A point-by-point response to the reviews

Respond to Referee 1:

Thank you for your comments concerning our manuscript which were posted on the NHESS Discussion page on October 31, 2018. Those comments are helpful and constructive for improving our manuscript and future research. The comments and our responses are presented below.

1. This study compared the field survey and remote sensing image for revealing the distributions of saline soil in Yellow River Delta. The study in this area is very important for crop growth and ecological restoration.

As a whole, this article was well-written and organized. The results were sound and interesting. I think it could be accepted after minor revision.

Response: We appreciate the encouraging comments on this study, and we revised the article carefully.

2. TitleïijŽ delete "region".

Response: We agree with the comment and the word "region" in the title was deleted in the revised manuscript. The title was revised as "Monitoring the seasonal dynamics of soil salinization in the Yellow River Delta of China using Landsat data".

3. Abstract: Why is necessary with distinct seasonal climates? I think some field results could be showed in the abstract.

Response: In regions with distinct seasons, the difference of rainfall or evaporation is great in different season, the change of soil moisture is obvious, and soil salinity has close relation to the soil moisture, then soil salinity between seasons varies usually greatly. Therefore it is very necessary to monitor seasonal dynamics of soil salinization with distinct seasonal climates. In order to show the variation of soil salt in four seasons, we agree with the comment and added some field results to the abstract in the revised manuscript.

Page 1 Line 19-20, "The results indicated that the SSC varied obviously between seasons in the YRD, and" was added.

4. This sentence "the SSC optimal model in each season was extracted, then, the spatial distributions and seasonal dynamics of SSC in four seasons were analysed." was repeated with the second sentence.

Response: We agree with the comment and deleted some repeated information in the revised manuscript.

5. In the introduction, what is the damage of saline soils in Yellow River Delta?

Response: In Yellow River Delta, soil salinization can result in large reduction of agricultural production and fragile ecological environment. We added some descriptions to the introduction in the revised manuscript about the damage of saline soils in Yellow River Delta.

Page 2 Line 5-6, "Moreover, as a form of land degradation, soil salinization can degrade soil quality and lead to ecosystem risks (Huang et al. 2015; Zhao et al. 2018)." was added.

6. Figure 1, some labels are not clear. Figure 3, the red underline should be deleted.

Response: We agree with the comment, the labels in Figure1 was revised to be clear and the red underline in Figure 3 was deleted in the revised manuscript.

7. This distribution pattern is consistent with the results of other studies (Weng et al. 2010; Yang et al. 2015) should be moved to the discussion part.

Response: We agree with the comment, the above-mentioned sentence was deleted in results and relative discussion was added to the revised manuscript.

Page 13 Line 11-18, the discussion of "In this work, we introduced the SWIR band and proposed an improved vegetation index to increase the accuracy of SSC inversion models. The spatial distributions of SSC in the four seasons showed similar characteristics. There was a gradually increasing trend of soil salinity from southwest to northeast in the study region, and this distribution pattern is consistent with the results of other studies (Weng et al. 2010; Yang et al. 2015). Weng et al. (2010) also established an SSC remote sensing revision model using the data from 2153 ~ 2254 nm and 1941 ~ 2092 nm in the region of YRD and achieved good results." was added.

8. In figure 5, it seems that the autumn is the most affected saline soil. I think some field results could also be indicated in the conclusion.

Response: From Figure 5 and Table 7, the SSC in autumn was largely dominated by severely saline soil and solonchak (combined proportion of 77.75%); in winter, the SSC was principally severely saline and solonchak, with the combined proportion of 99.19%, of which the severe saline soil contributed 80.71%. Therefore the winter is the most affected saline soil. In order to provide more clarity we agree with the comment and added some field results to the conclusion in the revised manuscript.

Page 16 Line 10-11, the statement of "These results are consistent with the results of field sampling, which showed that the SSC is highest in winter, followed by spring and autumn, and lowest in summer." was added.

9. Most of the last paragraph in discussion is not really discussion.

Response: The last paragraph of discussion provides the probable reason of the model selection results and the shortage based on data of the time point, some descriptions maybe are too redundant, we agree with the comment and deleted some descriptions of the last discussion paragraph in the revised manuscript.

Respond to Referee 2:

We are pleased to respond to the helpful and constructive comments, which were posted on the NHESS Discussion page on November 11, 2018. Your comments and our responses are presented below.

1. The title is better to revise to 'Monitoring seasonal dynamics of soil salinization in the Yellow River Delta region of China using Landsat data'

Response: We agree with the comment and the title was revised to 'Monitoring seasonal dynamics of soil salinization in the Yellow River Delta of China using Landsat data' in the revised manuscript.

2. Please revise the abstract, especially for the part of methods, from your abstract readers could not understand which regression models were used in the prediction model.

Response: We agree with the comment and added the description about regression models to the abstract in the revised manuscript.

Page 1 Line 12-17, the statement of "The article is to explore the optimal inversion models of soil salinity content (SSC) in different seasons and to achieve the spatial distribution and seasonal dynamics of SSC in Kenli district in the Yellow River Delta (YRD) region of China. Based on the Landsat data in 2013, the improved vegetation indices (IVI) were constructed, which were then applied in the SSC inversion model construction." was corrected as "The article took Kenli district in the Yellow River Delta (YRD) of China as the experimental area. Based on Landsat data from spring and autumn, improved vegetation indices (IVIs) were created, which were then applied to the inversion modeling of soil salinity content (SSC) by employing stepwise multiple linear regression, back propagation neural network and support vector machine methods.".

3. 'The SSC best inversion model of spring was also determined as the optimal model of winter, similarly, the best model of autumn was also as the optimal model of summer' this sentence was very confusing, please revise it.

Response: This experiment indicates that the best inversion model of spring could be applied for the SSC inversion of winter; at the same time, the best inversion model of autumn could also be applied to the SSC inversion of summer in the Yellow River Delta. We agree with the comment and made changes to the abstract in the revised manuscript.

Page 1 Line 21-23, the statement of "The SSC best inversion model of spring was also determined as the optimal model of winter, similarly, the best model of autumn was also as the optimal model of summer." was corrected as "The best SSC inversion model for spring could be applied to the SSC inversion in winter; similarly, the best model for autumn could also be applied to SSC inversion in summer.".

4. I am a bit confused about your four seasons inversion. You monitor four seasons dynamics of soil salinization; why didn't you build models for four seasons and just choose two season for models building. You may discuss the soil salinity content of spring was similar with that of winter, for example, while these two seasons vegetation was quite different. So why you applied the spring soil salinity model to that of winter. Please add this discussion.

Response: because the SSC is dynamic through the four seasons of a year, applying the same inversion model to analyze the SSC quantitatively in different seasons is not adequate, however, building a model for each season is cumbersome and impractical, so we chose two seasons for models building and studied the models applicability. Based on the data of time point, this experiment indicates the best inversion model of spring can be applied to winter. This model selection results may be due to the short time intervals, similar soil salt content and climatic conditions between February and April in the Yellow River Delta. In order to respond more accurately to the dynamic changes of soil salt, a period of SSC should be selected as the seasonal salt data, which will be the future research. The last paragraph of discussion provided the relative discussion; in order to provide more clarify we revised some description in the revised manuscript.

Page 15 Line 6-13, the discussion paragraph of "Based on the time point data, the results indicated that the SSC inversion model for spring could be applied to SSC inversion in winter, while the SSC inversion model for autumn could also be applied to SSC inversion in summer in the YRD. These model selection results may be due to the short time intervals, similar soil salt contents and climatic conditions between February and April and between August and November in the YRD. To respond more accurately to the dynamic changes in soil salt, a period of SSC data should be selected as the seasonal salt data, which will be further studied in future research." was added.

5. In the part of '2.5 Inversion model construction and optimization', the first six lines were too redundant, please simplify it.

Response: We agree with the comment and simplified the description in the revised manuscript.
Page 7 Line 22-25 and Page8 Line 1-3, the statement of "Two-thirds of the samples were chosen for the calibration set, and the remaining samples were used as the validation set. So, the 92 samples of spring were divided into two groups, specifically one group of 62 samples for calibration and the other group of 30 samples for validation. Among the 110 samples of autumn, 74 samples were used for calibration, and the remaining 36 samples were used for validation." was corrected as "Two-thirds of the samples were chosen for the calibration set, and the remaining samples were used as the validation set. Therefore, of the 92 samples collected during spring, 62 samples were used for calibration, and the other 30 samples were used for validation. Similarly, of the 110 samples collected during autumn, 74 samples were used for calibration, and the other 36 samples were used for validation.".
6. Conclusions should be simplified.
Response: We agree with the comment and the conclusions were simplified in the revised manuscript.
Page 15 Line 6-13, the discussion paragraph of "Based on the time point data, the results indicated that the SSC inversion model for spring could be applied to SSC inversion in winter, while the SSC inversion model for autumn could also be applied to SSC inversion in summer in the YRD. These model selection results may be due to the short time intervals, similar soil salt contents and climatic conditions between February and April and between August and November in the YRD. To respond more accurately to the dynamic changes in soil salt, a period of SSC data should be selected as the seasonal salt data, which will be further studied in future research." was added.
Page 15 Line 16-22, the statement of "In this experiment, the results showed that the extended ratio vegetation index (ERVI) and extended difference vegetation index (EDVI) were as IVI of spring, while the extended normalized difference vegetation index (ENDVI) and extended ratio vegetation index (ERVI) were as the IVI of autumn. The best and most stable accuracy of SSC was produced by the SVM models based on the IVI; therefore, these models were selected as the best SCC inversion models of spring and autumn. The experiment results would contribute to the quantitative and accurate monitoring of soil salinization with multispectral imaging." was corrected as "In this experiment, the results showed that the ERVI and EDVI were the IVIs for spring, while the ENDVI and ERVI were the IVIs for autumn. These models based on the IVIs that utilized the SVM method were selected as the best SSC inversion models for spring and autumn. The experimental results contribute to the quantitative and accurate monitoring of soil salinization with multispectral imaging and provide data and technical support for saline soil management and utilization and ecological environment protection.".
7. There were some mistakes in the manuscript, eg, line 6 of abstract, the word should be constructed. Please read carefully and avoid these minor mistakes.
Response: We appreciate your carefulness and we revised carefully this kind of mistakes in the revised manuscript.
8. The language should be polished before publication.
Response: We agree with the comment and the language was polished in the revised manuscript.

