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Effects of Warming and No-Tillage on Soil Carbon, Nitrogen, Phosphorus and Potassium Contents and pH of an Alpine Farmland in Tibet

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Abstract: There are still great uncertainties about effects of climate warming and no-tillage on soil carbon, nitrogen, phosphorus and potassium contents and pH in alpine farmlands. A warming (control; daytime warming, DW; nighttime warming, NW; all-day warming, DW + NW) and no-tillage (no-tillage vs. tillage) experiment was conducted in an alpine farmland of the Lhasa, Xizang since 2015. Soil organic carbon, total nitrogen, total phosphorus, total potassium (TK), available nitrogen, available phosphorus, available potassium, dissolved organic carbon (DOC), active organic carbon, particulate organic carbon (POC), light fraction organic carbon, and heavy fraction organic carbon contents and pH at four depths (0–5, 5–15, 15–25, and 25–35 cm) were measured. Warming effects on concerned soil variables differed with warming time, soil depth, and no-tillage. No-tillage effects on concerned soil variables differed with warming-time (daytime, nighttime, and all-day warming) and soil depths. Therefore, daytime warming and nighttime warming have different effects on soil variables, although the effects of nighttime warming on soil variables are not always greater than those of daytime warming. Effects of daytime warming and nighttime warming on soil variables are not simple addition or subtraction effects. There are interactions between diurnal asymmetrical warming and no-tillage on soil variables.

Keywords: climate warming; tillage; no-till; alpine region; Xizang

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Citation: Zhong, Z.; Qin, Y.; Zhang, G.; Fu, G. Effects of Warming and No-Tillage on Soil Carbon, Nitrogen, Phosphorus and Potassium Contents and pH of an Alpine Farmland in Tibet. *Agronomy* **2024**, *14*, 1327. https://doi.org/10.3390/agronomy14061327

Academic Editor: Yash Dang

Received: 12 May 2024
Revised: 13 June 2024
Accepted: 14 June 2024
Published: 19 June 2024

1. Introduction

Climate warming is an indisputable fact [1–3]. Food security is a realistic issue facing all mankind [4]. Grain is one of the most important foods for human beings, and cultivated lands are the basis of grain production [4]. The high-quality scientific utilization of cultivated land resources is the primary task to ensure food security [4]. Climate warming is affecting and will continue to affect the quality of cultivated soils and, in turn, food production, thereby affecting the improvement of human quality of life [5,6]. Carbon sequestration in cultivated lands is not only an important idea to mitigate climate warming, but also an important measure to improve soil organic matter content and farmland fertility [7,8]. No-tillage is an important farmland management measure, which has been proven by more and more studies to increase soil organic carbon content, soil microbial diversity, and even crop yield, reduce global warming potential, and maintain soil pH [7,9–11]. These scientific findings can provide important guidance for the protection and quality improvement of cultivated land resources and food security. However, compared with the single-factor of no-tillage or warming in-situ experiment studies [12–15], there are few two-factor (i.e., no-tillage and warming) experiment studies [16–19]. On one hand, these two-factor studies have confirmed the synergistic or antagonistic effects of no-tillage and climate warming on soil carbon and nitrogen and crop biomass [18,20,21]. Effects of climate warming or no-tillage alone on soil carbon, nitrogen, and crop biomass in cultivated lands may overestimate or underestimate the interactions of climate warming and no-tillage on soil carbon nitrogen and crop biomass in cultivated lands. On the other hand, these two-factor studies are carried out in temperate and subtropical farmlands but not alpine regions [22,23]. Food production in alpine areas is very important for food security in alpine areas, because many alpine food crops can only be grown in alpine areas [24,25]. Moreover, these experimental studies do not compare the effects of no-tillage under daytime and nighttime warming conditions. Although soil potassium is also an important nutrient affecting food crops, the experimental studies of these two factors have paid little attention to it. Therefore, it is necessary to strengthen the studies on the effects of no-tillage and climate warming on soil quality related factors such as carbon, nitrogen, phosphorus, and potassium, especially in alpine farmland areas.

Alpine cultivated lands in Xizang are an important representative of the global alpine cultivated lands, and are located in the main cultivation area and the origin area of highland barley in the world [26]. The cultivated lands in Xizang are an important resource base to guarantee the production and safety of highland barley [27]. Although some studies have investigated the responses of soil fungal community structure, soil respiration, and yield of highland barley to climate warming [27,28], no studies have investigated responses of soil carbon, nitrogen, phosphorus, potassium and pH to climate warming. Compared with experimental studies on effects of climate warming on agroecosystems [26,28,29], there are fewer experimental studies on responses of agroecosystems to no-tillage in Xizang. There is no relevant report on the experimental studies of no-tillage and climate warming. Therefore, how no-tillage and climate warming affect the quality of cultivated lands in Xizang remains to be further studied.

In this study, a warming and no-tillage experiment was conducted to investigate their effects on soil carbon, nitrogen, phosphorus, potassium and pH at multiple depths (0–5, 5–15, 15–25 and 25–35 cm) in a spring highland barley system of the Lhasa, Xizang Autonomous Region.

2. Materials and Methods

2.1. Experiment Design and Observations

The experiment platform was set up in the Lhasa Plateau Ecosystem Research Station (91°21′ E, 29°41′ N, 3688 m) in 2015. Mean annual precipitation and temperature were 425 mm and 7.9 °C, respectively. The crop was spring highland barley. Soil types were alpine tide soil [26–28]. A nested experimental design was used: warming treatments with four levels (CK, DW, NW, DW + NW) and soil management with two levels (tillage vs. no-tillage). There were eight treatments with four replicates, including no-warming and no-tillage treatment, no-warming and tillage treatment, daytime warming (DW, 8:00–20:00 Beijing time) with or without tillage treatments, nighttime warming (NW, 20:00–8:00 Beijing time) with or without tillage treatments, and all-day warming (DW + NW, 24 h) with or without tillage treatments. The distance between any two plots was greater than 5 m. Temperature was increased by infrared heaters (Kalglo Electronics Inc., Bethlehem, PA, USA) during the whole growing seasons of spring highland barley in 2014–2018. Growing season of spring highland barley was from 23 April to 24 August in 2015, from 15 April to 16 August in 2016, from 15 April to 18 August in 2017, and from 15 April to 23 August in 2018. During non-growing season, warming was not practiced.

Soils at 0–20 cm were ploughed by a small hand-tractor for all tillage plots. About 30.00 and 15.00 g m^{-2} diammonium phosphate and urea were added were added into soils for all plots. The sowing amount was 18.75 g m^{-2} and the row spacing was 25 cm. HOBO stations were used to monitor soil temperature and moisture at 5 cm depth [27]. The NW and DW + NW treatments increased soil temperature by 1.73 °C and 2.40 °C, respectively, but the DW treatment only tended to increase soil temperature by 0.37 °C during the whole growing season of spring highland barley in 2018 (Figure S1).

2.2. Soil Sampling and Analysis

We collected soils at the depths of 0–5, 5–15, 15–25, and 25–35 cm during the end of growing season of spring highland barley in 2018. For any one of the 32 experimental plots, a soil drill with a diameter of 5 cm was used to randomly collect 3 drills and mix them as the soil sample of the plot. We measured pH, contents of soil organic carbon (SOC), dissolved organic carbon (DOC), active organic carbon (AOC), particulate organic carbon (POC), light fraction organic carbon (LFOC), heavy fraction organic carbon (HFOC), total phosphorus (TP), total nitrogen (TN), total potassium (TK), available phosphorus (AP), available nitrogen (AN) and available potassium (AK). The method of atomic absorption-flame spectrophotometry, molybdenum antimony resistance colorimetry, Kjeldahl, and potassium dichromate was used to measure TK, TP, TN, and SOC, respectively [30]. Soil pH was determined by soil pH meter [30]. AN, AP, and AK were determined by the alkalolytic diffusion method, ammonium bicarbonate extraction molybdenum antimony resistance colorimetric, and atomic absorption-flame spectrophotometry, respectively [30]. DOC was measured using a Liqui TOC II Elementar analyzer (Elementar Liqui TOC, Elementar Co., Hanau, Germany) [30]. AOC and POC were determined by KMnO4 oxidation, and LFOC and HFOC were determined by potassium dichromate [31].

