Authors’ Response

Reply to Reviewer 1

We thank Reviewer 1 for his comments and suggestions. Below we document how we have changed our manuscript accordingly.

- page 5 top: provide a reference for the applied Penman Montheith approach

A reference to Allen et al. (1998) has been added.

- page 5 top: I doubt that the climatic AI indicator alone does indicate desertification rather than the "risk of desertification", as used also for the other single indicators. Please modify it.

Absolutely correct and we have changed this accordingly.

- page 5 ff: The scoring system of indicators remains unclear: explain for all individual indicators on which basis the scoring was defined. Is it artificial/subjective classification or was it calibrated? if yes, how it was done? is it based on other studies (provide references)?

The scoring of the quality indicators was based on a multi-factorial approach combining the multi-component GIS framework for desertification risk assessment by Santini et al. (2010) and the Environmentally Sensitive Areas (ESA) approach by Kosmas et al. (2006) and Basso et al. (2000).

- page 7: provide more information of applied climate scenarios: e.g. RCP type, mean temperature change, time slice....

We added a paragraph on the climate scenario that we used: “During the period 1958-2007, the average temperature increased by 0.5–0.7°C. Vietnam’s official scenarios for climate change (MONRE, 2009) fit these current trends. The medium emission scenarios corresponds to an increase in temperature of 1°C by 2050 and 2.4°C by 2100 with respect to the 1980-1999 baseline period. Rainfall in the middle of the rainy season would increase 10-15% with respect to the 1980-1999 baseline period in the South Central. On a year basis, rainfall is projected to increase with 1.7% by 2050 and 3.2% by 2100. This climate scenario corresponds to RCP4.5 with a radiative forcing of 4.5 W/m^2 and 650 ppm CO_2 equivalent in 2100.”

- page 8 top: which type of reference evapotranspiration? (provide reference, e.g. is it FAO grass reference?)

The Penman-Monteith evapotranspiration (Allen et al., 1998) was used. This has now been documented and referenced to in the manuscript.

- Figure 2 and 4: is the ESAI and ESA the same as the RI (see page 7 top) ? This is unclear. Please explain the difference or harmonize the terms, otherwise it remains confusing.

We agree. We have harmonized the manuscript and used ESAI throughout the document to denote the Environmentally Sensitive Area Indicator.

- Discussion: Please add a short description of uncertainties and limitations of the study and research needs /gaps.

We added a short description in the discussion section.

Reply to Reviewer N. Dalezios

Thank you for the review, Prof. Dalezios.

There are two questions clarifications to be provided by the authors:

1. A clear distinction should be made in the text between RI and ESA to avoid any confusion.

This comment is very pertinent and the confusion has been removed from the manuscript. We have opted for the very well-known terminology ESAI (Environmentally Sensitive Area Indicator).

2. An explanation is necessary for multi-criteria analysis, if it is applied, how and at what stage in the paper.

We have used a factorial approach and gave each factor equal weight in the Quality Indicators (QI), and in turn in the Environmentally Sensitive Area Indicator (ESAI). We did not use multi-criteria analysis in this research, but the suggestion is very valid and we have added the idea to the discussion section.

Reply to Reviewer #2

We thank reviewer 2 for the positive general comments.

A few minor revisions to be considered:

1. An explanation and clarification is necessary for ESAI and ESA: are the same? Also are the same with RI? If not, then specify the differences. This reflects Figures 2 and 4.

The confusion has been removed from the manuscript. We have opted for the known terminology ESAI (Environmentally Sensitive Area Indicator), and have adapted the text and figures accordingly.

2. An explanation is necessary for muli-criteria analysis and how it is connected with the whole methodology.

We have used a factorial approach and gave each factor equal weight in the Quality Indicators (QI), and in turn in the Environmentally Sensitive Area Indicator (ESAI). We did not use multi-criteria analysis in this research, but the suggestion is very valid and we have added the idea to the discussion section.

3. There is a need to clarify the scoring system of individual indicators. Is it objective or subjective?

The scoring of the quality indicators was based on a multi-factorial approach combining the multi-component GIS framework for desertification risk assessment by Santini et al. (2010) and the Environmentally Sensitive Areas (ESA) approach by Kosmas et al. (2006) and Basso et al. (2000). The scoring system as presented here, and adopted by a lot of studies is subjective and could benefit further from data mining techniques.

4. It would be useful if the authors could add any limitations and uncertainties of the methodology.

We have incorporated a section on the limitations of the methodology in the discussion section.

Reply to Reviewer #3

We thank Reviewer 3 for a thorough review and for highlighting interesting discussion points on the methodology used. Many of the comments raised in this review have helped reshape the discussion section or enabled a better explanation or justification of the methodology section.

The defined quality indicators are difficult to understand:

1. The climate quality indicator (CQI) is based on the average annual precipitation and reference aridity index and its temporal rate of change, neglecting the influence of other meteorological factors such as the wind, (the occurrence of strong land winds is mentioned in page 3, line 15), and the relative humidity. Why do not integrate these effects in a water balance in the air above the ground? Is there any rationale behind the selected threshold values used for the scores of the precipitation and aridity? Incidentally, the scores for the different magnitudes should have been better indicated in a table.

We have made the text clearer and clarified our methodology better. As the reviewer rightly points out there was confusion in the initially submitted manuscript. The initial formula of the aridity index includes temperature based evapotranspiration according to Thornthwaite (1948). When using the modified Penman-Monteith equation (Allen at al., 1998), wind and humidity are incorporated.

Both wind and relative humidity are important contributors to evapotranspiration, which is together with rainfall taken into account in the aridity index. An important improvement could indeed be a water balance and the incorporation of other variables in the climate quality indicator. We have taken up these points in the discussion section.

The scoring system is also included as a table in Annex I.

2. The soil quality indicator (SQI) includes the slope which is not properly an edaphic attribute. The texture scores should be based on the textural components, not on the units of a soil classification system what implies the contribution of other edaphic factors like rock presence, salinity, or depth, considered in other parts of the SQI. As in the previous indicator, the authors should have justified the limits between different categories. Why the presence of rocks and salinity are not better delimited?

We concentrated on pedological properties of soil development, and hence the choice for soil classification related properties: the presence of rocks, salinity, profile depth, soil texture and slope. The inclusion of edaphic properties is a very valid comment, which we have taken up in the discussion. However, this suggested approach requires soil data of at more sampling points than currently available in the study region.

3. The vegetation quality indicator (VQI) is loosely defined. Is the vegetation of the study region so homogeneous that does not require any specification of trees, shrubs, or herbaceous plants? Is it necessary to include both the NDVI and is time rate of change at the same level in the VQI?

Correct and we provided further clarification. The forest classification geo-database also includes other natural vegetation classes, ranging from broad-leaved evergreen humid forest to secondary natural dune vegetation. NDVI values are an indication of vegetation greenness and health; a declining change in NDVI indicates degradation.

4. The water management quality indicator (WMQI) is a mixture of very heterogeneous factors with the same level of influence. The water balance is not the volume of water used for irrigation. This volume should be expressed as volume per unit area to extend its potential use out of the study area. The groundwater capacity refers more precisely to a volume than to a discharge rate. The irrigation factors type and capacity are not similar as they appear in the WMQI equation. What relevance the canal density in the indicator? The existence of canals do not necessarily imply that they are in use.