Respond to Referee 3:
Thank you for your comments concerning our manuscript which were posted on the NHESS Discussion page on January 31, 2019. Those comments are helpful and constructive for improving our manuscript and future research. The comments and our responses are presented below.

1. The authors aimed to develop models to predict soil salinity over different seasons using an improved vegetation index. However, I found that the drawbacks of the earlier indices were not explained in the Introduction of the revised manuscript.

Response: We added some description about the drawbacks of the earlier indices in the Introduction of the revised manuscript.

Page 3 Line 1-13, the whole paragraph of "To a certain extent, information on the damage to vegetation caused by soil salinization can help to determine the degree and trend of soil salinization. Therefore, traditional vegetation indices (VIs), such as the normalized difference vegetation index (NDVI), the ratio vegetation index (RVI), and the difference vegetation index (DVI), can be used as indicators to determine the degree of soil salinization (Elmetwalli et al. 2012; Li et al. 2013; Goto et al. 2015). However, the accuracy of the models based on traditional VIs must be improved (Iqbal 2011). Traditional VIs involve the data from only two bands in the visible and near-infrared region, and there are often significant correlations between traditional VIs (USGS, 2013). Therefore, it is worth studying whether the addition of data from the shortwave infrared band, which has long wavelengths and contains considerable information, can improve the accuracy and stability of soil salinity content (SSC) inversion models." was added

2. The Discussion also needs to be improved, particularly the third paragraph since it only repeats the Results.

Response: We agree with the comment, the discussion was revised carefully. The third paragraph mainly discussed the results and disadvantages based on the data of time point. We deleted the repeat description of results in the revised manuscript.

Page 15, the discussion paragraph of "The article aimed to build optimal SSC inversion models for different seasons according to soil salinity condition in one year, and the SSC at the point of time was used as the corresponding seasonal salt data. The results indicated that the SSC inversion model of spring could be applied in winter resulting in R^2 of 0.66 and RMSE of 7.57 g/kg, while the SSC inversion model of autumn could also be applied in summer resulting in R^2 of 0.65 and RMSE of 3.60 g/kg within a year in the YRD region. This model selection results may be due to the short time intervals and similar soil salt climatic conditions between February and April and between August and November in the Yellow River Delta region. In order to respond more accurately to the dynamic changes of soil salt, a period of SSC should be selected as the seasonal salt data, which will be the future research, and the application of the SSC inversion models for different years will be explored." was deleted.

3. How did the authors ensure the accuracy of their select months compared to the other months?

Response: Only based on the data of time point in one season, it is really difficult to ensure the accuracy of the selected time point compared to the other months, so, in order to respond more accurately to the dynamic changes of soil salt, a period of SSC should be selected as the seasonal salt data, which will be the future research. We added related discussion in the revised manuscript.

Page 15 Line 6-13, the discussion paragraph of "Based on the time point data, the results indicated that the SSC inversion model for spring could be applied to SSC inversion in winter, while the SSC inversion model for autumn could also be applied to SSC inversion in summer in the YRD. These model selection results may be due to the short time intervals, similar soil salt contents and climatic conditions between February and April and between August and November in the YRD. To respond more accurately to the dynamic changes in soil salt, a period of SSC data should be selected as the seasonal salt data, which will be further studied in future research." was added.

4. It is also unclear why the samples collected in spring and autumn were used to develop the inversion models while the samples of winter and summer were used to validate the models.

Response: Firstly, in the YRD regions with distinct seasons, soil salinity between seasons varies usually greatly, it is not appropriate applying the same model to four seasons. Secondly, from the descriptive statistics of the soil samples SSC (Table 2), the SSC in spring is close to winter meanwhile the SSC in summer is close to autumn, so it is feasible to adopt the same model in spring and winter, meanwhile it is feasible to adopt the same model in autumn and summer. Thirdly, in the YRD regions soil salts aggregate to the soil surface in spring, spring is often chosen to study soil salinity inversion (Weng et al., 2010), and because the summer vegetation is too luxuriant, the autumn is more suitable for the study season than summer (Dehni & Lounis, 2012; Yang et al., 2015), so the samples collected in spring and autumn were used to develop the inversion models while the samples of winter and summer were used to validate the models.

5. P11L2 What is the relationship between 5 grades of soil salinization and figure 5?

Response: 5 grades of soil salinization are non-saline soil, mild saline soil, moderate saline soil, severe saline soil, and solonchak, the degree of soil salinization gradually increased. We added some description about the relationship between 5 grades of soil salinization in section 3.4.1 of the revised manuscript.

Page 11 Line 23-24 and Page 12 Line 1, "nonsaline soil, mild saline soil, moderate saline soil, severe saline soil, and solonchak, with the degree of soil salinization gradually increasing from nonsaline soil to solonchak" was added.

6. There are numerous convoluted sentences that can be simply re-written.

Response: We accept the comment, some of the most striking examples were revised one by one and some sentences were re-written, we revised the whole manuscript carefully.

7. I strongly suggest the authors to seek professional English proof-reader to help with the overall language presentation of the manuscript since there are also numerous grammatical errors.

Response: We accept the comment, we revised the grammatical errors listed one by one and sought professional English proof-reader to help.

8. What are the obvious geographical advantages?

Response: The obvious geographical advantages mainly refers to that the Yellow River Delta is located in the junction part of the Beijing-Tianjin-Hebei metropolitan and Shandong Peninsula, and there is a national-level high-efficiency ecological economic region in China.

In order to clarify clearly the information, we modified some description in the revised manuscript.
Page 3 Line 18-22, the statement of “The Yellow River Delta (YRD) region lies within the efficient ecological economic zone of China. With nearly 550,000 ha of unused land, it has obvious geographical advantages and abundant land resources.” was corrected as “The Yellow River Delta (YRD) is located at the junction of the Beijing-Tianjin-Hebei metropolitan area and Shandong Peninsula and lies within the efficient ecological economic zone of China, and this region has obvious geographical advantages. With nearly 550,000 ha of unused land, the land resources in this area are rich.”.

Respond to editor:
We would like to thank you for the in-depth comments and suggestions of our paper. You helped us to stay in line with the special issue and improve key points of the background and make the discussion and conclusion more valuable. The comments and our responses are presented below.
1. I suggest the authors should be think over the hazards/risk topic, and must stay in line with the special issue goals please.
Response: As a form of land degradation, soil salinization can degrade soil quality and lead to ecosystem risks, and as the main risk to farmland ecosystems in the Yellow River Delta, soil salinization can result in a large reduction in agricultural production and fragile ecological environments. In the revised manuscript, we added some description to the first and fourth paragraph of introduction and the first paragraph of conclusion.
Page 2 Line 5-6, “Moreover, as a form of land degradation, soil salinization can degrade soil quality and lead to ecosystem risks (Huang et al. 2015; Zhao et al. 2018).” was added. Page 4 Line 1-4, the statement of “which has seriously affected the utilization of land resources as well as the development of the regional economy and society (Yang et al. 2015; Weng et al. 2010).” was corrected as “As the main risk to farmland ecosystems in this region, soil salinization can result in a large reduction in agricultural production and fragile ecological environments; and, soil salinization seriously affects the utilization of land resources as well as the development of the regional economy and society (Yang et al. 2015; Weng et al. 2010).”. Page 15 Line 16-22, the statement of “In this experiment, the results showed that the extended ratio vegetation index (ERVI) and extended difference vegetation index (EDVI) were as IVI of spring, while the extended normalized difference vegetation index (ENDVI) and extended ratio vegetation index (ERVI) were as the IVI of autumn. The best and most stable accuracy of SSC was produced by the SVM models based on the IVI; therefore, these models were selected as the best SCC inversion models of spring and autumn. The experiment results would contribute to the quantitative and accurate monitoring of soil salinization with multispectral imaging.” was corrected as “In this experiment, the results showed that the ERVI and EDVI were the IVIs for spring, while the ENDVI and ERVI were the IVIs for autumn. These models based on the IVIs that utilized the SVM method were selected as the best SSC inversion models for spring and autumn. The experimental results contribute to the quantitative and accurate monitoring of soil salinization with multispectral imaging and provide data and technical support for saline soil management and utilization and ecological environment protection.”.

