

Article

Effect of Forest Thinning on Soil Phosphorus Stocks and Dynamics on a Global Scale

Yulian Yang ¹, Qing Dong ¹, Jiaping Yang ¹, Bo Tan ² , Zhenfeng Xu ², Qinggui Wu ^{1,*} and Hongwei Xu ^{2,*} 

¹ Ecological Security and Protection Key Laboratory of Sichuan Province, Mianyang Normal University, Mianyang 621000, China; yangyulian@mtc.edu.cn (Y.Y.); zhaohrchina@163.com (Q.D.); yangjiaping0108@mtc.edu.cn (J.Y.)

² College of Forestry, Sichuan Agricultural University, Chengdu 611130, China; bobotan1984@163.com (B.T.); xuzf@sicau.edu.cn (Z.X.)

* Correspondence: qgwu30@mtc.edu.cn (Q.W.); xuhongwei16@sicau.edu.cn (H.X.); Tel.: +86-28-86290957 (H.X.)

Abstract: As an important part of terrestrial ecosystems, the forest soil nutrient content is easily affected by thinning. However, the effects of thinning on soil phosphorus (P) stocks and dynamics have not yet been systematically analyzed. In this study, we aimed to investigate the effects of thinning on the soil P stock and rate of soil P stock change in the 0–30, 30–60, and 0–60 cm soil layers by integrating 237 data points on a global scale. In addition, we aimed to determine whether these factors are regulated by forest type, recovery time, and thinning intensity. The results indicated that thinning increased the soil P stock in the 0–30, 30–60, and 0–60 cm soil layers by 9.0, 13.2, and 10.2%, respectively, and the soil P stock change rates were 0.017, 0.013, and 0.025 Mg ha^{−1} yr^{−1}, respectively. Furthermore, the promoting effect of thinning on soil P stocks was greater in coniferous forests than in broadleaf and mixed forests. In addition, the stocks and change rates of soil P increased with recovery time and decreased with thinning intensity and mean annual precipitation. This study highlights the effects of thinning on forest soil P accumulation on a global scale. The results are of great significance for understanding soil nutrient cycling and sustainable forest management.

Keywords: thinning; forest management; soil nutrient cycling; soil nutrient accumulation; forest ecosystem; sustainable development



Citation: Yang, Y.; Dong, Q.; Yang, J.; Tan, B.; Xu, Z.; Wu, Q.; Xu, H. Effect of Forest Thinning on Soil Phosphorus Stocks and Dynamics on a Global Scale. *Forests* **2024**, *15*, 362. <https://doi.org/10.3390/f15020362>

Academic Editor: Heinz Rennenberg

Received: 24 January 2024

Revised: 10 February 2024

Accepted: 12 February 2024

Published: 13 February 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Forest thinning is an important method for forest ecosystem management [1]; it optimizes stand structure and improves the stand environment by regulating stand density, and also plays an important role in restoring degraded forest ecosystems [2,3]. Soil acts as a link between material and energy transmission in forest ecosystems [4], and the supply of soil nutrients directly affects the growth status and the yield of forest trees [5]. Soil phosphorus (P) is an important limiting factor for plant growth and development in terrestrial ecosystems [6], and an important nutrient index for soil fertility and soil quality [7]. The availability significantly affects the growth of forest trees and the sustainability of forest ecosystems [8]. Therefore, it is important to study the effects of thinning on soil P accumulation in order to gain an in-depth understanding of soil nutrient cycling and sustainable forest management [9,10].

Soil P is predominantly derived from the slow weathering of rocks over long periods of time [11], as well as from litter and plant root decomposition over short periods [12]. Thinning promotes plant growth and soil microbial activity by changing the microclimate of the forest (such as increasing light and soil temperature), thus affecting the soil P cycle [10]. For example, Iida et al. (2023) found that thinning significantly improves the light conditions of the tree canopy, increases plant productivity [13], and increases the litter and soil nutrient content [14]. Some studies have also confirmed that thinning significantly promotes the development of understory vegetation, enhances plant diversity and soil

microbial activity [10,15,16], and further accelerates the soil P cycle. However, Lindroth et al. (2018) pointed out that the removal of trees caused by thinning may also reduce plant productivity [17], thus reducing the soil P content. This difference may be related to the difference in soil microbial activity, as soil microbial community and enzyme activity are both significantly corrected with soil nutrient cycling [7]. In addition, this difference may be related to the different distributions of the study samples as soil microbial activity and nutrient cycling are significantly affected by environmental conditions (such as the mean annual precipitation and the mean annual temperature of the study site) [18,19]. Thus far, the effects of thinning on soil P accumulation have not been uniformly reported; therefore, it is necessary to conduct a global-scale analysis in order to explore the effects of thinning on soil P stocks and dynamics to fully reflect the soil nutrient cycling process.

The accumulation of soil P due to thinning is significantly affected by forest type because different forest types lead to differences in the quantity and quality of litter, which directly and indirectly affects the content of P input into the soil [20]. Generally, it is believed that coniferous forests have a lower litter mass and are difficult to decompose, whereas broadleaf forests have a higher litter mass and are easy to decompose. This difference in the decomposition rate leads to a large difference in soil nutrient returns [21,22]. However, at present, there is still a lack of the global-scale analyses of the effects of different forest types on soil P stocks and dynamics, which leads to a lack of comprehensive understanding of the soil material cycling processes within ecosystems.

Recovery time is also an important factor which affects soil P stocks and dynamics. There are two main mechanisms associated with recovery time: (1) recovery time affects the return amount of litter by influencing the growth and diversity of understory vegetation [23,24], thus affecting the accumulation of P; and (2) the recovery time affects the soil microbial community and activity by influencing the soil's physical and systematic stability, thus affecting the soil P cycle [10]. It is generally believed that with an increase in recovery time, understory vegetation, vegetation diversity, and litter content increase significantly [24,25], which promotes the accumulation of soil P. At the same time, with an increase in recovery time, the forest ecosystem gradually tends to become stable [23], and the activity of soil microorganisms is significantly enhanced [15,26], thus accelerating the soil P cycle. Thinning intensity also significantly affects the accumulation of soil P. Generally, we believe that with the increase of thinning intensity, understory plant diversity and productivity will significantly decrease [27,28], which will further affect soil P reserves. In addition, high-intensity thinning results in the removal of a large amount of vegetation, which may also lead to soil drought [29], thereby reducing soil microbial activity and nutrient cycling [24] and affecting soil P cycling. However, the effects of thinning on soil P on a global scale are currently poorly understood, and whether this effect is regulated by recovery time and thinning intensity has not yet been systematically assessed.