2.3. Calculations and Statistical Analysis

We calculated the ratios of SOC to TN (C:N), SOC to TP (C:P), SOC to TK (C:K), TN to TP (N:P), TN to TK (N:K), TP to TK (P:K), AN to AP (AN:AP), AN to AK (AN:AK), AP to AK (AP:AK), DOC to SOC (DOC:SOC), AOC to SOC (AOC:SOC), POC to SOC (POC:SOC), LFOC to SOC (LFOC:SOC), and HFOC to SOC (HFOC:SOC). Two-way analysis of variance was used to examine the main and interactive effects of warming and no-tillage on soil variables. The R4.2.2 software was used to process all statistical analysis and make figures.

3. Results

Overall, the effects of no-tillage on soil variables were stronger than those of warming, and their interactive effects on DOC at 0–5 cm and POC at 15–25 cm were significant (Table 1). Regardless of no-tillage, the NW treatment reduced AP by 16.26% (7.59 mg kg^{-1}) at 25–35 cm and AP:AK at 25–35 cm by 25.36%, but increased HFOC by 57.62% (3.97 g kg^{-1}) at 15–25 cm (Table 2). The DW increased HFOC by 65.78% (2.46 g kg^{-1}) at 25–35 cm, but reduced AP:AK at 15–25 cm by 23.53%, and at 25–35 cm by 27.54%, regardless of no-tillage (Table 2). Regardless of no-tillage, the DW + NW treatment increased DOC by 18.71% (11.65 mg kg^{-1}) at 0–5 cm, LFOC by 68.32% (0.69 g kg^{-1}) at 0–5 cm, HFOC by 36.94% (2.29 g kg^{-1}) at 25–35 cm, DOC:SOC by 33.33% and LFOC:SOC by 133.33%, but decreased AP:AK at 5–15 cm by 26.35%, at 15–25 cm by 26.14%, and at 25–35 cm by 28.99% (Table 2).

Regardless of warming, no-tillage increased TK at 0–5 cm, 5–15 cm, 15–25 cm and 25–35 cm by 14.06%, 17.11%, 25.24%, and 19.28% and C:N at 25–35 cm by 18.44%, but decreased TP at 0–5 cm by 6.44%, AN at 5–15 cm, 15–25 cm, and 25–35 cm by 63.54%, 64.75%, and 64.19%, AP at 0–5 cm by 15.97%, DOC at 0–5 cm by 11.67%, LFOC at 0–5 cm and 5–15 cm by 36.94% and 33.39%, HFOC at 0–5 cm and 25–35 cm by 32.29% and 30.84%, N:K at 15–25 cm and 25–35 cm by 33.56% and 24.57%, P:K at 0–5 cm, 5–15 cm, and 15–25 cm by 16.82%, 13.11%, and 23.26%, AN:AP at 5–15 cm, 15–25 cm, and 25–35 cm by 59.26%, 58.33%, and 65.07%, AN:AK at 5–15 cm, 15–25 cm, and 25–35 cm by 58.67%, 62.88%, and 63.58%, DOC 0–5 cm by 21.61%, LFOC:SOC at 0–5 cm, 5–15 cm, 15–25 cm, and 25–35 cm by 45.18%, 42.43%, 35.28%, and 28.41%, and HFOC:SOC at 0–5 cm, 15–25 cm, and 25–35 cm by 39.66%, 33.05%, and 34.27%, respectively (Table 3).

Table 1. Two-way (W—warming; NT—no-tillage) ANOVA for soil variables.

	0–5 cm			5–15 cm			15–25 cm			25–35 cm		
	W	**NT**	**W × NT**	**W**	**NT**	**W × NT**	**W**	**NT**	**W × NT**	**W**	**NT**	**W × NT**
SOC	0.72	1.17	0.23	0.26	0.09	0.80	0.91	0.12	1.01	0.86	0.45	0.35
TN	0.88	0.42	1.07	0.57	0.21	0.88	0.83	1.90	0.40	0.56	1.79	0.20
TP	0.49	5.30 *	1.93	0.65	0.56	1.71	1.85	0.11	0.14	0.81	0.25	0.27
TK	2.04	6.92 *	0.13	2.66	12.57 *	2.00	1.81	16.02 *	1.02	1.22	12.92 *	1.74
AN	0.60	0.51	0.76	0.22	5.89 *	0.24	0.30	5.48 *	0.26	0.62	4.91 *	0.37
AP	0.52	7.86 *	0.74	0.90	0.28	1.15	1.70	0.86	1.02	2.13	0.02	0.52
AK	0.57	4.00	1.05	1.62	0.03	0.83	0.50	1.39	0.24	1.22	1.21	1.26
pH	1.54	0.05	0.94	0.42	1.21	0.11	0.78	0.01	0.04	0.40	0.30	0.64
DOC	3.38 *	7.67 *	3.78 *	0.17	0.44	0.61	0.84	2.98	0.15	1.18	0.47	0.81
AOC	0.95	1.63	0.21	1.28	0.16	0.25	0.61	0.49	0.04	0.94	0.11	0.25
POC	0.10	0.00	0.71	0.89	1.18	0.84	1.58	2.21	3.97 *	0.26	0.47	0.58
LFOC	3.93 *	15.71 *	0.06	0.30	13.55 *	1.00	1.53	4.13	0.78	0.49	0.90	0.10
HFOC	0.61	10.83 *	0.31	2.35	0.41	0.54	0.55	3.05	1.64	2.93	8.71 *	0.78
C:N	0.27	2.17	0.35	0.08	0.43	0.65	0.24	3.23	1.46	0.24	4.20	0.89
C:P	0.54	2.10	0.39	0.11	0.00	0.75	0.55	0.01	0.98	0.56	0.26	0.37
C:K	2.19	0.01	0.27	0.70	1.22	0.93	1.25	3.75	0.97	1.96	0.18	1.07
N:P	0.91	0.67	1.02	0.43	0.09	0.49	0.64	3.36	0.53	0.23	3.63	0.48
N:K	1.39	0.11	1.24	0.91	0.21	0.56	0.38	10.58 *	0.77	1.03	4.05	0.41
P:K	1.91	7.60 *	0.56	1.62	5.08 *	0.58	0.69	6.93 *	0.54	1.31	2.80	0.92
AN:AP	0.90	0.11	0.60	0.34	5.51 *	0.23	0.65	5.36 *	0.34	0.57	4.75 *	0.26
AN:AK	0.62	0.13	0.79	0.13	6.14 *	0.35	0.23	6.75 *	0.24	0.45	5.79 *	0.20
AP:AK	0.66	0.06	0.17	2.37	0.05	1.89	3.27 *	3.61	1.70	3.57 *	1.71	0.53
DOC:SOC	3.35 *	6.39 *	0.80	0.35	2.25	2.09	1.52	1.01	0.62	0.60	0.50	0.26
AOC:SOC	0.76	0.06	0.16	0.38	0.49	0.95	0.10	0.00	0.39	0.71	0.00	0.10
POC:SOC	0.57	0.56	0.62	0.29	0.84	1.08	0.09	1.37	1.51	0.13	0.06	0.15
LFOC:SOC	3.53 *	12.24 *	0.42	0.35	13.80 *	0.60	0.36	7.52 *	0.19	0.72	4.30 *	0.44
HFOC:SOC	1.14	8.07 *	0.67	1.58	0.99	1.49	1.04	6.61 *	1.11	0.64	7.34 *	0.02

* indicates $p < 0.05$. All numbers are *F*-values.

Table 2. Comparison of soil variables among the four experimental treatments regardless of no-tillage.

