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Review Article

Remote Sensing of CO_2 Absorption by Saline-Alkali Soils: Potentials and Constraints

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CO_2 absorption by saline-alkali soils was recently demonstrated in the measurements of soil respiration fluxes in arid and semiarid ecosystems and hypothetically contributed to the long-thought "missing carbon sink." This paper is aimed to develop the preliminary theory and methodology for the quantitative analysis of CO_2 absorption by saline-alkali soils on regional and global scales. Both the technological progress of multispectral remote sensing over the past decades and the conjectures of mechanisms and controls of CO_2 absorption by saline-alkali soils are advantageous for remote sensing of such absorption. At the end of this paper, the scheme for remote sensing is presented and some unresolved issues related to the scheme are also proposed for further investigations.

1. Introduction

Energy shortage and environment security are hot issues on economy and social development in the world today [1–3]. Global trends of soil desertification and degradation pose a direct threat to the food safety and human survival and become the hottest part of the issues. Soil salinization is one of the main types of soil desertification and degradation. It is caused by soil water and salt movement, usually occurring in arid and semiarid areas of strong evaporation and high-table groundwater with dissolvable salt [4]. Because of the alternating affection of rainfall, irrigation, and evaporation, soil salt further accumulates in unsaturated zone and leads to the secondary salinization, which induces a great loss of the resources of arable land and the agricultural production and meanwhile poses a serious threat to biosphere and ecological environment [5]. In order to manage saline-alkali soils and prevent further soil degradation, people must be timely informed about the nature and geographic distribution of saline-alkali soils and the degrees of salinity/alkalinity. Therefore, accurately acquiring the information on saline-alkali soils is significant to protect soil quality and agricultural yield. Remote sensing data allows us to dynamically monitor saline-alkali soils on large scales [6]. Such information reflects the soil nature, geographical distribution, and its dynamic changes in the degrees of salinity/alkalinity, which is essentially significant for the reasonable planning of agricultural production and the steady development of social economy in arid and semiarid regions [4–6].

Exactly, such information not only can be used to monitor soil salinization, but also can be used to quantify the effects of other environmental processes, especially the geochemical processes related to the long-thought "missing carbon sink" [7]. It has been demonstrated that saline-alkali soils are absorbing CO_2 and may significantly contribute to the "missing carbon sink" [8–10]. A global quantification of CO_2 absorption by saline-alkali soils is important to readdress the "missing carbon sink" [7–9]. However, there is still no theory and methodology was developed for quantifying the CO_2 absorption by saline-alkali soils on large scales. Some empirical models are presented to approximately quantify the absorption on site scales, but the model was parameterized using the collected data from the Gubantonggut desert and the environmental controls on model parameters were poorly

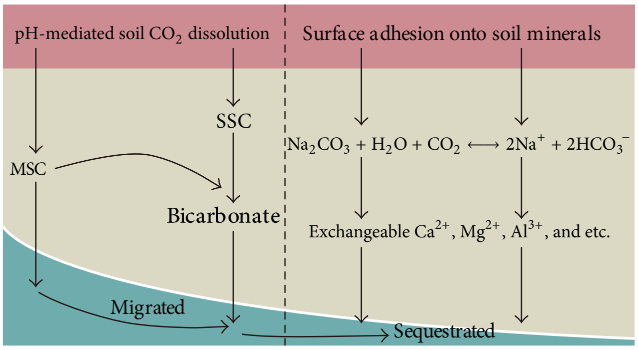


Figure 1: Conjectured mechanisms for CO_2 absorption by saline-alkali soils. Note: MSC (the molecular solubility of CO_2); SSC (the soil storage of CO_2).

understood [11–14]. It is emergent to take further readings in other arid and semiarid regions and develop theory and methodology for remote sensing of CO_2 absorption by saline-alkali soils on regional and global scales [13].

This paper is aimed to develop some preliminary theory and methodology for remote sensing of CO_2 absorption by saline-alkali soils on large scales. As a first attempt, the theory potentials of and constraints on applying the methodology are also discussed. Strategies against the constraints are presented. Theoretical feasibility for remote sensing of CO_2 absorption by saline-alkali soils on large scales is discussed. At the end of this paper, the strategies against the constraints and some unresolved issues about the theory and methodology are proposed.

