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Discussions

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Interactive comment

Interactive comment on "Early warning and drought risk assessment for the Bolivian Altiplano agriculture using high resolution satellite imagery data" *by* Claudia Canedo Rosso et al.

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General Comment

The authors thank the editor, reviewers, and third person's comments for time spent and efforts to improve the manuscript. We have revised the manuscript accordingly taking the reviewers' and third person's comments into due consideration. Below follow answers to the reviewer's comments and description of actions taken.

While the reviewers indicated that the article is of substantial interest and relevant for the journal they criticized the misleading title as well as the analysis to be "poorly executed". Furthermore, they reviewers indicated that the quality of the presented material is "not satisfactory" to support the results found. We agree with the reviewers in the sense that one major restriction to provide a sophisticated model between satellite imagery and agriculture risk is data limitation. However, the unavailability of data to be used for a sophisticated drought modelling approach are very common in a developing country context (World Bank 2016). One way to overcome this challenge is to apply a so-called iterative risk management approach, e.g. starting with baseline estimates using the best data currently available and updating risk estimates continuously over time (see IPCC 2012). Currently there are no studies for the Altiplano which relates satellite sourced imagery with agriculture risk, including possible associations with ENSO. The article tries to fill this gap. We acknowledge the fact that there are other studies in other countries which are using more sophisticated models, however, the situation in the Altiplano, especially the data limitations, restricts the use of such models and we provide a way forward to improve the data situation using high-resolution satellite imagery with a probabilistic approach for agriculture risk. Hence, for the current situation in Bolivia our approach can be regarded as one way forward, and can be used as a baseline case for further analysis in the future. As indicated, the situation is quite similar in other developing countries around the world and our approach can be seen as one way forward how to implement drought risk management under data scarcity including the important connection with the ENSO phenomenon. We also provided now much more detail on the strengths and limitations of the approach, including a detailed uncertainty analysis. Please find our detailed responses to the reviewer comments below.

The response to reviewers are structured following the recommendations of the editors:

i. Comment from referee

ii. Authors' response

iii. Author's changes in manuscript.

In addition the last section "Changes in manuscript" describes in more detail the author's changes in manuscript. Please notice that the figures R1, R5 and R6 are included in the response to referees, and the figures 1-3 and A1-A6 (appendix) are included in the manuscript.

Referee #2

1. i. The title does not reflect the essence of the work presented. Actually there is no "Early warning" of drought because it is only underlined that the early warning of ENSO warm and cold phases is of importance but a methodology of issuing warnings is missing in this work. "Early warning" have to be avoided in the title because it is not approved in the text.

ii. The authors agree and have modified the title of the study to "Drought risk assessment for the Bolivian Altiplano agriculture and its association with El Niño Southern Oscillation". The term "association with ENSO" is more appropriate than "early warning", considering the influence of ENSO on precipitation patterns, in consequence with agricultural production.

2. i. Introduction is too expanded with material, which is beyond the context of the paper. For example: P2/ln 6 'Regarding the prevention . . . .These include the setup of insurance and irrigation systems'; the topic is not how to overcome drought but to create a system for drought assessment? P2/ln 25 'Such an approach is now seen as the most 25 appropriate in data-scarce environments (see IPCC, 2012;and UN, 2015)'? Please note that the approach used in the paper here is still not introduced, first motivate the used approach. Instead of this, it is expected the Introduction section to include the state of the art on the specific problem, i.e. on early warning and drought risk assessment as it is declared in the title. Although the scarcity of data in the region, there is some international experience that should be summarized.

ii. The introduction and the second section "Data description" have been shortened. The new text includes only the relevant information for the study, we concisely described the general characteristics of the study area. The section introduction was reduced to include only the important information of the study.

iii. Please see the section Changes in manuscript.

3. i. P3/ln15 The aim is not relevant presented; it sounds like declaration of something already done? 'We therefore used new precipitation and vegetation satellite data that present full coverage of the spatial distribution in the study area. We combine. . .. . .'.? Why these data are classified as 'new'? The authors say that this HR satellite quasi-global rainfall dataset is available from 1981 (p4, ln32)?

ii. The authors agree and have reformulated the text. The aim of the study was reformulated to: "The objective of our paper is to present a methodology for assessing drought risk to mitigate its impacts on agriculture using observed gauge data and satellite based imagery data for the Bolivian Altiplano".

