Deep-ploughing reduced nutrient contents in plough layer of paddy field—a case study of Hunan Province, China

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Abstract. In this study, the data of the typical paddy fields from 63 soil series of hydric anthroposols (paddy soil) and 26 paddy fields under tobacco-rice rotation in Huan province of China were used to assess the current thickness of the plough layers of the paddy fields, set up the criterion of deep-ploughing (30 cm in this study) feasibility for the paddy fields, and predict the possible changes of soil nutrient contents in the new plough layers after deep-ploughing. The results showed that the mean thickness of current Ap1 was 15.3 cm, and 93.2% of the paddy fields were lower than the ideal depth of 20 cm. The criterion of deep-ploughing feasibility was established by comparing the textures and bulk densities of the plow-pan (Ap2) and the below adjacent hydric horizon (Br1), i.e., Br1 is not finer than Ap2 in texture and more compacted than Ap2 in bulk density, and was preliminarily validated by a real deep-ploughing test. 69.8% of the paddy fields were feasible to deep-ploughing according to the proposed feasibility criterion. The contents of main nutrients would be significantly decreased after deep-ploughing, which indicate more fertilizers should be applied after deep-ploughing in order to maintain and promote soil fertility and the crop yields.

1. Introduction
The required thickness is no less than 20 cm for the plough layer of the farmland in China [1]. But mainly attributed to the adoption of no-tillage [2] and rotary tillage [3] in recent years, the shallowing of plough layer has become more and more common in China [4], also occurred in the paddy fields in Hunan province [5]. Southeast Hunan, where most paddy fields were under tobacco-rice rotation[6], was the main planting region of flue-cured tobacco with burnt-pure sweet aroma in China [7]. Our surveys conducted in recent years had disclosed that the thickness of the plough layers of most paddy fields were only about 15 cm. Some studies proved that deep-ploughing most were 30 cm deep-ploughing could improve not only dryland soil physiochemical properties [8-11] but also the tobacco yield and quality [10-14], however, only one report [15] so far was on the deep-ploughing of paddy field which was focused on the effects of deep-ploughing on the temperature and humidity of paddy field, the root development and economic traits of tobacco. Whether deep-ploughing was feasible for the paddy fields was still in doubt because of the worry that the leakage of water and nutrients from the original plough layer would occur once the plow-pan was broken by deep-ploughing [13-14]. However, there was no criterion on the feasibility of deep-ploughing for the paddy fields and no information of the changes of soil nutrient contents in the new plough layers formed by from deep-ploughing. Therefore, based on the data of typical paddy field profiles in Hunan province, this study was armed to establish the criterion for
determining the feasibility of deep-ploughing 30 cm defined here for the paddy fields and to predict soil nutrient changes in the new plough layers after deep-ploughing in order to provide the scientific guidance for deep-ploughing in the region of tobacco-rice rotation in Hunan province and similar regions in China.

2. Methods and Materials

2.1. Feasibility criterion and verification of 30cm deep-ploughing for paddy field

According to the traditional view, water and nutrients in the plough layer (referred as Ap1 here) was prevented moving downwards by the plow-pan (referred as Ap2 here) which was more compacted than Ap1 [16-17]. Thus, from this point of view, it can be regarded that the paddy field could be ploughed deep, when the hydroponic redox layer (referred as Br1 here) adjacent below Ap2 was more compacted than Ap2, since soil compaction can be reflected by the two indices of the texture and bulk density, so, in other words, for a paddy field, as long as: (1) the texture of Br1 was not more coarse than that of Ap2, (2) the bulk density of Br1 was not lower than that of Ap2, then, deep-ploughing was feasible for the paddy field without the occurrence of leakage of water and nutrients because Br1 would play the same role as Ap2 in maintaining water and nutrients when Ap2 was broken. Therefore, we proposed here the criterion of the deep-ploughing feasibility for the paddy field as the conditions of (1) and (2) were satisfied simultaneously.