2. Theory and Methodology

Although there are a series of studies speculated the mechanisms of CO_2 absorption by saline-alkali soils, none of those speculations has been widely accepted. Conjectured mechanisms in the previous publications [7, 9, 10, 13] include (1) the soil storage of CO_2; (2) the molecular dissolution of CO_2 in soil water films; (3) the surface adhesion of CO_2 onto soil minerals; (4) pH-mediated CO_2 dissolution; and (4) migration and sequestration of CO_2 into groundwater. The molecular solubility of CO_2 (MSC) and the pH-mediated CO_2 dissolution are two determining physiochemical parameters [10].

Spectral data from laboratory and field observations suggested that spectral reflectance of saline-alkali soil was affected by soil salt, organic matter content, structure, and soil color [16]. In addition, the solar altitude and soil salt composition also affect the spectral response mode of saline-alkali soils. Spectral reflectance increases/decreases when soil salt content increases for the difference in soil salt composition [6]. Although spectral reflectance of saline-alkali soils is the integrated effect of a series of environmental factors, soil salts and soil minerals content, soil surface morphology and soil water content are more determining factors. These are right the materials that contribute to CO_2 absorption by saline-alkali soils (Figure 1).

Soil water not only directly affects the spectral characteristics of soils, but also controls the vertical movement of soil salt [16]. Saline-alkali soil usually contains Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, $SO_4^{\,2-}$, $CO_3^{\,2-}$, and so forth. Special salts (aqueous sodium chloride, sodium sulfate, potassium sulfate, calcium sulfate, and magnesium sulfate) absorb solar radiation and present additional spectral information [17–20]. These chemical materials, driven by soil water movements, are accumulated in the soil surface as salt crystals. Saline-alkali soils containing the heavier mass of sodium also have higher spectral reflectance than common saline-alkali soils [6]. Soil salinization and alkalization were caused by the increases of soluble salts (sodium carbonate, sodium sulfate, and sodium chloride) in soils. The higher sodium content in the soils implies more CO_2 can be dissolved [10]. The spectral characteristics also reflect the different stages of soil salinization and alkalization [21, 22], while the alkalinity degree is a determining factor of CO_2 absorption intensity [13].

Both the technological progress of multispectral remote sensing over the past decades and the conjectures of mechanisms and controls of CO_2 absorption by saline-alkali soils are advantageous for remote sensing of such absorption on large scales. As a preliminary attempt, we need only to know well about how much soil dew can be accumulated in these soils and how much CO_2 can be dissolved in the dew. These will help us to finally calculate the rate of CO_2 absorption by saline-alkali soils. Estimation of the soil CO_2 flux (i.e., soil respiration flux: F_c) along a field gradient of air temperature 10 cm above the soil surface (T) with $F_c = 2.58 * 1.17^{(T-10)/10} - 2.86$ ($R^2 = 0.86$, RMSE = 0.23) and the contribution analysis of soil dew in the unexplained part of F_c by the Q_{10} model (denoted by F_x) with $F_x = 4.07 * e^{-10*\mathrm{dew}} - 6.38$ (dew > 1 mm; $R^2 = 0.53$, RMSE = 0.75) present further evidence (Figure 3). It recommends that remote sensing of CO_2 absorption by saline-alkali soils should be based on the following equation. Let C_0 be the initial amounts of CO_2 in soil dew at t_0 and the rate of CO_2 increases in dew is r. Ignoring the restricting effect of history CO_2 absorption, it is straight that

$$\frac{dC(t)}{dt} = rC(t), \quad C(t_0) = C_0, \tag{1}$$

where $C(t)$ represents the CO_2 dissolution dynamics on time scales.

It is easy to see that the analytic solution of (1) is $C(t) = C_0 e^{r(t-t_0)}$. Noting that C_0 and r determine the dynamic changes of soil CO_2 dissolution and the absorption rate, remote sensing of CO_2 absorption by saline-alkali soils is equivalent to the retrieval of these two parameters. These two parameters are largely determined by soil pH (determines the amounts of soil CO_2 dissolution), soil water content (reflects the dynamic changes of dew amounts in the soil), and air temperature (controls the dew deposition/evaporation). Exactly, it was found that CO_2 absorption by saline-alkali soils correlates well with these three determining factors and an alternative form of (1) has been employed in large-scale applications [13].