We clarified the explanation of the water use balance calculation. The water use balance is expressed per irrigation perimeter, and reflects the balance between demand and supply. Irrigation water supply discharges were provided by the water board, and also cropping areas but no exact location of the crops; hence the choice to categorize and score the different perimeters.

The canal density refers to used canals, which were checked during field surveys in 2010.

We have checked the explanations of the WMQI to clarify the calculations that we performed.

5. The risk indicator demands a sound justification. There are some formal aspects in addition to the convenience of tables to show the different scores for indicators and their factors:
   a. Is there a necessity to reinforce some of the statements with a host of references? The abundance of multiple references might be more an obstacle than a help for the reader.

We agree. To avoid this confusion we have deleted the first paragraph of data and methods. The references and statements have been sufficiently covered in the introduction.

   b. Some sentences are rather obvious (e.g. page 2 lines 25-26; page 3 lines 24-25; page 3 lines 31-32, page 4 lines 1-3; page 11 lines 14-15).

We agree!

Page 2 lines 25-26; Page 3 lines 24-25; Page 3 lines 31-32: a sentence has been removed.

Page 4 lines 1-3; page 11 lines 14-15 have been rephrased to remove the rather obvious.

   c. Some references are missing in the final list as the FAO-UNESCO of page 5 line 6-

We have cross-checked the references; and added the missing reference to FAO-UNESCO-WMO.

Spatial indicators for desertification in south-east Vietnam

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Abstract. Desertification is influenced by different factors that relate to climate, soil, topography, geology, vegetation, human pressure and land and water management. The quantification of these factors into spatially explicit indicators and subsequent evaluation provides for a framework that allows to identify areas currently at risk of desertification and to evaluate important contributing bio-physical and socio-economic factors. Based on local knowledge of environmental contributing factors to risk of desertification in the Binh Thuan Province of south-east Vietnam, a baseline 2010 map showed that 14.4% of the area, mainly along the coast and in the north east, is desertified with another 35.4% at severe risk of desertification. The Ministry of Environment has defined the area with a ratio of rainfall to evapotranspiration smaller or equal to 0.65, which equals 1,233 km^2 or 15% of the province, as desertified area. The developed framework allows for decision support in a what if structure, and for the projection of potentially vulnerable areas under future scenarios. With projected climate change and current population growth the desertified area is expected to increase with 122% (or 137,850 ha) towards 2050. The methodology can be extended to neighbouring provinces that experience similar sensitivities to desertification.

1 Introduction

Desertification is "land degradation in arid, semiarid and dry sub-humid areas due to various factors, including climatic variations and human activities" (UNCCD, 2012). Land degradation in this context means the progressive loss of land productivity (Geist, 2005). The United Nations Convention to Combat Desertification advocates methods to improve the global monitoring and assessment of dryland degradation to support decision-making in land and water management (UNCCD, 2012). Vietnam is highly affected by weather-related hazards that are projected to increase in frequency with climate change (Gobin et al., 2015). Vietnam is not designated as an arid or semi-arid country. However, the coastal provinces in south-east Vietnam are strongly influenced by desertification, and therefore Vietnam ratified the convention in 1998 and formulated a national action programme in 2002.

The biophysical conditions related to desertification have originated models or frameworks involving the different processes of desertification to identify areas at risk (Schlesinger et al., 1990; Dirmeyer and Shukla, 1996; Kefi et al., 2007; Reynolds et al., 2007; Izzo et al., 2013; Jiang et al., 2019). Social, economic and in particular agricultural activities are considered as important pressures impacting on land degradation and desertification (Okin et al., 2001; Asner et al., 2004; Zhou et al., 2015; Hamidov et al., 2016). Integrating the monitoring and assessment of human and environmental variables poses major methodological challenges (Winslow et al., 2011) when assessing spatial desertification risks (Izzo et al., 2013; Zhou et al., 2015). Desertified areas have been detected using a multi-factorial approach such as the multi-component GIS framework for desertification risk assessment (Santini et al., 2010) or the Environmentally Sensitive Areas (ESA) approach (Kosmas et al., 2006; Basso et al., 2000). Though originally designed for European Mediterranean environments, the ESA methodology has increasingly been used for classifying sensitivity to desertification in different environments ranging from Egypt (Gad and Lotfy, 2008), Iran (Parvari et al., 2011) and Central Asia (Jiang et al., 2019) to the Dominican Republic (Izzo et al., 2013) and northwest China (Zhou et al., 2015). All of these approaches combine regional modelling methods with spatially explicit information to assess the sensitivity of different areas to desertification.

Monitoring and assessment of the underlying drivers of land condition changes helps target remedial actions to alleviate true causes of land degradation (Gobin et al., 1999; Winslow et al., 2011; Zhou et al., 2015). The integration of socio-economic and bio-physical factors is included in several assessment frameworks such as the Dryland Development Paradigm (Reynolds et al., 2007; Stringer et al., 2017), the Monitoring and Assessment Indicator System (Zucca et al., 2012), Global Drylands Observing System (Verstraete et al., 2011; Bestelmeyer et al., 2015) and monitoring Sustainable Land Management (Thomas, 2008; Hamidov et al., 2016). Focus on the integration of a particular component into a joint biophysical and socio-economic system is further elaborated for economic analysis (Salvati et al., 2008; Requier-Desjardins et al., 2011; Schild et al., 2018), population dynamics (e.g. Salvati and Bajocco, 2011; Schild et al., 2018), institutional knowledge (Stringer et al., 2009) and mainstreaming policies on degradation (Akhtar-Schuster et al., 2011). Eliciting the underlying factors that cause drought and desertification is a prerequisite to the further establishment of a monitoring and assessment systems to support decision-making on land and water management. The driving factors often relate to socio-economic developments with land use changes taken as valuable proxy indicators (Geist and Lambin, 2004; Hill et al., 2008; Hamidov et al., 2016). The observed relation between degradation and changes in ecosystem productivity have triggered the incorporation of remote sensing derived indicators (Cherlet et al., 2018; Jiang et al., 2019).

We hypothesised that the area currently at severe risk of desertification can be explained by different socio-economic and bio-physical factors, using local knowledge of environmental contributing factors as elucidated by Hai et al. (2013, 2014, 2016). The objectives were to develop a framework that integrates the important biophysical and socio-economic factors contributing to the risk of desertification, spatially delineate areas at risk of desertification in the year 2010 as a baseline, and demonstrate the developed framework for potential vulnerable areas under projected climate change and population growth. The method was developed for the Binh Thuan Province located in south-east Vietnam. The framework is designed to support policy makers in making informed decisions on combating desertification, analysing different scenarios and policy options, and formulating policies under what-if conditions.

2 South-east Vietnam

Vietnam has narrow deserts stretching along the central coastal areas, concentrated in 10 provinces from Quang Binh to Binh Thuan with a total area of about 419,000 ha. The U.S. Department of Agriculture recognised this problem in Vietnam in its world map of vulnerable desertification (USDA-NRCS, 2003). In August 1998 Vietnam ratified the UNCCD and formulated priority areas for natural resources management. In 2006, the "Vietnamese Action Plan against desertification for the period 2006 – 2010 with an outlook to 2020" was adopted. Vietnamese studies on climate change and related environmental problems show that scientific, technological and policy responses are all needed for successful adaptation (Adger et al., 2005; Adger, 1999). Research has been implemented to study climate change phenomena and their effects such as sea level changes (Boateng, 2012; Zeidler, 1997), floods (Thi et al., 2010; Thanh et al., 2004), storms (Kleinen, 2007) and drought (Sinha et al., 2011). Desertification, however, has received little attention in Vietnam.

