Mechanism of freeze–thaw action in the process of soil salinization in northeast China

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Abstract As a particular mechanism of soil salinization, freeze–thaw action has an obvious control on soil salinization in northeast China; it essentially differs from the present-day salinization process by involving violent evaporation. A special rule of water/salt movement is formed during the process of freezing and thawing, and the resultant soil profile is divided into three layers: frozen layer, semi-frozen layer, and unfrozen layer. It is evident that the salinity in the frozen layer increases, along with soil water and salt mass moves towards the frozen layer from the underlying beds, through the process of soil freezing. The salinity of the frozen layer assembles in the upper soil layer and violent vaporizing occurs. The salinization vaporization intensity resembles an "eruption" in springtime. Because the unthawed soil layer serves as a waterproof stratum and insulates unconfined water, soil salinization in the spring has no direct relation with the groundwater table, and is only affected by the thawed perched groundwater above the frozen layer. Therefore, it is not true that "the critical depth of groundwater" controls the springtime "eruption" salification in northeast China.

Keywords Soil salinization · Freeze–thaw action · Water/salt movement · "Eruption" salification · Northeast China

Introduction

M-M Bsuyef first described the notion of "groundwater critical depth of soil salinization" in 1914 (Liqun 1979) as follows: the upper soil layer will be salinized when the water table overlies some levels in the arid and semi-arid areas. Later, B-B Bolynof developed the notion further (Liqun 1979): groundwater critical depth of soil salinization is a constant, which will salinize the upper soil layer when the vertical distance from the soil surface to the water table is less than the constant. Professor Liqun redefined the notion: it is a burial depth of groundwater that cannot make the upper soil layer salinized in the seasons of the most violent evaporation in a year (Liqun 1979). Its significance not only concentrates on the cause but also emphasizes the prevention and cure of soil salinization.

Even though the notion of "groundwater critical depth" provided quantitative information for studying the cause of soil salinization and developing salinized land resources, it is a problem to determine whether this theory is applicable to different seasons or different regions. Earlier pedologists ascertained that 2–2.5 m (Zunqin 1993) or 2–3 m (Changhua 1964) is the "groundwater critical depth" of soil salinization in Songnen plain of northeast China. Changhua (1964) confirmed that soil could not be salinized when the free-water table was more than 3.5 m deep, because its capillary action cannot reach the earth's surface (Borong and Ruyong 1963). However, Zhand and Nianfeng (1999) discovered that soil salinization is very active in regions where the free-water table is between 3.5 and 5 m deep, and even occurs where it is more than 5 m deep in the west Jilin province of northeast China. This phenomenon cannot be explained by the theory of "groundwater critical depth of soil salinization", whether or not controlled by another active mechanism. Based on systematic analysis and sampling comparison, the authors think that it may be caused by freeze–thaw action.

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Land salinization in the west Jilin province of northeast China

The west Jilin province of northeast China is a region suffering from severe soil salinization (Zhang and others 2000). The saline–alkali soil area is as large as 1.667×10^6 ha, occupying 32.6% of the province's total land area. Salinized cropland has an area of 1.677×10^5 ha, severe salinized meadow 6.737×10^5 ha (Zhang and Nianfeng 1999). These areas are distributed mainly in the counties of

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Zhenlai, Tongyu, Da'an, Qianguo, Changling, and Qian'an (Table 1).

The trend of land salinization is that the saline–alkali soil area has expanded and the degree of salinization has been increasing in the west Jilin province of northeast China since the 1950s (Table 2).

Table 2
Evolution of land salinization in the west Jilin province

Period of time	Saline–alkali soil area ($\times 10^4$ ha)	Degree of salinity/alkalinity (%)		
		Slight	Moderate	Severe
1950s	107.9	48.9	24.2	26.9
1980s	144.0	37.3	20.3	42.4
1990s	166.7	32.4	27.4	40.2

The basic features of the climatic environment in northeast China

Northeast China is located on the transitional zones of a semi-arid and semi-humid climate; therefore it has the characteristics of both climatic zones. The Changbai Mountains obstruct the southeast ocean monsoon, and the Mongolia anticyclone affects this area. Therefore it has the characteristics of both a continental and monsoon climate (Zhang and others 2000). The four seasons are very distinct: the spring is arid and windy; summer is hot and rainy; autumn is cool and very different in temperature; winter is very long and cold (Fig. 1).

Soil is generally frozen from late October/early November until late June/early July of the next year. Not only is the freezing period long, but also the frozen soil layer is very thick, generally 1.2–1.5 m.