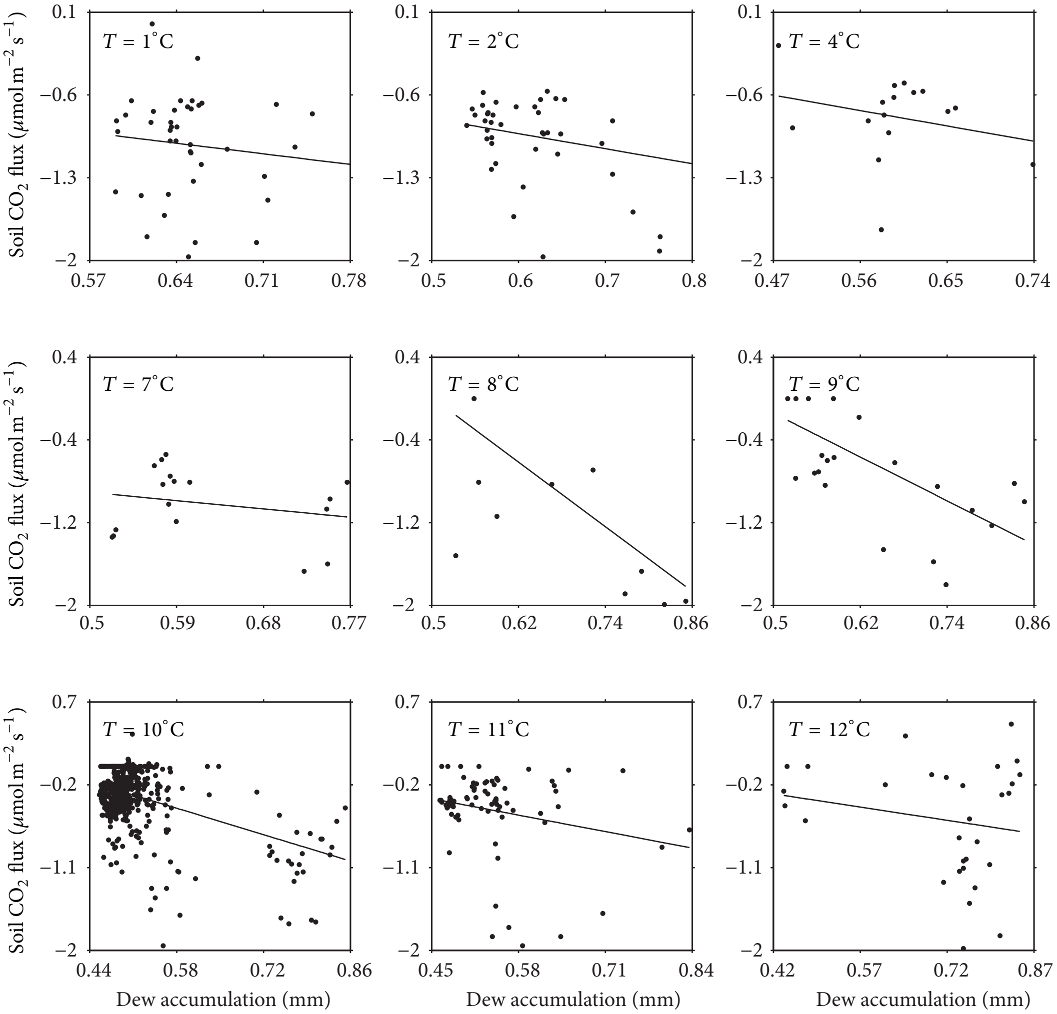


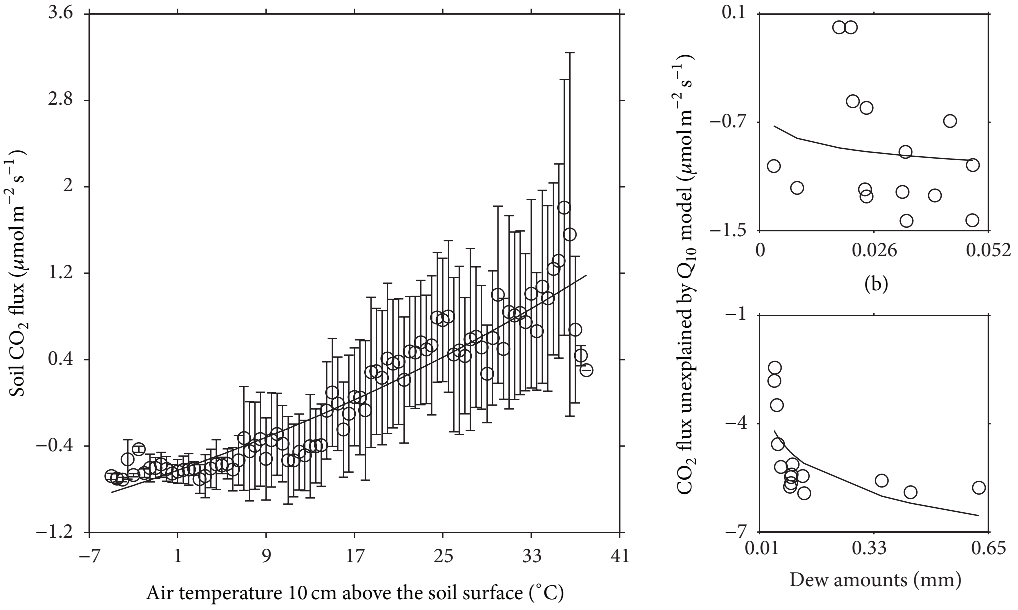
Figure 2: Variations of soil CO$_2$ fluxes (soil respiration fluxes) with dew accumulation along a laboratory gradient of colder air temperatures (from [12]).

It is worthy to be noted that soil CO_3^{2-} content largely determines soil alkalinity degree, which in turn determines the intensity of CO$_2$ absorption by saline-alkali soils. Soil CO_3^{2-} strongly absorbs infrared radiation and may present additional helpful spectral information [23]. When soils are sufficiently dry, salt crystal is accumulated onto the soil surface and hence the surface CO$_2$ adhesion onto soil minerals is increasingly important since it makes chances for this CO$_2$ on the soil surface to be further dissolved in soil water when soil dew amounts increase at lower temperatures (Figure 2). The significance of soil CO_3^{2-} content on CO$_2$ absorption by saline-alkali soils is mainly determined by its close relation with soil pH, soil water content, and air temperature.

3. Potential and Constraints

The spectral characteristics of saline-alkali soils are vulnerable to the effects of the external environmental factors. If such an issue is not properly addressed, then it is easy to generate cumulative errors, which increased the uncertainties in model parameters and in quantifying CO$_2$ absorption by saline-alkali soils. These external environmental factors are also the main determinants of the model parameters. So it is an inevitable challenge to the traditional multispectral remote sensing. Fortunately, the development of modern spectroscopic techniques, especially the development of hyperspectral technology, allows researchers to detect specific substances in the soil using spectral diagnosis characteristics and further reduces uncertainties in remote sensing of CO$_2$ absorption by saline-alkali soils.