Variable	Treatment	0–5 cm	5–15 cm	15–25 cm	25–35 cm
SOC	CK	31.75 a	30.61 a	24.66 a	19.36 a
	DW	33.29 a	30.87 a	26.71 a	21.62 a
	DW + NW	28.27 a	34.06 a	31.21 a	24.33 a
	NW	28.58 a	30.59 a	25.94 a	18.84 a
TN	CK	2.18 a	1.60 a	1.10 a	0.81 a
	DW	1.30 a	1.22 a	1.02 a	0.83 a
	DW + NW	1.20 a	1.33 a	1.23 a	0.97 a
	NW	1.31 a	1.24 a	1.17 a	0.85 a
TP	CK	0.80 a	0.81 a	0.80 a	0.68 a
	DW	0.82 a	0.79 a	0.72 a	0.68 a
	DW + NW	0.81 a	0.81 a	0.81 a	0.73 a
	NW	0.78 a	0.77 a	0.73 a	0.69 a
TK	CK	4.28 a	4.56 a	4.75 a	4.67 a
	DW	4.39 a	4.39 a	4.14 a	4.43 a
	DW + NW	4.70 a	4.76 a	4.95 a	4.35 a
	NW	5.01 a	5.18 a	4.63 a	4.89 a
AN	CK	40.88 a	42.6 a	37.35 a	23.45 a
	DW	86.17 a	42.56 a	38.95 a	30.38 a
	DW + NW	57.40 a	58.95 a	55.8 a	42.67 a
	NW	40.83 a	41.68 a	35.43 a	20.57 a
AP	CK	60.77 a	60.44 a	58.69 a	46.67 a
	DW	55.13 a	53.67 a	50.83 a	42.37 ab
	DW + NW	55.89 a	53.17 a	48.40 a	41.53 ab
	NW	58.49 a	52.81 a	50.42 a	39.08 b
AK	CK	59.72 a	41.95 a	40.38 a	36.83 a
	DW	65.24 a	41.72 a	44.17 a	43.14 a
	DW + NW	57.76 a	50.95 a	44.30 a	44.11 a
	NW	71.84 a	44.50 a	39.37 a	38.74 a

Table 2. *Cont.*

Variable	Treatment	0–5 cm	5–15 cm	15–25 cm	25–35 cm
pH	CK	7.14 a	6.92 a	6.98 a	7.06 a
	DW	6.98 a	6.96 a	7.03 a	7.15 a
	DW + NW	6.94 a	6.93 a	7.07 a	7.09 a
	NW	6.96 a	6.86 a	6.94 a	7.11 a
DOC	CK	62.26 b	69.98 a	76.39 a	71.44 a
	DW	62.67 b	66.63 a	71.63 a	71.60 a
	DW + NW	73.91 a	67.31 a	69.99 a	82.08 a
	NW	65.14 ab	70.74 a	74.98 a	76.25 a
AOC	CK	4.58 a	4.88 a	4.1 a	3.42 a
	DW	5.40 a	5.42 a	4.56 a	3.58 a
	DW + NW	5.27 a	4.89 a	4.87 a	3.55 a
	NW	5.06 a	4.74 a	4.26 a	2.60 a
POC	CK	3.62 a	3.32 a	2.59 a	1.98 a
	DW	3.74 a	3.07 a	2.69 a	2.33 a
	DW + NW	3.84 a	3.87 a	3.60 a	2.25 a
	NW	4.08 a	3.24 a	2.84 a	2.18 a
LFOC	CK	1.01 b	1.04 a	0.81 a	0.57 a
	DW	1.19 ab	1.13 a	0.74 a	0.68 a
	DW + NW	1.70 a	1.13 a	1.07 a	0.74 a
	NW	1.27 ab	1.21 a	0.77 a	0.76 a
HFOC	CK	7.62 a	6.89 b	5.96 a	3.74 b
	DW	8.61 a	7.05 b	8.34 a	6.20 a
	DW + NW	9.20 a	7.91 ab	6.83 a	6.03 a
	NW	9.37 a	10.86 a	7.88 a	5.22 ab
C:N	CK	23.63 a	24.18 a	24.00 a	26.05 a
	DW	26.00 a	25.75 a	26.38 a	26.84 a
	DW + NW	23.61 a	26.23 a	25.42 a	25.30 a
	NW	22.63 a	25.36 a	23.73 a	23.44 a
C:P	CK	40.33 a	38.50 a	31.88 a	28.35 a
	DW	41.69 a	39.56 a	37.02 a	31.84 a
	DW + NW	35.16 a	42.09 a	38.71 a	33.11 a
	NW	36.79 a	40.09 a	35.33 a	27.46 a
C:K	CK	7.77 a	6.86 a	5.36 a	4.16 a
	DW	7.63 a	7.02 a	6.96 a	5.04 a
	DW + NW	6.02 a	7.09 a	6.22 a	5.77 a
	NW	5.69 a	5.95 a	5.59 a	3.87 a
N:P	CK	2.75 a	1.91 a	1.39 a	1.20 a
	DW	1.61 a	1.56 a	1.41 a	1.21 a
	DW + NW	1.49 a	1.65 a	1.54 a	1.32 a
	NW	1.67 a	1.61 a	1.59 a	1.21 a
N:K	CK	0.50 a	0.35 a	0.24 a	0.18 a
	DW	0.30 a	0.28 a	0.28 a	0.20 a
	DW + NW	0.26 a	0.28 a	0.25 a	0.24 a
	NW	0.26 a	0.25 a	0.27 a	0.18 a
P:K	CK	0.20 a	0.19 a	0.17 a	0.15 a
	DW	0.19 a	0.18 a	0.19 a	0.16 a
	DW + NW	0.17 a	0.17 a	0.16 a	0.18 a
	NW	0.16 a	0.15 a	0.16 a	0.14 a
AN:ANP	CK	0.62 a	0.62 a	0.56 a	0.52 a
	DW	1.55 a	0.83 a	0.78 a	0.71 a
	DW + NW	0.94 a	1.02 a	1.05 a	1.05 a
	NW	0.64 a	0.75 a	0.63 a	0.57 a
AN:AK	CK	0.65 a	0.92 a	0.88 a	0.57 a
	DW	1.36 a	0.91 a	0.86 a	0.66 a
	DW + NW	0.93 a	1.17 a	1.20 a	0.96 a
	NW	0.63 a	0.98 a	0.91 a	0.6 a

Table 2. *Cont.*

Variable	Treatment	0–5 cm	5–15 cm	15–25 cm	25–35 cm
AP:AK	CK	1.03 a	1.48 a	1.53 a	1.38 a
	DW	0.87 a	1.35 ab	1.17 b	1.00 b
	DW + NW	0.97 a	1.09 b	1.13 b	0.98 b
	NW	0.96 a	1.21 ab	1.32 ab	1.03 b
DOC:SOC	CK	0.0021 b	0.0024 a	0.0035 a	0.0042 a
	DW	0.0019 b	0.0023 a	0.0029 a	0.0035 a
	DW + NW	0.0028 a	0.0021 a	0.0024 a	0.0037 a
	NW	0.0025 ab	0.0024 a	0.0031 a	0.0044 a
AOC:SOC	CK	0.16 a	0.17 a	0.17 a	0.20 a
	DW	0.17 a	0.19 a	0.18 a	0.17 a
	DW + NW	0.21 a	0.16 a	0.16 a	0.15 a
	NW	0.20 a	0.16 a	0.18 a	0.15 a
POC:SOC	CK	0.12 a	0.11 a	0.11 a	0.11 a
	DW	0.11 a	0.11 a	0.11 a	0.11 a
	DW + NW	0.14 a	0.13 a	0.12 a	0.10 a
	NW	0.16 a	0.11 a	0.11 a	0.12 a
LFOC:SOC	CK	0.03 b	0.04 a	0.03 a	0.03 a
	DW	0.04 b	0.04 a	0.03 a	0.03 a
	DW + NW	0.07 a	0.04 a	0.03 a	0.03 a
	NW	0.05 ab	0.04 a	0.03 a	0.04 a
HFOC:SOC	CK	0.27 a	0.23 a	0.26 a	0.23 a
	DW	0.27 a	0.26 a	0.30 a	0.29 a
	DW + NW	0.36 a	0.26 a	0.22 a	0.27 a
	NW	0.37 a	0.36 a	0.31 a	0.31 a

Different letters indicate significant differences.

Table 3. Comparison of soil variables between tillage and no-tillage regardless of warming.

