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THEORY AND METHOD FOR WETLAND BOUNDARY DELINEATION

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ABSTRACT: Based on the analysis of the subjectivity of wetland boundary criteria and their causes at present, this paper suggested that, under the condition that the mechanism of wetland formation process has not been understood, "black box" method of System Theory can be used to delineate wetland boundaries scientifically. After analyzing the difference of system construction among aquatic habitats, wetlands and uplands, the lower limit of rooted plants was chosen as the lower boundary criterion of wetlands. Because soil diagnostic horizon is the result of the long-term interaction among all environments, and it is less responsive than vegetation to short-term change, soil diagnostic horizon was chosen as the indicator to delineate wetland upper boundary, which lies at the thinning-out point of soil diagnostic horizon. Case study indicated that it was feasible using the lower limit of rooted plants and the thinning-out point of soil diagnostic horizon as criteria to delineate the lower and upper boundaries of wetland. In the study area, the thinning-out line of albic horizon was coincident with the 55.74m contour line, the maximum horizon error was less than 1m, and the maximum vertical error less than 0.04m. The problem on wetland definition always arises on the boundaries. Having delineated wetland boundaries, wetlands can be defined as follows: wetlands are the transitional zones between uplands and deepwater habitats, they are a kind of azonal complex that are inundated or saturated by surface or ground water, with the lower boundary lying at the lower limit of rooted plants, and the upper boundary at the thinning-out line of upland soil diagnostic horizon.
KEY WORDS: wetland boundary; "black box" method; soil diagnostic horizon; thinning-out point (line); wetland definition

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1 INTRODUCTION

There is no single and universally recognized wetland definition so far. More than 50 of wetland definitions have been developed (YANG, 2002; DUGAN, 1993; MITCH and GOSSELINK, 1996; NRC, 1995). Because wetlands form part of a continuous gradient between uplands and open water, the problem on wetland definition usually arises on the edges of wetlands, toward either wetter or drier conditions (NRC, 1995; MITSCH and GOSSELINK, 1996). What frequency, depth and duration should the land flood before we can declare that it is not a wetland? On the other edge, what frequency, depth and duration do we venture into a lake, pond, estuary, or ocean before we are no longer in a wetland? These problems are important parts of the mechanism on wetland formation process. Up to now, we have not understood them (NRC, 1995; MITSCH and GOSSELINK, 1996; SKAGGS and AMATYA, 1994). As a result, any criteria for wetland boundary delineation and related boundaries are to some extent arbitrary (YANG, 2002; NRC, 1995; MITSCH and GOSSELINK, 1996). Nevertheless, wetland definition and its boundaries delineation are important for both the scientific understanding of these systems and their proper management. The definition problem has caused confusion and inconsistency in the management, classification, and inventory of wetland systems (NRC, 1995; MITSCH and GOSSELINK, 1996; YU, 2001). Aiming to resolve the problems on wetland definition and boundary delineation and to achieve "no net loss" in the quantity, quality, and biological diversity of existing wetlands, some agencies have developed manuals to instruct users to delineat wetland boundaries. The primary document for wetland delineation is "1987 Corps Manual"(USACE, 1987).

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Table 1 Criterion for wetland boundary delineation in some manuals/definitions

Manual (source)	Hydrology		Vegetation threshold	Evidence for hydric soil
	Hydrologic threshold	Critical depth		
1987 Corps Manual (USACE, 1987)	Inundation or saturation at surface for > 12.5% of growing season	Root zone (12 in., 30cm)	> 50% of the dominant species OBL, FACW, or FAC	Saturation depth 12 in. (30cm)
1989 Interagency Manual (USFWS et al., 1989)	Inundation or saturation at surface for at least 7 days in growing season	0.5-1.5 ft depending on soil	> 50% of the dominant species OBL, FACW, or FAC	7-day flooding
1991 Proposed Manual (NRC,1995)	15-day inundation or 21-day saturation during growing season	Surface	Prevalence index < 3.0	15-day inundation or 21-day saturation
1994 NFSAM (NRCS, 1994)	Inundation at surface for 15 days for most areas; 7 days for potholes, playas, or pocosins	Surface	Prevalence index < 3.0	7-day flooding or 14-day saturation at or near surface
1995 NRC (NRC, 1995)	Inundation or saturation at surface for at least 14 days during growing season	Saturated depth 30cm	50% hydrophytic, or prevalence index< 3.0	14-day inundation or saturation
Ramsar criterion (RCIONFBC, 2001)	-	6m at low tide, all inland water body	-	-
Chinese criterion (WANG and XIAO, 1995; TONG and LIU, 1995)	Inundation 4 months in a year or 1/2 of growing season	2m	-	-