In order to verify the above proposed criterion, before the planting of late rice in July 2019, a typical paddy field was ploughed 30 cm deep, which was located in the long-term positioning test base with tobacco-rice rotation in Fangyuan Town, Guiyang County of Southeast Hunan. The original thickness, texture and buck density was 15 cm, silty loam and 1.12 g/cm$^3$ for Ap1, 10 cm, clay loam and 1.32 g/cm$^3$ for Ap2, and 22 cm, clay loam and 1.44 g/cm$^3$ for Br1, respectively. The subsequent monitoring found that the late rice grew normally and the rice yield in the deep-ploughed field were not lower than those of the nearby paddy fields under conventional ploughing (15 cm, rotary tillage), which proved the above-proposed criterion was feasible and acceptable. Moreover, the study of 30 cm deep-ploughing in 2018 by Liu et al. [15] in paddy fields with tobacco and rice rotation in Yongan Town, Liuyang City of Hunan neither found no restriction occurred on the growth and yield of late rice, which further proved again that the paddy field can be ploughed 30 cm deep.

2.2. Data sources of typical paddy fields

In this study, the data of soil species of paddy soils in the monograph of Hunan Soil Species was not used mainly because the data were obtained in the 1980s and were regarded out of date. The adopted data of paddy field profiles mainly came from two sources:

1) the typical profiles of 63 soil series of hydragric anthrosols (paddy soil, [18]) in Hunan province surveyed Hunan Agricultural University from 2014 to 2016, which included the complete information of the particle-size composition, texture and bulk density but without the information of main nutrients, therefore, these data were used here to evaluate the thickness of current plough layers and to predict whether can be ploughed deep according to the proposed criterion.

2) the typical profiles of 26 paddy fields under tobacco-rice rotation in Southeast Hunan in the monograph of Ecological Conditions in Typical Producing Areas of Flue-cured Tobacco in China [19], which included the complete information of nutrients, while the information not available of particle-size composition, texture and bulk density, therefore, these data were used here also to evaluate the thickness of current plough layers and predict the nutrient changes after deep-ploughing.

Because the principles of determining the spatial position of typical paddy fields, the information of soil forming factors, the methods of soil survey and sampling, and the methods of determination of soil physio-chemical properties all could be obtained from the above-mentioned two literatures, thus, this information were not described repeatedly here.

2.3. Calculation of nutrient contents in new plough layer
Since only soil nutrient content is predicted in this study, so the calculation method of nutrient contents in the new plough layer formed by 30 cm deep-ploughing was simply but acceptably defined as follows:

$$X_{ij30cm} = \frac{\sum (X_{ij} \times H_j)}{30}$$ \hspace{1cm} (1)

In formula (1), $X_{ij}$ is the current content of $i$ nutrient in the current $j$ layer, $X_{ij30cm}$ is the content of $i$ nutrient in 0~30 cm (thickness of the new plough layer), $H_j$ is the current thickness (cm) of the current $j$ layer. But it should be pointed out here that the parameters of soil bulk density and gravel content are not included in formula (1), because this formula is not used to calculate soil nutrient density or storage. In addition, no gravel was found in 0~30 cm depth in the studied soil profiles according to the original data.

The nutrients involved in this study included soil organic matter (SOM), alkali-hydrolyzed nitrogen (AN), available phosphorus (AP), available potassium (AK), water-soluble Cl$^-$ (Cl$^-$), available zinc (AZn), exchangeable Ca$^{2+}$ and Mg$^{2+}$ (Ex. Ca$^{2+}$ and Mg$^{2+}$).

**2.4. Data Processing and Statistics**

Microsoft Excel 2016 and IBM Statistics SPSS 22.0 software were used for statistical analysis of the data, and Duncan test method (P < 0.05) was used for analysis of variance and multiple comparisons (P= 0.05). Statistical descriptive indicators included range, mean value, standard deviation, and coefficient of variation, etc. [20-21].