Vegetation coverage can change spectral reflectance mode of saline-alkali soils and result in external interference [6, 24, 25]. Remote sensing of CO$_2$ absorption by saline-alkali soils deserves the remote sensing images of high spatial resolution. Currently, the CO$_2$ absorption phenomenon is mainly observed at saline-alkali sites of arid and semiarid regions. Remote sensing of the absorption on large scales should be naturally focused on arid and semiarid ecosystems. Some natural phenomena occurred at soil surface, such as the



(a) (c)

Figure 3: Estimation of soil CO_2 fluxes (soil respiration fluxes: F_c) along a field gradient of the air temperature 10 cm above the soil surface (T) with $F_c = 2.58 * 1.17^{(T-10)/10} - 2.86$ (a: $R^2 = 0.86$, RMSE = 0.23) and analysis of the contributions of dew amounts in F_x with $F_x = -0.82 * e^{10*\text{dew}} + 0.18$ (b: $R^2 = 0.1008$, RMSE = 0.4219) and $F_x = 4.07 * e^{-10*\text{dew}} - 6.38$ (c: $R^2 = 0.53$, RMSE = 0.75), where F_x is defined as the unexplained part of F_c by the Q_{10} model (from [12]).

dry river-bed, the erosion of soil surface, the muddy crust, and their dynamic changes may generate the spectral characteristics similar to saline-alkali soils and cause confusions of the spectrum. These bring technological difficulties in remote sensing of the dynamic changes of the soil salt content on time and spatial scales.