Binh Thuan Province is located in the southern part of Central Vietnam, covers an area of 7,856 km^2 and has about 250 km of coastline. Binh Thuan and the neighbouring Ninh Thuan Province have a typical semi-arid climate with low rainfall, and high evaporation, with a variety of typical desert lands including sand, stone or salt deserts and degraded land. The Tuy Phong and Bac Binh districts (Figure 1) face 6 to 9 dry months per year with less than 100 mm of monthly rainfall. The province is also subject to high temperatures and strong land winds that contribute to drought. The current desertification has a strong impact on overall production, environment and socio-economic activities.

As part of the National Action Plan to combat desertification, the Vietnam Ministry of Natural Resource and Environment (MONRE) delineated the desertified zone in Binh Thuan based on an aridity index, i.e. ratio of rainfall to evapotranspiration, smaller or equal to 0.65. The total desertified area is 1,233km^2, corresponding to 15% of the province (Figure 1). Desertification, however, is the result of a variety of different factors and we therefore challenge the current delineation which is solely based on meteorological variables.

3 Data and Methods

Based on local knowledge of environmental contributing factors to risk of desertification in the Binh Thuan Province of Vietnam (Hai et al., 2013, 2014, 2016), we included indicators for climate, soil-landscape, vegetation, water resources management, population density and human activities into a common framework. Each of these factors required a different methodology since different processes are involved that relate to land degradation and desertification. Indices were elaborated, compared with the current status of desertification and combined into zones at risk of desertification. The proposed scores for each index and indicator were implemented in a relational database, which allowed for transparent definition, the incorporation of socio-economic information and the iterative refinement of the selection rules in the future.

3.1 Database development

Spatial and/or temporal data were collected to characterise the climate, the soil-landscape, the vegetation, the water resources and the different human activities in the region. The resulting database contained information on soils (1:100,000); geology, hydro-geology, hydrology; topography; natural vegetation; land use / cover change; population; and, land and water resources. Soil resources, their characteristics and FAO-WRB classification were obtained from the Department of natural resources and environment of the Binh Thuan Province. Land cover changes were derived from Landsat ETM in 1994/1995 and SPOT4 in 2009/2010. The water resources potential for household use and agriculture including irrigation was derived from the hydrogeological database that includes groundwater reserves and exploitation, surface water distribution and flow characteristics, and operational and planned irrigation systems. Human activities were evaluated from land use in 2005 and 2010, and the province's master planning for 2010-2020 including a vision on 2050 (GSO, 2012). Population density and settlement distribution were obtained from statistics at the community level. In- and outward migration to and from the province included tourist activities. Economic statistics on agricultural activities covered data on cultivated land, crop types, grassland and livestock. Meteorological data included daily rainfall and daily minimum, maximum and mean temperature for the period 1960-2010 obtained from the Vietnam Institute of Meteorology.

3.2 Calculation of indicators

The scoring and scaling is explained for five different quality indicators (*QI*): climate (*CQI*), soil (*SQI*), vegetation (*VQI*), water management (*WMQI*) and the different human activities and demographic pressures (*HQI*). Each Quality Indicator comprises different sub-indicators calculated for each km² grid cell of the province (Figure 2). Soil characteristics, NDVI, land cover/use and water management were verified during field surveys in 2010. The scoring of the quality indicators was based on multi-factorial approach combining the multi-component GIS framework for desertification risk assessment by Santini et al. (2010) and the Environmentally Sensitive Areas (ESA) approach by Kosmas et al. (2006) and Basso et al. (2000).

The Climate Quality Indicator (*CQI*) is based on the Aridity Index (*AI*) and calculated for 13 meteorological stations according to:

$$CQI_{1991-2010} = (P_{1991-2010} \,.\, AI_{1991-2010} \,.\, \Delta AI_{1991-2010})^{1/3}$$

$$\Delta AI_{1991-2010} = \frac{AI_{1981-2010} - AI_{1991-2010}}{AI_{1981-2010}}$$

$$AI_{year} = \frac{P_{year}}{PET_{year}}$$

Where $\Delta AI_{1991\text{-}2010}$ is the change of the aridity index relative to a longer period; *P* is the yearly average annual rainfall and *PET* is the annual average potential evapotranspiration calculated according to the modified Penman-Monteith method (Allen et al., 1998), calculated for the periods 1991-2010 and 1981-2010. The aridity index, originally developed by FAO-UNESCO-WMO (1977) and based on temperature based evapotranspiration (Thornthwaite, 1948), was adapted by UNEP (1997) for more recent periods and based on potential evapotranspiration. Further developments include *AI* time series analysis to assess temporal changes and climatic impact (e.g. Dai, 2013). We used values for *AI* below 0.35 to indicate severe risk of desertification, between 0.35 and 0.75 risk of desertification, and above 0.75 indicate no risk of desertification. The change during 1991-2010 ($\Delta AI_{1991\text{-}2010}$) was quantified as the weighted departure from the average for the period 1981-2010. Values for *P*, *PET*, *AI* and ΔAI were interpolated using a nearest neighbour interpolation in ArcGIS Spatial Analyst, and classified after a scoring system. The scoring for annual rainfall was 1 (low) for more than 2000 mm; 1.2 for 1500 - 2000 mm; 1.4 for 1000 - 1500 mm; 1.6 for 500 – 1000 mm; 1.8 for 250 – 500 mm; and 2 for annual rainfall below 250 mm. The aridity index (*AI*) had score 2 when below 0.35; score 1.6 for values between 0.35 and 0.75; score 1.3 for values between 0.75 and 1.20; and, score 1 for values above 1.20. The score was 1.1 for ΔAI values between -0.2 and 0; and 1 for values between 0 and 0.2.

The Soil Quality Indicator (*SQI*) comprises a weighting of soil fertility, salinity, slope, soil depth, soil type and the presence of rocks. For each of the soil qualities a higher score indicates a higher vulnerability to desertification and degradation.

$$SQI_{2010} = \left(S_{texture} . S_{depth} . S_{slope} . S_{rock} . S_{salinity}\right)^{1/5}$$

The soil texture was derived from the World Reference Base for Soil Resources. Arenosols and Leptosols were considered most sensitive to desertification in the area and received a score 2, followed by Salic Fluvisols (1.8), Thionic Fluvisols (1.6), Gleyi-Umbric Fluvisols (1.4), Acrisols (1.2), Ferralsols (1.1) and Luvisols (1). A shallow soil depth of less than 30 cm received a high score of 2, followed by 30 – 50 cm (1.5) and 50 - 100 cm (1.2); well-developed soils with a profile depth deeper than 100 cm received score 1. A slope above 25° received a score of

2; a score of 1.5 was given to slopes between 8° and 25°; slopes between 3° and 8° received score 1.2; and, slopes below 3° score 1. The presence of salinity or rock fragments each received score 1.2, whereas their absence received score 1.