Therefore, this study evaluated the effects of thinning on soil P stocks and dynamics by integrating 237 data points published worldwide, and explored whether such effects were regulated by forest type, recovery time, and thinning intensity. We developed three hypotheses: (1) since thinning can promote the growth of understory vegetation, increase plant and microbial biodiversity, and increase litter content [10,15,16], we hypothesized that thinning can significantly promote the accumulation of soil P; (2) since the litter amount, decomposition rate, and nutrient content of litter in pure forests are all lower than those in mixed forests [21,30], we hypothesized that the promoting effect of thinning on P accumulation in mixed forests would be greater than that in coniferous and broadleaf forests; and (3) plant productivity, system stability, and microbial activity gradually increase with recovery time, but decrease with thinning intensity [10,23,29]. Therefore, we assumed that recovery time promotes soil P accumulation, whereas thinning intensity inhibits soil P accumulation.

2. Materials and Methods

2.1. Data Collection

In this study, three databases, namely Web of Science (<http://apps.webofknowledge.com/>), Google Scholar (<https://scholar.google.com>), and CNKI (<http://www.cnki.net>), were used to search for the relevant literature on December 10th, 2023. The search terms included thinning, forest management, silvicultural treatment, harvesting, selective cutting or management, soil P, soil nutrients, soil properties, soil microbial activity, soil microbial biomass, soil enzyme activity, and stoichiometry. To reduce the bias of the results, the following criteria were used for literature screening: (1) treatment and control groups must be included in the study; (2) forest type (coniferous, broadleaf, and mixed forest), recovery time, and thinning intensity must be defined in the study; and (3) the study must be treated as a single factor, excluding the interactions of other factors (such as nitrogen addition and warming) with thinning.

After screening, a total of 60 articles were included. The target data can be obtained in two ways: (1) directly from the table in the article, and (2) using GetData Graph Digitizer (version 2.24, Moscow, Russia) to retrieve the graph. A total of 237 data points were obtained in this study. In addition, we collected data on the longitude, latitude, mean annual temperature (MAT), mean annual precipitation (MAP), forest type, recovery time, and thinning intensity of the study plots.

2.2. Data Analysis

The soil P stock was calculated according to the soil P content, soil bulk density (BD) (g cm^{-3}), and soil depth (D) (cm) [31]:

$$\text{Soil P stock} = \frac{\text{Soil P content} \times \text{BD} \times D}{10} \quad (1)$$

To better understand the effect of thinning on soil P stocks, data obtained from different soil layers were converted into the soil P stock of the 0–30, 30–60, and 0–60 soil layers. The calculation method was as follows [32,33]:

$$\gamma = 1 - \beta^d \quad (2)$$

$$\text{soil P stock}_{0-30 \text{ or } 0-60} = \frac{1 - \beta}{1 - \beta^{d_0}} \times P_{d_0} \quad (3)$$

where γ is the cumulative proportion of the surface soil P content to depth d (cm), β is the relative change rate of soil P stock with soil depth (β is 0.9 on a global scale (Jobbagy and Jackson, 2000)), d_0 is the surface soil depth (cm), and P_{d_0} is the reported surface soil P stock. The soil P stock in the 30–60 cm soil layer was calculated as the difference between that in the 0–60 and 0–30 cm layers

The rate of soil P stock change ($\text{Mg ha}^{-1} \text{ yr}^{-1}$) was calculated as the difference between the soil P stock at different recovery times (P_i) and the initial soil P stock (P_0) [34]:

$$\text{Rate of soil P stock change} = \frac{P_i - P_0}{\Delta T} \quad (4)$$

In this study, forest types were grouped into coniferous, broadleaf, and mixed forests. Regression analysis was used to assess the relationship among recovery time, thinning intensity, and MAP with soil P stock and soil P stock change rates.

3. Results

3.1. Overview of the Dataset

The distribution of the soil phosphorus (P) stock and the soil P stock change rate after thinning are shown in Figure 1a,b. In total, 237 data points were included in this study, including 160 coniferous, 27 broadleaf, and 50 mixed forest data points (Figure 1c). In addition, there was a significant positive correlation between MAT and MAP (Figure 1d).

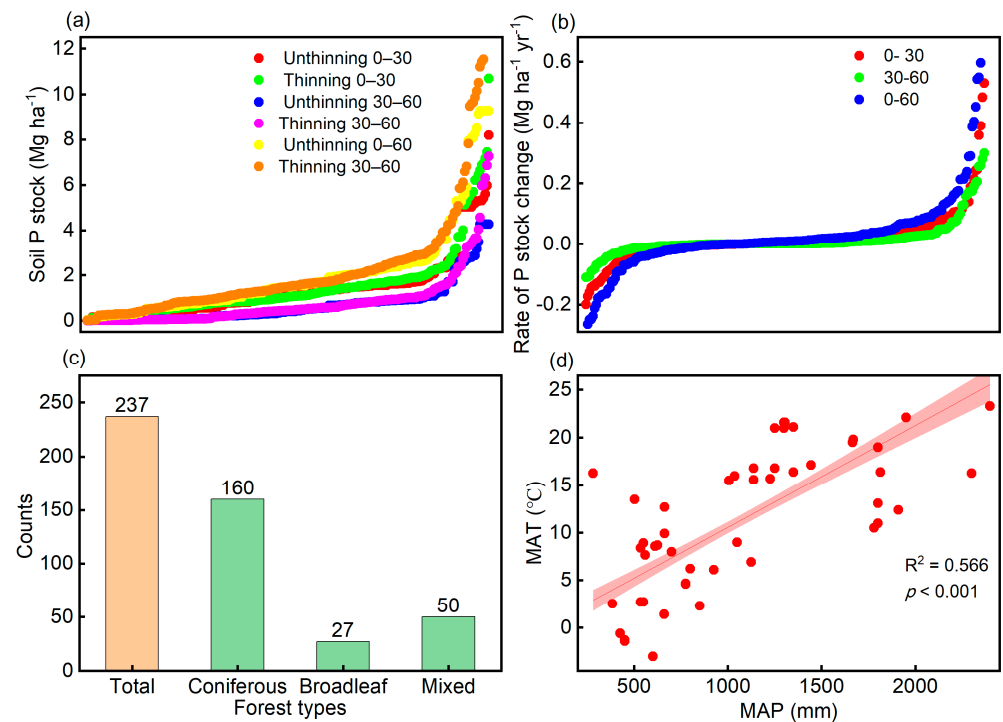


Figure 1. The distribution of the soil phosphorus (P) stock (a), the rate of soil P stock change after thinning (b), the counts of sampling sites used in this study (c), and the relationships between mean annual precipitation (MAP) and mean annual temperature (MAT) (d).