The spectral characteristics are also closely related to the surface morphology of saline-alkali soils, including the salt incrustation of different thickness and salt content, the loose soil structure with aggregated and crystalline salt, and the loose formation caused by wind erosion. Soil surface roughness of different surface morphology is different and the spectral reflectance characteristics become different [26]. These external interferences can affect the surface spectral information of soil surface texture and caused bigger errors in the retrieval of model parameters [27–29]. Other physical and chemical characteristics also affect the spectral characteristics of saline-alkali soils [30–32]. Human farming causes higher surface roughness because the soils are reconstructed and soil surface roughness is significantly increased. However, spatial and spectral resolution of the multispectral remote sensing are relatively low and it is difficult to differentiate the complex spectral characteristics of soil surface and to obtain the precise and quantitative results if we only use the soil spectral characteristics [33]. When the salt content is less than 10~15%, it is almost impossible to distinguish saline-alkali soils from other soils [34].

Hyperspectral images are feasible for the synchronization acquisition of spatial features, radiation information, and spectral characteristics. These images of higher spectral resolution can even reflect the subtle characteristics of landmark spectrum. Quantitative analysis of the distribution of saline-alkali soils and their surface morphology becomes possible, reducing the interference from external environmental factors [35–38]. Hyperspectral remote sensing data improve the accuracy of classification of halophyte and the degrees of salinity/alkalinity [39, 40], which further cut down the subjective errors in remote sensing of the model parameters.

4. Schemes for Remote Sensing

Quantitative mapping of the properties of global saline-alkali soils according to hyperspectral data (including soil salinity) is feasible. Exactly, some scientists have proved the feasibility on regional scales [41–43]. In addition, hyperspectral remote sensing can be provided for each pixel the information of high-quality (similar to the laboratory accuracy) and can accurately monitor the vegetation information (such as the growth and distribution of different types of vegetation). This allows a pretreatment of the vegetation-covered part in hyperspectral images, overcomes the interference of vegetation, and helps to indirectly infer the salinity and alkalinity of the soil according to the vegetation types [44–46], since the vegetation types reflect the ranges of soil salt content and soil pH. These preliminary illustrations present necessary theoretical basis for remote sensing of CO_2 absorption by saline-alkali soil on large scales.

Now we are going to design remote sensing schemes for CO_2 absorption by saline-alkali soil on the global scale. First, collect the representative soil samples for chemical, physical analysis, and the field and laboratory measurements

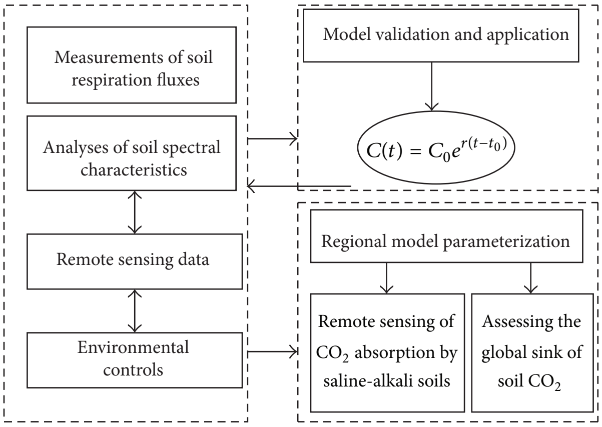


FIGURE 4: Remote sensing schemes for CO_2 absorption by saline-alkali soil on large scales.

of the soil spectral characteristics. This helps to obtain the spectral information related to physical and chemical characteristics. The model parameters are determined by the sampling measurements of soil CO_2 fluxes. Second, conduct the atmospheric correction of high reflectance spectrum image, the retrievial of soil surface reflectance, and the pretreatment of vegetation-covered areas. The retrieval of model parameters is implemented using multiple stepwise regression analyses. Finally, the model with the determined parameters is employed in remote sensing of CO_2 absorption by saline-alkali soil on region scales and then integrated to the global scale. Sketch of the full scheme for quantitative remote sensing of CO_2 absorption by saline-alkali soils on the global scales is presented in Figure 4.

Over the last three decades, the sources of remote sensing data became more abundant and the methods for retrieval became more sophisticated. Saline-alkali soils and other soils can be easily distinguished according to the spectral characteristics from the hyperspectral images when combined with the GIS assessment of the degrees of soil salinity and alkalinity. Soil salt content can also be accurately predicted by the standard reflectance spectrum, using the data-mining technologies (such as PLSR and ANN) [47]. Spectral reflectance of saline-alkali soils has been applied in studies on soil science, ecology, environmental science, biophysiology, ecology, and economics [48–51]. The scheme for retrieval of CO_2 absorption by saline-alkali soil on the global scale seems feasible under the strong backgrounds. However, there are still some unresolved issues to be investigated for further reducing uncertainties in the retrieval as follows.

