Dynamic Changes in Energy Balance During Salt Crust Soil Formation and Development: Postprint

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Abstract

Surface energy balance constitutes a critical component of land-atmosphere interactions, and investigating the surface energy balance characteristics of different underlying surfaces is of great significance for understanding land surface heat transfer. However, research on the variation characteristics of energy balance during the formation of salt-crusted soils has not been reported. The primary difficulty lies in the absence of a calculation method for soil surface albedo during salt crust formation, which severely impedes precise quantitative characterization of heat transfer in salinized soils. Therefore, this study employs simulation experiments combined with an energy balance model and applies an albedo calculation method to quantitatively analyze the dynamic variation characteristics of energy balance during the formation and development of salt-crusted soils. The results demonstrate that: (1) The Logistic growth model provides an excellent fit for the formation and development process of salt crusts on the soil surface (R^2=0.99). (2) Under continuous irradiation conditions (1000 $W \cdot m^{-2}$, 16 d), as the salt crust continues to develop, the albedo of salt-crusted soils is 0.15–0.41 higher than that of the control, which significantly reduces soil heat absorption and results in a 16 °C lower surface temperature of salt-crusted soils compared to the control. (3) Under the influence of albedo and surface temperature, the net radiation, sensible heat flux, latent heat flux, and soil heat flux of salt-crusted soils are reduced by 47.9%, 52.4%, 46.8%, and 47.4%, respectively, relative to the control, significantly impacting soil profile temperature. These findings hold significant scientific value for further exploration of soil water-heat transfer processes under salt crust influence.

Full Text

Preamble

Dynamic Variation of Energy Balance Under the Influence of Salt-Crusted Soil Formation and Development

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Abstract: Surface energy balance is a crucial component of land-atmosphere interactions, and investigating its characteristics across different underlying surfaces is essential for understanding surface heat transfer. However, no studies have reported on the variation characteristics of energy balance during the formation process of salt-crusted soil. The primary challenge lies in the lack of calculation methods for soil surface albedo during salt crust development, which severely affects the accurate quantitative description of heat transport in saline soils. Therefore, this study employed simulation experiments combined with an energy balance model and albedo calculation methods to quantitatively analyze the dynamic variation characteristics of energy balance during the formation and development of salt-crusted soil. The results showed that: (1) The logistic growth model could effectively simulate the formation and development process of salt crust on the soil surface ($R^2 = 0.99$). (2) Under continuous irradiation conditions (1000 $W \cdot m^{-2}$, 16 d), the albedo of salt-crusted soil was 0.15–0.41 higher than that of the control treatment as the salt crust continuously developed, thereby significantly reducing soil heat absorption and decreasing the surface temperature of salt-crusted soil by 16°C (mean value) compared to the control. (3) The net radiation, sensible heat flux, latent heat flux, and soil heat flux of salt-crusted soil decreased by 47.9%, 52.4%, 46.8%, and 47.4% (mean values), respectively, compared to the control under the influence of albedo and surface temperature, which significantly affected the soil profile temperature. These findings provide important scientific value for further investigation of soil water-heat transport processes under the influence of salt crust.

Keywords: salt crust; albedo; soil surface temperature; energy balance

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Introduction

In arid and semi-arid regions, intense evaporation causes shallow saline groundwater to continuously rise to the soil surface, where salts precipitate and crystallize, aggregating with soil particles to form salt crusts. Salt-crusted soils are widely distributed in these areas and can trigger land degradation and reduce soil microbial activity. The high albedo and thermal conductivity of salt crusts alter radiation input and output, heat exchange, and water transport processes at the soil surface. Specifically, surface salt crystallization blocks soil pores and inhibits surface evaporation. Previous studies have found that salt crusts have a snow-cover-like effect, significantly increasing soil surface albedo, which rises with salt crust accumulation. This albedo change directly affects incoming shortwave radiation and consequently alters surface radiation conditions. Fujimaki et al. demonstrated that salt crusts increase albedo while reducing soil surface temperature, which is a key factor influencing sensible and latent heat fluxes. Sensible heat flux depends on the temperature difference between the soil surface and the environment, and the reduced surface temperature caused by salt crusts changes this temperature gradient, thereby affecting sensible heat flux. Latent heat flux is jointly influenced by soil surface temperature and evaporation. Numerous studies have reported that salt crusts significantly inhibit evaporation while lowering soil surface temperature, leading to changes in latent heat flux.