3.2. Responses of Soil P Stock to Forest Thinning

Our results suggested that thinning changed the soil P stock and soil P stock change rate on a global scale (Figure 2). Thinning increased the soil P stock in the 0–30, 30–60, and 0–60 cm soil layers by 9.0, 13.2, and 10.2%, respectively (Figure 2a). The soil P stock change rates in the 0–30, 30–60, and 0–60 cm soil layers were 0.017, 0.013, and 0.025 Mg ha⁻¹ yr⁻¹, respectively (Figure 2b). In addition, the soil P stock and soil P stock change rate in the 0–30 cm soil layer were higher than those in the 30–60 cm soil layer (Figure 2a,b).

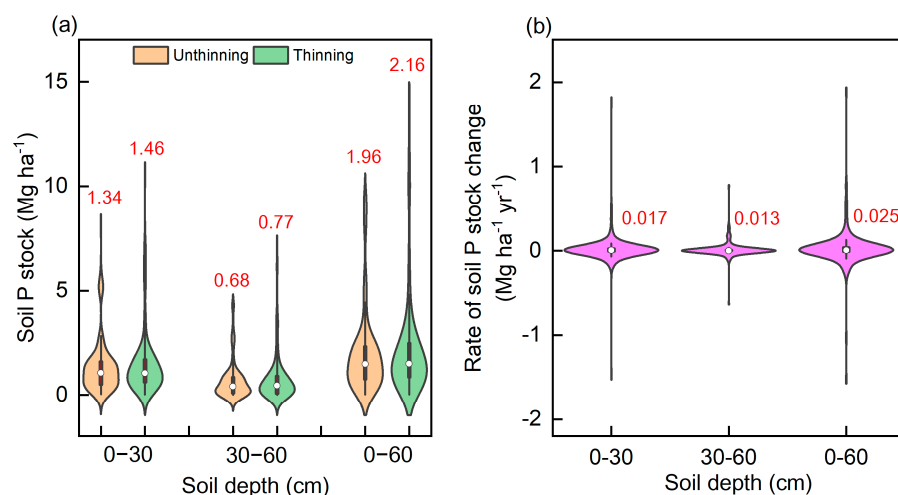


Figure 2. The effects of thinning on the soil phosphorus (P) stock at different soil depths (a) ($n = 237$) and on the rate of soil P stock change at different soil depths (b). Note: the numbers in the figure represent the mean of the soil P stock or rate of soil P stock change.

3.3. Factors Affecting Responses of Soil P Stock to Thinning

In terms of the different forest types, thinning increased the soil P stock in coniferous, broadleaf, and mixed forests (except for the 0–60 cm soil layer in the broadleaf forest) (Figure 3). The soil P stock in the 0–30, 30–60, and 0–60 cm soil layers of the coniferous forest increased by 8.9, 11.4, and 9.7%, respectively (Figure 3a); those in the broadleaf forest increased by 3.5, 4.0, and -1.2% , respectively (Figure 3b); and those in the mixed forest increased by 11.6, 20.5, and 15.0% , respectively (Figure 3c). The soil P stock change rates of the 0–30, 30–60, and 0–60 cm soil layers in the coniferous forest were 0.010, 0.005, and $0.016 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, respectively (Figure 3d); those in the broadleaf forest were 0.009, 0.008, and $-0.029 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, respectively (Figure 3e); and those in the mixed forest were 0.045, 0.041, and $0.086 \text{ Mg ha}^{-1} \text{ yr}^{-1}$, respectively (Figure 3f). In addition, the soil P stock and soil P stock change rate of the mixed forest were higher than those of the coniferous and broadleaf forests, and those in the 0–30 cm soil layer were higher than those in the 30–60 cm soil layer (Figure 3a–f).

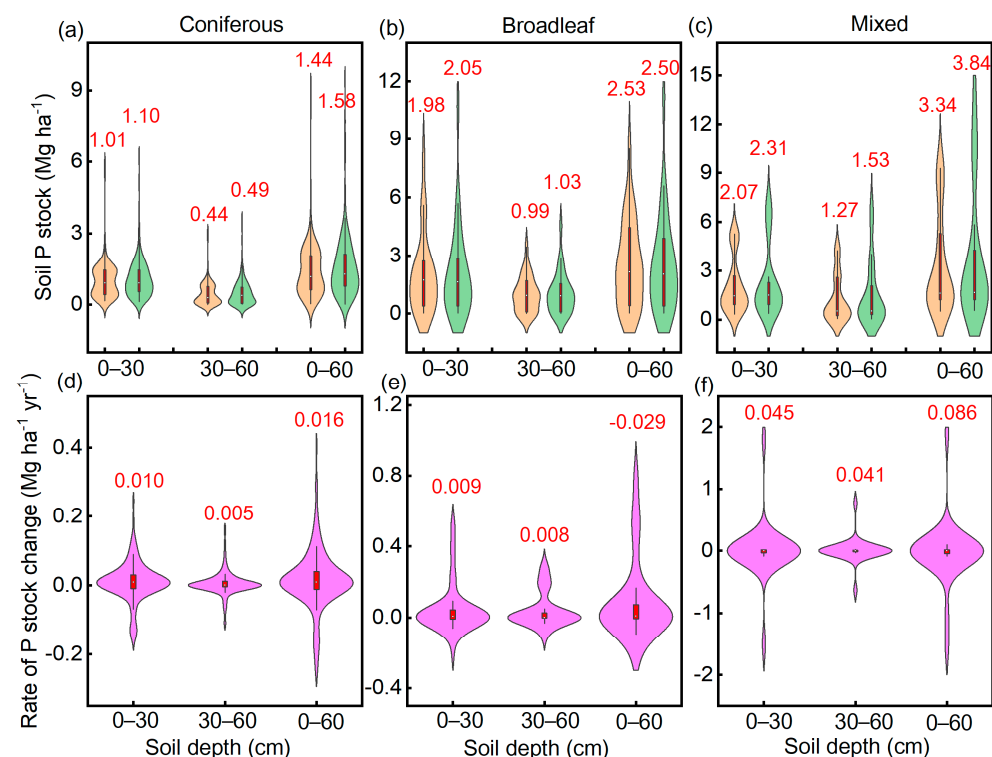


Figure 3. The effects of thinning on the soil phosphorus (P) stock of coniferous (a) ($n = 160$), broadleaf (b) ($n = 27$), and mixed (c) ($n = 50$) forests, and on the rate of soil P stock change of coniferous (d), broadleaf (e), and mixed (f) forests. Note: the numbers in the figure represent the mean of the soil P stock or rate of soil P stock change.