(1) Visual interpretation remains as an important means of monitoring and analysis on saline-alkali soil and its dynamics [52]. But in fact, the imaging characteristics of saline-alkali soils can vary depending on the resolution and the image sensor at different times. Interpretation of saline-alkali soils should be done not only in accordance with their image features, but also in accordance with a comprehensive analysis of the geographical and landscape features of the saline-alkali soils [53–56].

(2) Remote sensing of CO_2 absorption by saline-alkali soils deserves a better understanding of spectral reflectance of the different types of saline-alkali soils and the relationship between them and the degrees of soil salinity and alkalinity. This deserves the hyperspectral images of high spatial resolution, which is essentially significant to enhance the reliability of retrieval of model parameters. But the access of hyperspectral remote sensing data remains too expensive, especially, when the retrieval is considered on the global scale.

(3) Salts dissolution in the soil during the rainy seasons and salts migration due to the seasonal changes of land-cover changes will also cause interference in the extraction of information for saline-alkali soils. These will increase the difficulty of detecting dynamic changes in remote sensing data, which is partly because of the integrated effects of vegetation and soil types and other factors on spectral information of the pilot land farming. This can be resolved using the multitemporal image and by the adoption of different tillage.

Study on these issues will not only help us to distinguish different types of saline-alkali soils, but will also imply the comprehensive applications of multitemporal remote sensing data in zoning soil CO_2 source or sink over arid and semiarid regions [15, 57–59]. In addition, the large-scale effort on measuring soil respiration fluxes in arid and semiarid ecosystems around the world must be organized for a reliable quantitative inversion of soil CO_2 absorption. This is a laborious challenge and needs the common attention by the world scientific communities.

5. Conclusions

With the increases of the spectral resolution, the radiation resolution, the time resolution, and the spatial resolution of remote sensing data, retrieval of soil salt content becomes more active and researches on the mechanisms are prized. In particular, research on the applications of the hyperspectral remote sensing data on soil salinization and alkalization has tremendous potential. Utilizing the hyperspectral remote sensing data, it becomes possible to accurately distinguish the special salt content in the soils (Figure 5). Remote sensing of CO_2 absorption by saline-alkali soils is theoretical feasible. However, the spectroscopy studies on the saline-alkali soil are mainly restricted to monitor the salinity degree, the spatial scope, and the geographic distribution of saline-alkali soils, mainly using the multispectral remote sensing data (the hyperspectral remote sensing data were less employed because it is expensive). As a first attempt, this paper presented remote sensing scheme for CO_2 absorption by saline-alkali soil on large scales. But the qualitative research of spectral reflectance properties of saline-alkali soils was less focused on CO_2 absorption by saline-alkali soil, which is partly because of traditional ignoring of such absorption. There are still a series of unresolved issues to be further addressed before the remote sensing scheme is carried out.

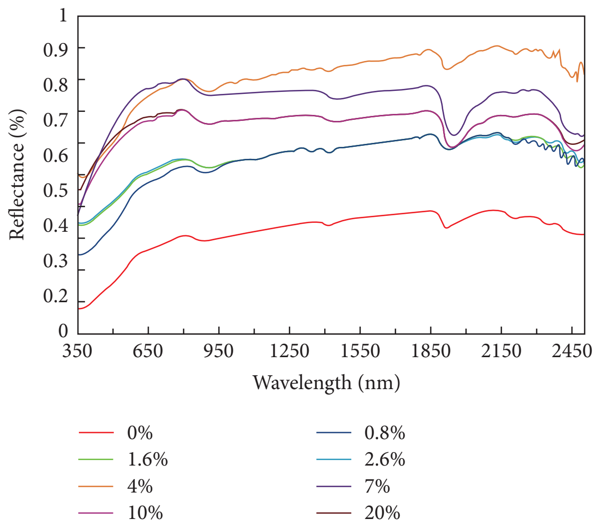


Figure 5: Reflectance of soils rich in Na_2SO_4 with different salt content (adapted from [15]).

Conflict of Interests

The authors declared that there is no conflict of interests regarding the publication of this paper.

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