The average annual rainfall is 400–500 mm, 70–80% of which occurs in July and August. The average annual evaporation capacity is as high as 1,500–1,900 mm, which is more than three times the average annual rainfall. As the ascending motion of capillary water is greater than its descending motion because of high aridity, the soluble salts in the soil and groundwater accumulate on the earth's surface with the upward flow and are subject to evaporation and concentration.

The west Jilin plain is intensively affected by the East Asia monsoon. The winter climate is characterized by a low temperature, and is arid and rainless; the northwest wind prevails during the Mongolia anticyclone. Summer is very hot, humid and rainy; the southeast wind prevails and leads to low pressure. Figure 2 shows rainfall throughout the year. Its distribution in the different seasons is as follows: 49 mm rainfall in spring (months 3–5), which is 11.5% of the total for the year; 303 mm in summer (months 6–8), 71.2%; 67.2 mm in autumn (months 9–11), 15.8%; 6.2 mm in winter (months 12–2), 1.5%.

Water/salt movements in soil are controlled by the effects of the monsoon (Zunqin 1993). The soil salinity changes with the seasons, so that the whole year can be divided into four active periods: the salinization period in spring, the desalination period in summer, the re-aggregation period in autumn, and the latent period in winter. Although rainfall in the summer can desalt, the desalting time is comparatively short at only 3 months; however, salinization time may be as long as 5–6 months. The general trend of water/salt movement is that it is accumulating more than eluviating. Drainage is very difficult because of the low–flat relief to the west of the Jilin plain, so waterlogging frequently takes place, and the water table is widely raised in the rainy season. It will bring about intense salt-return on a large scale during the next spring with violently ascensional motion and sidewise movement of soil capillary

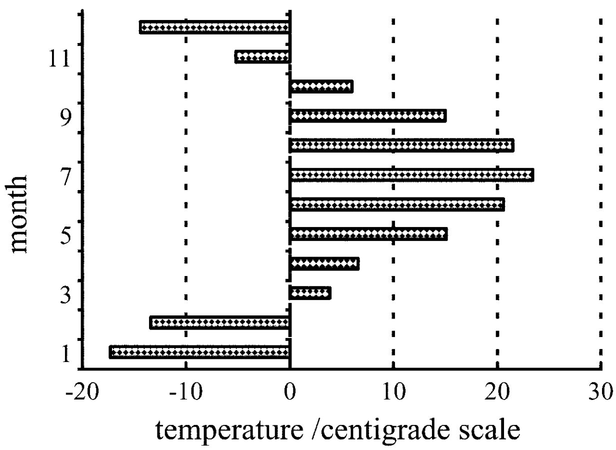

Fig. 1
The annual distribution of average air temperature in west Jilin province

Table 1
Saline–alkali soil distribution in the west Jilin province of northeast China

County	Saline–alkali soil area ($\times 10^4$ ha)	Saline–alkali ratio (%)	Areas with different degrees of salinity/alkalinity ($\times 10^4$ ha)		
			Slight	Moderate	Severe
Zhenlai	17.15	31.9	4.66	3.66	8.83
Tongyu	34.25	40.4	17.39	9.41	7.45
Da'an	28.78	59.0	5.71	1.74	21.33
Qianguo	19.13	29.9	9.51	3.76	5.86
Changling	16.43	28.9	6.02	6.15	4.26
Qian'an	14.03	39.7	4.13	2.24	7.66

water. Native farmers summarize this as “salt goes with waterlog”.

The movement of water/salt in the freeze–thaw process

The west Jilin plain lies at a high latitude. It is cold, and winter lasts for 5 months from the middle of November to the end of April of the next year. The frozen soil depth can reach to 1.5 m in a cold winter. For a long time most pedologists paid more attention to “groundwater critical depth” of soil salinization in northeast China, and the effect of freeze–thaw action on soil salinization was neglected. It did not accord with the practical situation of northeast China as that of using phreatic water as the only water source that affected soil salinization.

The structural changes of the soil profile in the freeze–thaw process

The freeze–thaw action causes the structure of the soil profile to change in northeast China. The soil profile turns into three layers in the process of soil freezing. From the top down these are frozen layer, semi-frozen layer, and unfrozen layer.

Because the temperature always remains below zero degrees centigrade in the frozen layer, the soil moisture is frozen and is in a solid state. Soil interstices increase because of frost heave; soil moisture will remain in a hypersaturated state when moisture can be supplied ceaselessly; and the depth of the frozen layer can reach to 0.8–1.0 m. The thickness of the semi-frozen layer under the frozen layer is usually 0.2–0.4 m; its temperature remains about 0 °C all the time. The position of the semi-frozen layer moves downwards with temperature reduction and thickening of the frozen layer. Its humidity remains low because the semi-frozen layer continually supplies moisture for the frozen layer. The unfrozen layer lies under the semi-frozen layer; its temperature remains above zero degrees centigrade and the soil water retains its liquid state all the time.