By exploring the relationship among soil P stocks and soil P stock change rates, and the recovery time and thinning intensity, we observed that the soil P stocks and soil P stock change rates in the 0–30, 30–60, and 0–60 cm soil layers exhibited an increasing trend with recovery time and a decreasing trend with thinning intensity (Figure 4a–d). Simultaneously, the soil P stocks and soil P stock change rates in the 0–30, 30–60, and 0–60 cm soil layers decreased with an increasing MAP (Figure 5a,b).

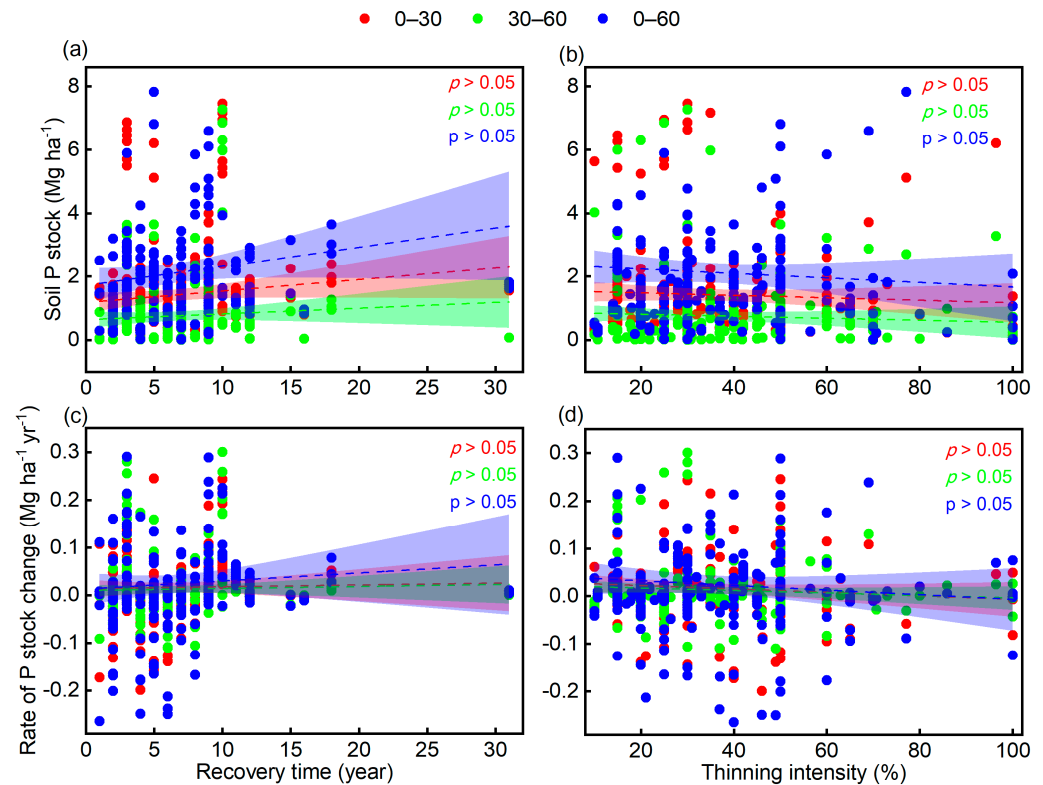


Figure 4. The effects of recovery time and thinning intensity on soil phosphorus (P) stock (a,b) and the rate of soil P stock change (c,d). Note: dashed lines indicate insignificance.

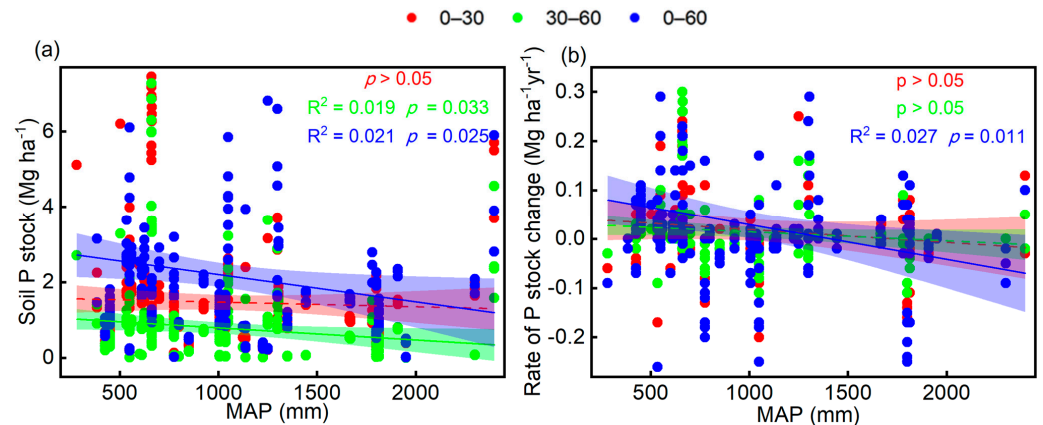


Figure 5. The effects of the mean annual precipitation (MAP) on the soil phosphorus (P) stock (a) and the rate of soil P stock change (b). Note: solid lines indicate significance and dotted lines indicate insignificance.