Soil surface properties critically affect energy balance, including surface color, thermal conductivity, and moisture content. However, most previous studies have focused on stable-state salt crusts, neglecting the formation and development process. Salt crust development causes continuous changes in soil surface albedo, and ignoring this dynamic process severely affects the accurate quantitative analysis of soil energy balance. Currently, research on energy balance characteristics during salt crust development is lacking because traditional albedo calculation methods do not account for salt-crusted soils, and the changing albedo during crust development remains unclear. While Fujimaki et al. established a relationship between albedo and salt crust mass, their method has limitations when salt crust growth is concentrated in specific surface areas. Recent studies indicate that salt crust development follows a nonlinear logistic growth pattern, with coverage area increasing according to a logistic model. Therefore, this study established a relationship between albedo and salt crust coverage area based on traditional albedo calculation methods, proposed a method for determining the albedo of salt-crusted soil, and improved the energy balance model to analyze the dynamic variation characteristics of energy balance during salt crust development.

1.1 Experimental Design

The indoor simulation experiment used sandy soil collected from sand dunes in the upper reaches of the Tarim River (40°27 31 N, 81°19 30 E). The basic physical and chemical properties of the sandy soil are shown in . The soil was uniformly packed into columns with an inner diameter of 7.5 cm and height of 14 cm. Before the experiment, the soil columns were initially saturated from bottom to top using either distilled water or salt solution (10 $\mathrm{g \cdot L^{-1}}$ NaCl) via capillary suction. The 10 $\mathrm{g \cdot L^{-1}}$ salt solution concentration approximates natural soil solution salinity. After the soil surface became wet, the columns were covered with plastic film to prevent evaporation during saturation, which lasted 24 hours to ensure adequate soil moisture equilibrium. After saturation, gravitational water was drained from the bottom, and the columns were wrapped with insulation material. The columns were placed on an automatic weighing platform (Beijing Shiyutong Technology Co., Ltd., precision 0.1 g). A lamp above the columns drove evaporation, with incoming radiation controlled at 1000 $\mathrm{W \cdot m^{-2}}$. Evaporation changes over time were automatically recorded by the weighing platform. During the experiment, an infrared thermal imager (FLIR Systems, Inc., precision 0.1°C) captured thermal images of the soil surface, which were processed using FLIR Tools to obtain surface temperature. A digital camera (Sony ILCE-6000, Sony (China) Co., Ltd.) recorded the growth of salt crust on the soil surface, and visible-light photos were processed using ImageJ software to obtain salt crust coverage area. Environmental temperature and humidity were automatically recorded by a thermo-hygrometer (Shandong Renke Measurement and Control Technology Co., Ltd., Cos_{03}). Surface soil water content was measured using a partial repeated withdrawal method, where surface soil from replicate columns was removed and oven-dried at different time points to obtain water content, which was then interpolated for the entire experimental period. Net radiation, sensible heat flux, and latent heat flux at the soil surface were calculated using the energy balance model based on measured environmental temperature, humidity, soil surface temperature, and evaporation.

1.2 Albedo Model for Salt Crust Development

This study established a coupling relationship between albedo and salt crust coverage area to predict changes in soil surface albedo during salt crust development:

$$A = A_0 + a \cdot A_{sc}$$

where A and A_0 are the surface albedos of salt-crusted and salt-free (control) soils, respectively; A_{sc} is the salt crust coverage area ($\mathrm{m^2}$); and a is a fitting parameter with a value of 0.15–0.41.

Based on the logistic growth model for salt crust coverage area over time proposed by Fujimaki et al., this study modified the formula to account for changes in soil surface area:

$$A_{sc} = \frac{1}{1 + e^{-b(t-c)}}$$

where t is the experimental time (h), and b and c are fitting parameters with values of 0.25 and 18, respectively.

The albedo calculation formula for salt-free conditions is:

$$A_0 = \begin{cases} 0.10 & \theta_{top} < 0.10 \\ 0.11 + 0.40 \cdot \theta_{top} & 0.10 \le \theta_{top} < 0.25 \\ 0.25 & \theta_{top} \ge 0.25 \end{cases}$$

where θ_{top} is the surface soil water content ($\mathrm{m}^3 \cdot \mathrm{m}^{-3}$).