The Vegetation Quality Indicator (*VQI*) comprises the normalised difference vegetation index (*NDVI*), changes in **NDVI** (*ΔNDVI*) and vegetation type.

$$VQI_{2010} = (VT_{2010}.NDVI_{2010}.\Delta NDVI_{1995-2010})^{1/3}$$

The vegetation type (*VT*) was extracted from the 2010 forest classification and nature cover geo-database, that includes 18 vegetation classes ranging from broad-leaved evergreen humid forest to secondary natural dune vegetation. Each vegetation class was subsequently evaluated as having a high (2), medium (1.5) or low risk (1) to degradation. $NDVI_{2010}$ was calculated as the average km² value based on SPOT Vegetation images from 2010. *NDVI* changes were calculated from Landsat TM on 1994/1995 and SPOT on 2009/2010 ($\Delta NDVI_{1995\text{-}2010}$). Both *NDVI* and vegetation types were scored according to their vulnerability to desertification and degradation. Dense forests and high *NDVI* values received lower scores than sparse forest cover or low *NDVI* values. *NDVI* values are an indication of vegetation greenness and health; a declining change in *NDVI* indicates degradation. An $NDVI_{2010}$ value below or equal to 0.1 received a high scoring of 2; a value between 0.1 and 0.6 received 1.5; and, a value equal or above 0.6 received a score of 1. $\Delta NDVI_{1995\text{-}2010}$ values above 0 are scored 2; values equal to 0 were scored 1.5; and, values below 0 were scored 1.

The Water Management Quality Indicator (*WMQI*) has three major components that include an assessment of the water use balance, groundwater capacity and irrigation characteristics.

$$WMQI_{2010} = (WB_{2010}.GW_{2010}.IT_{2010}.IC_{2010}.CD_{2010})^{1/5}$$

Where *WB* is the water use balance calculated per irrigation perimeter, *GW* is the groundwater capacity, *IT* is the irrigation type, *IC* is the irrigation capacity, and *CD* is the canal density. The water use balance (*WB*) was assessed from the volume of water extracted for irrigation and expressed as water short to meet irrigation demands in the irrigation perimeter. The water use balance was calculated as the balance between the total water demands for each agricultural crop and water supply of each irrigation perimeter in 2010. Irrigation water supply discharges and cropping areas were provided by the water board, but no exact location of the crops was possible; hence we chose to score the perimeters on the basis of the water use balance. A shortage in the water use balance of above 5.10^7 m³ was scored 2, below 5.10^7 m³ 1.5 and no shortage was scored 1. The assessment of the groundwater capacity (*GW*) was based on discharge data. Zero well discharges received score 2, followed by discharges below 0.5 m³/h (1.6), 0.5-5.0 m³/h (score 1.3) and 5-10 m³/h (score 1). The irrigation characteristics were the irrigation type (*IT*); the irrigation capacity (*IC*) in percentage of the area under operational irrigation; and, the canal density (*CD*) calculated as the length of used irrigation canals per km² grid. Three irrigation types were distinguished: no irrigation with score 2, supplementary irrigation with score 1.5 and full irrigation with score 1. For a zero used canal density a score of 2 was assigned; a density between 0 and 0.25 km/km² received a score of 1.5; and, a density above 0.25 received 1. The irrigation capacity was scored as follows: 0 % (score 2); > 0-30% (score 1.6); 30-50% (score 1.4); 50% - <100% (score 1.2); and, 100% (score 1).

The human pressure and activities quality indicator is assessed on the basis of land use, land use change and population density.

$$HQI_{2010} = (LU_{2010}.LUC_{2005-2010}.PD_{2010})^{1/3}$$

Where *LU* is the land use in 2010; *LUC* is the land use change between 2005 and 2010 and *PD* is the 2010 population density. The classification and scoring focused on vulnerability to desertification. The land use was scored as follows: bare land (score 2); agriculture and settlements (score 1.5); and, forest and water (score 1). Land use changes to bare land were scored 2; changes of forest and water to other land uses were scored 1.5; and, the absence of changes were scored 1. A population density higher than 500 persons/km² received score 2; densities between 200 and 500 received score 1.5; and, densities below 200 received score 1.

All the above Quality Indicators are combined into one indicator for assessing the risk of each km² grid cell to desertification.

$$ESAI = (CQI.SQI.VQI.WMQI.HQI)^{1/5}$$

Where *ESAI* is the Environmentally Sensitive Area Indicator, *CQI* is Climate Quality Indicator, *SQI* is Soil Quality Indicator, *VQI* is Vegetation Quality Indicator, *WMQI* is Water Management Quality Indicator and *HQI* is Human Pressure and activities Indicator.

We distinguished four major types of areas at risk based on the Environmentally Sensitive Area Indicator (*ESAI*). Critical areas included areas that were already desertified and presented a threat to the environment of the surrounding areas, with C3 being highly critical (*ESAI* > 1.53); C2 being medium critical (1.42 ≤ *ESAI* ≤ 1.53); and, C1 being low critical (1.38 ≤ *ESAI* < 1.42). Fragile areas were areas in which any change in the balance of natural resources and human activities was likely to bring about degradation and desertification, with F3 highly fragile (1.33 ≤ *ESAI* < 1.38); F2 medium fragile (1.27 ≤ *ESAI* < 1.33); and, F1 low fragile: (1.23 ≤ *ESAI* < 1.27). Potential area at risk were areas threatened by degradation under significant climate change, if a particular combination of land use was implemented or where offsite impacts would produce severe problems elsewhere (1.17 ≤ *ESAI* < 1.23). Areas not at risk were areas with a wet climate, well drained, well developed soils and/or with a dense vegetation cover; they were not considered as threatened by desertification (*ESAI* < 1.17).

3.3 Scenarios

A scenario of climate change and population growth was established as an example of how the framework could be used to support policy options.

During the period 1958-2007, the average temperature increased by 0.5–0.7°C. Vietnam's official scenarios for climate change (MONRE, 2009) fitted these current trends. The emission scenario corresponded to an increase in temperature of 1°C by 2050 and 2.4°C by 2100 with respect to the 1980-1999 baseline period. Rainfall in the middle of the rainy season would increase 10-15% with respect to the 1980-1999 baseline period in the South Central. On a year basis, rainfall is projected to increase with 1.7% by 2050 and 3.2% by 2100. The climate scenario used corresponds to RCP4.5 with a radiative forcing of 4.5 W/m² and 650 ppm CO_2 equivalent in 2100. The climate scenario was downscaled at the different meteorological stations using the MAGICC/SCENGEN software (Wigley, 2008).

Human activities and population growth were taken from the master planning for 2010-2020 including a vision on 2050. The vision includes planned irrigation schemes which will in conjunction with climate change alter the water use balance. Based on governmental statistics (GSO, 2012) the province has a population of 1.1 million people with a population growth of 1.4% during the last decade.

4 Results

4.1 Climate

The aridity index (*AI*) showed the occurrence of semi-arid regions in the northern coastal area (Figure 3). Based on the *AI* comparison for different periods, drought is rising in the northern and the central coastal areas with up to 26% whereas in the northwest of the province *AI* has increased with 10%. The value of *CQI* was high along the northern coastal area (Figure 3), stretching to the south and gradually moving to the east of the province indicating enhanced sensitivity to desertification.