4. Discussion

4.1. Effects of Forest Thinning on Soil P Accumulation

The forest soil nutrient content is an important part of terrestrial ecosystems, and is easily affected by forest thinning [35,36]. Research on the effects of thinning on soil P stocks and dynamics is of great significance for an in-depth understanding of soil nutrient cycling and sustainable forest management [9,37]. In this study, we found that thinning increased the soil P stock, and the soil P stock change rate was positive (Figure 6), which is consistent with the results of previous studies [10], confirming hypothesis 1. Although P in soil mainly originates from rock weathering, some studies have confirmed that soil P is significantly affected by litter and plant roots [12,38]. Therefore, the increase in the soil P stock observed in this study can be explained by the following four aspects: (1) thinning

improves the environmental conditions for plant and microbial life [13]. For example, thinning reduces the forest canopy density, increases light and soil temperature, produces more suitable environmental conditions for the proliferation of soil microorganisms, and increases the diversity and biological activity of soil microorganisms [10,15], thus accelerating the accumulation of soil P. (2) An increase in light also promotes the development of understory vegetation, enhances plant diversity, accelerates the decomposition of litter, and further increases the contents of soil nutrients [3,16]. (3) The thinning process generates a large number of cutting residues, such as branches and stumps [39], thus enhancing the transformation of litter into soil organic matter and nutrients. (4) Soil microbial biomass P is an important source of soil P. Studies have confirmed that thinning significantly increases the soil microbial biomass P content [40], thus contributing to the soil P stock. This study emphasized that thinning promotes forest P accumulation on a global scale from the perspective of soil P stocks.

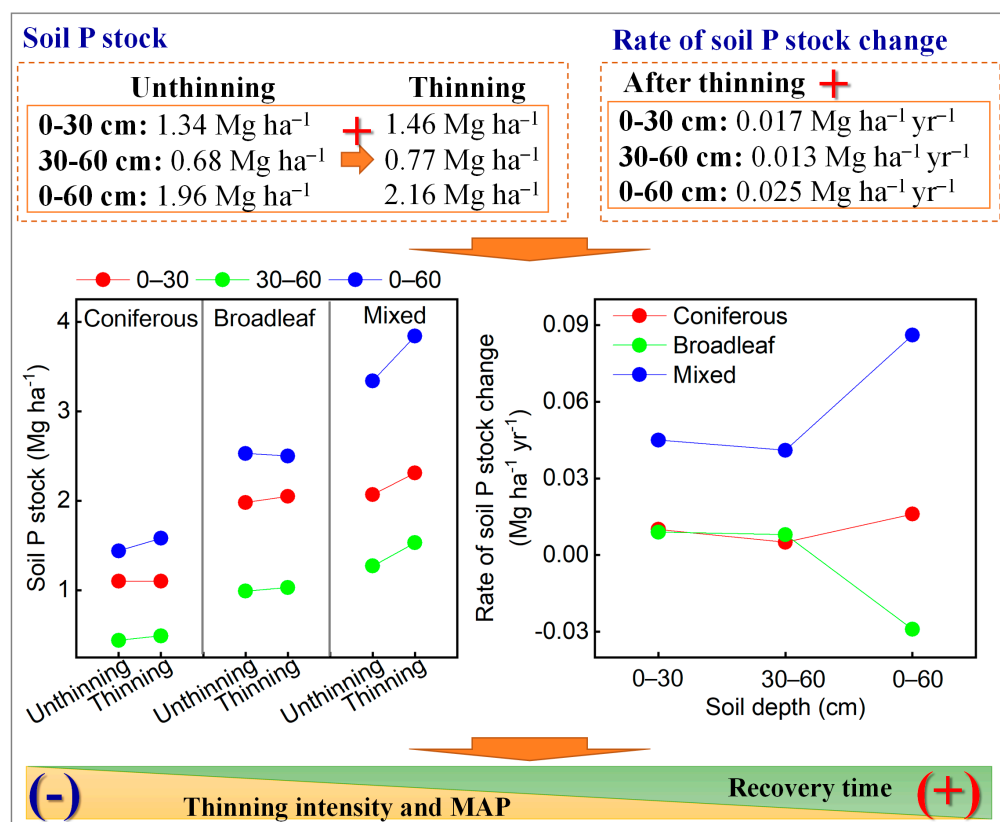


Figure 6. Conceptual framework of the effects of thinning on soil phosphorus (P) stock.

4.2. Effects of Forest Types on Soil P Accumulation

Different forest types lead to differences in the quantity and quality of litter, which may directly or indirectly affect the nutrient content input into the soil [20]. This study revealed that, during thinning, the soil P stock and soil P stock change rate in mixed forests in the 0-30, 30-60, and 0-60 cm soil layers were generally higher than those in coniferous and broadleaf forests (Figure 6), confirming hypothesis 2, which is consistent with previous reports suggesting that mixed forests are an important way to enhance soil nutrient cycling [41]. First, this may be because the litter amount and decomposition rate of single species forests are smaller than those of mixed forests [21]. Second, studies have confirmed that the nutrient content of litter in pure forests containing a single tree species is significantly lower than that in mixed forests [30], thus reducing the amount of nutrient input to the soil. In addition, this may be because mixed forests (849.8 mm) are usually distributed in areas with a low average annual rainfall, whereas coniferous (1015.8 mm)

and broadleaf (1593.3 mm) forests are typically distributed in areas with a high average annual rainfall (Table S1), which can easily lead to P loss.

4.3. Effects of Recovery Time and Thinning Intensity on Soil P Accumulation

Recovery time significantly affects soil P stock. We found that the soil P stock and soil P stock change rates in the 0–30, 30–60, and 0–60 cm soil layers exhibited an increasing trend with recovery time, confirming hypothesis 3. The results indicated that the recovery time enhanced the fixation ability of soil P. First, in the early stage of restoration, plant roots are underdeveloped and there is less litter. Vegetation succession tends to be stable with an increase in recovery time [23]; understory vegetation gradually develops and matures; and a stable understory plant community [42] is generated, which improves soil microbial and phosphatase activities [15,26], thereby affecting the P cycling process and the P content in the soil. Second, with an increase in the recovery time, the P input of litter, existing litter, and plant roots caused by plant growth gradually increases [24,25], which increases the return of soil P. In addition, studies have confirmed that with an increase in recovery time, the physical structure of the soil gradually improves, and environmental conditions suitable for the growth of plants and microorganisms are generated [10,38], which accelerates the accumulation of P. Conversely, the soil P stock and soil P stock change rate exhibited a decreasing trend with thinning intensity, confirming hypothesis 3. With an increase in thinning intensity, especially at high thinning intensities, soil drought [29] results in an environment that is not conducive to the growth of microorganisms [24], thus reducing the accumulation of soil nutrients. At the same time, high-intensity thinning significantly affects the growth of surface plants and reduces the plant productivity and litter return [27,28]. The effects of recovery time and thinning intensity on soil P stocks and dynamics were investigated using global-scale data, and it was found that the recovery time increased, whereas the thinning intensity decreased the soil P accumulation.