4. i. P3 Section 2 'Case Study Region and Data Availability. Again too many words not in the essence of the work Why such details about the population and cities in a scientific paper on drought are included? Do the readers really need from Table A1 or a map with the location of the stations will be enough and more informative?

ii. The section "Case Study Region and Data Availability", was changed to "Data description". The section was modified and shortened.

iii. Please see the section Changes in manuscript.

5. i. P5/ section 2.3 Why crop production and vegetation data in the section title are considered as two different items? Can you provide any finding about the reason for distinguish both? Is it possible to have crop without vegetation?

ii. There are two main reasons to use NDVI in addition to crop yield for the analysis. One is the spatial resolution of NDVI, that is higher than the available agricultural data during the study period. Crop yield data are available only at local scale (administrative division), NDVI is available at 0.08áţŠ. The second reason to use NDVI is the temporal resolution, NDVI data have a semi-monthly time resolution, allowing to analyze the

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monthly NDVI average with monthly precipitation total and the monthly temperature average. As discussed currently there are no studies for the Altiplano which relate satellite sourced imagery with agriculture risk, including possible associations with ENSO. The article tries to fill this gap.

iii. This explanation is now included in the manuscript.

6. i. P5/Ln 17 It is declared that "the Normalized Difference Vegetation Index (NDVI) was used in our study in order to relate climate, vegetation". Actually NDVI is still not used, this is expected to be done in the results section. The author should give proper credit to previous and other related work with clear indication of specific contribution in using NDVI here.

ii. The authors agree and the text was modified.

iii. The new text is: "The Normalized Difference Vegetation Index (NDVI) can be used to estimate the vegetation vigour (Ji and Peters, 2003) and crop phenology (Beck et al., 2006). NDVI was assembled from the Advanced Very High Resolution Radiometer (AVHRR) sensors by the Global Inventory Monitoring and Modelling System (GIMMS) at semi-monthly (15 days) time steps with a spatial resolution of 0.08áţŠ. NDVI 3g.v1 (third generation GIMMS NDVI from AVHRR sensors) data set spans from July 1981 to December 2015. Note, the NDVI is an index that presents a range of values from 0 to 1, bare soil values are closer to 0, while dense vegetation has values close to 1 (Holben, 1986). NDVI 3g.v1 GIMMS provides information to differentiate valid values from possible errors due to snow, cloud, and interpolation errors. These errors were eliminated from the dataset and where replaced with the nearest neighbour value. In our study we used the NDVI to simulate crop production".

7. i. P6/section 3.1. The procedure for validation satellite data using only qualitative 'Yes/No' evaluation is not relevant. For validation purposes of satellite product, rain quantities from the two sources of measurements should be compared, moreover that you are speaking that the 'accuracy' is tested (p.1/Ln 17). Also for the purposes of

drought assessment the rain quantity is the essential point.

ii. The procedure for validation of satellite data uses both qualitative and quantitative evaluation. To evaluate the satellite product, it was compared with gauged precipitation data. As described in the methods section: “For the quantitative statistics, mean error (ME) or bias, and root mean squared error (RMSE) were calculated based on Wilks (2006), and Nash Sutcliffe efficiency (NSE) coeïňČcient based on Nash and Sutcliffe (1970) was used as well. Spearman rank correlation was used to estimate the goodness of fit to observations, the bias to show the degree of over- or underestimation (Duan et al., 2015), the root mean square error (RMSE) to compute the average magnitude of the estimated errors (values closer to zero generally indicate smaller magnitude of error), and finally the Nash SutcliïňĂe EïňČciency coeïňČcient that evaluates the prediction accuracy compared to observations (1 corresponds to a perfect match between gauge observation and satellite-based estimate and zero indicates that the satellite estimations are as accurate as the mean of the observed data; negative values indicate that the observed mean is better than satellite-based estimate, see Nash and Sutcliffe (1970) for more details)”.

iii. We improved the description of the results obtained in the manuscript. However, we consider that the method used for the satellite validation analysis with a statistical approach is suitable to qualify the accuracy of the estimations, in which the spearman rank correlation, mean error, root mean squared error, and Nash Sutcliffe efficiency were computed.

8. i. P6, p.7 Not relevant titles of the section 3.2 and 3.3. please explain why crop yield and vegetation are two different things?

ii. The relationship between NDVI and crop field was analyzed to show the capability of NDVI for crop yield estimation. Crop yield is represented with the relation of the production (t) and the area (ha) and it is available at major administrative national level in the study area. And the Normalized Difference Vegetation Index (NDVI) can simulate the crop phenology (Beck et al., 2006). In contrast to the crop yield, NDVI can be related with the precipitation and temperature at a monthly time scale and with a spatial resolution of 0.08 degrees.

iii. This information is included in the manuscript.