With climate change, an increase of 10.4% in reference evapotranspiration was projected in the northwestern districts of Duc Linh, Tanh Linh and Ham Thuan Bac (Location see Figure 1; Table 1); a 12.2% increase in the southcentral districts of Ham Thuan Nam, Ham Tan and Phan Thiet; and, a 13.9% increase in the eastern districts of Tuy Phong and Bac Binh. The rainfall was projected to increase with up to 5% in the northwestern districts, remained the same in the central districts and decreased with more than 10% in the northeastern districts. Overall this led to a projected decrease in the ratio rainfall to evapotranspiration. Climate is a key factor as confirmed by similar studies in the region (MONRE, 2009). The distinction between climate regimes and gradients within the province could be seen from the *AI* isolines (Figure 4).

4.2 Soil and vegetation

The soil quality characteristics were evaluated with areas at risk displaying high *SQI* values (Figure 3). Poor soil quality due to shallow profile development, steep slopes or low fertility added to the risk. Deforested or eroded areas are mostly located in the mountains. Riverine areas with a good soil quality (low *SQI*, Figure 3) offer opportunities for farming or are vegetated with dense forest. The soil quality indicator (*SQI*) provided for the clearest relation with desertification but could not be interpreted on its own. Thin soils, steep slopes, vulnerability to erosion and sparse vegetation showed a high risk for degradation in the mountains, whereas the plains and coastal areas were at risk due to salinisation and sandy soil textures.

Forests covered nearly half of the province and were located in the province's mountainous regions in the northwest and northeast. The vegetation quality indicator (*VQI*) displayed a distinct pattern of low values (Figure 3) in the east where mountains with dense-forests dominate the landscape and high values in the southeast and coastal areas where residential areas and agriculture are the principal land use. Low *NDVI* values indicated the presence of sparse vegetation with increased risks to degradation. At the same time afforestation or reforestation are important mitigation measures to combat desertification. *VQI* therefore reflected both adaptation and mitigation measures.

4.3 Water Management

Binh Thuan Province has three major rivers with several tributaries mostly originating in the province itself or in the highlands of the neighbouring province. Two major lakes and several artificial lakes add to the surface water bodies that together with groundwater provide for water during the dry season. Water resources management such as the development of sustainable irrigation systems help alleviate drought and desertification. A water management quality indicator (*WMQI*) was therefore included in the ESA methodology. The results showed the effect of irrigation on the *WMQI* in the north east (Figure 3). The canal density and irrigation capacity determined the amount of fields that could be irrigated during the dry season. The *WMQI* reflected the availability of water resources and exploitation potential. Water supply and management had a large impact on alleviating the negative effects of desertification (Figure 4), and therefore represented important adaptation measures.

4.4 Human pressure

The human pressure was evaluated using population density and land use intensity, the latter as a combination of land use and land use change (Figure 3). The population density ranged from around 1000/km^2 in Phan Thiet to less than 100/km^2 in the rural areas. As a result of strong population growth in the cities along the coast, urbanisation increased with 1% during the last decade, making Binh Thuan one of the most urbanised provinces of the South Central Coast in Vietnam.

The plains and coastal areas undergo a stronger human influence than the hills and mountains. Despite its large forested area, the province has about 37% of agricultural land, which is the largest figure among all provinces of the central coast regions (GSO, 2012). One third of the agricultural land is used to cultivate rice. Though many mountains showed clear signs of deforestation, there is an active policy towards reforestation and protection particularly of the dense forests in the northeast. The consequences of forest degradation may lead to further desertification and drought impacts on the coastal areas and plains. The human pressure and activities quality indicator (*HQI*) reflected the influence that population density could have on natural resources use. Higher population pressures resulted in land use and vegetation changes, and gave rise to a higher water demand for both agricultural and household use.

4.5 Areas at risk of desertification

The areas at risk of degradation in the Binh Thuan Province (Figure 3) show a zoning of sensitivity with around 85% of the province. Desertified areas accounted for 14.4% of the province, mainly the north-east and coastal areas. Another 35.4% was highly fragile and at immediate risk of desertification; this area is yearly affected by severe drought occurring during the dry season. In the northern districts the coastal zones suffer from shifting sand dunes and the plains from excessive drought and salinisation causing sparse vegetation and serious degradation. These districts experience a high risk of spreading desertification. According to the analysis, the most vulnerable districts (Table 2; Figure 1) were located along the coastal areas of Tuy Phong (C: 370.9 km² or 49.3% of the district's area; F3: 288.1 km² or 38.3%), Ham Thuan Nam (C: 212.3 km² or 20.1%; F3: 503.1 km² or 47.7%), Bac Binh (C: 169.3 km² or 9.1%; F3: 686.7 km² or 36.9%) and Ham Thuan Bac (C: 127.2 km² or 49.3% of its area; F3: 486.6 km² or 38.3%) Districts. The densely populated coastal district of Phan Thiet (C: 102 km² or 51.8%; F3: 91.2 km² or 46.3%) seemed very vulnerable to moving sand dunes.

The trend of desertification under climate change and population growth was towards the southwest with a projected increase of 1,379 km² land totalling 2,509 km² or 31.9% of the entire province being desertified towards 2050. The affected area is enlarging most in the districts of Ham Thuan Bac with 458 km², followed by Ham Tan with 258 km² and Ham Thuan Nam with 210 km² (Table 2; Figure 1). The largest increases in desertification are expected in La Gi, Ham Thuan Bac and Ham Tan Districts where desertification is projected to increase with 490%, 360% and 277% respectively.

5 Discussion

According to MONRE the land affected by drought and desertification is about 43% of the Binh Thuan Province based on an aridity index below 0.8 which reflects the occurrence of a six-month dry season. A simple aridity index may provide a good indicator for the meteorological conditions but does not reflect the pressures nor the remedial actions that can be undertaken to alleviate the risk of desertification. In some areas irrigation systems to have been developed along with sustainable management practices such as adapted cropping systems and policies to protect water resources through reforestation schemes, e.g. in Bac Binh District.

The world vulnerability map of desertification (USDA-NRCS, 2003) presents the southern coastal zone of Vietnam as sensitive with the northern coastal zone of the Binh Thuan Province highlighted as highly sensitive. Despite the years of difference between our analysis and the USDA map the general picture is similar with the most sensitive areas being identified in both maps. In comparison to 1998 when Vietnam ratified the UNCCD, desertification has spread towards the southwest, a tendency that is continued under a scenario of climate change and population growth. Furthermore some areas in the centre have benefitted from irrigation schemes, whereas reforestation has taken place in parts of the northeast changing the sensitivity to desertification and justifying the incorporation of land and water management indicators in the approach.