4.4. Effects of MAP and Soil Depths on Soil P Accumulation

In this study, we found that the soil P stock and soil P stock change rates in the 0–30, 30–60, and 0–60 cm soil layers decreased with increasing MAP. Severe nutrient loss can occur in regions with higher rainfall [19], thus attenuating the positive effects of thinning on P stocks. In contrast, in regions with low annual rainfall, the P loss is less, and thinning activities improve the conditions of the plant (light, growth, and litter) and soil environment (physical structure and microbial activity) [15,43], and accelerate the accumulation of P. We also observed that the soil P stock and soil P stock change rates were affected by soil depth and were higher in the surface layer (0–30) than those in the lower layer (30–60). First, the surface layer is adjacent to the atmosphere, and is therefore more susceptible to the effects of light and temperature. The enhancement of light after thinning changes the environmental conditions and microbial activity of the surface layer of soil and, in contrast, has little impact on deep soil [44,45]. Secondly, litter is mainly concentrated on the soil surface, and its decomposition has a direct effect on the return of soil nutrients to the surface layer [46,47], resulting in little impact on the soil P in deeper layers. In addition, studies have confirmed that deep-soil P is more susceptible to leaching [48], which does not impact the positive effects of thinning on the P stocks.

4.5. Limitations and Uncertainties

Although this study explored the effects of thinning on soil P stocks and dynamics using global-scale data, there are still some limitations. (1) The data points collected in this study are not uniform, and most of them are distributed in short or medium-to-long periods, while long-term sample points exceeding 20 years are scarce; therefore, we require more and longer time-scale data for verification. (2) The sample size of broadleaf forests was very limited (only 27), which led to a limitation in our group analysis. (3) The change in soil P stocks is affected by litter, understory plant diversity, microbial activity, and other factors [23,36,43]. However, this study did not discuss the mechanism of soil P stock change

from the perspective of environmental factors; therefore, it is necessary to strengthen the relevant research in the future to address this deficiency.

5. Conclusions

This study explored the effects of thinning on soil P stocks and dynamics using global-scale data. The effect of thinning on soil P storage was positive, and the effect of mixed forests on P storage was greater than that of single forests (coniferous and broadleaf forests). Simultaneously, the recovery time increased, whereas the thinning intensity decreased the P reserves and rate. In addition, the P storage and rate decreased with increasing MAP and soil depth. This study emphasizes that thinning enhances the ability of global-scale forest ecosystems to accumulate soil P, and the results of this study provide a reference for model construction to reveal the response of soil nutrient cycling to forest management strategies. However, there is still a lack of research on the mechanisms underlying soil P stock changes due to forest thinning, and relevant research should be strengthened in the future.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/f15020362/s1>, Table S1: Mean annual precipitation (MAP) in coniferous, broadleaf, and mixed forests.

Author Contributions: Conceptualization, Y.Y., Q.W. and H.X.; methodology, Q.D., J.Y. and B.T.; software, Y.Y.; validation, Y.Y. and Z.X.; data curation, H.X.; writing—original draft preparation, Y.Y. and H.X.; writing—review and editing, Y.Y., Q.W. and H.X.; visualization, Y.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (32071747, 42307571), the Natural Science Foundation of Sichuan Province (2023NSFSC1194), the Innovation Team Project of Mianyang Normal University (CXTD2023LX01), the Scientific Research Initiation Project of Mianyang Normal University (QD2020A18, QD2023A01), and the Open Fund of Ecological Security and Protection Key Laboratory of Sichuan Province, Mianyang Normal University (ESP2302).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: Many thanks to Han Li and Li Zhang for their statistics assistance.

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

References

- Kim, S.; Kim, C.; Lee, S.T.; Son, Y. Multi-site assessment of soil nitrogen stocks across temperate forests under different thinning intensities, recovery times, and site conditions. *Sci. Total Environ.* **2023**, *894*, 164996. [CrossRef] [PubMed]
- Vesterdal, L.; Dalsgaard, M.; Felby, C.; Raulundrasmussen, K.; Jorgensen, B. Effects of thinning and soil properties on accumulation of carbon, nitrogen and phosphorus in the forest floor of Norway spruce stands. *For. Ecol. Manag.* **1995**, *77*, 1–10. [CrossRef]
- Ring, E.; Lofgren, S.; Hogbom, L.; Ostlund, M.; Wiklund-McKie, M.L.; McKie, B.G. Long-term effects on water chemistry and macroinvertebrates of selective thinning along small boreal forest streams. *For. Ecol. Manag.* **2023**, *549*, 121459. [CrossRef]
- Alvarenga, L.C.B.R.; da Costa, M.G.; Gama-Rodrigues, A.C.; Aleixo, S.; Gama-Rodrigues, E.F.; Goncalves, J.L.D.M. Soil organic phosphorus in *Eucalyptus* plantations, Brazil: Extraction methods. *Sci. Agric.* **2024**, *81*, e20220131. [CrossRef]
- Xu, S.; Gu, C.; Rodrigues, J.L.M.; Li, C.; Bohannan, B.; Nuesslein, K.; Margenot, A. Soil phosphorus cycling across a 100-year deforestation chronosequence in the Amazon rainforest. *Glob. Chang. Biol.* **2024**, *30*, e17077. [CrossRef]
- Rui, Y.; Wang, Y.; Chen, C.; Zhou, X.; Wang, S.; Xu, Z.; Duan, J.; Kang, X.; Lu, S.; Luo, C. Warming and grazing increase mineralization of organic P in an alpine meadow ecosystem of Qinghai-Tibet Plateau, China. *Plant Soil* **2012**, *357*, 73–87. [CrossRef]
- Liu, S.; Li, H.; Xie, X.; Chen, Y.; Lang, M.; Chen, X. Long-term moderate fertilization increases the complexity of soil microbial community and promotes regulation of phosphorus cycling genes to improve the availability of phosphorus in acid soil. *Appl. Soil Ecol.* **2024**, *194*, 105178. [CrossRef]
- Geng, X.; Zuo, J.; Meng, Y.; Zhuge, Y.; Zhu, P.; Wu, N.; Bai, X.; Ni, G.; Hou, Y. Changes in nitrogen and phosphorus availability driven by secondary succession in temperate forests shape soil fungal communities and function. *Ecol. Evol.* **2023**, *13*, e10593. [CrossRef]
- Baena, C.; Andrés-Abellán, M.; Lucas-Borja, M.; Martínez-García, E.; García-Morote, F.; Rubio, E.; López-Serrano, F. Thinning and recovery effects on soil properties in two sites of a Mediterranean forest, in Cuenca Mountain (South-eastern of Spain). *For. Ecol. Manag.* **2013**, *308*, 223–230. [CrossRef]