	0–5 cm		5–15 cm		15–25 cm		25–35 cm	
	No-Tillage	Tillage	No-Tillage	Tillage	No-Tillage	Tillage	No-Tillage	Tillage
SOC	32.04	28.91	32.03	31.04	27.64	26.62	21.94	20.13
TN	1.66	1.34	1.40	1.29	1.06	1.20	0.80	0.93
TP	0.78 b	0.83 a	0.80	0.79	0.77	0.76	0.70	0.69
TK	4.90 a	4.29 b	5.10 a	4.35 b	5.14 a	4.10 b	4.99 a	4.18 b
AN	46.43	66.21	24.82 b	68.08 a	21.83 b	61.94 a	15.43 b	43.10 a
AP	52.57 b	62.57 a	54.02	56.03	50.48	53.69	42.54	42.28
AK	55.29	71.99	44.47	45.09	44.18	39.93	42.44	38.97
pH	7.01	7.00	6.96	6.88	7.00	7.01	7.09	7.12
DOC	61.91 b	70.09 a	67.05	70.28	70.47	76.03	73.76	76.92
AOC	5.31	4.84	5.03	4.93	4.60	4.29	3.37	3.21
ROC	3.82	3.82	3.17	3.57	3.20	2.66	2.29	2.09
LFOC	1.00 b	1.58 a	0.90 b	1.35 a	0.72	0.97	0.63	0.74
HFOC	7.03 b	10.38 a	7.79	8.56	6.00	8.51	4.33 b	6.26 a
C:N	25.99	21.95	26.41	24.35	27.15	22.61	28.43 a	22.39 b
C:P	41.49	35.49	40.12	40.00	35.96	35.52	31.11	29.27
C:K	6.75	6.81	6.38	7.08	5.41	6.65	4.58	4.84
N:P	2.13	1.62	1.72	1.65	1.37	1.59	1.12	1.34
N:K	0.35	0.31	0.28	0.30	0.21 b	0.31 a	0.17 b	0.23 a
P:K	0.16 b	0.20 a	0.16 b	0.18 a	0.15 b	0.20 a	0.15	0.17
AN:AP	0.86	1.01	0.47 b	1.15 a	0.44 b	1.06 a	0.37 b	1.05 a
AN:AK	0.81	0.97	0.58 b	1.41 a	0.52 b	1.40 a	0.37 b	1.02 a
AP:AK	0.97	0.95	1.29	1.27	1.20	1.38	1.03	1.16
DOC:SOC	0.0020 b	0.0026 a	0.00	0.00	0.00	0.00	0.00	0.00
AOC:SOC	0.18	0.19	0.16	0.18	0.17	0.17	0.17	0.17

Table 3. *Cont.*

	0–5 cm		5–15 cm		15–25 cm		25–35 cm	
	No-Tillage	**Tillage**	**No-Tillage**	**Tillage**	**No-Tillage**	**Tillage**	**No-Tillage**	**Tillage**
POC:SOC	0.13	0.15	0.11	0.13	0.12	0.10	0.11	0.11
LFOC:SOC	0.03 b	0.06 a	0.03 b	0.05 a	0.03 b	0.04 a	0.03 b	0.04 a
HFOC:SOC	0.24 b	0.40 a	0.25	0.30	0.22 b	0.33 a	0.22 b	0.33 a

Different letters indicate significant difference.

The DW, NW, and DW + NW treatments did not alter SOC content, TN content, TP content, AN content, AK content, pH, C:P, N:P, AN:AP, AN:AK, AOC content, AOC:SOC, or POC:SOC at all soil depths (Figures 1–5). DW, NW and DW + NW did not alter N:K and HFOC:SOC at all soil depths (Figures 2 and 5).

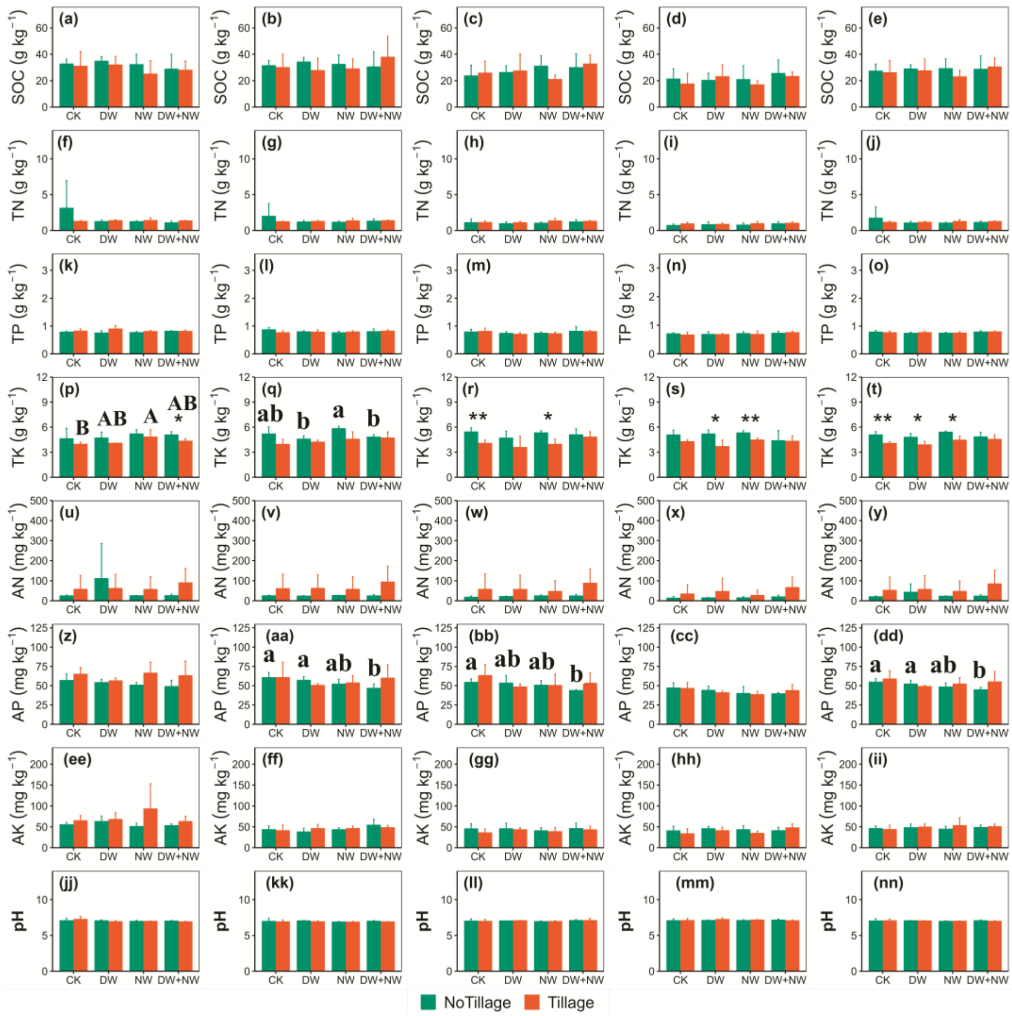

Figure 1. Comparison of (**a**–**e**) soil organic carbon (SOC) content, (**f**–**j**) total nitrogen (TN) content, (**k**–**o**) total phosphorus (TP) content, (**p**–**t**) total potassium content, (**u**–**y**) available nitrogen (AN) content, (**z**–**dd**) available phosphorus content, (**ee**–**ii**) available potassium content, and (**jj**–**nn**) pH at (**a**,**f**,**k**,**p**,**u**,**z**,**ee**,**jj**) 0–5 cm, (**b**,**g**,**l**,**q**,**v**,**aa**,**ff**,**kk**) 5–15 cm, (**c**,**h**,**m**,**r**,**w**,**bb**,**gg**,**ll**) 15–25 cm, (**d**,**i**,**n**,**s**,**x**,**cc**,**hh**,**mm**) 25–35 cm, and (**e**,**j**,**o**,**t**,**y**,**dd**,**ii**,**nn**) 0–35 cm between the no-tillage and tillage treatments, or among the control (CK), daytime warming (DW), nighttime warming (NW), and all-day warming (DW + NW) treatments. Different uppercase letters indicate comparisons among the four warming treatments under tillage conditions. In contrast, different lowercase letters indicate comparisons among the four warming treatments under no-tillage conditions. * and ** indicate the significant difference between the tillage and no-tillage conditions at $p < 0.05$ and $p < 0.01$, respectively.