3. Results

3.1. Status of Nutrient contents in current plough layer

Table 1 shows that the statistical information of the thickness of current plough layers of 89 typical paddy fields in Hunan province. It can be seen from Table 1 that the thickness of current plough layer ranged from 10 to 22 cm with an average of 15.3 cm, and no significant difference at the P<0.05 level was found between the thickness of the current plough layers of paddy fields of soil series (15.2 cm) and paddy fields under tobacco-rice rotation (15.5 cm). The above results show that the average thickness of the current plough layers of paddy fields in Hunan province was 4.7 cm lower than that required by national high-standard paddy field construction (20 cm) [1], and among them, 83 paddy fields (93.2% of the total paddy fields) were less than 20 cm in the thickness of current plough layer, which further indicates that the shallowing of the plough layer was common in the paddy fields in Hunan and it was really needed to be deep-ploughed at least to 20 cm depth.

| Typical paddy field | Paddy field of soil series | Paddy field under tobacco-rice rotation | Total |
|---------------------|---------------------------|----------------------------------------|-------|
| Paddy field number  | 63                        | 26                                     | 89    |
| Thickness of current plough layer | Range (cm) | 10~22 | 11~19 | 10~22 |
| Mean ± SD (cm)      | 15.2±2.9a                 | 15.5±1.7a                             | 15.3±2.6 |
| C.V. (%)            | 19.3                      | 10.9                                   | 17.2  |

Note: Values in the same line followed by same letter are not significantly different at the 0.05 level.

3.2. Feasibility evaluation of deep-ploughing for rice field

Table 2 and Table 3 show the statistical information of the texture types (USDA system [22]) and bulk densities of the plow-pan (Ap2) and the below adjacent hydragric horizon (Br1) of 63 typical soil series of hydragric anthrosols in Hunan province, respectively.

| Soil texture | Plow-pan (Ap2) | Below adjacent hydragric horizon (Br1) |
|--------------|----------------|---------------------------------------|
There were six texture types, included sandy loam, silt loam, loam, sandy clay loam, silt clay loam and clay loam. 42 paddy fields (66.7% of the total number of paddy fields) were in the same texture for Br1 and Ap2, and 10 paddy fields (15.9% of the total number of paddy fields) had finer texture in Br1 than those of Ap2, in total, the textures of Br of 52 paddy fields (82.5% of the total number of paddy fields) were not coarser than those of Ap2.

The bulk densities of 53 paddy fields (84.1% of the total paddy fields) were higher than those of Ap2, which was 1.9% ~ 62.6% higher with a mean of 16.1%. Combined with the two indicators of texture and bulk density, 44 paddy fields were feasible to be ploughed 30 cm deep, accounting for 69.8% of the total paddy fields, which indicated that at least 2/3 of the paddy fields could be ploughed 30 cm deep.

Table 3. Statistics of soil bulk densities of plow-pan (Ap2) and adjacent hydragric horizon (Br1) of typical paddy fields in Hunan.

| Soil bulk density (g/cm³)          | Plow-pan (Ap2)       | Below adjacent hydragric horizon (Br1) |
|------------------------------------|----------------------|----------------------------------------|
| Range                              | 0.91~1.67            | 1.15~1.74                              |
| Mean ± SD                          | 1.30±0.16a           | 1.45±0.15b                             |

Note: Values in the same line followed by different letters are significantly different at the 0.05 level.

3.3. Predicted nutrient changes in new plough layer after 30cm deep-ploughing

Table 4 shows that the nutrient contents and their changes before and after 30 cm deep-ploughing in 26 typical paddy fields under tobacco-rice rotation in Hunan province. It can be seen from Table 4 that the contents of soil organic matter, alkali-hydrolyzed nitrogen, available phosphorus, rapid available potassium, and available zinc all were significantly decreased, and the decrease range was between 18.41% ~ 37.26%, while the contents of water-soluble Cl- and exchangeable Mg²⁺ showed insignificant decreasing trend at P<0.05 level and only the content of exchangeable Ca²⁺ showed an insignificant increasing trend at P<0.05 level.