1.3 Energy Balance Model

The energy balance equation is expressed as:

$$R_n = H + LE + G$$

where R_n is net radiation ($\mathrm{W} \cdot \mathrm{m}^{-2}$), H is sensible heat flux ($\mathrm{W} \cdot \mathrm{m}^{-2}$), LE is latent heat flux ($\mathrm{W} \cdot \mathrm{m}^{-2}$), and G is soil heat flux ($\mathrm{W} \cdot \mathrm{m}^{-2}$).

Net radiation R_n is calculated as:

$$R_n = (1 - A) \cdot R_s + \varepsilon_a \sigma T_a^4 - \varepsilon_s \sigma T_s^4$$

where R_s is total radiation ($\mathrm{W} \cdot \mathrm{m}^{-2}$), ε_a is atmospheric emissivity, ε_s is soil emissivity, σ is the Stefan-Boltzmann constant (5.67$×10^{-8}$ $\mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-4}$), T_a is air thermodynamic temperature (K), and T_s is soil surface thermodynamic temperature (K).

Sensible heat flux H is calculated as:

$$H = h_c(T_s - T_a)$$

where h_c is the convective heat transfer coefficient ($\mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-1}$).

Latent heat flux LE is calculated as:

$$LE = (2.501 - 2.361 \times 10^{-3} \cdot T_s) \cdot E$$

where E is soil evaporation ($\mathrm{kg} \cdot \mathrm{m}^{-2} \cdot \mathrm{h}^{-1}$).

Results

2.1 Salt Crust Formation and Development

The most direct manifestation of salt crust development is the increase in coverage area. As shown in [Figure 1: see original paper], the salt crust completely covered the soil surface by 12–48 hours of the experiment. Soil salts crystallize only after reaching saturation state. During the initial experimental stage (<18 h), salt crust coverage increased slowly, then grew rapidly after 18 h, and essentially covered the entire soil surface after 48 h. The logistic model simulation of salt crust coverage area showed good consistency with the measured growth process ($R^2 = 0.99$, RMSE = 1.18), indicating that the logistic growth model is highly suitable for predicting salt crust coverage area changes.

2.2 Dynamic Variations of Energy Balance Parameters

2.2.1 Net Radiation Under identical radiation conditions, the average net radiation of salt-crusted soil decreased by 47.9% compared to the control treatment, with markedly different trends during the experimental period ($P < 0.05$). For the control, net radiation decreased slowly by 14.4% during the first 2 days, then declined rapidly from 629.3 $W \cdot m^{-2}$ to 227.8 $W \cdot m^{-2}$ between days 2-6 (a 64.8% reduction), after which it stabilized at an average of 625.7 $W \cdot m^{-2}$. In contrast, net radiation in salt-crusted soil decreased sharply by 43.3% during the first 12 hours, dropping to 319.3 $W \cdot m^{-2}$, after which no significant changes occurred. The maximum difference between salt-crusted soil and control occurred at 54.2% of the experimental period, with salt-crusted soil net radiation being 62.6% lower than the control. Thus, changes in salt crust coverage area constitute an important cause of differences in soil net radiation.

2.2.2 Sensible Heat Flux Under identical radiation conditions, sensible heat flux in salt-crusted soil and control showed different trends. Control sensible heat flux increased rapidly from 141.8 $W \cdot m^{-2}$ to 227.8 $W \cdot m^{-2}$ during the first 3–5 days (a 26.7% increase), then stabilized at a high value (>250 $W \cdot m^{-2}$). In contrast, salt-crusted soil sensible heat flux decreased rapidly from 141.8 $W \cdot m^{-2}$ to 116.9 $W \cdot m^{-2}$ during the first 12 hours, after which no significant changes occurred (average 130.3 $W \cdot m^{-2}$). Compared to the control, salt-crusted soil sensible heat flux decreased by 52.4% on average. The minimum difference between treatments occurred at 10.3% of the experimental period, with salt-crusted soil sensible heat flux only 14.4% lower than the control. Because control surface temperature increased rapidly during the first 12 hours, the temperature difference with the environment increased, causing sensible heat flux to rise accordingly. Salt-crusted soil surface temperature remained relatively stable, resulting in a smaller temperature difference with the environment compared to the control, which led to rapidly increasing differences in sensible heat flux between the two treatments during the first 12 hours.

