences could be partially explained by soil texture (i.e., a positive effect of the soil clay/silt fraction on soil C and N) [34]. Yet, these two soil types were still on the poor nutrient side of the gradient among the different soils studied by Lu [34]. This points to the fact that, even when considering the poor C levels in our study areas, soil colloids or other soil mineral-fraction-related mechanisms influence the absorption of C and N litter-derived compounds, something that has been long discussed for more mesic areas [35]. Similarly, in a study of C and N mineralization in three soils in the Black Land Prairie region of Texas, soil type was the primary factor controlling the relative contribution of litter C to soil C mineralization [36], which is similar to the results obtained for the arid and semiarid areas considered in this study. On the other hand, the negative effect of precipitation on the dynamic soil C buildup was mainly apparent in the driest precipitation treatment of −60% (Figure 1), which coincided with the reduction in the C-derived litter observed in our long-term experiment [21]. This points to a potential negative effect of the reduction in litter-derived C in response to extreme drought events in arid and semiarid areas on soil C accrual [37].

Nitrogen was the second kind of nutrient that we studied in terms of the controls of its dynamic soil buildup. As with C, Urat had a higher baseline N content than Naiman (Figure A2), which we interpreted as being the result of pedogenic processes that have culminated in soil textural differences between the sites (as discussed above). On the other hand, the strong site × time interaction observed for the dynamic N buildup was the result of the differences between Naiman and Urat in early vs. late soil N accumulation (Figure 2). In this way, the highest dynamic N buildup occurred in Naiman during the early stages of litter decomposition, especially under the precipitation surplus treatments (although the three-way interaction was not significant; Table 1). This observation for N might be due to the higher precipitation levels that occur in Naiman and the subsequent higher leaching of soluble N from litter at early stages (Figure 2).

Finally, the last group of soil nutrients, in terms of what controls their dynamic buildup, included P and K. For these nutrients, soil temperature was the main controlling factor; however, they were also responsive to site differences and precipitation treatments (Table 1). Both the baseline K and P contents were much higher in Naiman than in Urat, and such differences point to site-specific pedogenic processes as the main cause of the differences in their baseline values (e.g., a main difference in parent materials or depositional loads between the sites). However, the dynamic P buildup was higher in Urat (suggesting a similar textural explanation as for C and N; see above) but higher in Naiman for K. Nonetheless, the dynamic buildups of P and K in the soil were mainly controlled by soil temperature (Table 1), as their rates increased as the soil temperature increased. In fact, the dynamic K and P buildups, unlike those of C and N, presented very striking seasonal oscillations, with peaks of accumulation in the sampling dates after summer and minimum to null accumulation rates in the sampling dates shortly after winter (Figures 3 and 4). In the same experiment, Qu observed that temperature had a significant effect on the mass loss of P and K from litter, suggesting that their buildups in soil (as observed here) are mediated by microbial activity [21]. However, whereas temperature also affected the N mass loss from litter [21], it did not affect its dynamic buildup in the soil. This suggests the microbes controlled the K, P, and N input from litter (see below, as K presented particular trends), but microbes only controlled the dynamic buildups of P and K.

4.2. Total Soil Nutrient Buildup: Interactive Effects of Precipitation with Site

Regarding the research question focused on the effects of precipitation and site on litter-derived soil nutrient buildup, our experiment made it clear that precipitation strongly controlled total buildup; however, this control was site-dependent, as suggested by the significant site × precipitation interactions for all nutrients (Table 2). Furthermore, the nature of this interaction varied depending on the nutrient (Figure 5). In the case of C and P, Urat had clearly higher total buildups than Naiman, but the interaction demonstrated that the total nutrient buildup was nonlinear with respect to the differences in the amount of precipitation between the two sites. Thus, the highest buildup was observed under the +20% treatment for C in both Urat and Naiman and with the +40% treatment for P in Urat; meanwhile, for the +40% and +60% treatments for P in Naiman, the total buildup decreased or did not change. Zhao observed seasonal variations in the soil P fractions at an aeolian semiarid site in Inner Mongolia, including total soil P [38]. They reported that such variation (mainly that of the fraction associated with soil microbial biomass) was positively associated with soil moisture availability. This partially agrees with our results, and, thus, it is likely that soil microbial activity is an important determinant of total soil P buildup (although the microbial fraction of P is itself relatively small). Yet, under higher soil moisture availability, the litter-derived C and P did not change (Naiman) or even decreased (Urat). Regarding site differences in total C and P buildup, it has been shown that differences in parent materials can affect the capacity of soils to accumulate soil nutrients [39]. Wu also observed that soils rich in the sand fraction had lower C pools than other soils with a higher fraction of colloids in southern China [40]. Thus, the lower capacity in Naiman for accumulating litter-derived C and P might be related to the aeolian nature of its parent materials. Note, however, that the baseline P level was higher in Naiman, suggesting some aeolian accumulation [41]. Unlike C and P, no site had higher total N and K buildups under all precipitation treatments. Thus, the site × precipitation interactions for N and K indicated that the precipitation effects were asymmetric depending on the site (i.e., under some, but not all treatments, total buildup was higher at one site). Along this line, precipitation increased the total N buildup in Naiman only at the high end of the precipitation treatment gradient, whereas in Urat, the same treatments decreased the total N buildup (Figure 5). On the other hand, precipitation increased the total K buildup steadily in Urat but not in Naiman, where there was a lower total buildup under the reduced precipitation treatments, and the high precipitation treatments did not differ from the control (Figure 5). Interestingly, these observations of total buildup in relation to precipitation only relate partially to the total amount of nutrient input derived from the litter [21]. As such, for all nutrients, the highest mass input from the litter was always observed under the +60% precipitation treatment. This suggests that under the highest precipitation treatment, nutrients were lost from the litter–soil system through leaching. Thus, precipitation is an important control of total litter-derived nutrients. In the cases of C and P, aridity did not necessarily equate to lower total buildup, as there was a nonlinear response between maximum total nutrient buildup and precipitation. In the cases of N and K, the effect of precipitation could not be isolated from site effects.