2. As for the manuscript, the Introduction is short to show the frontiers on remote sensed SSC. Why the seasonal inversion is urgently needed has not been well explained.
Response: We agree with the comment, some description about the frontiers on and the drawbacks of the earlier spectra indices used to monitoring soil salt was added in the third paragraph of the introduction and the reason why the seasonal inversion of soil salt content is urgently needed was added in the fourth paragraph of the introduction in the revised manuscript.
Page 3 Line 1-13, the whole paragraph of "To a certain extent, information on the damage to vegetation caused by soil salinization can help to determine the degree and trend of soil salinization. Therefore, traditional vegetation indices (VIs), such as the normalized difference vegetation index (NDVI), the ratio vegetation index (RVI), and the difference vegetation index (DVI), can be used as indicators to determine the degree of soil salinization (Elmetwalli et al. 2012; Li et al. 2013; Goto et al. 2015). However, the accuracy of the models based on traditional VIs must be improved (Iqbal 2011). Traditional VIs involve the data from only two bands in the visible and near-infrared region, and there are often significant correlations between traditional VIs (USGS, 2013). Therefore, it is worth studying whether the addition of data from the shortwave infrared band, which has long wavelengths and contains considerable information, can improve the accuracy and stability of soil salinity content (SSC) inversion models." was added. Page 4 Line 5-9, the statement of "Moreover, the SSC in the YRD region has obvious seasonal characteristics because of the seasonal climate. Real-time, continuous monitoring of soil salinization is particularly important in this region." was corrected as "Moreover, in regions with distinct seasons, the differences in rainfall and evaporation between different seasons are great, the changes in soil moisture are obvious, and soil salinity exhibits a close relation with soil moisture; thus, the soil salinity usually varies greatly between seasons. Therefore, it is particularly necessary to monitor the seasonal dynamics of soil salinization in this region.".
3. In the Discussion, literature comparison with former studies should be added.
Response: we agree with the comment and added some comparison with former studies to the first and third paragraph of the discussion in the revised manuscript.
Page 13 Line 13-18, the discussion of "There was a gradually increasing trend of soil salinity from southwest to northeast in the study region, and this distribution pattern is consistent with the results of other studies (Weng et al. 2010; Yang et al. 2015). Weng et al. (2010) also established an SSC remote sensing revision model using the data from 2153 ~ 2254 nm and 1941 ~ 2092 nm in the region of YRD and achieved good results." was added. Page 15 Line 2-4, the statement of "Lu et al. (2016) presented that SSC exhibits seasonal variation in the YRD and that the SSC in spring was higher than that in autumn in the Kenli district, which is consistent with our results." was added.
4. It seems that there are too many tables, it may be better to remain no more than 4 tables in the manuscript.
Response: We agree with the comment, Table 1 was deleted and some relevant description was added to the section 2.4; Table 3 was deleted and some relevant description was added to the section 3.2; Table 2 and Table 6 were merged, so there are remain 4 tables in the revised manuscript.
5. Besides, the language should be polished by a native English speaker.

Response: We agree with the comment and sought a native English speaker to help.

Respond to Short Comment 1:

Thank you for your comments concerning our manuscript which were posted on the NHESS Discussion page on October 31, 2018. Those comments are helpful and constructive for improving our manuscript and future research. The comments and our responses are presented below.

1. This study compared the field survey and remote sensing image for revealing the distributions of saline soil in Yellow River Delta. The study in this area is very important for crop growth and ecological restoration.

As a whole, this article was well-written and organized. The results were sound and interesting. I think it could be accepted after minor revision.

Response: We appreciate the encouraging comments on this study, and we revised the article carefully.

2. TitleïijŽ delete "region".

Response: We agree with the comment and the word "region" in the title was deleted in the revised manuscript. The title was revised as “Monitoring the seasonal dynamics of soil salinization in the Yellow River Delta of China using Landsat data”.

3. Abstract: Why is necessary with distinct seasonal climates? I think some field results could be showed in the abstract.

Response: In regions with distinct seasons, the difference of rainfall or evaporation is great in different season, the change of soil moisture is obvious, and soil salinity has close relation to the soil moisture, then soil salinity between seasons varies usually greatly. Therefore it is very necessary to monitor seasonal dynamics of soil salinization with distinct seasonal climates. In order to show the variation of soil salt in four seasons, we agree with the comment and added some field results to the abstract in the revised manuscript.

Page 1 Line 19-20, “The results indicated that the SSC varied obviously between seasons in the YRD, and” was added.

4. This sentence "the SSC optimal model in each season was extracted, then, the spatial distributions and seasonal dynamics of SSC in four seasons were analysed." was repeated with the second sentence.

Response: We agree with the comment and deleted some repeated information in the revised manuscript.

5. In the introduction, what is the damage of saline soils in Yellow River Delta?

Response: In Yellow River Delta, soil salinization can result in large reduction of agricultural production and fragile ecological environment. We added some descriptions to the introduction in the revised manuscript about the damage of saline soils in Yellow River Delta.

Page 2 Line 5-6, “Moreover, as a form of land degradation, soil salinization can degrade soil quality and lead to ecosystem risks (Huang et al. 2015; Zhao et al. 2018).” was added.

6. Figure 1, some labels are not clear. Figure 3, the red underline should be deleted.

Response: We agree with the comment, the labels in Figure1 was revised to be clear and the red underline in Figure 3 was deleted in the revised manuscript.

7. This distribution pattern is consistent with the results of other studies (Weng et al. 2010; Yang et al. 2015) should be moved to the discussion part.

Response: We agree with the comment, the above-mentioned sentence was deleted in results and relative discussion was added to the revised manuscript.

Page 13 Line 11-18, the discussion of "In this work, we introduced the SWIR band and proposed an improved vegetation index to increase the accuracy of SSC inversion models. The spatial distributions of SSC in the four seasons showed similar characteristics. There was a gradually increasing trend of soil salinity from southwest to northeast in the study region, and this distribution pattern is consistent with the results of other studies (Weng et al. 2010; Yang et al. 2015). Weng et al. (2010) also established an SSC remote sensing revision model using the data from 2153 ~ 2254 nm and 1941 ~ 2092 nm in the region of YRD and achieved good results." was added.

8. In figure 5, it seems that the autumn is the most affected saline soil. I think some field results could also be indicated in the conclusion.

Response: From Figure 5 and Table 7, the SSC in autumn was largely dominated by severely saline soil and solonchak (combined proportion of 77.75%); in winter, the SSC was principally severely saline and solonchak, with the combined proportion of 99.19%, of which the severe saline soil contributed 80.71%. Therefore the winter is the most affected saline soil. In order to provide more clarity we agree with the comment and added some field results to the conclusion in the revised manuscript.

Page 16 Line 10-11, the statement of "These results are consistent with the results of field sampling, which showed that the SSC is highest in winter, followed by spring and autumn, and lowest in summer." was added.

9. Most of the last paragraph in discussion is not really discussion.

Response: The last paragraph of discussion provides the probable reason of the model selection results and the shortage based on data of the time point, some descriptions maybe are too redundant, we agree with the comment and deleted some descriptions of the last discussion paragraph in the revised manuscript.

A list of all relevant changes made in the manuscript

1. Page 1 Line 1-2, the title was revised as "Monitoring the seasonal dynamics of soil salinization in the Yellow River Delta of China using Landsat data".
2. Page 1 Line 12-17, the statement of "The article is to explore the optimal inversion models of soil salinity content (SSC) in different seasons and to achieve the spatial distribution and seasonal dynamics of SSC in Kenli district in the Yellow River Delta (YRD) region of China. Based on the Landsat data in 2013, the improved vegetation indices (IVI) were constructed, which were then applied in the SSC inversion model construction." was corrected as "The article took Kenli district in the Yellow River Delta (YRD) of China as the experimental area. Based on Landsat data from spring and autumn, improved vegetation indices (IVIs) were created, which were then applied to the inversion modeling of soil salinity content (SSC) by employing stepwise multiple linear regression, back propagation neural network and support vector machine methods.".
3. Page 1 Line 19-20, "The results indicated that the SSC varied obviously between seasons in the YRD, and" was added.
4. Page 1 Line 21-23, the statement of "The SSC best inversion model of spring was also determined as the optimal model of winter, similarly, the best model of autumn was also as the optimal model of summer." was corrected as "The best SSC inversion model for spring could be applied to the SSC inversion in winter; similarly, the best model for autumn could also be applied to SSC inversion in summer.".
5. Page 1 Line 25, the statement of "its seasonal dynamics were as that" was corrected as "it also underwent the following seasonal dynamics:".
6. Page 2 Line 5-6, "Moreover, as a form of land degradation, soil salinization can degrade soil quality and lead to ecosystem risks (Huang et al. 2015; Zhao et al. 2018)." was added.
7. Page 2 Line 10, "then help to reduce ecological risks" was added.
8. Page 2 Line 16-19, The statement of "Due to the low cost and the ability to map extreme surface expressions of salinity of the imagery, multispectral satellite data, such as Landsat, System Probatoired' Observation dela Terre (SPOT), IKONOS, QuickBird, and the Indian Remote Sensing (IRS) series of satellites, have been used for mapping and monitoring of soil salinity and other properties" was corrected as "Multispectral satellite data, such as Landsat, SPOT, IKONOS, QuickBird, and the Indian Remote Sensing (IRS) series of satellites, have been used to map and monitor soil salinity and other properties due to the low cost and the ability to map extreme surface expressions of salinity".
9. Page 3 Line 1-13, the whole paragraph of "To a certain extent, information on the damage to vegetation caused by soil salinization can help to determine the degree and trend of soil salinization. Therefore, traditional vegetation indices (VIs), such as the normalized difference vegetation index (NDVI), the ratio vegetation index (RVI), and the difference vegetation index (DVI), can be used as indicators to determine the degree of soil salinization (Elmetwalli et al. 2012; Li et al. 2013; Goto et al. 2015). However, the accuracy of the models based on traditional VIs must be improved (Iqbal 2011). Traditional VIs involve the data from only two bands in the visible and near-infrared region, and there are often significant correlations between traditional VIs (USGS, 2013). Therefore, it is worth studying whether the addition of data from the shortwave infrared band, which has long wavelengths and contains considerable

information, can improve the accuracy and stability of soil salinity content (SSC) inversion models." was added to descript the frontiers on and the drawbacks of the earlier spectra indices used to monitoring soil salt.

10. Page 3 Line 18-22, the statement of "The Yellow River Delta (YRD) region lies within the efficient ecological economic zone of China. With nearly 550,000 ha of unused land, it has obvious geographical advantages and abundant land resources." was corrected as "The Yellow River Delta (YRD) is located at the junction of the Beijing-Tianjin-Hebei metropolitan area and Shandong Peninsula and lies within the efficient ecological economic zone of China, and this region has obvious geographical advantages. With nearly 550,000 ha of unused land, the land resources in this area are rich.".

11. Page 4 Line 1-4, the statement of "which has seriously affected the utilization of land resources as well as the development of the regional economy and society (Yang et al. 2015; Weng et al. 2010)." was corrected as "As the main risk to farmland ecosystems in this region, soil salinization can result in a large reduction in agricultural production and fragile ecological environments; and, soil salinization seriously affects the utilization of land resources as well as the development of the regional economy and society (Yang et al. 2015; Weng et al. 2010).".