Notes: OBL: Obligate wetland plant; FACW: Facultative wetland plant; FAC: Facultative plant

As Table 1 showed, there were fewer controversies on the criterion of wetland lower boundary. Most of manuals (except "Ramsar Convention") agreed that the boundary between wetland and deepwater habitat in the Marine and Estuarine Systems coincided with the elevation of the extreme low water of spring tide; the boundary between wetland and deepwater habitat in the Riverine and Lacustrine Systems lied at a depth of 2m (6.6 feet) below low water (COWARDIN et al., 1985).

For the criteria of wetland upper boundary, most of the manuals focused on the indicators of water depth, inundated/saturated frequency, inundated/saturated duration during the growing season, the percentage of the dominant species content and so on. Because we have not fully understood the mechanism of wetland formation processes so far, all criteria on inundation/saturation frequency, depth, and duration were "man-prescribed". When using hydric soil indicators to delineate wetland boundary, water table depth to the surface and saturation duration during growing season were always chosen as important indicators. Therefore, hydric soil criteria were usually related to hydrological criteria.

Although vegetation was often the most readily observed parameter, many plant species, due to their broad ecological tolerances, could grow successfully in both wetlands and uplands (e.g. Acer rubrum and Calamagrostics angustifolia) (WSDE, 1997; STEVE et al., 1995). We have not understood the ambiguities of communities that cannot be easily classified, and the average annual duration of inundation or soil saturation did not preclude the occurrence of plant species typically adapted for life in aerobic soil conditions. So, the vegetation criteria applying to delineating wetland boundary were also arbitrary criteria to some extent (WSDE, 1997; STEVE et al., 1995).

The wetland definition given in "Ramsar Convention" was popularly accepted (WANG and XIAO, 1995; ZOLTAI and VITT, 1995; PENG, et al., 2003; LU, 2005), which defined wetlands as areas of marsh, fen, peatland or waters, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salty, including areas of marine waters with water depth below six meters at low tide. This wetland definition is not a perfect one, not only because it prescribed the lower limit of wetlands arbitrarily, but also did not present criteria to delineate wetland upper boundary.

In conclusion, under the condition that the mechanism of wetland formation process has not been fully understood, all criteria for delineating wetland boundaries were "man-prescribed". Wetland boundaries based on man-prescribed criteria were not natural wetland boundaries, because the natural boundaries of any complex could only be cognized, not be man-prescribed. This was why any wetland boundary criterion and related wetland boundary were arbitrary and a universally recognized wetland definition had not been developed so far. Even if there was no controversy on the criteria, it was usually impractical to measure the indicators in the field accurately, because it took repeated visits over a lengthy (several years) period of time, and both seasonal conditions and recent weather conditions should be considered when applying these indicators (WSDE, 1997; STEVE et al., 1995).

The purpose of the paper is to, under the condition that the mechanism of wetland formation process has not been fully understood, develop a scientific and objective rather than arbitrary and subjective method to delineate wetland boundaries.

2 THEORY AND METHOD FOR DELINEATING WETLAND BOUNDARY

Because wetlands might be bordered by both wetter areas (deepwater habitats) and by drier areas (uplands), criteria for wetland delineation must be presented for both the wetter boundary (the lower boundary) and the drier boundary (the upper boundary) (MITSCH and GOSSELINK, 1996; USACE, 1987).

2.1 Theory and Method for Delineating Wetland Lower Boundary

It was accepted that wetlands are transition zone between terrestrial and aquatic ecosystems and exhibit some of the characteristics of each (MITSCH and GOSSELINK, 1996; NRC, 1995; SMITH, 1980), but what characteristics of terrestrial and aquatic ecosystems did wetlands exhibit? Comparing the construction difference among aquatic ecosystem, wetland ecosystem, and upland ecosystem, we can find that they support different food chains: aquatic ecosystem supports food chains based on phytoplankton; upland ecosystem based on rooted vegetation; wetland ecosystem based on the both. The components of aquatic ecosystem preclude rooted-plants, so, it is reasonable considering that, along the topographic gradient from uplands to aquatic habitats, the lower limit of rooted-plants can be regarded as the lower boundary of wetlands.