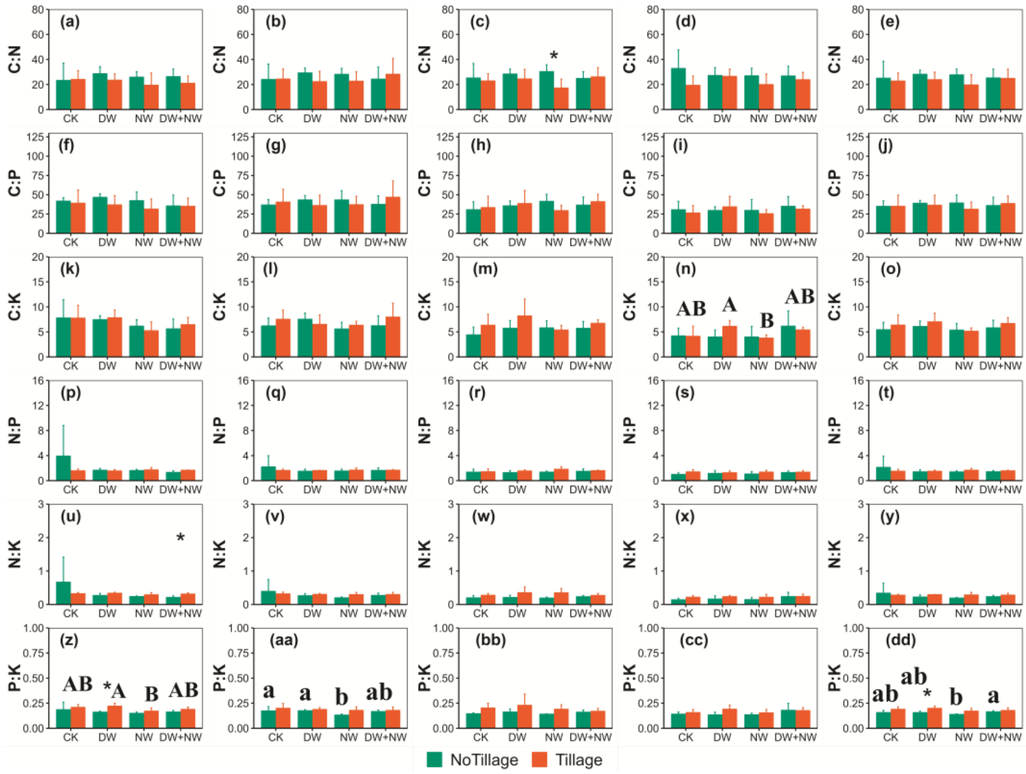

Figure 2. Comparison of (**a**–**e**) ratio of soil organic carbon to total nitrogen (C:N), (**f**–**j**) ratio of soil organic carbon to total phosphorus (C:P), (**k**–**o**) ratio of soil organic carbon to total potassium (C:K), (**p**–**t**) ratio of total nitrogen to total phosphorus (N:P), (**u**–**y**) ratio of total nitrogen to total potassium (N:K), and (**z**–**dd**) ratio of total phosphorus to total potassium (P:K) at (**a**,**f**,**k**,**p**,**u**,**z**) 0–5 cm, (**b**,**g**,**l**,**q**,**v**,**aa**) 5–15 cm, (**c**,**h**,**m**,**r**,**w**,**bb**) 15–25 cm, (**d**,**i**,**n**,**s**,**x**,**cc**) 25–35 cm, and (**e**,**j**,**o**,**t**,**y**,**dd**) 0–35 cm between the no-tillage and tillage treatments, or among the control (CK), daytime warming (DW), nighttime warming (NW), and all-day warming (DW + NW) treatments. Different uppercase letters indicate comparisons among the four warming treatments under tillage conditions. In contrast, different lowercase letters indicate comparisons among the four warming treatments under no-tillage conditions. * indicate the significant difference between the tillage and no-tillage conditions at $p < 0.05$.

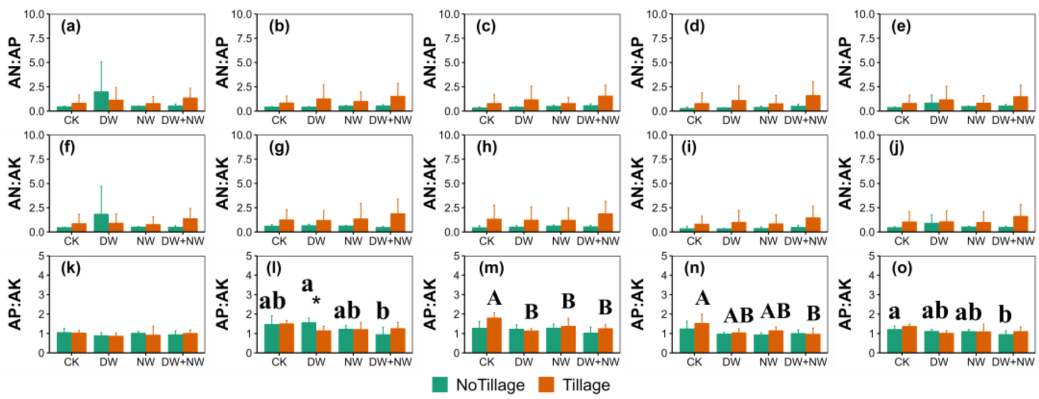

Figure 3. Comparison of (**a**–**e**) ratio of available nitrogen to available phosphorus (AN:AP), (**f**–**j**) ratio of available nitrogen to available potassium (AN:AK), and (**k**–**o**) ratio of available phosphorus to available potassium (AP:AK) at (**a**,**f**,**k**) 0–5 cm, (**b**,**g**,**l**) 5–15 cm, (**c**,**h**,**m**) 15–25 cm, (**d**,**i**,**n**) 25–35 cm, and (**e**,**j**,**o**) 0–35 cm between the no-tillage and tillage treatments, or among the control (CK), daytime

warming (DW), nighttime warming (NW), and all-day warming (DW + NW) treatments. Different uppercase letters indicate comparisons among the four warming treatments under tillage conditions. In contrast, different lowercase letters indicate comparisons among the four warming treatments under no-tillage conditions. * indicate the significant difference between the tillage and no-tillage conditions at $p < 0.05$.

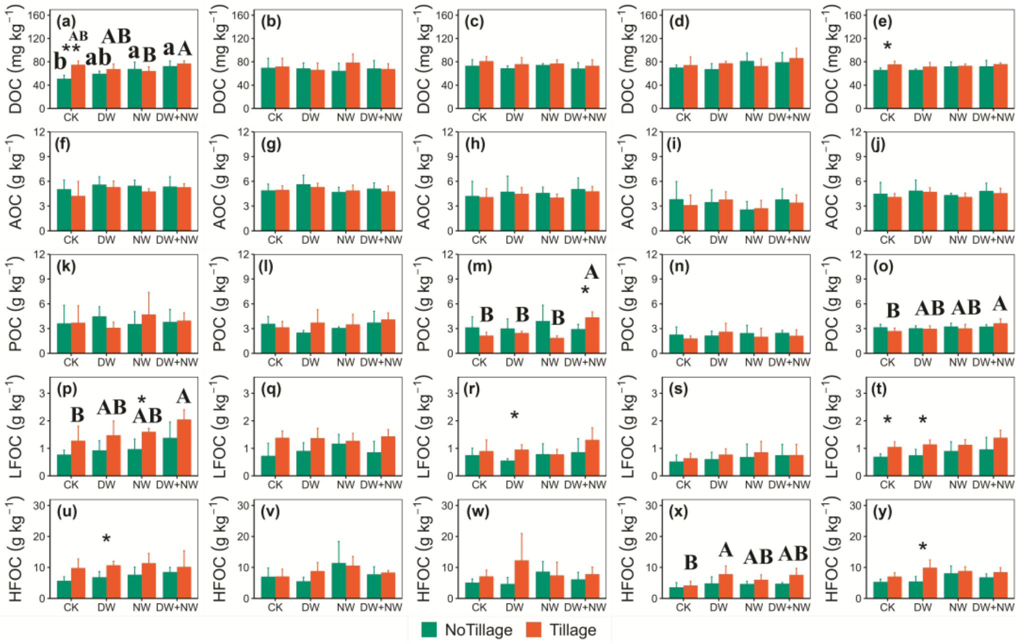

Figure 4. Comparison of content of (**a**–**e**) dissolved organic carbon (DOC), (**f**–**j**) active organic carbon (AOC), (**k**–**o**) particulate organic carbon (POC), (**p**–**t**) light fraction organic carbon (LFOC), and (**u**–**y**) heavy fraction organic carbon (HFOC) at (**a**,**f**,**k**,**p**,**u**) 0–5 cm, (**b**,**g**,**l**,**q**,**v**) 5–15 cm, (**c**,**h**,**m**,**r**,**w**) 15–25 cm, (**d**,**i**,**n**,**s**,**x**) 25–35 cm, and (**e**,**j**,**o**,**t**,**y**) 0–35 cm between the no-tillage and tillage treatments, or among the control (CK), daytime warming (DW), nighttime warming (NW), and all-day warming (DW + NW) treatments. Different uppercase letters indicate comparisons among the four warming treatments under tillage conditions. In contrast, different lowercase letters indicate comparisons among the four warming treatments under no-tillage conditions. * and ** indicate the significant difference between the tillage and no-tillage conditions at $p < 0.05$ and $p < 0.01$, respectively.