Table 4. Statistics of nutrient contents in tillage layers before and after 30 cm deep-ploughing of typical farmlands in Hunan.

| Nutrient       | Current PL   | Mean ± SD 30 cm DP | Change (%) | C.V. % 30 cm DP |
|----------------|--------------|--------------------|------------|-----------------|
| SOM g/kg       | 41.76 ±13.85A | 34.07±12.32B       | -18.41     | 33.2            |
| AN mg/kg       | 180.98 ±40.79A | 145.74±32.60B      | -19.47     | 22.5            |
| AP mg/kg       | 48.25 ±24.17A | 30.27±13.33B       | -37.26     | 50.1            |
| AK mg/kg       | 270.77 ±98.28A | 200.82±59.84B      | -25.83     | 36.3            |
| Cl- mg/kg      | 21.55 ±14.52A | 19.66±10.19a       | -8.77      | 67.4            |
| AZn mg/kg      | 4.31 ±4.59A   | 3.04±3.59B         | -29.47     | 106.7           |
| Ex. Ca²⁺ cmol (+)/kg | 24.23 ±20.72a | 24.63±19.84a        | 1.65       | 85.5            |
| Ex. Mg²⁺ cmol (+)/kg | 1.48 ±0.70a  | 1.45±0.66a          | -2.03      | 47.3            |
matter content, mechanical composition, and composition of layer formed by deep ploughing was complicated, which need to consider more factors, such as organic produc... 

regarded more reasonable for paddy fields. 

50 cm deep, which was about 5 times of 30 cm deep and quality of flue... 

assert the effects of 40 cm or 50 cm deep and promote the root growth and grain yield of upland rice [30]. 

in the new plough layer formed by deep ploughing breaks Ap2, Br1 can and will play the role of maintaining water and nutrients as the original Ap2, and we think Br1 would be developed into a new plow-pan (Ap2) eventually. Based on the information of the textures and bulk densities of current Ap2 and Br1 of 63 typical soil series of hydragric anthrosols in Hunan, we estimated that at least 2/3 of these soil series could be ploughed 30 cm deep, which can provide theoretical basis and scientific guidance for the deep-ploughing of paddy fields in Hunan and in other similar regions. 

Although the effects of deep-ploughing in improving soil properties and increasing the crop yield have been proved by many studies [23-29], and some studies showed that deep tillage could improve soil physical properties (such as bulk density, porosity, aggregate stability, and penetration resistance) and promote the root growth and grain yield of upland rice [30-33]. but some studies have shown that the effect of yield-increasing can only last for about 3~5 years [34]. Our study shows that after 30 cm deep-ploughing, the contents of organic matter, alkali-hydro nitrogen, available phosphorus, potassium and zinc were significantly decreased when compared with the original plough layer, firstly, this reduced trend is normal, because of the long-term fertilization and straw returned to field usually lead to the nutrient accumulation in the plough layer [35], which causes the nutrient contents are generally higher in the plough layer than in the lower layers; secondly, it also reminds us that the change of soil nutrients in the new plough layer formed by deep-ploughing should be monitored in order to timely apply sufficient fertilizers to maintain and improve soil fertility for crop normal growth and realize the sustainable application of soil resources. 

As to whether the ploughing was 30 cm deep or deeper, some studies showed that it was hard to assert the effects of 40 cm or 50 cm deep-ploughing were better than 30 cm deep-ploughing in the yield and quality of flue-cured tobacco [9,13]. We found that it took about 7.5 h to plough 15 hm² paddy fields to 50 cm deep, which was about 5 times of 30 cm deep-ploughing, without considering the cost of fuel consumption and the possible damage to tillage machinery. Therefore, 30 cm ploughing could be regarded more reasonable for paddy fields. 

In addition, soil pH was also the important factors affecting the yield and quality of tobacco production [36-38], but it was not considered in this study, because the pH calculation of new plough layer formed by deep ploughing was complicated, which need to consider more factors, such as organic matter content, mechanical composition, and composition of clay minerals [39-41], these factors were
different in layers of Ap1, Ap2 and Br1, thus, could not adopt simply the calculation formula of soil nutrients.

5. Conclusion
Our study showed that current plough layer was universally shallow in the paddy fields in Hunan province, and most paddy fields can be ploughed to 30 cm deep, but the contents of main nutrients in the new plough layer formed by 30 cm deep-ploughing would be significantly lower than those of the current plough layer, which indicated more fertilizers should be applied possibly for maintaining or improvement soil fertility of the plough layer and the growth and yields of crops.

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