In many literatures (USACE, 1987; TONG and LIU, 1995; COWARDIN et al., 1985; SMITH, 1980; WSDE, 1997), inland aquatic habitats were defined as areas that were permanently inundated at mean annual water depths >2m (6.6ft) or permanently inundated areas <2m in depth that did not support rooted-emergent or woody plant species. The 2m lower limit for inland wetlands was selected because it represented the maximum depth to which emergent plants normally grown (LEWIS et al., 1985). Considering the diversities of hydrological regime and aquatic plant species, the 2m lower limit does not represent the maximum depth to which all emergent plants always grow. Therefore, when delineating wetland lower boundary, the rooted-plant criterion is more reasonable than a maximum lower criterion, because, in some wetlands, the lower limits of rooted plants are naturally within or beyond the 2m boundary.

2.2 Theory and Method for Delineating Wetland Upper Boundary

2.2.1 Theory on delineating wetland upper boundary

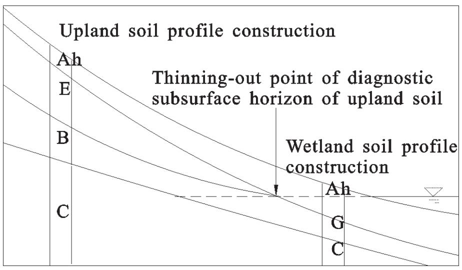
The controversy on the criterion of wetland upper boundary always resulted from the lacking of understanding to the mechanism of wetland formation process. From System Theory perspective (HE, 1990; CHANG, 2004; LAI and DENG, 2004; WEI and ZENG, 1999), system boundary was an important structure factor of a system. No boundary, no system. Studying on any kind of system, its boundary must be identified firstly. When the mechanism of system process has not been fully understood, and if the output result could be measured accurately, "black box" method could be used to study system structure and function.

Furthermore, according to Geographic System Theory (SUO, 1991), when selecting indicator to delineate the distribution boundary of geographic process, invariable indicator should be chosen and boundary based on instantaneity indicator is unrepeatable and controversial.

Therefore, under the condition that the mechanism of wetland formation process has not been fully understood, wetland boundaries could also be identified scientifically, but the indicators chosen must meet the following two qualifications: 1) reflecting the result of long-term interaction among all environmental elements, which makes it satisfy the requirement of "black box" method; and 2) relative invariability, which can eliminate the effect of seasonal or short-term hydrological fluctuation on the field survey result, consequently, ensure the survey result repeatable.

From geography perspective, soil diagnostic horizon acted as "the mirror of nature", which meant that it could factually reflect the result of long-term interaction among all environmental elements (MITSCH and GOSSELINK, 1996; NRC, 1995; LI et al., 2004; WU and CAI, 2004; GONG, 1999). Soil diagnostic horizon is less responsive than vegetation to short-term change, which made soil diagnostic horizon relatively invariable (MITSCH and GOSSELINK, 2000; NRC, 1995; WU and CAI, 2004). Therefore, soil diagnostic horizon satisfies the two qualifications.

Although wetland is also a kind of continuum, this kind of continuum is different from the zonal continuum. The formation process of zonal continuum is driven by zonal climate, which makes the zonal continuum has a very gentle environmental gradient in horizon direction. Micro-variation of climate may cover extensive scope. As a kind of azonal continuum (WU and CAI, 2004; ZUO, 1990), the formation process of wetland was driven by the intersection of topographic slope and water table (Fig. 1), which made the continuum has a very large environmental gradient along the slope. Micro-variation of water table may cause great change in soil characteristics. What is more, because the intersection of topographic slope and water table, water table depth and the thickness of soil diagnostic horizon thin out along topographic gradient, especially the thinning-out point of upland soil diagnostic horizon is a kind of critical point. It is reasonable considering that there are no the conditions for forming upland soil beyond the thinning-out point. Uplands and wetlands develop different soil diagnostic horizon. If the thinning-out point of upland soil diagnostic horizon can be identified, it can be regarded as the boundary of wetlands.