12. Page 4 Line 5-9, the statement of "Moreover, the SSC in the YRD region has obvious seasonal characteristics because of the seasonal climate. Real-time, continuous monitoring of soil salinization is particularly important in this region." was corrected as "Moreover, in regions with distinct seasons, the differences in rainfall and evaporation between different seasons are great, the changes in soil moisture are obvious, and soil salinity exhibits a close relation with soil moisture; thus, the soil salinity usually varies greatly between seasons. Therefore, it is particularly necessary to monitor the seasonal dynamics of soil salinization in this region.".

13. Page 4 Line 15-16, the statement of "Specifically, we bulit the vegetation indices by introducing the additional data of the short-wave infrared band (SWIR) available in Landsat data." was corrected as "Specifically, VIs were constructed by introducing data from the shortwave infrared band (SWIR) of Landsat data.".

14. Page 5 Line 8-10, the statement of "the levels of soil profile are obvious with salt accumulating in the soil surface while relatively little and well-distributed in the middle and lower part of the soil profile (below the core soil)." was corrected as "salt accumulates on the soil surface, and salt is relatively rare and well-distributed in the middle and lower parts of the soil profile (below the core soil).".

15. Page 6 Line 3-5, the statement of "during August 14~15, 2013, 30 summer samples were collected; 110 autumn samples were collected during November 9~ 13, 2013, and 56winter samples were collected during February 26~ 29, 2014." was corrected as "30 summer samples were collected from August 14-15, 2013; 110 autumn samples were collected from November 9-13, 2013; and 56 winter samples were collected from February 26-29, 2014.".

16. Page 7 Line 1, the statement of "from the Exelis Visual Information Solutions" about the ENVI 5.1 software manufacturer was added.

17. Page 7 Line 13-16, the statement of "including normalized difference vegetation index (NDVI), difference vegetation index (DVI), and ratio vegetation index (RVI) which was shown in Table 1." was corrected as "including the extended normalized difference

vegetation index (ENDVI, (NIR+SWIR-R)/(NIR+SWIR+R)), extended difference vegetation index (EDVI, NIR+SWIR-R), and extended ratio vegetation index (ERVI, (NIR+SWIR)/R). The SWIR band refers to either of the two SWIR bands." and Table 1 was deleted.

18. Page 7 Line 22-25 and Page8 Line 1-3, the statement of "Two-thirds of the samples were chosen for the calibration set, and the remaining samples were used as the validation set. So, the 92 samples of spring were divided into two groups, specifically one group of 62 samples for calibration and the other group of 30 samples for validation. Among the 110 samples of autumn, 74 samples were used for calibration, and the remaining 36 samples were used for validation." was corrected as "Two-thirds of the samples were chosen for the calibration set, and the remaining samples were used as the validation set. Therefore, of the 92 samples collected during spring, 62 samples were used for calibration, and the other 30 samples were used for validation. Similarly, of the 110 samples collected during autumn, 74 samples were used for calibration, and the other 36 samples were used for validation.".

19. Page 8 Line 6-10 and Page8 Line 1-3, the statement of "At the same way, the best model of SSC for autumn was built on the IVI and selected. Finally the best model for spring and autumn was respectively decided and applied to the summer and winter data, then the optimal inversion models of SSC according to soil salinization conditions in different seasons were selected." was corrected as "Using the same procedures, the SSC models for autumn were built on the IVIs, and the best model was selected. Finally, the best models for spring and autumn were selected and applied to the summer and winter data, and then the optimal SSC inversion models according to the soil salinization conditions in different seasons were selected.".

20. Page 9 Line 21-22 and Page 10 Line 1-2, the statement of "The correlation coefficients between the EVI and the SSC of the soil samples are shown in Table 3." was corrected as "In spring, the correlation coefficients between the EVIs and the SSC of the soil samples were -0.52 for ENDVI, -0.69 for ERVI and -0.70 for EDVI; similarly in autumn, the correlation coefficients between the EVIs and the SSC of the soil samples were -0.73 for ENDVI, -0.69 for ERVI and -0.69 for EDVI." and Table 3 was deleted.

21. Page 10 Line 4-5, the statement of "From Table 3, we can see that the correlation between the ERVI or EDVI and the SSC was very significant with the correlation coefficient above 0.69. So the ERVI and EDVI were selected as the IVI for spring, at the same way the ENDVI and ERVI were selected as the IVI for autumn." was corrected as "The results show that the correlation coefficients between the ERVI or EDVI and SSC were very significant (R^2>0.69; P<0.01) in spring. Based on these findings, ERVI and EDVI were selected as the IVIs for spring, while ENDVI and ERVI were selected as the IVIs for autumn.".

22. Page 10 Line 10, the headline of "3.3 The best inversion models of SSC and its application in different seasons" was corrected as "3.3 The best SSC inversion models and their application to different seasons".

23. Page 10 Line 11, the headline of "3.3.1 Inversion models of SSC with VI and IVI" was corrected as "3.3.1 SSC inversion models with VIs and IVIs".

24. Page 10 Line 12-15, the statement of "Results of the SSC inversion models in spring based on the IVI are shown in Table 4. In comparing the performance of three modelling methods, the prediction accuracy of the SVM models was the highest followed by the BPNN models, and the SMLR models had the lowest accuracy." was corrected as "The results of the

SSC inversion models in spring based on the IVIs are shown in Table 2. The performances of the three modeling methods were compared, which showed that the prediction accuracy of the SVM models was the highest followed by the BPNN models, and the SMLR models had the lowest accuracy." and Table 2 and Table 6 were merged.

25. Page 11 Line 3-4, the statement of "Table 5 shows the estimation accuracy" was corrected as "Based on the estimation accuracy (Table 3)".

26. Page 11 Line 16-18, the statement of "The descriptive statistics of the inversed SSC in four seasons are shown in Table 6, which are close to those of the collected samples (Table 2)" was corrected as "The descriptive statistics of the inversed SSC in four seasons are shown in the lower half of Table 1, which are close to those of the collected samples (the upper half of Table 1)".

27. Page 11 Line 23-24 and Page 12 Line 1, "nonsaline soil, mild saline soil, moderate saline soil, severe saline soil, and solonchak, with the degree of soil salinization gradually increasing from nonsaline soil to solonchak" was added.

28. Page 12 Line 2-4, the statement of "The distribution of soil salinity grades in the four seasons were mapped (Fig. 5). The spatial distributions of SSC in the four seasons showed similar characteristics. There was a gradually increasing trend of soil salinity from the south-west to the north-east part of the study region, and this distribution pattern is consistent with the results of other studies (Weng et al. 2010; Yang et al. 2015)." was corrected as "The distributions of the soil salinity grades in the four seasons were mapped (Fig. 5) and showed similar characteristics. There was a gradually increasing trend of soil salinity from southwest to northeast in the study region.".

29. Page 13 Line 11-18, the discussion of "In this work, we introduced the SWIR band and proposed an improved vegetation index to increase the accuracy of SSC inversion models. The spatial distributions of SSC in the four seasons showed similar characteristics. There was a gradually increasing trend of soil salinity from southwest to northeast in the study region, and this distribution pattern is consistent with the results of other studies (Weng et al. 2010; Yang et al. 2015). Weng et al. (2010) also established an SSC remote sensing revision model using the data from 2153 ~ 2254 nm and 1941 ~ 2092 nm in the region of YRD and achieved good results." was added.

30. Page 15 Line 2-4, the statement of "Lu et al. (2016) presented that SSC exhibits seasonal variation in the YRD and that the SSC in spring was higher than that in autumn in the Kenli district, which is consistent with our results." was added.

31. Page 15, the discussion paragraph of "The article aimed to build optimal SSC inversion models for different seasons according to soil salinity condition in one year, and the SSC at the point of time was used as the corresponding seasonal salt data. The results indicated that the SSC inversion model of spring could be applied in winter resulting in R^2 of 0.66 and RMSE of 7.57 g/kg, while the SSC inversion model of autumn could also be applied in summer resulting in R^2 of 0.65 and RMSE of 3.60 g/kg within a year in the YRD region. This model selection results may be due to the short time intervals and similar soil salt climatic conditions between February and April and between August and November in the Yellow River Delta region. In order to respond more accurately to the dynamic changes of soil salt, a period of SSC should be selected as the seasonal salt data, which will be the future research, and the application of the SSC inversion models for different years will be explored." was

deleted.

32. Page 15 Line 2-4, the statement of “Lu et al. (2016) presented that SSC exhibits seasonal variation in the YRD and that the SSC in spring was higher than that in autumn in the Kenli district, which is consistent with our results.” was added.

33. Page 15 Line 6-13, the discussion paragraph of “Based on the time point data, the results indicated that the SSC inversion model for spring could be applied to SSC inversion in winter, while the SSC inversion model for autumn could also be applied to SSC inversion in summer in the YRD. These model selection results may be due to the short time intervals, similar soil salt contents and climatic conditions between February and April and between August and November in the YRD. To respond more accurately to the dynamic changes in soil salt, a period of SSC data should be selected as the seasonal salt data, which will be further studied in future research.” was added.

34. Page 15 Line 16-22, the statement of “In this experiment, the results showed that the extended ratio vegetation index (ERVI) and extended difference vegetation index (EDVI) were as IVI of spring, while the extended normalized difference vegetation index (ENDVI) and extended ratio vegetation index (ERVI) were as the IVI of autumn. The best and most stable accuracy of SSC was produced by the SVM models based on the IVI; therefore, these models were selected as the best SCC inversion models of spring and autumn. The experiment results would contribute to the quantitative and accurate monitoring of soil salinization with multispectral imaging.” was corrected as “In this experiment, the results showed that the ERVI and EDVI were the IVIs for spring, while the ENDVI and ERVI were the IVIs for autumn. These models based on the IVIs that utilized the SVM method were selected as the best SSC inversion models for spring and autumn. The experimental results contribute to the quantitative and accurate monitoring of soil salinization with multispectral imaging and provide data and technical support for saline soil management and utilization and ecological environment protection.”.