2.2.3 Latent Heat Flux Under identical radiation conditions, the average latent heat flux of the control was 46.8% higher than that of salt-crusted soil. Both treatments showed declining trends in latent heat flux, but with different patterns. Control latent heat flux decreased gradually by 14.4% during the first 2 days, then dropped rapidly from 418.4 $\mathrm{W \cdot m^{-2}}$ to 132.1 $\mathrm{W \cdot m^{-2}}$ between days 2-3 (a 68.4% reduction), before stabilizing at a high value (>350 $\mathrm{W \cdot m^{-2}}$). Salt-crusted soil latent heat flux decreased rapidly from 418.4 $\mathrm{W \cdot m^{-2}}$ to 147.4 $\mathrm{W \cdot m^{-2}}$ during the first 12 hours (a 64.8% reduction), after which the declining trend slowed. The maximum difference between treatments occurred at 56.5% of the experimental period, with salt-crusted soil latent heat flux being 64.8% lower than the control. Evaporation is the key parameter affecting latent heat flux. Studies have found a positive correlation between salt crust coverage area and evaporation resistance—the larger the coverage area, the stronger the resistance to evaporation. In this study, salt crust completely covered the soil surface by 12–48 hours, exerting strong inhibition on evaporation and causing rapid latent heat flux reduction. Control evaporation was unaffected by salt crust, and studies have shown that under gradually drying conditions, evaporation in salt-free soil decreases due to insufficient surface moisture, but this reduction is far less severe than that caused by salt crust inhibition. Consequently, the control maintained relatively high evaporation rates until day 2–3, when it entered the third stage of evaporation where surface moisture no longer supported latent heat flux.

2.2.4 Soil Heat Flux Under identical radiation conditions, the average soil heat flux of the control was 47.4% higher than that of salt-crusted soil. Both treatments showed rapid initial increases followed by stabilization, but with different patterns. Control soil heat flux increased sharply from 133.7 $\mathrm{W \cdot m^{-2}}$ to 227.8 $\mathrm{W \cdot m^{-2}}$ during the first 2 days (a 70.4% increase), then stabilized at a high value (>250 $\mathrm{W \cdot m^{-2}}$). Salt-crusted soil soil heat flux decreased rapidly from 133.7 $\mathrm{W \cdot m^{-2}}$ to 81.7 $\mathrm{W \cdot m^{-2}}$ during the first 12 hours (a 38.9% reduction), then showed a stage of increasing first rapidly, then slowly, then rapidly again, rising from 81.7 $\mathrm{W \cdot m^{-2}}$ to 210.6 $\mathrm{W \cdot m^{-2}}$ between days 2-7 (a 22.4% average daily increase), before stabilizing at an average of 141.2 $\mathrm{W \cdot m^{-2}}$. The maximum difference between treatments occurred at 42.2% of the experimental period, with salt-crusted soil soil heat flux being 62.6% lower than the control. This occurred because the control' s latent heat flux decreased rapidly during days 2–3, and although its sensible heat flux increased rapidly, the energy gain from sensible heat was smaller than the energy loss from latent heat, resulting in decreased net radiation that was converted into increased soil heat flux. In contrast, salt-crusted soil net radiation and sensible heat flux remained relatively stable during days 2–3, so the reduction in latent heat flux corresponded to increased soil heat flux, though at a lower absolute value.

2.3 Mechanism of Salt Crust Influence on Energy Balance

Salt-crusted soil showed varying degrees of difference from the control in net radiation, sensible heat flux, and latent heat flux. Salt crust altered the trend of soil heat flux, thereby affecting the energy balance status. Cai et al. demonstrated that surface albedo is the primary determinant of net radiation. Fujimaki et al. found that salt crusts increase surface albedo, leading to lower net radiation and surface temperature compared to salt-free conditions, while also reducing evaporation and affecting latent heat flux.