Ah: histic epipedon; E: albic horizon; B: claypan layer; G: gley horizon; C: parent material

Fig. 1 Thining-out sketch of diagnostic subsurface horizon of upland soil at wetland upper limit

Because the upper boundary of wetland lies between wetland and upland, it is also the lower boundary of uplands. The viewpoint that upland ecosystem was well defined (MITSCH and GOSSELINK, 1996; NRC, 1995) was illogical, because there would not be any controversy on the boundary between uplands and wetlands if upland lower boundary was well identified. So, wetland upper boundary identification can be carried out from two directions: 1) based on wetland indicator criterion in the direction from wetlands to uplands; and 2) based on upland indicator criterion in the direction from uplands to wetlands. Especially for wetlands that wetland vegetation can not grow and wetland soils do not develop, the latter is especially effective. In most of wetland boundary delineation manuals, wetland indicators were usually chosen to identify wetland boundary, but upland indicators were ignored.

2.2.2 Method and step

During the period of field observation, the thinning-out point identification requires digging holes to a certain depth along the topographic gradient from uplands to wetlands, and observing the thickness variation of soil diagnostic horizon. If the soil types of two adjacent sample sites are upland soil and hydric soil, respectively, we can affirm that the thinning-out point of upland soil diagnostic horizon must lie at somewhere between the two holes. Although it is difficult to identify the exact "point", if only enough holes were examined, the precision would be improved.

Specific methods and steps are described in case study.

3 HOW TO FIND THINNING-OUT POINT —CASE STUDY

3.1 Study Area

Aiming to verify the existing of the thinning-out point, a case study was carried out during September 14-16, 2005. The study site is located at the Sanjiang Mire Wetland Experimental Station, Chinese Academy of Sciences, in Tongjiang City, Heilongjiang Province, China, at approximately 47°35′N, 133°31′E. The altitude of study site varies from 55.3 to 56.6m above sea level, the average annual precipitation is around 600mm and the mean annual temperature is 1.9℃. The Quercus mongolica-Betula platyphylla community is the main upland vegetation. Because the distribution pattern of the community is just like islands, the upland vegetation is called tree island. As Fig. 2 showed, the area of study site is about 100hm^2, and there are several tree islands and open waters in the study area. Former studies (GONG, 1999; LMBHP and OHSI, 1992; YANG et al., 2004; LIU et al., 2005a; 2005b) on the soil series in the area indicated that the typical upland soil was albic soil, and the albic horizon was the diagnostic horizon; the soil type beneath Salix brachypoda-Salix myrtilloides-Calamagrostis angustifolia community, which is the community adjacent to tree island, belonged to hydric soil. So, the thinning-out point of albic horizon was chosen as the criterion of wetland upper boundary.

3.2 Method

Method for conducting wetland upper boundary identification is as follows.

(1) To acquire and compare the difference of diagnostic horizons between upland soil and hydric soil.

Sampling transect was chosen as Fig. 2 showed, and sample sites were showed in Fig. 3. Sample site 1 was located within the Quercus mongolica-Betula platyphylla

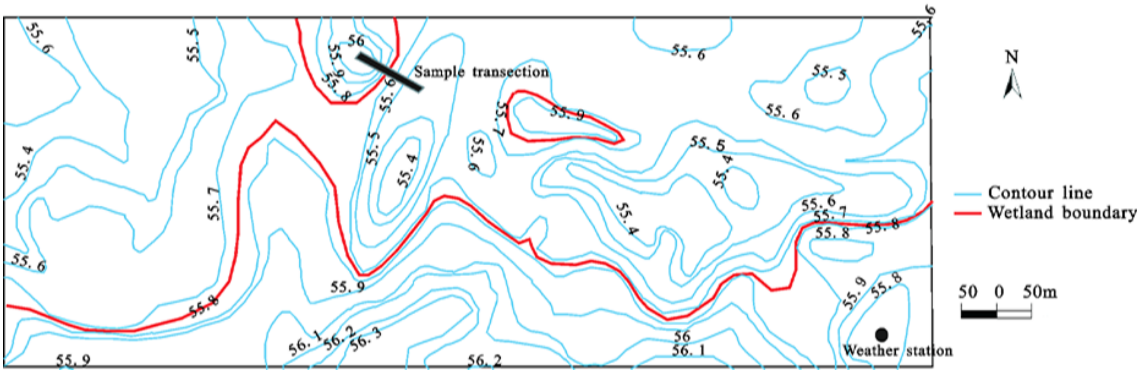


Fig. 2 Sketch map of contour lines, sample transection, and wetland boundary in study area