Desertification and land degradation is the result of many factors, the characteristics of which differ for each region as for example in the Dominican Republic (Izzo et al., 2013), Italy (Basso et al., 2000), northwest China (Zhou et al., 2015), Central Asia (Jiang et al., 2019), Nigeria (Gobin et al., 1999) and Iran (Gad et Lotfy, 2008). In the Binh Thuan Province, different indices influence the environmental sensitivity in a different manner as demonstrated for five comprehensive quality indices, i.e. climate, soil, vegetation, water management and human pressure. Climate impacts will alter in the first place the climate quality indicator (*CQI*) mainly through temperature rises and increased rainfall variability. Temperature rises affect evapotranspiration and the crop water demands, and the uncertain onset of the rainy season will affect crop water management and irrigation demands, both having an impact on water management (*WMQI*). The concept of the water footprint could help quantify crop water management (Gobin et al., 2017). Population growth alters the dynamics of land use demand and in turn affects water demands and water use balances. Land and water management seems a priority policy domain for alleviating the problems related to land degradation and desertification in the area.

The combination of different indices into the Environmentally Sensitive Area Indicator (*ESAI*) allows for identifying zones at risk of desertification and for eliciting the most important factors influencing desertification; and provides for a method that is applicable across different regions in the world (e.g. Izzo et al., 2013; Jiang et al., 2019). Monitoring the different spatial indicators and quality indices is an important part of an approach to combat desertification and allows for informed decision making (Winslow et al., 2011). Subsequent studies could enlarge the area to regions at current or potential risk, and could benefit from other land degradation related risk assessment research (Gobin et al., 1999; Kefi et al., 2007) or the incorporation of different indicators related to causes and processes of land degradation (Kosmas et al., 2014) such as soil morphology (Gobin et al., 2000), erosion (Gobin et al., 2004) or the water balance and water stress (Gobin et al., 2017). Depending on data availability, these edaphic soil properties could be included to reflect soil-vegetation relationships. A perceived major shortcoming of the method is the subjective sensitivity scoring system, with scores typically in the range of 1.0 to 2.0, and based on existing research data or on the importance to land degradation and desertification (Kosmas et al., 2014). Future efforts could benefit from data mining techniques and machine learning to establish meaningful relations between the different indices, quality indicators and the risk of desertification. In addition, multi-criteria decision analysis could help optimise natural resources management and reduce the risk of desertification. The present scoring system, however, allows for easy comparison of the different contributing indicators between regions or zones and therefore elucidates major contributing factors within a certain area.

The spatially explicit regional indices provide a comparative overview (Reynolds et al., 2007) and define areas where more detailed studies or policy attention are needed for determining the contributing factors and mitigating risks (Salvati et al., 2008; Hamidov et al., 2016). With changing scales, the dominant controlling factors such as for example land management, water resources development and vegetation cover may change (Gobin et al., 2001; Santini et al., 2010; Zhou et al., 2015). Individual farming practices may be different too such that remediation strategies at the community level must be adapted to this scale. Monitoring at multiple scales therefore provides for a nested strategy of focussing on environmentally sensitive areas (Gobin et al., 2004) which may require remedial measures to be taken at different levels of decision making.

6 Conclusions

The approach of identifying environmental sensitive areas based on a factorial combination of quality indicators, elucidated using local knowledge, allows for mapping current areas at risk of desertification and projecting trends. The area at risk of desertification in the Binh Thuan Province of south-east Vietnam is expected to increase from 14.4% in 2010 to 31.9% in 2050 under projected climate change and population growth.

The factorial combination of several indices and quality indicators proved useful for identifying environmentally sensitive areas now and under environmental change, and for elucidating relationships between factors and areas at risk of desertification. The key factors related to human impact on land cover, soil management and irrigation water capacity can be influenced through policies encouraging the sustainable management of natural resources. The method can be extended to neighbouring areas experiencing similar environmental threats.

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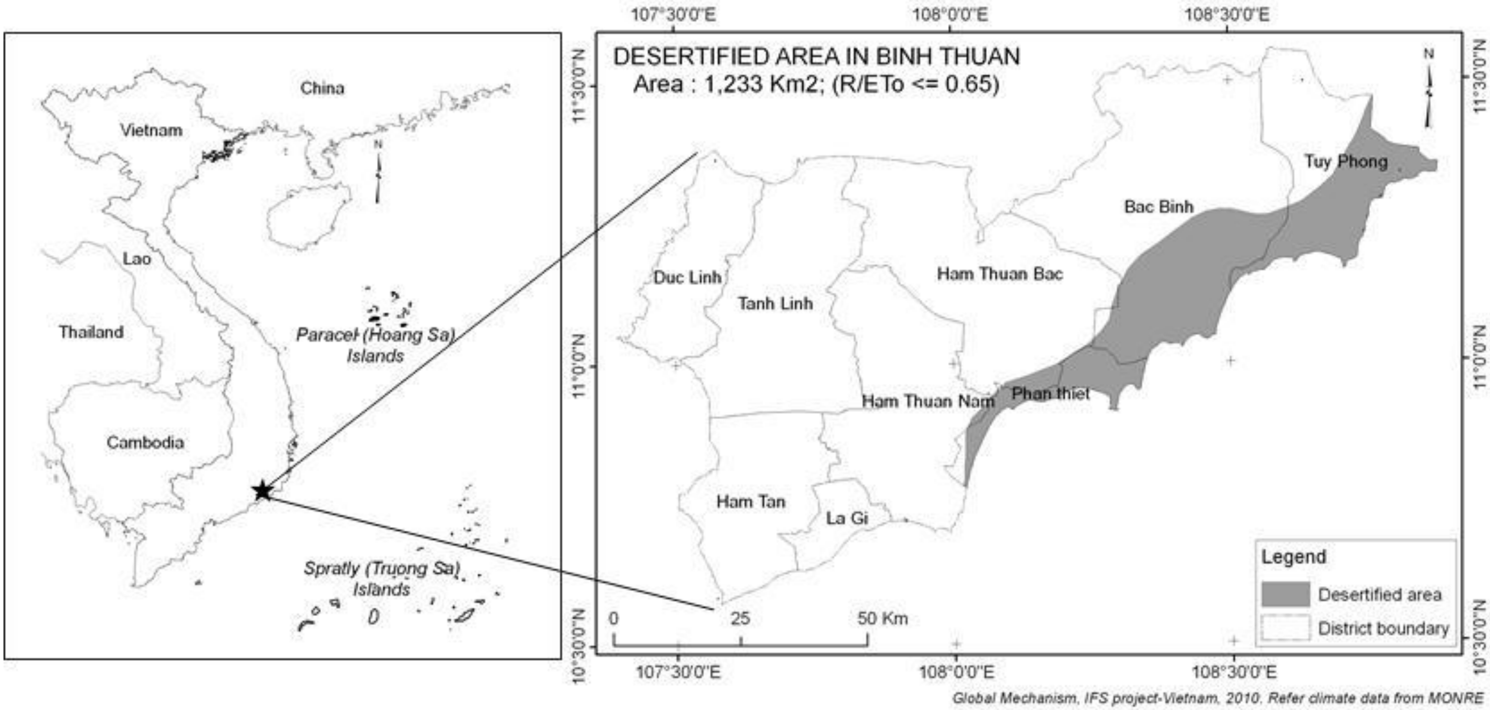


Figure 1: Location of the desertified area in Binh Thuan Province in Vietnam, based on rainfall to evapotranspiration smaller or equal to 0.65.