9. i. P12 /ln7 The authors should specify which aspect of their work is a first attempt to relate agricultural drought in relation with ENSO? Not enough credit to previous works on this is given.

ii. The authors intend to improve the scientific understanding to reduce the risks of drought events on agriculture in association with the warm ENSO phase in regions were climate gauged observations are scare or uneven distributed. The spatial resolution of the satellite precipitation data and the NDVI permit to perform the analysis at the entire study area. NDVI and crop yield were compared, and the grids with correlations above 0.6 were selected, because they better estimate the crop yield. Afterwards, a linear regression between the selected NDVI grids and the climate variables were developed. The results show the regions were crop yield is more vulnerable to a reduction of precipitation. And a reduction of precipitation is shown due to warm ENSO phases in the study area. With this information, we could define in which areas are more vulnerable to lack of rain, and in consequence to a warm ENSO phase. Previous studies have found associations between ENSO and precipitation (e.g. Seiler et al., 2013; Garreaud, 2009; Vuille et al., 2000; Francou et al., 2004). Other authors have for example, studied ENSO-based seasonal forecasting (Lupo et al., 2017), and crop relation with climate variability (Garcia et al., 2007; Porter and Semenov, 2005). However, few studies have incorporated remote sensing data to relate drought events and ENSO (e.g. Liu and Juárez, 2001).

iii. This information is now included in the new text.

10. i. P12/Ln10 it is 0 a significant influence of precipitation on vegetation and crop yields in the region was identified'. Everywhere, for each region precipitation has in-

fluence on vegetation and crop yield. This cannot be considered as a result from this study.

ii. The authors agree and have reformulated the conclusion “a significant influence of precipitation on vegetation and crop yields in the region was identified”. It is obvious that precipitation has an effect on crop yield. The novelty of the study is to improve the drought risk management based on the association of ENSO and crop yield, by using satellite and gauged data.

11. i. Ln12 It is claimed by the authors ‘Our study provides valuable information for early warning systems, primarily by providing information of the relationship between crop production and vegetation, and subsequently a relation between vegetation and climatological parameters’. What would be the difference between crop production and vegetation if any, please precise terminology so the results to be evident.

ii. NDVI can estimate the crop production. The NDVI is an index, and therefore the values are from 0 to 1 [-], in contrast crop yield is the production (t) in relation of the area (ha). In this study the NDVI is used to simulate the crop production, to apply a regression with the climate variables.

iii. The “Conclusions” section was modified (please see the section Changes in manuscript).

12. i. There are a lot of references but scare information is used in convincing the results and discussion sections.

ii. The results and discussion sections were improved (please see the section Changes in manuscript).

13. i. The overall presentation is not well structured; there is no relevant balance between results -discussion sections and other parts. The readability of the text is not sufficient.

ii. Major modifications were included in the manuscript. All the sections of the

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manuscript were modified. The first section “Introduction” and the second section “Data Description” where shortened to the relevant information. The third section “Methods” was modified as well, a new analysis of the relationship of the NDVI and the crop yield was done. The section with major changes is “Results”, because we incorporated the new results of the relationship between NDVI and crop yield, and the new regression of NDVI and climate variables The discussion was also modified to suit with the new aim and findings. Finally the las section “Conclusions” were adapted to the new manuscript content.

iii. The new text is described in Changes in Manuscript.

Changes in manuscript

In general, there was an improvement in the manuscript redaction and structure. The title was modified to “Drought risk assessment for the Bolivian Altiplano agriculture and its association with El Niño Southern Oscillation”. The new objective of our paper is to present a methodology for assessing drought risk to mitigate its impacts on agriculture using observed gauge data and satellite based imagery data for the Bolivian Altiplano. The description of the modifications of the manuscript will be dived by sections: 1) Introduction, 2) Data Description, 3) Methods, 4) Results, 5) Discussion and, 6) Conclusion. The sections 1) Introduction and 2) Data Description where shortened to the relevant information. The section 3) Methods was modified as well, a new analysis of the relationship of the NDVI and the crop yield was done. The section with major changes is 4) Results, because we incorporated the new results of the relationship between NDVI and crop yield, and the new regression of NDVI and climate. Finally, the section 5) Discussion was also modified to suit with the new aim and findings, and 6) Conclusions” were adapted to the new manuscript content.