35. Page 16 Line 7-11, the statement of “The SSC spatial distribution of each season in the study area was determined using the SCC inversion model optimized for each season. In the Yellow River Delta region, the spatial distribution of SSC shows a gradually increasing trend from the south-west to the north-east. The seasonal dynamics of SSC are such that soil salts accumulate in spring, decrease in summer, rise in autumn, and peak in winter.” was corrected as “In the YRD region, the spatial distribution of SSC shows a gradually increasing trend from southwest to northeast. The seasonal dynamics of SSC are such that soil salts accumulate in spring, decrease in summer, increase in autumn, and peak in winter. These results are consistent with the results of field sampling, which showed that the SSC is highest in winter, followed by spring and autumn, and lowest in summer.”.

36. Page 17, Line 26-32, the references of “Elmetwalli, A. M. H., A. N. Tyler, P. D. Hunter, and C. A.: Salt Detecting and Distinguishing Moisture-and Salinity-induced Stress in Wheat and Maize through in Situ Spectroradiometry Measurements. Remote Sensing Letter 3: 363–372. DOI: 10.1080/01431161.2011.599346, 2012.” and “Goto, K. , Goto, T. , Nmor, J. C. , Minematsu, K. , and Gotoh, K. . Evaluating Salinity Damage to Crops Through Satellite Data Analysis: Application to Typhoon Affected Areas of Southern Japan. Natural Hazards, 75(3), 2815-2828. doi: 10.1007/s11069-014-1465-0, 2015.” were added.

37. Page 18, Line 16-23, the references of “Li, P., L. Jiang, and Z. Feng.: Cross-comparison

of Vegetation Indices Derived from Landsat-7 Enhanced Thematic Mapper Plus (ETM) and Landsat-8 Operational Land Imager (OLI) Sensors. Remote Sensing 6: 310–329. doi: 10.3390/rs6010310, 2013.” and “Lu, Q. , Bai, J. , Fang, H. , Wang, J. , Zhao, Q. , and Jia, J.: Spatial and Seasonal Distributions of Soil Sulfur in Two Marsh Wetlands with Different Flooding Frequencies of the Yellow River Delta, China. Ecological Engineering, 96(96), 63-71. doi: 10.1016/j.ecoleng.2015.10.033, 2016.” were added.

38. Page 20, Line 13-16, the reference of “Yang, S.Q., Zhao, W.W., Liu, Y.X., Wang, S., Wang, J., Zhai, R.J.: Influence of Land Use Change on the Ecosystem Service Trade-offs in the Ecological Restoration Area: Dynamics and Scenarios in the Yanhe Watershed, China. Science of the Total Environment, 644: 556–566. doi: 10.1016/j.scitotenv.2018.06.348, 2018.” was added.

39. Page 20, Line 21-23, the reference of “Zhao, W.W., Wei, H., Jia, L.Z., Zhang, X., Liu, Y.X.: Soil Erodibility and its Influencing Factors on the Loess Plateau of China: A Case Study in the Ansai Watershed. Solid Earth, 9, 1507–1516, 2018.” was added.

40. Page 21, Line 2, the title of Table 1 was corrected as “Table 1. SSC descriptive statistics of samples and inversion”.

41. Page 22, Figure 1 was revised to be clear.

42. Page 22, Figure 3, the red underline was deleted.

43. Page 24, the cross heading of Figure 4 was formatted.

44. The whole manuscript was revised by a professional English proof-reader.

The marked-up manuscript version

Monitoring the seasonal dynamics of soil salinization in the Yellow River Delta of China using Landsat data

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Abstract. It is necessary to monitor the seasonal dynamics of soil salinization in regions with distinct seasonal climates. The article took Kenli district in the Yellow River Delta (YRD) of China as the experimental area. Based on Landsat data from spring and autumn, improved vegetation indices (IVIs) were created, which were then applied to the inversion modeling of soil salinity content (SSC) by employing stepwise multiple linear regression, back propagation neural network and support vector machine methods. Finally, the optimal SSC model in each season was extracted, and the spatial distributions and seasonal dynamics of SSC in a year were analyzed. The results indicated that the SSC varied obviously between seasons in the YRD, and the support vector machine method resulted in the best inversion models. The best SSC inversion model for spring could be applied to the SSC inversion in winter; similarly, the best model for autumn could also be applied to SSC inversion in summer. The SSC exhibited a gradually increasing trend from southwest to northeast in Kenli district, and it also underwent the following seasonal dynamics: soil salinity accumulates in spring, decreases in summer, increases in autumn, and peaks in winter. This work provides data support for the treatment and utilization of saline-alkali soil in the YRD.

Keywords: Soil salinity; Remote sensing inversion; Vegetation index; Multispectral imaging; Seasonal dynamics

1. Introduction

Saline soils, which are widespread throughout the world, especially in arid, semiarid and some subhumid regions, cause severe environmental degradation that can impede crop growth as well as overall regional production (Metternicht and Zinck 2003). Moreover, as a form of land degradation, soil salinization can degrade soil quality and lead to ecosystem risks (Huang et al. 2015; Zhao et al. 2018). Obtaining information on soil characteristics, such as the degree of salinity and geographical distribution of saline soil in real time, and improving our ability to forecast soil salinization dynamics are necessary prerequisites for scientific management, reasonable improvement and utilization of regional saline soil, then help to reduce ecological risks (Melendez-Pastor et al. 2012; Yang et al. 2018). Remote sensing technology provides an important and rapid approach for the quantitative monitoring and mapping of soil salinization (Dehni and Lounis 2012; Tayebi et al. 2013; Shoshany et al. 2013; Sidike et al. 2014; Wu et al. 2014; Guo et al. 2015; Sturari et al. 2017).

Multispectral satellite data, such as Landsat, SPOT, IKONOS, QuickBird, and the Indian Remote Sensing (IRS) series of satellites, have been used to map and monitor soil salinity and other properties due to the low cost and the ability to map extreme surface expressions of salinity (Dwivedi et al. 2008; Abbas et al. 2013; Allbed et al. 2014; Mahyou et al. 2016; Mehrjardi et al. 2008; Yu et al. 2010; Ahmed and Iqbal 2014; Rahmati and Hamzehpour 2016). Extensive studies have shown that models based on multispectral satellite data are still the preferred method for mapping soil salinity over large spatial domains (Allbed and Kumar 2013; Scudiero et al. 2015; Taghizadeh-Mehrjardi et al. 2014).

To a certain extent, information on the damage to vegetation caused by soil salinization can help to determine the degree and trend of soil salinization. Therefore, traditional vegetation indices (VIs), such as the normalized difference vegetation index (NDVI), the ratio vegetation index (RVI), and the difference vegetation index (DVI), can be used as indicators to determine the degree of soil salinization (Elmetwalli et al. 2012; Li et al. 2013; Goto et al. 2015). However, the accuracy of the models based on traditional VIs must be improved (Iqbal 2011). Traditional VIs involve the data from only two bands in the visible and near-infrared region, and there are often significant correlations between traditional VIs (USGS, 2013). Therefore, it is worth studying whether the addition of data from the shortwave infrared band, which has long wavelengths and contains considerable information, can improve the accuracy and stability of soil salinity content (SSC) inversion models.

Existing studies primarily focus on SSC inversion models for a single study area at a specific time (Herrero and Castañeda 2015; He et al. 2014); nevertheless, because the SSC is dynamic over time, such as through the four seasons of a year, the application of the same inversion model to quantitatively analyze the SSC in different seasons is not adequate. The Yellow River Delta (YRD) is located at the junction of the Beijing-Tianjin-Hebei metropolitan area and Shandong Peninsula and lies within the efficient ecological economic zone of China, and this region has obvious geographical advantages. With nearly 550,000 ha of unused land, the land resources in this area are rich. However, soil salinization is a widespread and serious concern in this region (Mao et al. 2014). Approximately 85.7% of the total area in the region is covered with saline soil, and there has been an increasing trend in the amount of coastal saline soil in recent years. As the main risk to farmland ecosystems in this region, soil salinization can result in a large reduction in agricultural production and fragile ecological environments; and, soil salinization seriously affects the utilization of land resources as well as the development of the regional economy and society (Yang et al. 2015; Weng et al. 2010). Moreover, in regions with distinct seasons, the differences in rainfall and evaporation between different seasons are great, the changes in soil moisture are obvious, and soil salinity exhibits a close relation with soil moisture; thus, the soil salinity usually varies greatly between seasons. Therefore, it is particularly necessary to monitor the seasonal dynamics of soil salinization in this region. Seasonal SSC inversion models would greatly improve the accuracy of SSC modeling and therefore enhance our ability to monitor soil salinization in the region continuously and in real time.

The objectives of this paper are to (1) build optimal SSC inversion models for different seasons according to soil salinity conditions; (2) map the spatial distribution and seasonal dynamics of SSC in the YRD of China. Specifically, VIs were constructed by introducing data from the shortwave infrared band (SWIR) of Landsat data. The SSC inversion models in spring and autumn were built using stepwise multiple linear regression (SMLR), back propagation neural network (BPNN) and support vector machine (SVM) methods, and the best models for spring and autumn were selected and applied to the other seasons. Once the optimal soil salinity inversion model was determined for each season, it was applied to map the SSC distribution and analyze the seasonal SSC dynamics.