community. Digging a hole at least the depth of the bottom of albic horizon, the soil profile showed that the surface soil layer (0-15cm) was histic epipedon (Ah horizon), the subsurface soil layer (15-27cm) was albic horizon (E horizon), beneath the albic horizon was the claypan layer (B horizon). The most notable feature of albic horizon was its albic color resulting from the lateral eluviation of Fe^{2+} and Mn^{2+} seasonally. Sample site 2 was located at the middle point of Salix brachypoda-Salix myrtilloides-Calamagrostis angustifolia community. The distance between the two sample sites was 7m. The soil profile of sample 2 showed that the surface horizon (0-17cm) was histic epipedon (Ah horizon), the subsurface soil layer was gley horizon (G horizon). Comparing to albic horizon, the most notable feature of gley horizon is its bice to black color resulting from the accumulation of Fe^{2+} and Mn^{2+}, and organic material accumulation in the horizon also contributes to its color. Because the two soil types represented typical upland soil and wetland soil, respectively, the thinning-out point of albic horizon must lie at somewhere between the two sample sites.

(2) To identify the location of the thinning-out point of albic horizon.

In the study area, the boundary of tree island is the most readily observed boundary. In order to check if the boundary is coincidence with the thinning-out point of albic horizon, sample site 3 was located at the edge of tree island. The distance between sample site 3 and sample site 1 is 4m. The soil profile of sample 3 showed that the surface horizon (0-16cm) was histic epipedon, the subsurface horizon was still gley horizon, which meant that the thinning-out point of albic horizon was not coincident with the boundary of tree island, and the thinning-out point must lie at somewhere between sample 3 and sample site 1. So, sample site 4 was located at the middle point between the two sample sites. The profile showed that the surface layer (0-15cm) was histic epipedon, the subsurface layer was still albic horizon, but the thickness decreased to 4cm. Because the soil types of sample 3 and sample 4 were hyric soil and albic soil, respectively, the thinning-out point must lie at between sample 3 and sample 4. The distance between sample 3 and 4 was 2m. Sample 5 was located at the middle point of sample site 3 and 4. The soil profile of sample 5 showed that the thickness of histic epipedon was 15cm, the subsurface presents the transition characteristics from albic horizon to gley horizon, which meant that sample 5 was in the transition zone between ablic soil and gley soil, the thinning-out point of albic horizon must be near sample 5.

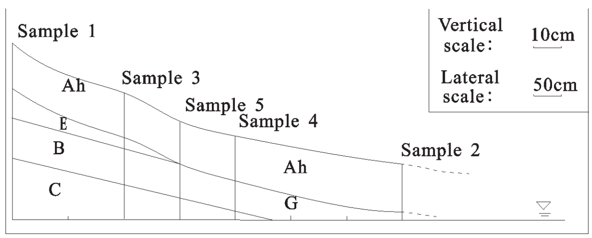


Fig. 3 Thinning-out sketch of the albic horizon along sample transection in study area

The transition characteristics at sample 5 make it very difficult to identify the exact location of the thinning-out point of albic horizon, because the criterion differentiating albic and gley horizon must be understood before identifying the thinning-out point. In order to avoid the controversy resulting from man-prescribed criterion, we chose the accuracy to express the possible location of the thinning-out point. Because the soil types of sample 3 and sample 4 are hyric soil and albic soil, respectively, and the distance between the two sites is 2m, if site 5 is chosen as the thinning-out point, the maximum horizon error would be less than 1m.

(3) To identify the boundary of wetlands in the study

area.

Water level of all sample holes had been at the same height after two days lateral seepage. The relative heights above groundwater level of the five sample sites were measured on the third day. The result showed that the relative height of sample 5 was 0.35m above groundwater level. At the same time, the relative height of the point of altitude 56.6m was 1.21m above groundwater level. So, the altitude of the site 5 is 55.74m.