4.3. All Nutrients in Mass Balance, but K Is a Conundrum

Although we ignored several potential nutrient input sources (e.g., weathering for P or biological fixation and deposition for N), our approach revealed that most of the nutrients we studied were close to mass balance with those coming from litter decomposition (Figures 1–4). C, N, and P were in a state of balance, and the decomposition amount of the litter was basically similar to the increase in the respective nutrient levels in the soil. However, it was also observed from the experiment that the increase in K in the soil far exceeded K losses from the decomposition of litter itself. The reasons for this phenomenon need to be further analyzed. In our experiment, the potassium loss rate of the litter was fastest in the early stages of decomposition, while the loss rate was basically stable and slow in the later stages. This pattern of K loss has been explained in terms of the solubility of K [42]. In Attiwill's (1968) experiments, the K content in dead leaves reached 60% in the first three months of decomposition, 60–80% was leached from decomposed leaves within 6 months, and 10% of the original K content still retained after two years [43]. The observed K losses in our experimental litter were similar to those previously observed [21], but the buildup of K in the soil was different. The mass of K calculated from the dynamic buildup rate was higher than the decomposition loss (exceeding the K released by litter decomposition by 60 to 120 times). Using long-term data from the Hubbard Brook experiment, Schlesinger (2021) stated that the main external source of K is from weathering [44]. There are reports that point toward the capacity of plants to mobilize K from the soil matrix through rhizospheric secretions in order to be able to absorb it, thus causing the content of K in the rhizosphere to increase [45,46]. In our case, given such a high increase in the total K pool in the soil, it is unlikely that the external K was derived from parent material weathering or plant-driven mobilization; thus, the main source was likely atmospheric through deposition (in the Hubbard Brook experiment, there was a significant amount of atmospheric deposition of K in the system [47]). This atmospheric source has explained the differences in K budgets in other semiarid environments [48]. Interestingly, although the dynamic rate of buildup of K had a strong seasonal pattern with marked peaks in summer (autumn sampling), it was higher in Naiman, and it was mainly controlled by soil temperature. All of this suggests that microbe-driven and soil-type effects also participated in the buildup of externally derived K.

4.4. Implications

Our research focused on the dynamic and total buildups of litter-derived nutrients in the top soils in arid and semiarid areas over a period of five and a half years in order to determine how precipitation and site effects control these processes. Such buildup is of paramount importance in nutrient-poor soils in arid and semiarid areas, as it determines key soil properties and is an important source of plant and microbial nutrition [26]. Our results are likely not representative of the nutrients stabilized through the long-term storage mechanisms in the soil (i.e., aggregate protection) but instead represent the transient dynamics associated with litter-derived nutrients (at least for C, N, and P). Our baseline values for total C, N, P, and K in Naiman were similar to those of nondegraded areas observed in other studies [49–51]. Cao et al. (2008) observed similar increases (threefold) in the total C and N after 20 years of restoration with shrubs in an area poor in soil nutrients close to the Naiman site, although our absolute values were higher [52]. This suggests that our observations are not the result of spurious measurements but are within the ranges of landscape variability in soil nutrients observed in these systems [34]. Overall, the changes in precipitation patterns in these arid and semiarid areas have the potential to greatly affect the nutrient cycles we focused on through their effects on both litter decomposition and litter-derived buildup in soil. Yet, for C and P, higher precipitation was not conductive to higher buildup (nonlinear effect). For N, high buildup was maintained across a range of precipitation treatments (from −20% to +20%), then reduced at both sites. Finally, for K, buildup was strongly controlled by non-litter-derived sources, and it was lower at the dry end of the precipitation treatments in Naiman, whereas it increased steadily for Urat across the precipitation gradient. Overall, this indicates that reductions in precipitation might decrease soil nutrients; however, the effects vary depending on the nutrient and the particular soil type/parent material in question. Apart from the changes in nutrient levels brought about by changes in precipitation, land degradation (e.g., wind erosion) also has the potential to reduce the capacity of arid and semiarid systems to store nutrients in the soil through their deleterious effects on the proportion of some of the fractions of fine particles [50], although this latter mechanism needs to be studied in more detail.