Under CK conditions, no-tillage increased TK content at 15–25 cm and TK content at 0–35 cm, but decreased DOC content at 0–5 cm, DOC content at 0–35 cm, LFOC content at 0–35 cm, and LFOC:SOC at 5–15 cm (Figures 1, 4 and 5). Under DW conditions, no-tillage increased TK content at 25–35 cm, TK content at 0–35 cm, and AP:AK at 5–15 cm, but decreased LFOC content at 0–35 cm, HFOC content at 0–35 cm, LFOC:SOC at 0–35 cm, HFOC:SOC at 0–35 cm, P:K at 0–5 cm, P:K at 0–35 cm, LFOC content at 15–25 cm, HFOC content at 0–5 cm, DOC:SOC at 0–5 cm, LFOC:SOC at 15–25 cm, HFOC:SOC at 0–5 cm, and HFOC:SOC at 15–25 cm (Figures 1 and 3–5). Under NW conditions, no-tillage increased TK content at 15–25 cm, TK content at 25–35 cm, TK content at 0–35 cm, and C:N at 15–25 cm, but decreased LFOC content at 0–5 cm and LFOC:SOC at 0–5 cm (Figures 1, 2, 4 and 5). Under DW + NW conditions, no-tillage increased TK content at 0–5 cm, but decreased N:K at 0–5 cm and POC content at 15–25 cm (Figures 1, 2 and 4).

The DW, NW, and DW + NW may have significant effects on soil carbon, nitrogen, phosphorus, and potassium (Figures 1–5). Under tillage conditions, DW treatment increased HFOC content at 25–35 cm, but decreased AP:AK at 15–25 cm (Figures 3 and 4). Under no-tillage conditions, NW treatment increased DOC content at 0–5 cm, but decreased P:K at 5–15 cm (Figures 2 and 4). Under tillage conditions, NW treatment increased TK content at 0–5 cm, but decreased AP:AK at 15–25 cm (Figures 1 and 3). Under no-tillage conditions, DW + NW treatment increased DOC content, DOC:SOC, and LFOC:SOC at

0–5 cm, but decreased AP content at 5–15 cm, 15–25 cm, and 0–35 cm, and AP:AK at 0–35 cm (Figures 1 and 3–5). Under tillage conditions, DW + NW treatment increased POC content at 15–25 cm, POC content at 0–35 cm, and LFOC content at 0–5 cm, but decreased AP:AK at 15–25 cm and 25–35 cm (Figures 3 and 4).

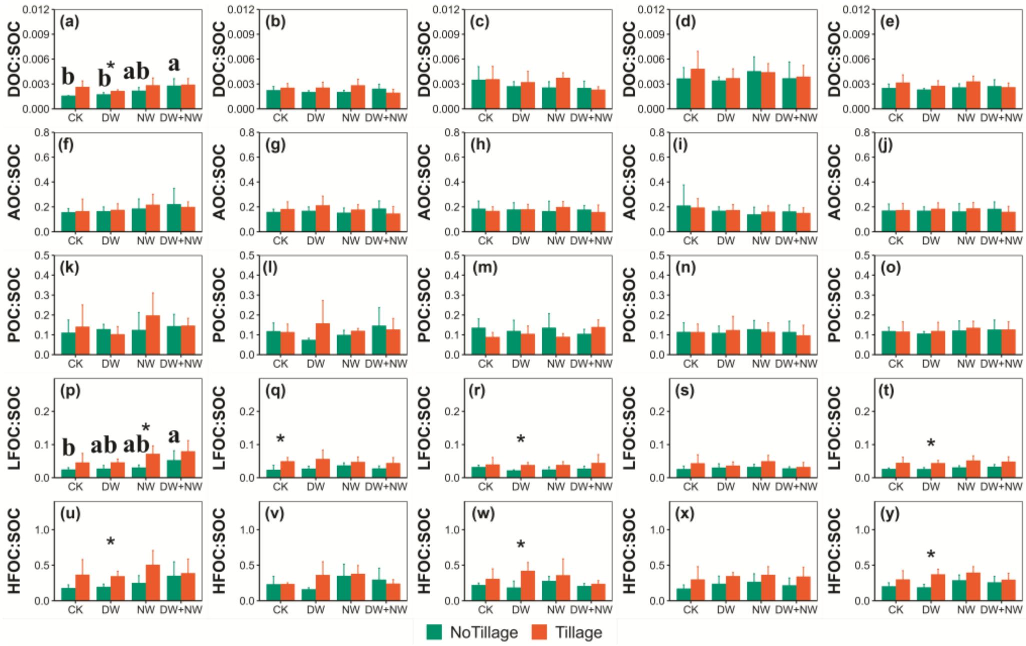

Figure 5. Comparison of (**a**–**e**) ratio of dissolved organic carbon to soil organic carbon (DOC:SOC), (**f**–**j**) ratio of active organic carbon to soil organic carbon (AOC:SOC), (**k**–**o**) ratio of particulate organic carbon to soil organic carbon (POC:SOC), (**p**–**t**) ratio of light fraction organic carbon to soil organic carbon (LFOC:SOC), and (**u**–**y**) ratio of heavy fraction organic carbon to soil organic carbon (HFOC:SOC) at (**a**,**f**,**k**,**p**,**u**) 0–5 cm, (**b**,**g**,**l**,**q**,**v**) 5–15 cm, (**c**,**h**,**m**,**r**,**w**) 15–25 cm, (**d**,**i**,**n**,**s**,**x**) 25–35 cm, and (**e**,**j**,**o**,**t**,**y**) 0–35 cm between the no-tillage and tillage treatments, or among the control (CK), daytime warming (DW), nighttime warming (NW), and all-day warming (DW + NW) treatments. Different lowercase letters indicate comparisons among the four warming treatments under no-tillage conditions. * indicate the significant difference between the tillage and no-tillage conditions at $p < 0.05$.

There were also some significant differences among the three warming treatments (Figures 1–5). Compared to NW treatment, DW and DW + NW treatments increased P:K at 5–15 cm and P:K at 0–35 cm, but decreased TK content at 5–15 cm under no-tillage conditions (Figures 1 and 2). Compared to DW treatment, NW treatment decreased C:K at 25–35 cm and P:K at 0–5 cm under tillage conditions (Figure 2). In contrast, compared to DW treatment, DW + NW treatment increased DOC:SOC at 0–5 cm, but decreased AP content at 5–15 cm and 0–35 cm, and AP:AK at 5–15 cm under no-tillage conditions (Figures 1, 3 and 5). Compared to DW + NW treatment, DW treatment reduced DOC content at 0–5 cm and POC content at 15–25 cm, but NW treatment reduced POC content at 15–25 cm (Figure 4).