2. Materials and methods

2.1 Study area

The study area is the Kenli district in the YRD region (37°24′~38°06′N, 118°14′~119°11′E), which is located in Dongying city, Shandong Province, China, and on the southern shore of the Bohai Sea (Fig. 1). This area has a characteristic plain landscape and coastal saline soil type. There are three types of soil subgroups: tidal soil, salinized tidal soil and coastal tidal saline soil. The soil parent material is the Yellow River alluvial material, and the soil texture is light; salt accumulates on the soil surface, and salt is relatively rare and well-distributed in the middle and lower parts of the soil profile (below the core soil). The main types of land use in this area are cultivated land, unused land and grassland. The main crops are wheat, corn, rice and cotton. The main natural vegetation includes white grass, reed, horse trip grass, tamarix and suaeda. Owing to the low, flat terrain, high groundwater table, high mineralization rate, poor drainage conditions, and the infiltration and mounting of seawater associated with the Yellow River in this region, soil salinization at the surface is generally severe and widespread (Yang et al. 2015; Weng et al. 2010). Due to the temperate climate and four distinct seasons, the soil salt content exhibits obvious seasonal dynamics. The soil salinization process in the region is shown in Fig. 2.

2.2 Soil sampling and chemical analyses

To achieve an accurate representation of the seasonality, we selected April, August, November and February (in the following year) to represent the spring, summer, autumn, and winter seasons, respectively. According to the climate characteristics and soil salinization conditions in the different seasons, the samples collected in spring and autumn were used to develop the SSC inversion models, while the samples from winter and summer were used to validate the inversion models. Overall, 92 spring samples were collected from April 27-May 2, 2013; 30 summer samples were collected from August 14-15, 2013; 110 autumn samples were collected from November 9-13, 2013; and 56 winter samples were collected from February 26-29, 2014. Sample points were designated by considering the degree of soil salinization, soil surface morphology and microtopography, and uniformity of the sample distribution (Fig. 1). Topsoil samples were collected at each sample point at a depth < 20 cm, and GPS coordinates were recorded. *In situ* environmental information was also recorded. The collected soil samples were naturally air dried, crushed, purified, passed through a 2 mm sieve, and mixed evenly. The concentrations of Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-, K^+, Na^+, Ca^{2+}, and Mg^{2+} were measured in extracted solutions of a 1:5 soil-water mixture. The SSC was defined as the combined concentration of the eight ions mentioned above.

2.3 Acquisition and pretreatment of imaging data

Multispectral Landsat data were acquired in line with the sample collection time. We employed Landsat 7 ETM+ data from May 6, 2013, and Landsat 8 OLI data from August 18, 2013, November 6, 2013, and February 26, 2014. Landsat 7 ETM+ data include one panchromatic band (520–900 nm), four multispectral bands in the visible and near-infrared wavelength range (blue (450–515 nm), green (525–605 nm), red (630–690 nm) and NIR (775–900 nm)), and two shortwave infrared (SWIR) bands (1550–1750 nm, 2090–2350 nm). The Landsat 8 OLI data the same bands as ETM+, while the band ranges are slightly different. Image pretreatment, including geometric rectification, radiation calibration, and atmospheric correction, was conducted in ENVI

5.1 software from the Exelis Visual Information Solutions. Geometric rectification was completed in reference to the 1:10000 terrain map of the study area, and then radiation calibration and Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) atmospheric correction were subsequently applied. The output images were projected to the Gauss–Kruger coordinate system and cropped to the study area. Then, the water body, building and traffic land areas were masked according to the current land use situation. Finally, the reflectance of the samples was extracted from the processed images using ArcGIS 10.1 software.

2.4 Calculation and improvement of vegetation indices

The extended vegetation indices (EVIs) were all calculated based on the Landsat data by adding the SWIR band data to the traditional VIs, including the extended normalized difference vegetation index (ENDVI, (NIR+SWIR-R)/(NIR+SWIR+R)), extended difference vegetation index (EDVI, NIR+SWIR-R), and extended ratio vegetation index (ERVI, (NIR+SWIR)/R). The SWIR band refers to either of the two SWIR bands. The correlations between the SSC and EVIs were analyzed, and then the EVIs with significant correlation coefficients were selected as the improved vegetation indices (IVIs). Finally, the IVIs were used as the inputs to the SSC inversion models.

2.5 Inversion model construction and optimization

First, soil samples collected in spring and autumn were sorted and separated according to the SSC. Two-thirds of the samples were chosen for the calibration set, and the remaining samples were used as the validation set. Therefore, of the 92 samples collected during spring, 62 samples were used for calibration, and the other 30 samples were used for validation. Similarly, of the 110 samples collected during autumn, 74 samples were used for calibration, and the other 36 samples were used for validation. Second, the SSC inversion model for spring was built by employing the SMLR, BPNN and SVM methods based on the VIs and corresponding IVIs. The performance of the SSC inversion models was evaluated by the coefficient of determination (R^2), root-mean-square error (RMSE) and ratio of performance to deviation (RPD). Using the same procedures, the SSC models for autumn were built on the IVIs, and the best model was selected. Finally, the best models for spring and autumn were selected and applied to the summer and winter data, and then the optimal SSC inversion models according to the soil salinization conditions in different seasons were selected.

For the SMLR method, the variance inflation factor (VIF) was set to less than 5 to control multicollinearity. The BPNN method was conducted using the MATLAB R2012a program. During the calculation, the transfer functions of the hidden layer and the output layer were set to tansig and logsig, respectively. The network training function was traingdx, and the learning rate, the maximum training time, and the model expectation error were set to 0.01, 15000, and 0.01, respectively. The SVM models were built in the Libsvm 3.11 toolbox in MATLAB R2012a. In this model, we selected the 4th SVM type (v-SVR) and the 2nd kernel function (RBF), and the penalty parameter C and the kernel parameter g of the RBF were determined according to the minimum mean-squared deviation by using the cross-validation and grid search method.

2.6 SSC distribution mapping and year-round dynamics analysis

The reflectance spectra were extracted from the Landsat data from the four seasons in the study area, and the seasonal IVIs were calculated. Then, the SSC distribution maps of the four seasons were obtained via calculations based on the corresponding optimal models. The spatial distribution characteristics and seasonal dynamics of soil salinity in the YRD were analyzed and compared.

The methodological flow of this article is shown in Fig. 3.

3. Results

3.1 The soil samples data

The statistical results of the SSC samples from the four seasons (the upper half of Table 1) showed that the SSC in the study area remained high with a mean > 5.32 g/kg throughout the year. As determined from the minimum, maximum, and mean values, our results showed that the SSC reached its maximum concentration in winter (the mean = 9.50 g/kg) and decreased gradually, and the SSC varied obviously between seasons. The standard deviation and coefficient of variation showed that the SSC gradient was significant overall, especially in winter and spring.

3.2 Improved vegetation indices (IVIs)

In spring, the correlation coefficients between the EVIs and the SSC of the soil samples were -0.52 for ENDVI, -0.69 for ERVI and -0.70 for EDVI; similarly in autumn, the correlation coefficients between the EVIs and the SSC of the soil samples were -0.73 for ENDVI, -0.69 for ERVI and -0.69 for EDVI.

The results show that the correlation coefficients between the ERVI or EDVI and SSC were very significant (R^2>0.69; P<0.01) in spring. Based on these findings, ERVI and EDVI were selected as the IVIs for spring, while ENDVI and ERVI were selected as the IVIs for autumn. For each season, the chosen IVIs and their corresponding VIs were used to build the SSC inversion models.

3.3 The best SSC inversion models and their application to different seasons

3.3.1 SSC inversion models with VIs and IVIs

The results of the SSC inversion models in spring based on the IVIs are shown in Table 2. The performances of the three modeling methods were compared, which showed that the prediction accuracy of the SVM models was the highest followed by the BPNN models, and the SMLR models had the lowest accuracy. In terms of the calibration values, the SVM models based on the IVIs had the best and most stable SSC inversion accuracies for both the calibration set (R^2> 0.72, RMSE <6.34 g/kg) and the validation set (R^2 > 0.71, RMSE <6.00 g/kg, and RPD >1.66). These models were then selected as the best SSC inversion models for the SSC in spring and autumn.

The calibration and validation precision of the SSC inversion models in spring and autumn are shown in Fig. 4.

3.3.2 Application of the best SSC inversion models with IVIs in different seasons

The best *SSC* inversion models for spring and autumn were applied to the SSC estimation of summer and winter, respectively. Based on the estimation accuracy (Table 3), the best SSC inversion model for spring can be applied to that in winter, with R^2 of 0.66 and RMSE of 7.57 g/kg. Meanwhile, the best SSC inversion model for autumn can also be applied to that in summer, resulting in R^2 of 0.65 and RMSE of 3.60 g/kg. In response to the soil salinity conditions, the SSC inversion model for spring based on the IVIs in combination with the SVM method was selected as the optimal SSC model for spring and winter, while the SSC inversion model for autumn based on the IVIs in combination with the SVM method was selected as the optimal SSC model for autumn and summer in the YRD.

3.4 Distribution and seasonal dynamics of SSC in the YRD region

3.4.1 Distribution of SSC in four seasons

Based on the processed Landsat data and the optimal SSC inversion model for each season, the SSC inversion maps in the four seasons were obtained. The descriptive statistics of the inversed SSC in four seasons are shown in the lower half of Table 1, which are close to those of the collected samples (the upper half of Table 1); the inversion results also showed that the SSC in winter was highest, followed by that in spring, and the SSC in autumn and summer were relatively low.

According to the classification standard of coastal saline soil in the semihumid area of China, the study area was divided into 5 grades of soil salinization: nonsaline soil, mild saline soil, moderate saline soil, severe saline soil, and solonchak, with the degree of soil salinization gradually increasing from nonsaline soil to solonchak. The distributions of the soil salinity grades in the four seasons were mapped (Fig. 5) and showed similar characteristics. There was a gradually increasing trend of soil salinity from southwest to northeast in the study region. The main reason for this gradual increase in SSC is that the terrain of the southwest part of the study area is high and flat, and the flood-prone land is used for agricultural production. The central part of the region, near the banks of the Yellow River, has alternating hillocks, slopes and depressions, which were formed by the repeated diversion of the Yellow River; thus, each grade of soil salinization was also alternately distributed, and the northeast part of the region, which has low terrain and is closest to the sea, has the most severe soil salinization.