Movement of soil moisture in the freeze–thaw process

The movement of soil moisture follows a particular regularity under the influence of temperature gradient in the soil freeze–thaw period. It can be divided into two phases, as detailed below.

In the freezing period

The surface soil begins to freeze when the surface temperature drops to zero degrees centigrade; the temperature of the surface soil is clearly lower than that of subsoil. The subsoil moisture moves towards the frozen layer because of the temperature gradient. The void space of the soil gradually increases because of frost heave; the moisture ceaselessly moves into the interstices of soil and then freezes. The moisture content in the frozen layer can be in a hypersaturated state with a water content of 40–60%. The moisture content of the semi-frozen layer needs to be 25–30% for it to supply the frozen layer in the freezing process. The moisture content is 28–33% in the unfrozen layer. With the supply of underground water, the moisture content of the frozen and unfrozen layers is more than that of the semi-frozen layer (Fig. 3).

In the thawing period

The thawing of the frozen layer begins from the top and bottom at the same time. The unthawed layer in the middle of the soil profile acts as a water-resisting layer. The thawed soil water in the topsoil, obstructed by the unthawed layer, temporarily becomes perched water, and the uppermost content of soil water can reach about 50% at depths of 0.4–0.6 m. As surface evaporation occurs, the soil water of the top-thawing layer moves upwards and evaporates. Soil water content decreases gradually from the bottom up, and is less than 20% in the topsoil. Soil

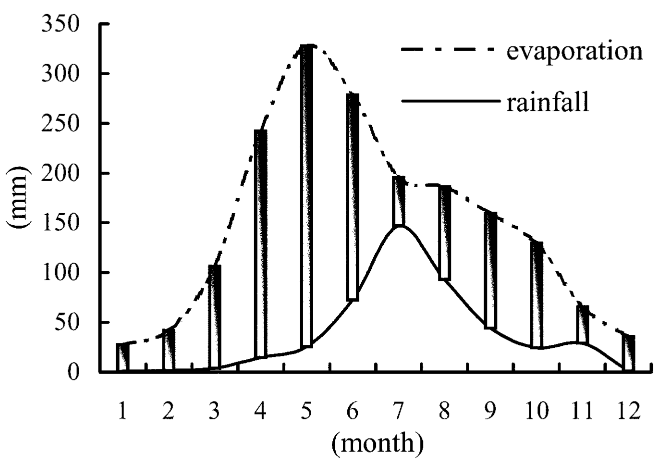

Fig. 2
The annual distribution of rainfall and evaporation in west Jilin province

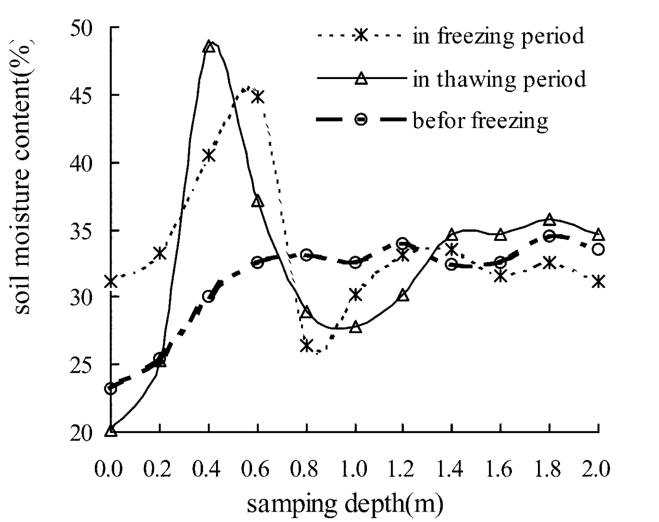

Fig. 3
Travel of soil moisture in the freeze–thaw process

water of the bottom-thawing layer seeps down and supplies groundwater, and thawing causes the rising of the water table again.

Compared to the pre-frozen period, maximum soil water occurs in the frozen layer during the freezing period. The minimum appears in the semi-frozen layer. The soil moisture of the unfrozen layer is slightly less than that in the pre-frozen period. In the thawing period, the maximum of soil moisture content appears above the frozen layer and becomes temporarily perched water, and the soil moisture content under the frozen layer is more than that during the pre-frozen period.

Movement of salt in the freeze–thaw process

In the freezing period

The salt of the soil layer under the frozen layer and groundwater accumulates towards the frozen layer along with soil moisture during the freezing process; therefore, the salt content in the whole frozen layer clearly increases (Fig. 4). For the semi-frozen layer, which moves down step by step along with frozen-layer thickening, salt is distributed uniformly throughout the soil profile. The salt in the frozen layer tends to move and accumulate towards the top. There is little liquid water in the frozen soil layer, and it moves very quickly because of the temperature gradient (Rulin 1982).