5. Conclusions

Our research showed that in the arid and semiarid areas studied, precipitation limited the soil nutrient buildup of C, N, P, and K, although the observed effects were dependent on site characteristics and the nutrient. (1) The buildups of C and N were positively controlled by the precipitation amount and seemingly negatively controlled by textural differences between the site soils, particularly the proportion of coarse mineral fractions that has resulted from the differences in the pedogenetic processes between Urat and Naiman. (2) The buildups of P and K were also positively controlled by the precipitation amount, but they showed strong seasonal effects; as such, the main factors controlling these nutrients seem to be related to regulating microbial activity such as temperature. Finally, (3) unlike those of P, the K buildup dynamics indicated a large exogenous source that was clearly not litter-derived. While our results most likely represent the transient dynamics of litter-derived nutrient buildup in soil, they demonstrate how changes in precipitation patterns and land degradation can exacerbate the already low nutrient levels in arid and semiarid areas.

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Data Availability Statement: Data are available on request due to restrictions, e.g., privacy or ethical The data presented in this study are available upon request from the corresponding author.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

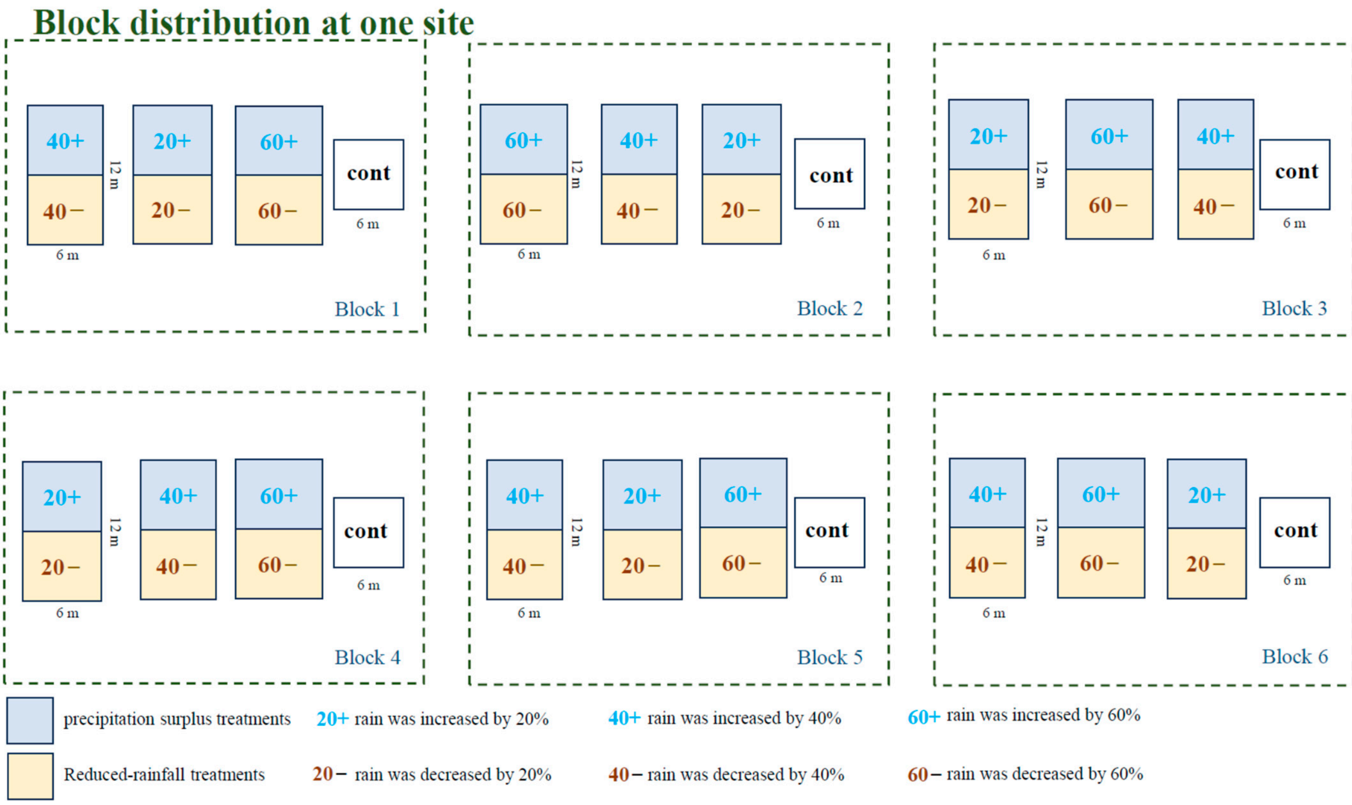

Figure A1. Block distribution of the experiments at each site (from [19]; reused with permission from Springer−Nature).

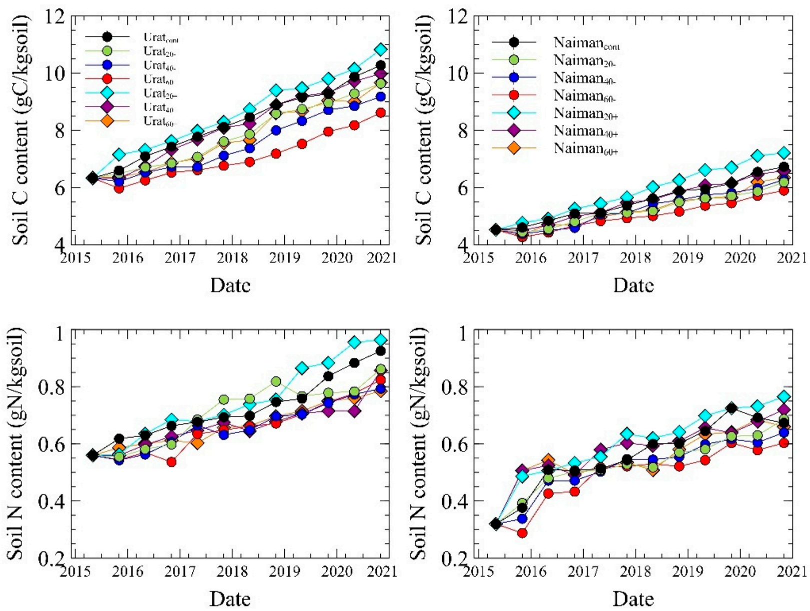

Figure A2. *Cont.*

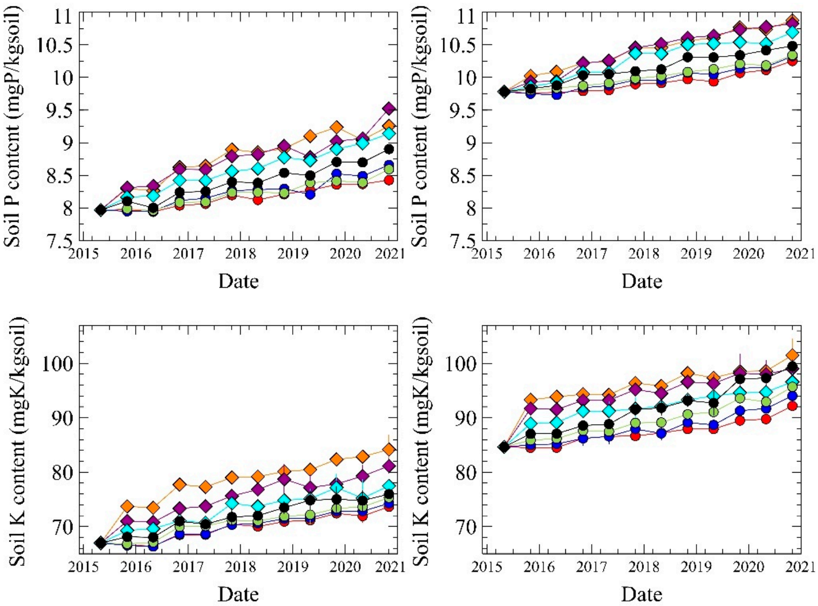

Figure A2. Total soil contents of C, N, P, and K along a five and a half year decomposition experiment that manipulated precipitation inputs at two sites (arid Urat and semiarid Naiman) in Inner Mongolia, China. Precipitation treatments included precipitation background (cont); precipitation decreases by 20, 40, and 60%; and precipitation surpluses of 20, 40, and 60%.

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