1. Introduction

Agricultural production is highly sensitive to weather extremes, including droughts and heat waves. Losses due to such extreme hazard events pose a significant challenge to

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farmers as well as governments worldwide (UNISDR, 2015). Worryingly, the scientific community predicts an amplification of these negative impacts due to future climate change (IPCC, 2013). Especially in developing countries as Bolivia, drought is as a major natural hazard. However, the impacts vary on a seasonal and annual timescale, on the hazard intensity, and the capacity to prevent and respond to droughts (UNISDR, 2009). Regarding the former, the El Niño Southern Oscillation (ENSO) plays an important role. ENSO triggers droughts in several regions around the world, driving losses in agricultural crops and increased food insecurity (Kogan and Guo, 2017).

Bolivia have experienced large socio-economic losses in the past due to droughts. Generally, agricultural productivity in the Bolivian Altiplano is low due to high susceptibility to the climate, poor soil conditions, and the mainly manual labour. Poor agricultural production is also associated with the ENSO climate phenomena (Buxton et al., 2013). Droughts are generally driven by the ENSO warm phases (Vicente-Serrano et al., 2015; Garreaud and Aceituno, 2001; Thompson et al., 1984). Most important rainfed crops in the region include quinoa and potato. The Sustainable Development Goals (SDGs) state that the priority areas for adaptation to climate change are water and agriculture. These in turn, are related to the largest climate hazards including floods, droughts, and higher temperatures (UN, 2016). Additionally, the implementation of early warning is fundamental for drought disaster risk management, proactive planning, and mitigation policy measures in vulnerable regions, including Latin American countries such as Bolivia (Verbist et al., 2016).

Various studies of the relationship between ENSO and precipitation were developed previously, and they show a negative relationship between ENSO warm phase (El Nino) and precipitation, meaning that El Nino periods have been linked with a decrease of precipitation (Vicente-Serrano et al., 2015; Garreaud and Aceituno, 2001; Thompson et al., 1984; Francou et al., 2004; Vuille et al., 2000; Vuille, 1999). Other authors have studied ENSO-based seasonal forecasting (Lupo et al., 2017), and crop relation with climate variability (Garcia et al., 2007; Porter and Semenov, 2005). On the other hand, previous research of the relationship between ENSO and crop production was developed at global scale (Iizumi et al., 2014) and in South America (Anderson et al., 2017). Moreover, previous studies have already proposed ENSO based crop management in South America (Ramirez-Rodrigues et al., 2014). However, few studies have incorporated remote sensing data to relate drought events and ENSO (e.g. Liu and Juárez, 2001), and they are not developed in the Altiplano. In consequence, there is a gap of a drought risk assessment for the Bolivian Altiplano agriculture and its association with El Niño Southern Oscillation, using observed gauge data and satellite based imagery data.

To lessen the long term impacts of these events, the national government has allocated a large budget for emergency operations to compensate part of the losses, which are usually evaluated in an ex-post approach. However, based on ENSO forecasting, an El Nino event can be predicted 1 to 7 months ahead (Tippett et al., 2012). For this time period it may be possible to implement ex-ante policies to reduce societal vulnerability to droughts, stressing preparedness, and improve risk management strategies. We are especially interested in how a risk based approach can be used to determine the potential need of resources as well as ways to determine hotspots where it is likely that these resources need to be distributed. A constraint to study drought occurrence is the uneven and scarce distribution of weather and crop related ground data in the region. We therefore use precipitation and vegetation satellite data that present full coverage of the spatial distribution in the study area. We combine this information with gauged precipitation, temperature, and crop yield data to enhance the knowledge and provide consistent results for climate and vegetation variability. Based on these observations, the objective of our paper is to present a methodology for assessing drought risk to mitigate its impacts on agriculture using observed gauged data and satellite based imagery data for the Bolivian Altiplano.

Our paper is organized as follows. Given the importance of data limitations in our case study region, we first introduce in section 2 the recently available datasets employed for our analysis. In section 3 we discuss the methods employed to (i) test the validity of the new datasets in our analysis, (ii) show how the relationship between climate and vegetation data was estimated, and (iii) how ENSO was incorporated in our analysis. After this, section 4 presents results and our proposed framework. Finally, section 5 ends with a conclusion, ways forward, and outlook to the future.