4. Discussion

There is no doubt that changes in the contents of SOC and carbon components (e.g., DOC), nitrogen, phosphorus, and potassium nutrients actually depend on the relative changes of the input and output of these components under no-tillage and warming conditions [32]. The input processes of these components mainly include the application of exogenous organic and inorganic fertilizers, nitrogen deposition and phosphorus deposition, and the degradation of plant residuals, root exudates, soil microorganisms, and soil animal carcasses. The output processes of these components mainly include leaching, soil respiration, methane emission, nitric oxide emission, soil microbial retention, absorption of plant nitrogen, phosphorus, and potassium. No tillage and climate warming regulate the changes of soil organic carbon and its carbon components, soil nitrogen, phosphorus, and potassium nutrients through influencing the above processes in agricultural ecosystems. First, air temperature and precipitation can directly or indirectly affect soil temperature and moisture, the proportion of water and air in soil pores, nutrient leaching, pH, soil enzyme activity, mineralization rates of carbon, nitrogen, phosphorus, and potassium, soil microbial community structure and microbial activity, root growth, and decomposition of secretions, etc. Air temperature and precipitation are often closely related to the type of crops (species, varieties, etc.) and planting systems (e.g., single- and double-cropping). For example, highland barley is the main characteristic crop on the Qinghai-Tibet Plateau [26]. Second, inherent properties of soils, such as soil texture and organic matter content, regulate the responses and/or adaptations of soil systems to external disturbances [11,33]. For example, compared with sandy soil, loamy soil has better water and fertilizer retention performance. Soils with different textures may have different crop types and varieties suitable for planting. There should be a certain degree of coupling between crop types/varieties and soil texture types. Soil depth can affect the balance of water and air in soil systems. Moreover, soil organic matter has an adsorption effect on nitrogen, phosphorus, and potassium, so the increase or decrease of soil organic matter can generally increase or decrease the content and availability of nitrogen, phosphorus, and potassium in soils, respectively [34]. Third, water and fertilizer managements can be generally important management measures of farmland ecosystems and important measures to ensure food production and security. Farmland irrigation can change the proportion of water and air in soil pores, thus affecting the uptake of water and nutrients by plant roots, root respiration and soil microbial respiration, soil microbial community structure (e.g., changing the proportion of aerobic and anaerobic microorganisms), nutrient leaching (e.g., $NO_3{}^{-}$-N leaching), and soil pH [35,36]. Inorganic nitrogen, phosphorus, and potassium fertilizers can directly increase the content of available nitrogen, phosphorus, and potassium in soils, which may improve the nutrient absorption by crop roots, and change the entire soil microbial community structure by changing the abundance of nitrogen fixing bacteria, phosphorus solubilizing bacteria, and potassium solubilizing bacteria [37]. Organic fertilizer can not only directly increase the contents of soil organic carbon, total nitrogen, total phosphorus, and total potassium, but also change soil carbon components and available nitrogen, phosphorus, and potassium through soil microbial mediated carbon, phosphorus, and potassium mineralization processes. Since extra organic fertilizers generally contain their own specific microorganisms, the application of organic fertilizers will lead to the mixing of extra microorganisms in organic fertilizers and indigenous microorganisms in soils, breaking the dynamic balance of indigenous microorganisms in soils, and eventually forming a dynamic new balance of soil microbial community structure. Changes in soil microbial community structure can in turn affect the decomposition of soil organic matter and soil pH, in turn altering soil carbon and nutrients [38]. Changes in crops caused by water and fertilizer management can, in turn, feed back into soil systems. Fourth, crop stubble or not is also a very important field management measure. The amount and quality of crop stubble can vary with crop types/varieties, which in turn may have different feedbacks to soil systems.

Changes in soil pH under extra disturbances may mainly be due to dynamic balance of soil nitrate nitrogen and ammonium nitrogen, dynamic balance of water and air in soil porosity, and changes in soil microbial community structure, plant community structure, soil temperature, and soil moisture [39,40].

4.1. No-Tillage Effects

No-tillage did not alter contents of SOC, TN, TP, and their ratios without the interference of warming (Figures 1 and 2), which was not exactly consistent with previous studies. Meta-analyses demonstrated that no-tillage increased contents of SOC [7,9–11], TP [7], and TN [11]. In contrast, other meta-analyses showed that no-tillage did not alter soil TN content [7,10] and C:N [7]. These different findings should be attributed to the following reasons. First, these meta-analyses included different numbers of studies [7,9–11]. Second, climate regions can affect the influence of no-tillage on soil physicochemical parameter [7,9,41]. For example, no-tillage had positive effects on soil TN in temperate climate region and continental climate region but not dry climate region (e.g., the study area) and tropical climate region [41]. Moreover, the positive effects of no-tillage on contents of SOC and TN under higher mean annual temperature conditions (≥10 °C) can be greater than lower mean annual temperature conditions (<10 °C) [33]. The positive effects of no-tillage on soil TN content under the medium-level mean annual precipitation (600–1000 mm) can be generally greater than low- (<600 mm) and high-level (>1000 mm) mean annual precipitation [33]. Similarly, the positive effects of no-tillage on large macro-aggregate and small macro-aggregate organic carbon under the medium-level mean annual precipitation are generally the largest among the three precipitation ranges [33]. Mean annual temperature was 7.9 °C, and mean annual precipitation was 425 mm [27]. Third, the effects of no-tillage on contents of SOC and TN varied with soil depth [7,9,41], soil types, initial soil organic matter, and pH [42]. However, the effects of no-tillage on contents of SOC and TN were independent of soil depth (Figure 1). The positive effect of no-tillage on SOC content in loam soils was greater than that in sandy soils [9,11]. The soil texture was sandy soils in this study, whereas many loam soils were included in previous meta-analyses [9,11]. No-tillage had a greater effect on large macro-aggregate TN content in soils with medium-level initial soil organic matter (10–20 g kg^{-1}) than soils with low- (<10 g kg^{-1}) and high-level (>20 g kg^{-1}) initial soil organic matter [33]. Soil organic matter was 27.20–25.99 g kg^{-1} under the control conditions (Figure 1). Fourth, the positive effects of no-tillage on contents of SOC and/or TN may increase with no-tillage duration [7,11,41,43]. The no-tillage treatment in this study lasted less than four years. However, previous meta-analyses included many long-term (>10 and even >20 years) no-tillage studies [7,11]. Fifth, the positive effects of no-tillage on SOC content increased with nitrogen addition rate [11,44]. No-tillage with medium-level nitrogen addition rate (10–20 g N m^{-2}) had a greater positive effect on soil TN content than no-tillage with low-level nitrogen addition rate (0–10 g N m^{-2}) [11]. In contrast, no-tillage with high-level nitrogen addition rate (>20 g N m^{-2}) did not alter soil TN content [11]. In this study, the nitrogen addition rate was <20 g N m^{-2} [27]. Last, no-tillage without stubble generally had a greater positive effect on contents of SOC and TN than no-tillage with stubble [7,11,44]. The barley stubble was all removed and not left in the field in this study. However, previous meta-analyses included data of both no-tillage with stubble and without stubble [7,11]. Moreover, cropping systems may also affect the response of contents of SOC and TN to no-tillage [41,42,44].

No-tillage increased TK content at 15–25 cm and 0–35 cm without the interference of warming (Figure 1r,t). Similarly, compared to tillage with returning crop straws, two years or eight years of no-tillage with returning crop straws increased TK content at 0–4 cm or 0–5 cm but not 4–12 cm, 5–12 cm, and >12 cm in three paddy fields [45]. Two years of no-tillage increased TK content at 0–10 cm and 10–20 cm, but decreased TK content at 20–40 cm in a dryland maize field [46]. In addition, 17 years of no-tillage increased TK content at 0–15 cm in a winter wheat and summer rice rotation system [47]. In contrast, compared to tillage without returning crop straws, two years of no-tillage without returning crop straws did not alter TK content in a paddy field [45]. Therefore, the effect of no-tillage on soil TK content can be relied on soil depth, crop type, and cropping intensity.

No-tillage did not affect contents of AN, AP, and AK and their ratios without the interference of warming (Figures 1 and 3), which was not exactly consistent with previous studies. Some meta-analyses demonstrated that no-tillage did not alter contents of AP [10] and AN [7]. In addition, no-tillage did not alter AK content in Mediterranean-type climate soils [48]. In contrast, other meta-analyses demonstrated that no-tillage increased AP content [7,9] and exchangeable potassium [9]. These different findings may be attributed to one or more of the following reasons. First, different numbers of studies were included in these previous meta-analyses [7,9,10]. Second, climate regions/conditions may regulate the effects of no-tillage on soil available nutrients [49]. For example, the positive effects of no-tillage on soil AP content was only found in temperate regions but not the continental, arid or tropical regions [9]. The study area belongs to arid climate in this study. Third, no-tillage generally increased soil AP content in medium soil texture but not coarse soil texture [9], and soil texture in this study belongs to coarse type. No-tillage generally increased exchangeable potassium at 0–10 cm but not 10–20 and 20–30 cm [9]. In addition, no-tillage increased extractable phosphorus and exchangeable potassium at 0–25 cm and 25–70 cm, but decreased extractable phosphorus and exchangeable potassium 70–200 cm in semiarid Morocco [50]. However, the effects of no-tillage on soil contents of AN, AP and AK were independent on soil depth (Figures 1 and 2). Fourth, the effects of no-tillage on soil available nutrients and their ratios are related to no-tillage duration and crop types [49,51], and crop residues may be an important source of soil contents of AN, AP and AK [49]. However, when the spring highland barley was harvested, barley straw was removed from the experiment plots in this study. Fifth, no-tillage may increase soil bulk density [52,53], which in turn may reduce soil nitrogen mineralization rate [54,55]. Last, the response of soil AP content to no-tillage was generally related to that of soil pH [7], indicating that the negligible effect of no-tillage on soil pH may be important mechanism in the negligible change in soil AP content under no-tillage in this study.