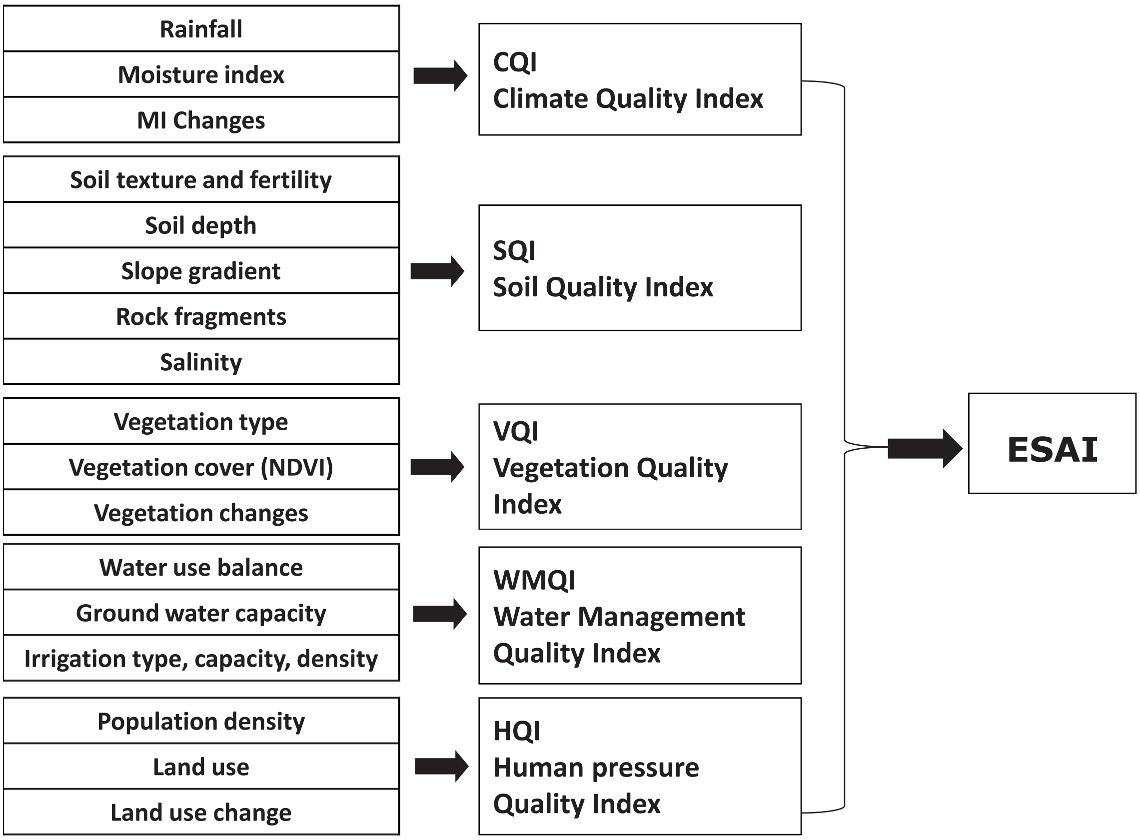
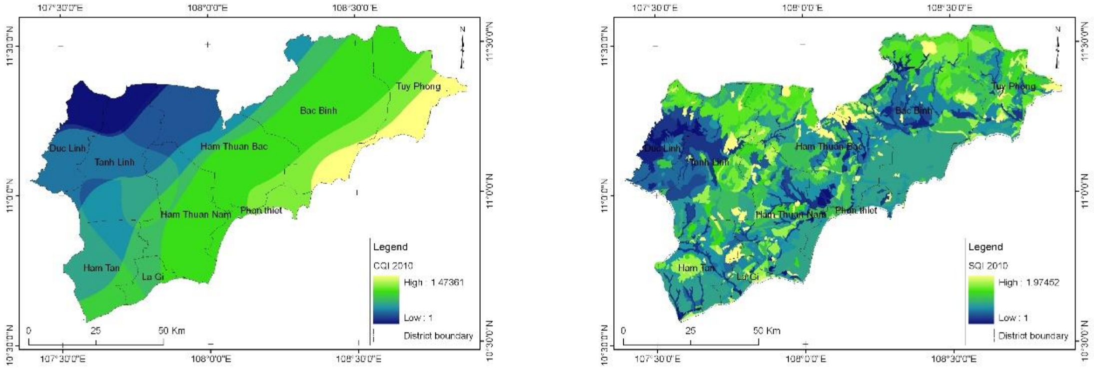


Figure 2: Spatially distributed indices for identifying environmentally sensitive areas to desertification.



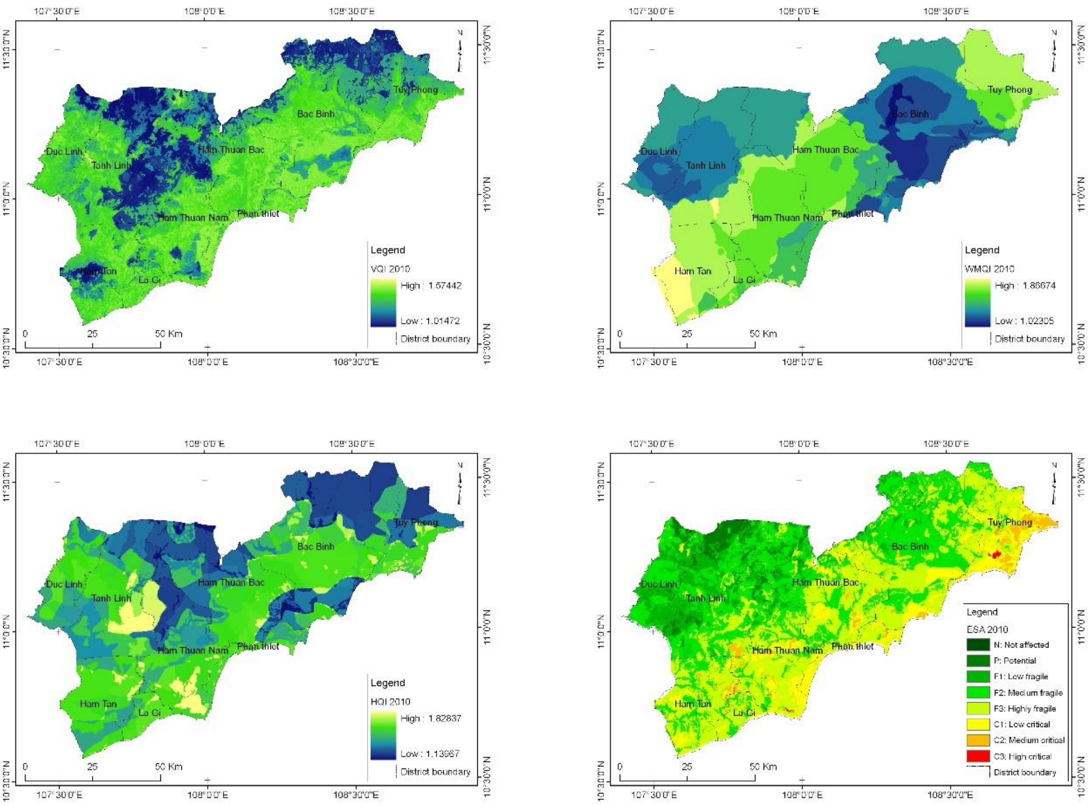


Figure 3: Results of the Climate Quality Indicator (CQI), Soil Quality Indicator (SQI), Vegetation Quality Indicator (VQI), Water Management Quality Indicator (WMQI), Human Pressure Indicator (HQI) and the Environmentally Sensitive Area Indicator (ESAI).