10. Zhou, T.; Wang, C.; Zhou, Z. Thinning promotes the nitrogen and phosphorous cycling in forest soils. *Agric. For. Meteorol.* **2021**, *311*, 108665. [\[CrossRef\]](#)
11. Zhao, Q.; Zeng, D. Phosphorus cycling in terrestrial ecosystems and its controlling factors. *Chin. J. Appl. Ecol.* **2005**, *29*, 153–163, (In Chinese with English Abstract).
12. Wang, M.; Zhang, C.; Chen, S.; Zhang, Y.; Yu, T.; Xue, X.; Wu, L.; Zhou, W.; Yun, X.; Yan, R.; et al. Moderate grazing increased carbon, nitrogen and phosphorus storage in plants and soil in the Eurasian meadow steppe ecosystem. *Sci. Total Environ.* **2024**, *914*, 169864. [\[CrossRef\]](#)
13. Iida, S.; Noguchi, S.; Levia, D.F.; Araki, M.; Nitta, K.; Wada, S.; Narita, Y.; Tamura, H.; Abe, T.; Kaneko, T. Effects of forest thinning on sap flow dynamics and transpiration in a Japanese cedar forest. *Sci. Total Environ.* **2023**, *912*, 169060. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Ogaya, R.; Escola, A.; Liu, D.; Barbeta, A.; Penuelas, J. Effects of thinning in a water-limited holm oak forest. *J. Sustain Forest.* **2020**, *39*, 365–378. [\[CrossRef\]](#)
15. Zeng, L.; Xiao, W.; Liu, C.; Lei, L.; Jian, Z.; Shen, Y.; Li, M. Effects of thinning and understorey removal on soil extracellular enzyme activity vary over time during forest recovery after treatment. *Plant Soil* **2023**, *492*, 457–469. [\[CrossRef\]](#)
16. Kuo, C.; Wei, C.; Chen, J.; Chen, C.; Hsieh, Y. Effects of thinning intensities on litterfall characteristics and decomposition in the natural secondary lowland forests of Southeastern Taiwan. *Scan. J. For. Res.* **2023**, *38*, 166–173.
17. Lindroth, A.; Holst, J.; Heliasz, M.; Vestin, P.; Lagergren, F.; Biermann, T.; Cai, Z.; Mölder, M. Effects of low thinning on carbon dioxide fluxes in a mixed hemiboreal forest. *Agric. For. Meteorol.* **2018**, *262*, 59–70. [\[CrossRef\]](#)
18. Xu, H.; Wang, M.; You, C.; Tan, B.; Xu, L.; Li, H.; Zhang, L.; Wang, L.; Liu, S.; Hou, G.; et al. Warming effects on C:N:P stoichiometry and nutrient limitation in terrestrial ecosystems. *Soil Tillage Res.* **2024**, *235*, 105896. [\[CrossRef\]](#)
19. Xu, H.; Qu, Q.; Li, G.; Liu, G.; Geissen, V.; Ritsema, C.J.; Xue, S. Impact of nitrogen addition on plant-soil-enzyme C-N-P stoichiometry and microbial nutrient limitation. *Soil Biol. Biochem.* **2022**, *170*, 108714. [\[CrossRef\]](#)
20. Zhou, S.; Butenschoten, O.; Barantal, S.; Handa, I.T.; Makkonen, M.; Vos, V.; Aerts, R.; Berg, M.P.; McKie, B.; Van Ruijven, J.; et al. Decomposition of leaf litter mixtures across biomes: The role of litter identity, diversity and soil fauna. *J. Ecol.* **2020**, *108*, 2283–2297. [\[CrossRef\]](#)
21. Wang, W.; Zhang, Q.; Sun, X.; Chen, D.; Insam, H.; Koide, R.T.; Zhang, S. Effects of mixed-species litter on bacterial and fungal lignocellulose degradation functions during litter decomposition. *Soil Biol. Biochem.* **2020**, *141*, 107690. [\[CrossRef\]](#)
22. Yang, Y.; Mohammad, A.; Feng, J.; Zhou, R.; Fang, J. Storage, patterns and environmental controls of soil organic carbon in China. *Biogeochemistry* **2007**, *84*, 131–141. [\[CrossRef\]](#)
23. Gong, C.; Tan, Q.; Liu, G.; Xu, M. Forest thinning increases soil carbon stocks in China. *For. Ecol. Manag.* **2021**, *482*, 118812. [\[CrossRef\]](#)
24. Zhou, T.; Wang, C.; Zhou, Z. Impacts of forest thinning on soil microbial community structure and extracellular enzyme activities: A global meta-analysis. *Soil Biol. Biochem.* **2020**, *149*, 107915. [\[CrossRef\]](#)
25. Li, X.; Li, Y.; Zhang, J.; Peng, S.; Chen, Y.; Cao, Y. The effects of forest thinning on understory diversity in China: A meta-analysis. *Land Degrad. Dev.* **2020**, *31*, 1225–1240. [\[CrossRef\]](#)
26. Xu, M.; Liu, H.; Zhang, Q.; Zhang, Z.; Ren, C.; Feng, Y.; Yang, G.; Han, X.; Zhang, W. Effect of forest thinning on soil organic carbon stocks from the perspective of carbon-degrading enzymes. *Catena* **2022**, *218*, 106560. [\[CrossRef\]](#)
27. Banerjee, T. Impacts of forest thinning on wildland fire behavior. *Forests* **2020**, *11*, 918. [\[CrossRef\]](#)
28. Makineci, E. Long term effects of thinning on soil and forest floor in a sessile oak (*Quercus petraea* (Mathusch) Lieb.) forest in Turkey. *J. Environ. Biol.* **2005**, *26*, 257–263. [\[PubMed\]](#)
29. Sohn, J.A.; Hartig, F.; Kohler, M.; Huss, J.; Bauhus, J. Heavy and frequent thinning promotes drought adaptation in *Pinus sylvestris* forests. *Ecol. Appl.* **2016**, *26*, 2190–2205. [\[CrossRef\]](#)
30. Yang, K.; Zhu, J.; Zhang, W.; Zhang, Q.; Lu, D.; Zhang, Y.; Zheng, X.; Xu, S.; Wang, G. Litter decomposition and nutrient release from monospecific and mixed litters: Comparisons of litter quality, fauna and decomposition site effects. *J. Ecol.* **2022**, *110*, 1673–1686. [\[CrossRef\]](#)
31. Don, A.; Schumacher, J.; Freibauer, A. Impact of tropical land-use change on soil organic carbon stocks—A meta-analysis. *Glob. Chang. Biol.* **2011**, *17*, 1658–1670. [\[CrossRef\]](#)
32. Jobbagy, E.G.; Jackson, R.B. The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecol. Appl.* **2000**, *10*, 423–436. [\[CrossRef\]](#)
33. Deng, L.; Liu, G.B.; Shangguan, Z.P. Land-use conversion and changing soil carbon stocks in China's "Grain-for-Green" Program: A synthesis. *Glob. Chang. Biol.* **2014**, *20*, 3544–3556. [\[CrossRef\]](#)
34. Li, D.; Niu, S.; Luo, Y. Global patterns of the dynamics of soil carbon and nitrogen stocks following afforestation: A meta-analysis. *New Phytol.* **2012**, *195*, 172–181. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Chen, L.F.; He, Z.B.; Zhao, W.Z.; Ma, L.; Liu, S.E.; Zhao, L.W.; Yang, S.P.; Feng, X.Y. The long-term effects of thinning on soil respiration vary with season in subalpine spruce plantations. *Agric. For. Meteorol.* **2023**, *342*, 109756. [\[CrossRef\]](#)
36. Liu, Q.; Sun, Y.; Wang, G.; Cheng, F.; Xia, F. Short-term effects of thinning on the understory natural environment of mixed broadleaf-conifer forest in Changbai Mountain area, Northeast China. *PeerJ* **2019**, *7*, e7400. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Zhang, X.; Chen, L.; Wang, Y.; Jiang, P.; Hu, Y.; Ouyang, S.; Wu, H.; Lei, P.; Kuzyakov, Y.; Xiang, W. Plantations thinning: A meta-analysis of consequences for soil properties and microbial functions. *Sci. Total Environ.* **2023**, *877*, 162894. [\[CrossRef\]](#) [\[PubMed\]](#)