3.4.2 Seasonal dynamics of SSC

The number of pixels and proportion of pixels per SSC grade were calculated for each season (Table 4). Fig. 5 and Table 4 demonstrate that the SSC in the study area is clearly different among the four seasons. The SSC in spring consisted primarily of moderate saline soil, severe saline soil, and solonchak (combined proportion of 90.05%); in summer, the area of the four grades from the mild saline soil to solonchak was relatively uniform (each grade accounting for 22–28%); the SSC during autumn was largely dominated by severe saline soil and solonchak (combined proportion of 77.75%); in winter, the SSC was principally severely saline and solonchak, with the combined proportion of 99.19%, of which the severe saline soil contributed 80.71%.

The seasonal SSC inversion values and the proportion of pixels per SSC grade indicated that the change in SSC between different seasons is relatively apparent. The degree of soil salinization was lowest in summer, and the SSC in autumn was relatively low except for the solonchak in coastal areas. In spring, the soil salinization became more obvious, with most of the study area belonging to the moderate to severe saline soil and solonchak group. Meanwhile, the soil salinization was the most severe in winter. In summary, soil salinity in the study area usually accumulates in spring, decreases in summer, increases in autumn, and peaks in winter.

4. Discussion

In this work, we introduced the SWIR band and proposed an improved vegetation index to increase the accuracy of SSC inversion models. The spatial distributions of SSC in the four seasons showed similar characteristics. There was a gradually increasing trend of soil salinity from southwest to northeast in the study region, and this distribution pattern is consistent with the results of other studies (Weng et al. 2010; Yang et al. 2015). Weng et al. (2010) also established an SSC remote sensing revision model using the data from 2153 ~ 2254 nm and 1941 ~ 2092 nm in the region of YRD and achieved good results.

We can see that the best SSC inversion models for spring and autumn are based on different IVIs. In spring, the weather is characteristically dry and windy with strong evaporation, and the coverage of natural vegetation is low; however, crops such as wheat and corn are in a vigorous growth stage, which results in strong vegetation reflectance spectra. Generally, the RVI and DVI are sensitive to vegetation, especially when vegetation coverage is high; thus, the inversion accuracies based on the ERVI and EDVI are higher than those of other vegetation indices. In autumn, rainfall and temperature are reduced, and there is little coverage of natural vegetation. At this time, cotton has been collected, and only withered cotton leaves and rods remain in the field, and wheat has just begun to emerge out of the soil. Therefore, the reflectance spectra of vegetation are relatively weak in autumn. NDVI has low sensitivity to high vegetation areas and is suitable for monitoring in low and moderate vegetation coverage areas, so the inversion accuracies based on the ENDVI and ERVI are higher than those based on the other vegetation indices. The results were obtained without considering some factors (e.g., soil moisture and temperature) that vary with season and affect the SSC. The influence of some key factors will be studied to remove these factors in future studies.

The seasonal dynamics of SSC are closely related to the climate of the study area. With droughts, windy weather, and strong evaporation in spring from March to May, soil salts aggregate at the soil surface as the soil moisture increases, which forms the first peak of salt accumulation, with a total of 90.05% of moderate saline soil, severe saline soil, and solonchak. Rainfall and floods occur in the summer from June to August, and as precipitation infiltrates into the soil, the soil surface is desalinated, with a uniform proportion from the mild saline soil to solonchak. In the autumn from September to November, rainfall decreases and SSC increases slightly, and the area is largely dominated by severe saline soil and solonchak (combined proportion of 77.75%). Due to drought in winter from December to February, combined with decreased evaporation, soil salinization is relatively severe and remains latent at the soil surface, with 99.19% of the area covered by severe saline and solonchak. By the end of the season, the SSC will reach the peak. Lu et al. (2016) presented that SSC exhibits seasonal variation in the YRD and that the SSC in spring was higher than that in autumn in the Kenli district, which is consistent with our results.

Based on the time point data, the results indicated that the SSC inversion model for spring could be applied to SSC inversion in winter, while the SSC inversion model for autumn could also be applied to SSC inversion in summer in the YRD. These model selection results may be due to the short time intervals, similar soil salt contents and climatic conditions between February and April and between August and November in the YRD. To respond more accurately to the dynamic changes in soil salt, a period of SSC data should be selected as the seasonal salt data, which will be further studied in future research.

5. Conclusion

In this experiment, the results showed that the ERVI and EDVI were the IVIs for spring, while the ENDVI and ERVI were the IVIs for autumn. These models based on the IVIs that utilized the SVM method were selected as the best SSC inversion models for spring and autumn. The experimental results contribute to the quantitative and accurate monitoring of soil salinization with multispectral imaging and provide data and technical support for saline soil management and utilization and ecological environment protection.

This experiment indicates that the best inversion model for spring could be applied for the SSC inversion in winter, and the optimal SSC model for spring and winter was selected in response to the soil salinity conditions. At the same time, the best inversion model for autumn could also be applied for the SSC inversion in summer and was selected as the optimal SSC model for autumn and summer in the study region.

In the YRD region, the spatial distribution of SSC shows a gradually increasing trend from southwest to northeast. The seasonal dynamics of SSC are such that soil salts accumulate in spring, decrease in summer, increase in autumn, and peak in winter. These results are consistent with the results of field sampling, which showed that the SSC is highest in winter, followed by spring and autumn, and lowest in summer.

Author contributions. Hongyan Chen analyzed the data and prepared the manuscript. Gengxing Zhao developed the framework for the study. Danyang Wang and Ying Ma collected and analyzed the data. Yuhuan Li provided technical support throughout different stages of the study. All coauthors provided a manuscript review.

Competing interests. The authors declare that they have no conflict of interest.

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Tables

Table 1. SSC descriptive statistics of samples and inversion

	Seasons	Minimum (g/kg)	Maximum (g/kg)	Mean (g/kg)	Standard deviation (g/kg)	Coefficient of variation	Sample points
Soil samples SSC	Spring	1.10	46.70	8.60	11.50	1.34	92
	Summer	1.34	29.20	5.32	5.95	1.12	30
	Autumn	0.90	36.70	7.80	8.20	1.05	110
	Winter	2.00	61.50	9.50	12.00	1.26	56
Inversion SSC	Spring	0.86	53.44	8.79	10.26		
	Summer	1.00	35.50	7.00	4.18		
	Autumn	0.82	35.15	8.28	9.21		
	Winter	1.12	58.10	9.21	13.78		

Table 2. Inversion models of SSC with IVIs from Landsat data

	Spring					Autumn				
Modeling methods	Calibration set		Validation set			Calibration set		Validation set		
	R^2	RMSE (g/kg)	R^2	RMSE (g/kg)	*RPD*	R^2	RMSE (g/kg)	R^2	RMSE (g/kg)	*RPD*
SMLR	0.42	9.03	0.62**	6.83	1.36	0.65**	3.42	0.56	3.81	2.01
BPNN	0.60**	7.56	0.57**	7.30	1.47	0.72**	3.39	0.68**	3.38	2.15
SVM	0.72**	6.34	0.71**	6.00	1.66	0.75**	3.48	0.78**	3.02	2.56

Significance levels: [**] 0.01

Table 3. Application of the best SSC inversion models

	The best inversion model for spring		The best inversion model for autumn	
	R^2	RMSE (g/kg)	R^2	RMSE (g/kg)
Summer samples (30)	0.23	5.31	0.65**	3.60
Winter samples (56)	0.66**	7.57	0.28	10.98

Significance levels: [**] 0.01

Table 4. The pixel number and proportion of pixels per SSC grade in four seasons

Grades	Spring		Summer		Autumn		Winter	
	Pixel number	Proportion %	Pixel number	Proportion %	Pixel number	Proportion %	Pixel number	Proportion %
Nonsaline soil (<2.0 g/kg)	10705	0.67	16	0	46439	2.89	3	0
Mild saline soil (2.0~4.0 g/kg)	84805	5.29	450331	28.07	127262	7.93	12	0
Moderate saline soil (4.0~6.0 g/kg)	451291	28.13	427216	26.63	182589	11.37	13045	0.81
Severe saline soil (6.0~10.0 g/kg)	597607	37.25	371641	23.16	305762	19.05	1294867	80.71
Solonchak (>10.0 g/kg)	459989	28.67	355193	22.14	942345	58.70	296470	18.48