In the thawing period

The salt, accumulated in the frozen layer during the freezing period, gathers towards the surface layer along with the thawed soil moisture in the upper part of the frozen layer which moves up and evaporates. The salt content of the surface soil greatly increases and mostly concentrates in the 0–10 cm soil layer (frost boil and salt return). The salt in the lower thawed layer moves to underground water with thawed water infiltrating down.

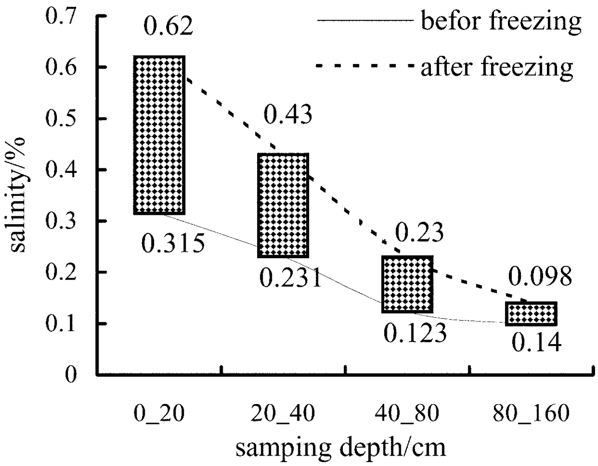

Fig. 4
The enrichment of salinity during the soil freezing process

Preliminary analysis of the mechanism of freeze–thaw action in soil salinization

The changes of soil water/salt are related to the freeze–thaw action in northeast China; soil freezing and thawing form a specific rule of water/salt movement. As well as the two salinization seasons of spring and summer, there is another covered salinization process with soil freezing in winter, which differs from the present-day salinization process by violent surface evaporation. Especially in the spring salinization period, the process of soil salinization is directly affected by the perched water of the thawed soil and has no direct connection with the underground water. In the west plain of Jilin province, soil begins to freeze from late October/early November and cannot thaw until late June/early July of the next year. In the soil freezing process, the soil moisture of the lower soil layer moves towards the frozen layer, because the temperature gradient between the soil frozen layer and the unfrozen layer causes soil capillary moisture to move. Salt also climbs up and accumulates in the frozen layer. The content of moisture and salt in the frozen soil underlayer declines. When underground water is continually supplied to the frozen layer by capillary action, water and salt will abundantly accumulate in the frozen layer as the frozen layer thickens and develops downwards. So the process of covered salinization has a definite relationship with underground water in winter. When spring returns and the air temperature rises again, the frozen layer begins to thaw from the top downwards. The gravitational water above the unthawed layer is called temporary perched water, and consists of thawed soil water and atmospheric precipitation. In the west plain of Jilin province, the rainfall is 49 mm in spring, which accounts for 11.5% of total annual rainfall, but the quantity of evaporation is five times more than the rainfall. The excessive soil evaporation makes salt that had slowly accumulated in the frozen layer assemble rapidly and in quantity towards the soil surface. Its intensity is like an "eruption". This process lasts until the frozen layer thaws completely. The frozen layer, before thawing completely, obstructs the contact of perched water above the frozen layer and underground water beneath the frozen layer. Violent spring salinization has no direct relation with the groundwater table. It is out of line with the practical situation in northeast China that violent spring soil salinization is explained only by "groundwater critical depth". Until the end of June/beginning of July, thawed soil water supplies underground water, but as the frozen layer is thawed through, and meets with precipitation during the rainy season (months 6–8) so the groundwater table rises in a combined action. Although the groundwater table is topmost in the rainy season, the soil profile is still in the process of desalting for eluviation. In the autumn (months 9–11), the evaporation capacity increases as the amount of precipitation decreases. Here the groundwater table will have a direct influence on soil salinization. The local farmers sum this up as: "soil is like sieve in July and August, salt will climb up in September and October". This adage implies desalting in summer and salinizing in autumn.

Conclusion and advice

Even though phreatic water has some contribution to winter covered salinization, the "explosive salinization" in spring has no direct relation with phreatic water. Up to now a convincing cause for the mechanism of soil salinization has not been gained in the northeast plain of China, because most pedologists still stick to the notion of "groundwater critical depth of soil salinization". The soil freeze-and-thaw action is an objective reality in the northeast plain of China, so its influence on soil salinization is not negligible, and may be a decisive factor. Pedologists should pay more attention to the freeze–thaw mechanism of soil salinization, and do much more research on the mechanism of water/salt movement by means of laboratory simulation and field observation.

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