38. Zhang, X.; Zhao, Q.; Wei, L.M.; Sun, Q.Y.; Zeng, D.H. Tree roots exert greater impacts on phosphorus fractions than aboveground litter in mineral soils under a *Pinus sylvestris* var. *mongolica* plantation. *For. Ecol. Manag.* **2023**, *545*, 121242. [[CrossRef](#)]
39. Saunders, M.; Tobin, B.; Black, K.; Gioria, M.; Nieuwenhuis, M.; Osborne, B.A. Thinning effects on the net ecosystem carbon exchange of a Sitka spruce forest are temperature-dependent. *Agric. For. Meteorol.* **2012**, *157*, 1–10. [[CrossRef](#)]
40. Liu, X.; Cheng, X.; Tian, H.; Liu, L.; Han, H. Effects of thinning and litter manipulation on soil phosphorus dynamics in a *Larix principis-rupprechtii* plantation. *Acta Ecol. Sin.* **2019**, *39*, 7686–7696, (In Chinese with English Abstract).
41. He, Y.; Zhang, Q.; Wang, S.; Jiang, C.; Lan, Y.; Zhang, H.; Ye, S. Mixed plantations induce more soil macroaggregate formation and facilitate soil nitrogen accumulation. *Forests* **2023**, *14*, 735. [[CrossRef](#)]
42. Sohn, J.A.; Saha, S.; Bauhus, J. Potential of forest thinning to mitigate drought stress: A meta-analysis. *For. Ecol. Manag.* **2016**, *380*, 261–273. [[CrossRef](#)]
43. Tian, D.; Chen, Y.; Shi, Y.; Lian, S.; Bian, L.; Tang, L. Effects of thinning and fertilization on soil microbial characteristics in a near-mature Chinese fir plantation. *J. Forest. Environ.* **2023**, *43*, 569–578, (In Chinese with English Abstract).
44. Nazari, M.; Pausch, J.; Bickel, S.; Bilyera, N.; Rashtbary, M.; Razavi, B.; Zamanian, K.; Sharififar, A.; Shi, L.; Dippold, M.; et al. Keeping thinning-derived deadwood logs on forest floor improves soil organic carbon, microbial biomass, and enzyme activity in a temperate spruce forest. *Eur. J. For. Res.* **2022**, *142*, 287–300. [[CrossRef](#)]
45. Xu, H.; Qu, Q.; Wang, M.; Li, P.; Li, Y.; Xue, S.; Liu, G. Soil organic carbon sequestration and its stability after vegetation restoration in the Loess Hilly Region, China. *Land Degrad. Dev.* **2020**, *31*, 568–580. [[CrossRef](#)]
46. Bashir, M.A.; Rehim, A.; Liu, J.; Imran, M.; Liu, H.; Suleman, M.; Naveed, S. Soil survey techniques determine nutrient status in soil profile and metal retention by calcium carbonate. *Catena* **2019**, *173*, 141–149. [[CrossRef](#)]
47. Tian, L.; Zhao, L.; Wu, X.; Fang, H.; Zhao, Y.; Yue, G.; Liu, G.M.; Chen, H. Vertical patterns and controls of soil nutrients in alpine grassland: Implications for nutrient uptake. *Sci. Total Environ.* **2017**, *607*, 855–864. [[CrossRef](#)] [[PubMed](#)]
48. Shah, S.B.; Hutchison, K.J.; Hesterberg, D.L.; Grabow, G.L.; Huffman, R.L.; Hardy, D.H.; Parsons, J.T. Leaching of Nutrients and Trace Elements from Stockpiled Turkey Litter into Soil. *J. Environ. Qual.* **2009**, *38*, 1053–1065. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.