No-tillage did not alter soil pH without the interference of warming (Figure 1), which was in line with some meta-analyses [7,11]. However, this finding was not consistent with another meta-analysis which demonstrated that no-tillage generally caused soil acidification [52]. These different findings should be attributed to the following reasons. First, more studies on the effect of no-tillage on soil pH were included in [52] than [7,11]. Second, no-tillage did not cause soil acidification or alkalization in areas (e.g., this study area) with an annual temperature of <8 °C and annual precipitation of <600 mm [52]. Third, soil texture can affect the response of soil pH to no-tillage [11,52]. Silty soils were included in [52] but not in [11]. Moreover, no-tillage had a greater negative effect on subsoil pH than topsoil (0–15 cm) pH [52]. In contrast, in this study, the effect of no-tillage on soil pH was not correlated with soil depth at 0–35 cm. Fourth, long-term no-tillage is more likely to lead to soil acidification than short-term no-tillage [11,52]. There were more studies, especially more long-term no-tillage studies in [52] than [11] and this study. Fifth, no-tillage caused soil acidification under double-cropping conditions but not single- and more-cropping systems [52]. For this study, since 2015, we have only planted one-growing-season spring highland barley per year (i.e., single-cropping). Sixth, no-tillage with stubble tended to cause a greater soil acidification than no-tillage without stubble [11], because microbial decomposition of crop residues may produce organic acids which can reduce soil pH [56,57]. However, there were no highland barley residues in this study. Seventh, no-tillage with high-level nitrogen addition rate (>20 g N m^{-2}) can generally cause soil alkalization, but no-tillage with low- and medium-level nitrogen addition rates cannot cause soil acidification or alkalization [11]. Last, nitrate nitrogen leaching can be an important mechanism in regulating soil pH [58]. Thus, a no-tillage-induced increase in nitrate nitrogen leaching [59] can be an important cause of potential soil acidification under no-tillage conditions. However, the positive effect of no-tillage on nitrate nitrogen leaching declined with increasing initial soil organic carbon [59]. This phenomenon implied that the relatively higher SOC content in this study area (Figure 1) can dampen the positive effect of no-tillage on nitrate nitrogen leaching.

No-tillage reduced DOC content at 0–5 cm and 0–35 cm, LFOC at 0–35 cm, and LFOC:SOC at 5–15 cm in this study area with a sandy soil texture (Figures 4a,e,t and 5q). This finding was in contrast with some studies which demonstrated that long-term (>10 years) no-tillage increased DOC content at 0–5 cm or 0–10 cm in winter wheat and summer maize rotation systems with a silt loam soil texture [21,22,60]. Moreover, the positive effects of long-term (>10 years) no-tillage on DOC content in maize season were stronger than wheat season [22]. In contrast, long-term (>10 years) no-tillage did not increase DOC content at 0–5 cm when soils were incubated at 15 °C and 21 °C [61]. Therefore, these different results may be related to their different crop types, cropping intensities, soil types, background temperatures, and no-tillage duration. In addition, nitrogen addition rates (>20 g N m^{-2}) in these previous studies [21,22,60,61] were greater than that (<20 g N m^{-2}) in this study. Compared to these previous studies (mean annual precipitation > 550 mm, mean annual temperature > 13 °C), the study area was colder and drier. All the crop residues were removed in this study but not these previous studies.

4.2. Warming Effects

The negligible effects of warming on contents of SOC, TN and TP (Figure 1) were consistent with the results observed by meta-analyses on the Tibetan plateau [62] and at a global scale [63–65]. The effects of warming on contents of SOC and TN were independent on warming method, warming duration, warming magnitude, local temperature conditions and ecosystem types [62,63]. The effect of warming on soil TP content was also independent on warming method and warming magnitude [65]. However, <1 °C warming caused a decline in SOC content [64], which was in contrast with the fact that 0.37 °C daytime warming did not alter SOC content. The sensitivity of soil TP to warming in alpine ecosystems can be lower than that in temperate ecosystems [65]. Moreover, short-term (<3 years) warming, but not long-term (>3 years) warming, increases soil TP, and the warming treatment in this study lasted for four growing seasons of spring highland barley [65]. The sensitivity of soil TP content to warming in alpine ecosystems can be lower than that in temperate ecosystems [65]. Warming combined with nitrogen addition, but not warming alone, decreased soil TP [65]. Therefore, the increased and decreased magnitudes of contents of SOC, TN, and TP caused by warming tend to be in dynamic equilibrium, which may be the main reason why contents of SOC, TN, and TP did not change in this study. In addition, the negligible change in soil TP content under warming conditions can also be due to its relatively long-term warming duration, and the relatively low temperature sensitivity and local nitrogen content in this study.

The negligible effect of warming on soil AN content (Figure 1) was not consistent with three meta-analyses [62,63], and may be due to the following reasons. First, the positive effect of warming on soil AN content increased with increasing warming magnitude [63]. The warming magnitude in this study was relatively low. Second, all-year warming but not growing-season warming can increase soil AN content [63]. In this study, soils were heated only during the growing season of spring barley. Third, the positive effect of an infrared radiator on soil AN content was lower that of a heating cable [63]. Fourth, soil microorganisms are important mediators of soil nitrogen cycling. The effect of warming on soil fungal community composition was negligible, and only nighttime warming increased topsoil α-diversity of fungal species [27,28].

The negative effect of warming on soil AP content under no-tillage conditions (Figure 1) was in line with a recent meta-analysis [65]. This finding may be due to the following reasons. First, the negative effect of warming on soil AP content declined with warming duration, but 3–6 years warming still reduced soil AP content [65]. Second, although $\geq$1.5 °C warming had a less negative effect on soil AP content than <1.5 °C warming, its negative effect was obvious [65]. However, all-day warming (2.40 °C), but not daytime warming (0.37 °C) and nighttime warming (1.73 °C), decreased soil AP content (Figure 1). The effect of diurnal asymmetrical warming on soil AP content in the alpine soils may be greater than that of warming magnitude. Third, infrared indicators, but not open top chambers, had an obvious negative effect on soil AP content [65].

The positive effects of warming on soil labile carbon composition (Figure 4) were in line with a meta-analysis [62] but not another meta-analysis [66] on the Tibetan Plateau. The cases number of [62] was greater than that of [66], which can explain the inconsistent findings of these two meta-analyses. The increase in DOC content may increase soil respiration under warming conditions in the croplands tested in this study. This speculation was in line with the finding observed by meta-analyses [62,64,66].

4.3. Interactive Effects of No-Tillage and Warming

Warming can increase or decrease the effects of no-tillage on soil carbon components (i.e., DOC and POC), and no-tillage can also increase or decrease the effects of warming on soil carbon, nitrogen, phosphorus, and potassium (Figures 1–5 and Table 1). This finding was in line with some previous studies [17,22,23,67], and can be related to the following reasons. No-tillage can generally decrease soil temperature [68] but increase soil moisture [17,69]. In contrast, warming can generally increase soil temperature but decrease soil moisture.

5. Conclusions

In summary, this is the first experimental study to investigate the effects of two-levels soil management (tillage vs. no-tillage) and four-levels of warming (control, daytime warming, nighttime warming, and all-day warming) on soil carbon, nitrogen, phosphorus, potassium, and pH at multiple depths (0–5, 5–15, 15–25, and 25–35 cm) in cultivated lands of Xizang Autonomous Region. The following conclusions can be drawn from the study: (1) both effects of warming and no-tillage on soil variables varied with soil depth; (2) the influence of daytime warming and nighttime warming on soil variables were different, and relationships between them were not always antagonistic or synergistic. Scientific findings of this study can provide services for soil carbon sequestration and nutrient management in alpine farmlands under climate warming, at least for Xizang region.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14061327/s1, Figure S1: Comparison of soil temperature (a), and soil moisture (b) between the control (CK), daytime warming (DW), nighttime warming (NW), and daily warming (DW + NW).

Author Contributions: Writing—original draft preparation, Z.Z., Y.Q., G.Z. and G.F.; writing—review and editing, Z.Z., Y.Q., G.Z. and G.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Pilot project of Chinese Academy of Sciences [XDA26050501], China National Natural Science Foundation [31370458], Chinese Academy of Sciences Youth Innovation Promotion Association [2020054], Lhasa Science and Technology Plan Project [LSKJ202422], Xizang Autonomous Region Science and Technology Project [XZ202301YD0012C; XZ202202YD0009C; XZ202201ZY0003N; Z202101ZD0007G; XZ202101ZD0003N], and Construction of Zhongba County Fixed Observation and Experiment Station of First Support System for Agriculture Green Development.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon request.

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

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