2.3.1 Albedo Under identical radiation conditions, salt crust grew rapidly and covered the soil surface during the first 12 hours, causing salt-crusted soil albedo to increase quickly from 0.10 to 0.25 and gradually stabilize thereafter. In contrast, control albedo was strongly dependent on surface soil moisture, showing a relatively gentle increase during the first 2 days, then rising rapidly to 0.25 during days 2–6 before stabilizing. The maximum difference between treatments occurred at 54.1% of the experimental period, with salt-crusted soil albedo being 0.15 higher than the control, while the minimum difference occurred at 10.3% of the period. Salt-crusted soil average albedo was 0.15 higher than the control. Fujimaki et al. also reported that with continuous salt crust mass increase, albedo of salt-crusted soil can be 0.41 higher than salt-free soil. These consistent findings confirm that salt crust development increases soil surface albedo.

Differences in albedo directly affect incoming shortwave radiation. Guo et al. noted that high surface albedo reduces incoming shortwave radiation, thereby decreasing net radiation. This study found that the trend of incoming shortwave radiation for both treatments was consistent with net radiation but opposite to albedo. Under albedo influence, salt-crusted soil received less incoming shortwave radiation than the control throughout the experimental period. Since incoming shortwave radiation is the main component of net radiation, salt-crusted soil also had consistently lower net radiation. Thus, the rapid albedo increase caused by salt crust growth during the first 12 hours was the main reason for the rapid decline in salt-crusted soil net radiation, consistent with findings from Li et al. and Guo et al. However, the specific mechanisms by which salt crust surface characteristics (such as color and roughness) affect albedo require further investigation.

2.3.2 Soil Surface Temperature Salt-crusted soil and control surface temperatures showed high consistency with sensible heat flux trends, but with significant differences between treatments. Control surface temperature increased rapidly during the first 12 hours, then showed a slow increasing trend. Salt-crusted soil surface temperature decreased during the first 12 hours due to increased albedo reducing heat absorption, then gradually stabilized as albedo stabilized, and began fluctuating upward from day 7. Overall, salt-crusted soil surface temperature (average 38.9°C) was 16°C lower than the control (average

54.8°C), consistent with results from Shokri et al. and Tang et al. Thus, salt crust growth altered surface temperature trends, which in turn caused differences in sensible heat flux between the two treatments.

2.3.3 Soil Evaporation Latent heat flux is influenced by both surface temperature and evaporation, but evaporation has a significantly greater impact. In this study, both treatments showed rapidly declining evaporation trends that stabilized later, but for different reasons. For the gradually drying control, evaporation declined slowly during the first 12 hours while the surface remained moist, then decreased rapidly after 12 hours as surface moisture was lost, entering the vapor diffusion stage by day 2–3. For salt-crusted soil, the rapid increase in salt crust coverage area created increasing evaporation resistance, causing rapid evaporation decline during the first 12 hours. Salt crust inhibition preserved soil moisture, allowing salt-crusted soil evaporation to enter the vapor diffusion stage later than the control, though remaining higher than the control ($<1.0\ \mathrm{kg \cdot m^{-2}}$). The different timing of entering the vapor diffusion stage caused the maximum difference in latent heat flux between treatments to occur at 56.5% of the experimental period.

Conclusion

This study used indoor simulation experiments combined with an energy balance model to improve existing soil surface albedo models by establishing a relationship between salt crust development and albedo. Using salt crust coverage area to couple albedo in salt-crusted soil, the energy balance model was improved to quantitatively analyze dynamic variations in energy balance during salt crust formation and development for the first time. The main conclusions are: (1) Under continuous irradiation ($1000\ \mathrm{W \cdot m^{-2}}$, 16 d), salt crust developed rapidly in the early stage and completely covered the soil surface (coverage >95%). The development process followed a logistic growth model ($R^2 = 0.99$). (2) The high albedo of salt-crusted soil significantly reduced heat absorption, decreasing surface temperature by 16°C and reducing average net radiation by 47.9% compared to the control. (3) Salt-crusted soil average sensible heat flux decreased by 52.4% compared to the control due to reduced surface temperature. (4) Salt crust presence reduced average latent heat flux by 46.8% but prolonged the duration of latent heat exchange. (5) The combined effects on net radiation, sensible heat, and latent heat fluxes reduced average soil heat flux by 47.4% in salt-crusted soil compared to the control. In summary, albedo changes during salt crust development significantly affected soil heat balance.

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