Because the hydrologic regime is the same in the area, it is reasonable to consider that the all thinning-out points of albic horizon are at the same altitude. So, all thinning-out points of albic horizon in the study area form several annular lines around tree islands (Fig. 2). The thinning-out line of albic horizon is coincident with a certain contour line. The height measurement showed that the thinning-out line is coincident with the 55.74m contour line. Because sample 5 was chosen as the thinning-out point, and sample 4 is 8cm higher than sample 3, the maximum vertical error was less than 0.04m.

Although there are open waters within the study area, the bottoms of all open waters are covered by rooted-plants. So, there is no deepwater habitat within the study area. The lower boundary of rooted-plants is very intuitionistic, and can be identified using simple vegetation investigation method. No case study was carried out on wetland lower boundary identification.

3.3 Results

The thinning-out line of albic horizon in the study area, namely the upper boundary of wetlands, is coincident with the 55.74m contour line. There were many advantages using upland soil diagnostic horizon to identify wetland boundary: 1) because of the relative invariability of soil diagnostic horizon, the boundary could be identified at one field visit, and it is repeatable; 2) although there are accuracy problem, the subjectivity and controversy resulting from man-prescribed criteria are avoided; 3) it is very effective for the boundary identification of wetlands without hydric soil and hydrophyte vegetation; and 4) because there are the same hydrological regime in the study area, it is reasonable considering that all thinning-out points of upland soil diagnostic horizon are at the same height. The thinning-out line was coincident with a certain contour line. As a result, wetland boundary could be expressed with a contour line.

4 CONCLUSION AND DISCUSSION

4.1 Conclusion

When the mechanism of wetland formation process has not been fully understood, "black-box" method can be used to delineate wetland boundary, and the thinning-out point of upland soil diagnostic horizon can be regarded as the upper boundary of wetlands. The case study indicated that it is feasible using upland soil diagnostic horizon to identify wetland upper boundary, and the altitude of wetland upper boundary in the study areas is 55.74m contour line, the maximum horizontal error is less than 1m and the maximum vertical error is less than 0.04m. Because deepwater habitats, wetlands, and uplands support different food chains, the lower limit of rooted-plants can be regarded as the lower boundary of wetlands. For the wetlands without rooted-plants, the water depth of lower rooted-plants limit of other wetlands with the same hydrological regime can be regarded as its lower boundary criterion.

Because the problem on wetland definition always arises on the boundaries, when the boundary problem has been resolved (having delineated wetland boundaries), wetlands can be defined as follow: wetlands are transition zone between uplands and deepwater habitats, it is a kind of azonal complex that are inundated or saturated by surface or ground water, with the lower boundary lying at the lower rooted-plants limit, and the upper boundary at the thinning-out line of upland soil diagnostic horizon.

4.2 Discussion

4.2.1 Artificial wetland boundary and wetland regulatory boundary

Artificial wetlands usually have obvious man-made boundary. Wetland regulatory boundaries can be prescribed according to its objective. If the regulatory objective is not achieved under the present boundary criterion, the criterion can be broadened. But scientific wetland definition must be accurate and relative invariable. If the regulatory objective is to protect the wetland absolutely, without regard to other considerations, the obvious choice would be to place a regulatory boundary at the outermost limit of the transition zone. Alternatively, regulatory practice that attempts to minimize economic dislocation while still protecting the core wetland area might set the boundary at the innermost part of the transition zone.

4.2.2 Hysteresis of soil diagnostic horizon

The hysteresis of soil diagnostic horizon (USACE, 1987; NRC, 1995; MITSCH and GOSSELINK, 1996; USFWS et al., 1989; NFSAM, 1994; LI et al., 2004) may result from following two aspects: 1) hydrophytic vegetation and hydric soils may persist for decades following alteration of hydrology that will render an area a upland; and 2) upland soil diagnostic horizon may last considerable duration after the hydrological condition supporting wetland habitats have presented in uplands. Because soil diagnostic horizon reflects the long-term interaction result of all environmental elements, if only upland soil diagnostic horizon exists or does not exist, the long-term interaction result still presents upland or wetland characteristics. Therefore, the hysteresis of soil diagnostic horizon does not affect the scientificity of the wetland boundary delineation based on the criteria of thinning-out point.

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