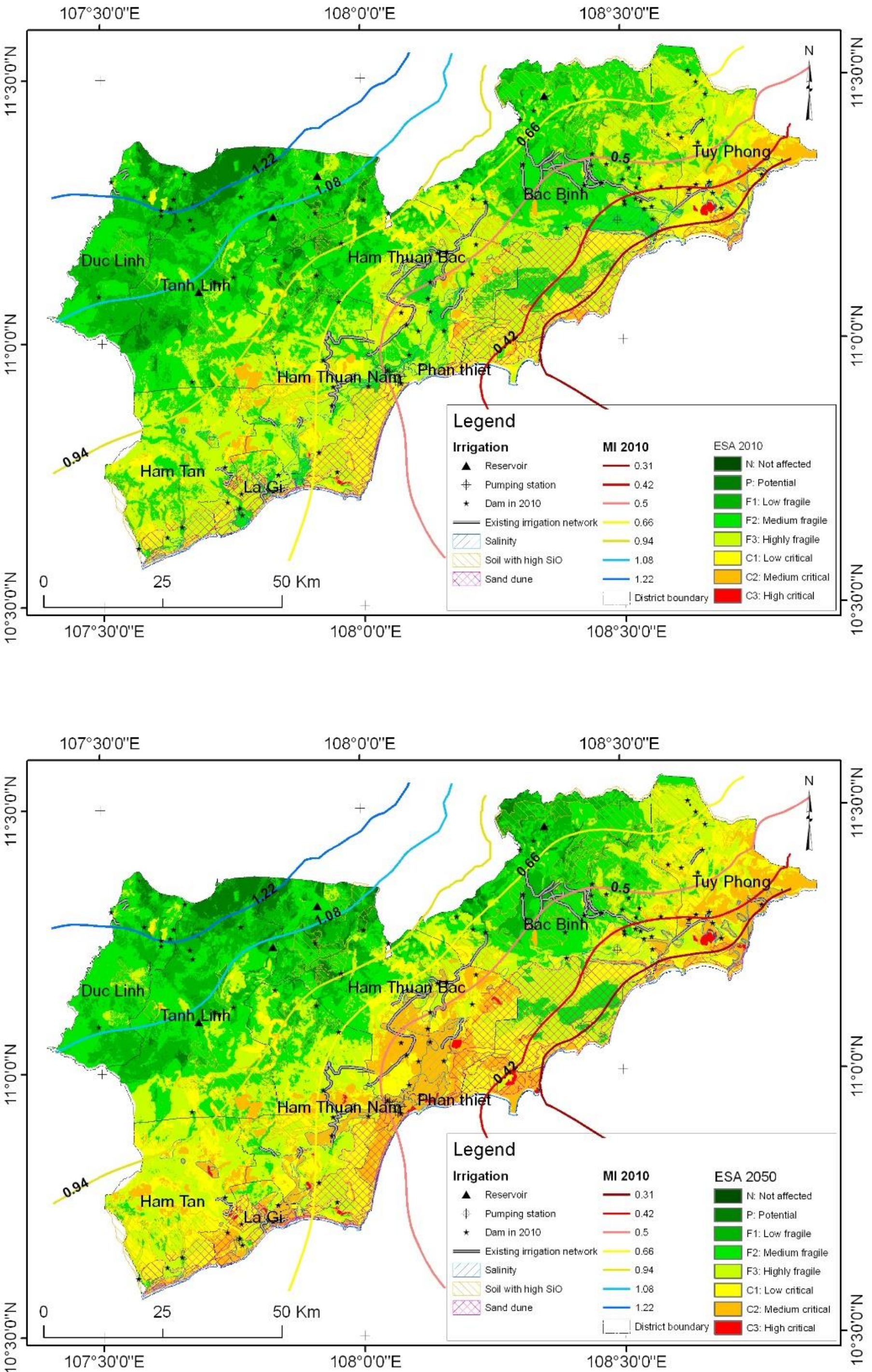


Figure 4: Spatial distribution of the Environmentally Sensitive Area Indicator (ESAI) in 2010 (top) and projections of ESAI for 2050 (bottom) under climate change and population growth.

Table 1: Rainfall to reference evapotranspiration (P/PET) for 13 meteorological stations in the Binh Thuan Province for observed 1981-1990 and 1991-2010 periods, and projected for 2050 according to MONRE's high climate scenario for Vietnam.*

District	Station	LON	LAT	1981-1990 (P/PET)*	1991-2010 (P/PET)*	2050 (P/PET)*
Tuy Phong	Lien Huong	108°43'	11°13'	0.23	0.35	0.27
Tuy Phong	Song Mao	108°30'	11°15'	0.33	0.48	0.37
Bac Binh	Bau Trang	108°25'	11°04'	0.30	0.35	0.29
Phan Thiet	Mui Ne	108°17'	10°56'	0.40	0.44	0.38
Phan Thiet	Phan Thiet	108°06'	10°55'	0.50	0.55	0.49
Ham Thuan Bac	Dong Giang	108°00'	11°13'		0.97	0.91
Ham Thuan Nam	Ma Lam	108°03'	11°06'	0.39	0.53	0.45
Ham Tan	Ham Tan	$107^0$49'	$10^0$41'	0.78	0.74	0.75
Tanh Linh	La Ngau	107°47'	11°10'	0.98	1.07	0.95
Tanh Linh	Ta Pao	107°46'	11°07'	1.19	1.09	1.03
Tanh Linh	Suoi Kiet	107°42'	11°07'		0.93	0.87
Duc Linh	Me Pu	107°37'	11°13'	1.31	1.27	1.15
Duc Linh	Vo Xu	107°36'	11°11'	1.17	1.09	1.02

* Where P is rainfall and PET is the reference evapotranspiration calculated according to the modified Penman-Monteith method (Allen et al., 1998); For location of the districts see Figure 1.

Table 2: Surface area covered by areas at risk of desertification in the Binh Thuan Province in 2010 and projections for 2050, calculated using the Environmentally Sensitive Area Indicator.

District	ESAI type (km^2) in 2010			ESAI type (km^2) in 2050		
	N + P	F	C	N + P	F	C
Phan thiet	0.0	95.1	102.0	0.0	8.3	188.8
Tuy Phong	0.0	381.1	370.9	0.0	271.4	480.6
Bac Binh	6.8	1684.4	169.3	34.4	1541.9	284.2
Ham Thuan Bac	37.0	1199.3	127.2	82.7	695.7	585.1
Ham Thuan Nam	13.3	828.5	212.3	0.9	630.9	422.3
La Gi	0.0	156.5	21.1	0.0	53.2	124.4
Ham Tan	0.0	635.2	93.2	0.0	376.9	351.5
Duc Linh	33.9	497.0	3.2	13.4	516.0	4.7
Tanh Linh	159.2	998.5	31.3	113.9	1007.8	67.3
Total	250.3	6475.5	1130.5	245.3	5102.0	2509.0
% of total area	3.2	82.4	14.4	3.1	64.9	31.9

Where N= not affected; P= potential; F= Fragile; C= Critical. Location see Figure 1.