Figures

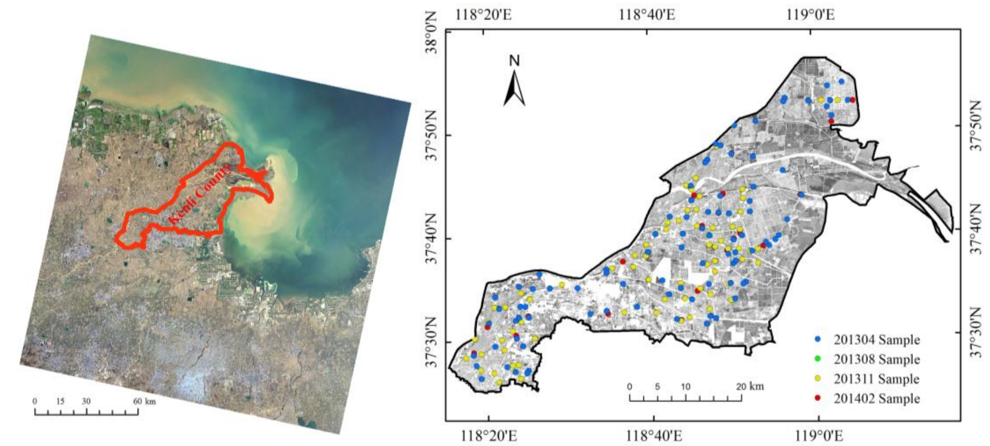

Figure 1. Location of the study area and sampling points

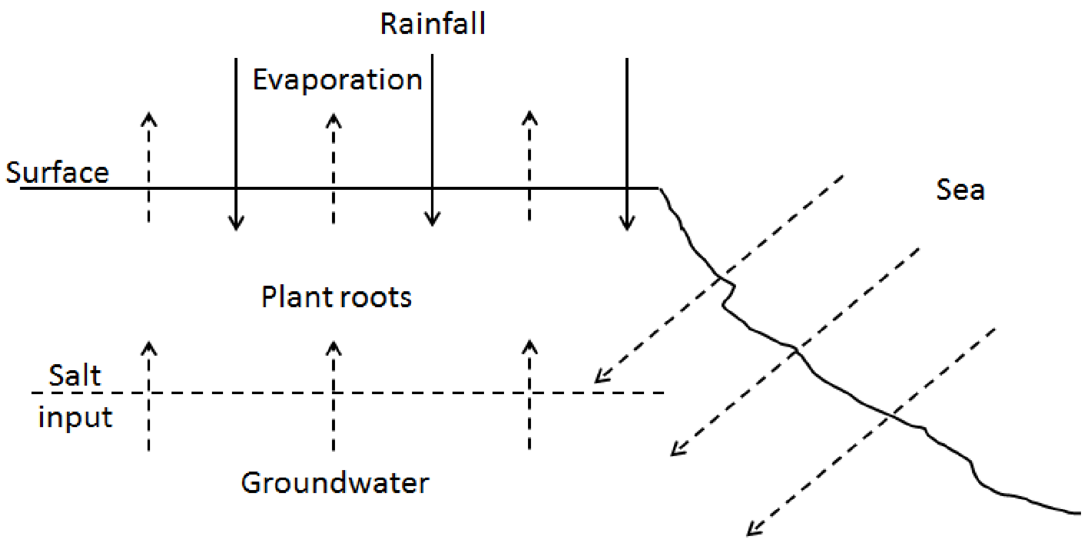

Figure 2. Soil salinization process in the study area

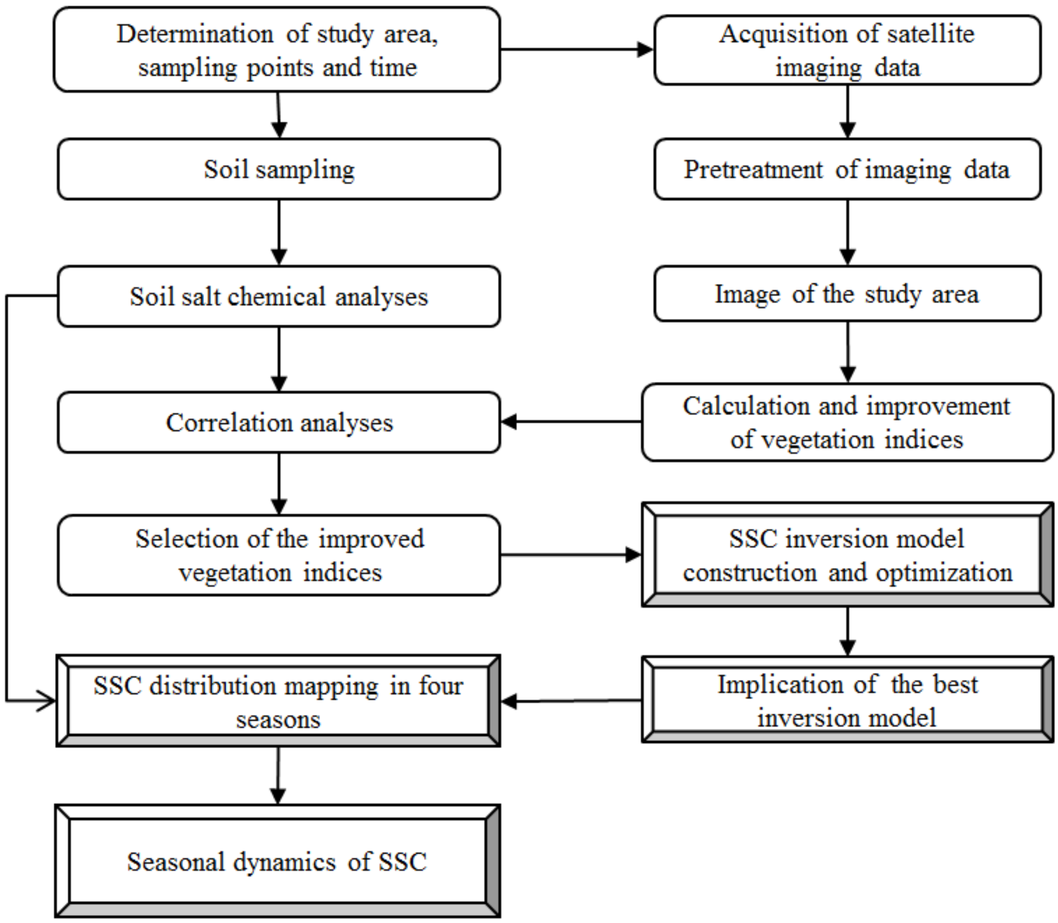

Figure 3. The methodological flow chart

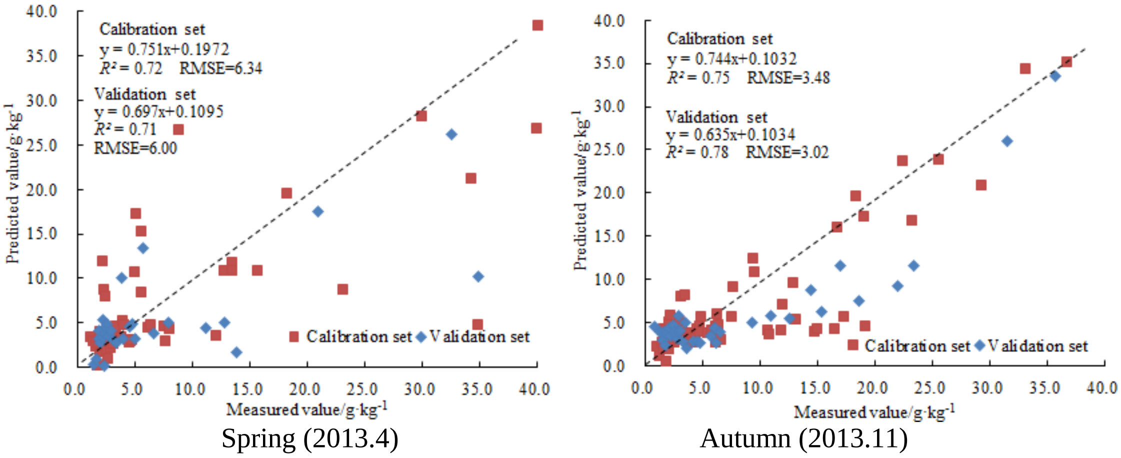

Figure 4. The calibration and validation precision of SSC inversion models in spring and autumn

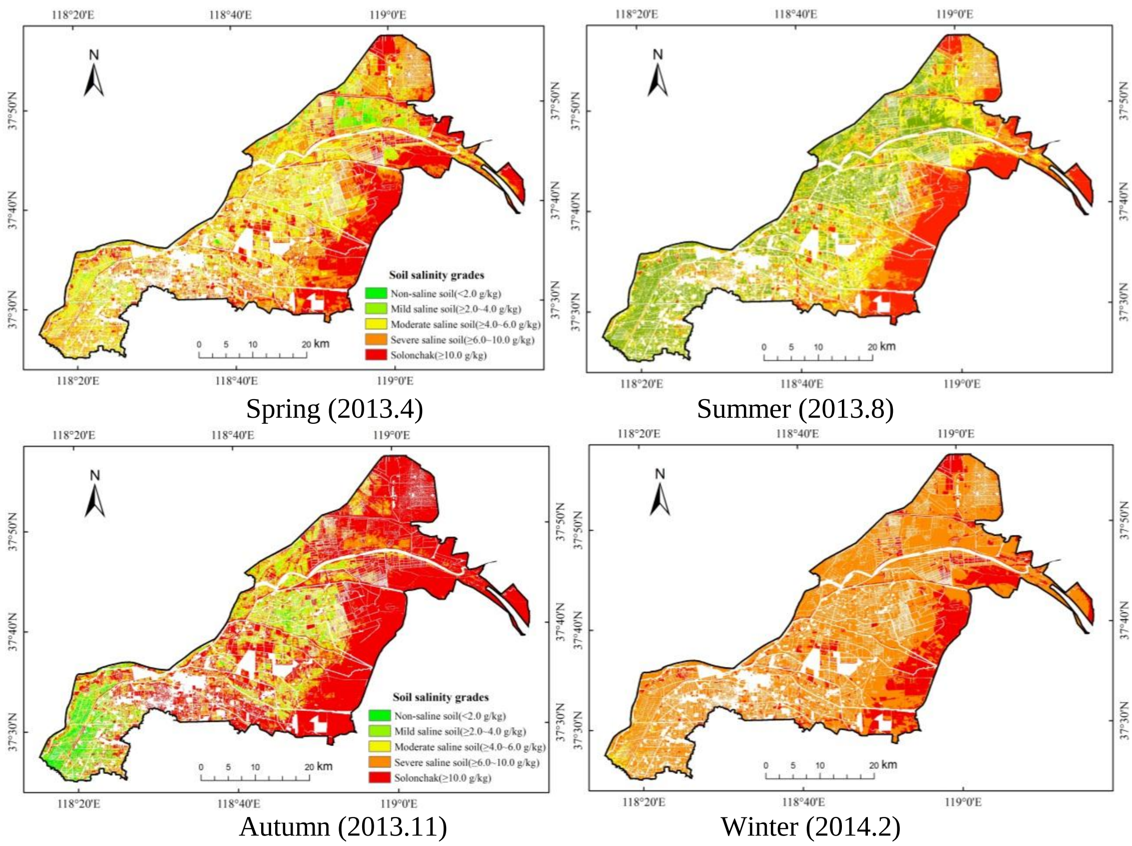

Figure 5. The inversion and distribution of SSC in four seasons