2. Data Description

The Bolivian Altiplano covers about 150,000 km2. It contains more than 70% of the total Altiplano surface area, the remaining percentage is located in southern Peru and northern Chile. La Paz, Oruro, and Potosi are the major administrative regions in the Bolivian Altiplano. The Altiplano has a pronounced southwest-northeast gradient (200–900 mm year−1) in annual precipitation with the wet season occurring from November to March (Garreaud et al., 2003). Over 60% of the annual precipitation occur during the summer months (DJF) in association with the South American Monsoon (SAM) (see Fig. A1).

2.1 Climate Variables: Precipitation and Temperature Data

Time series of observed monthly precipitation at 23 locations and mean, maximum, and minimum temperature at 15 locations from July 1981 to June 2016 were obtained from the National Service of Meteorology and Hydrology (SENAMHI; see Appendix Table A1). Initially, the available precipitation data sets included 65 gauges but only 23 were used since they have less than 10% of missing data. The data gaps were filled with the mean monthly value of the whole dataset to provide full time series. Outliers were identified by comparing with neighbouring monthly data. The inter-annual temperature at the 15 locations varied considerably between summer (DJFM) and winter (JJAS), including a larger variance for the minimum temperature (Fig. A2a). Regions close to the Lake Titicaca present lower inter-annual variability (Copacabana [10], Fig. A2b). In contrast, Uyuni [22] presents larger inter-annual oscillations (Fig. A2c). The precipitation gauges have an uneven spatial distribution and are mainly concentrated in the northern Bolivian Altiplano. To improve the spatial coverage of rainfall data, monthly quasi-rainfall time series from satellite data were included in our study. The Climate Hazards Group InfraRed Precipitation with station data (CHIRPS) quasi-global rainfall dataset was used. CHIRPS presents a 0.05° resolution satellite imagery and is a quasi-global rainfall dataset from 1981 to the near present with a satellite resolution of 0.05° (Funk et al., 2015). The information about CHIRPS is described in http://chg.geog.ucsb.edu/data/chirps/.

2.2 El Niño Southern Oscillation Data

The Oceanic Niño Index (ONI) is usually used to identify El Niño (warm) and La Niña (cool) years (http://www.cpc.ncep.noaa.gov/). ONI is the 3 month running mean of Extended Reconstructed Sea Surface Temperature (ERSST v5) anomalies in the El Niño 3.4 region. The El Niño 3.4 anomalies represent the average equatorial SSTs in the equatorial Pacific Ocean (5oN to 5oS latitude, and 120o to 170oW longitude). Five consecutive overlapping three month periods at or above +0.5°C anomaly represents warm events (El Niño), and at or below the -0.5 anomaly are cold (La Niña) events.

2.3 Crop Production and Vegetation Data

As indicated above, quinoa and potato are the main crops in the Bolivian Altiplano and still gaining importance. The quinoa growing season is from September to April and, for potato from October to March. Data for quinoa and potato yield were obtained from the National Institute of Statistics (INE) of Bolivia from July 1981 to June 2016 for La Paz, Oruro, and Potosi (Fig. 1). No crop yield data at local scale are available and this is a major limitation that needs to be addressed in the future. The annual datasets represent production (t) in relation of the area (ha) at regional level. Additionally, the Normalized Difference Vegetation Index (NDVI) can be used to estimate the vegetation vigour (Ji and Peters, 2003) and crop phenology (Beck et al., 2006). NDVI was assembled from the Advanced Very High Resolution Radiometer (AVHRR) sensors by the Global Inventory Monitoring and Modelling System (GIMMS) at semi-monthly

(15 days) time steps with a spatial resolution of 0.08áţŠ. NDVI 3g.v1 (third generation GIMMS NDVI from AVHRR sensors) data set spans from July 1981 to December 2015. Note, the NDVI is an index that presents a range of values from 0 to 1, bare soil values are closer to 0, while dense vegetation has values close to 1 (Holben, 1986). NDVI 3g.v1 GIMMS provides information to differentiate valid values from possible errors due to snow, cloud, and interpolation errors. These errors were eliminated from the dataset and where replaced with the nearest neighbour value. In our study we used the NDVI to simulate crop production.

3. Methods

3.1 NDVI simulation of crop yield

The maximum 15-days NDVI of March, April and May for every year was identified. Only the time from March to May was considered because this period represents the maximum phenological development of quinoa and potato crops. The maximum NDVI of each grid was compared to the annual crop yield at La Paz, Oruro, and Potosi. The NDVI grids and crop yield correlations larger than 0.6 (spearman correlation, $p = 0.001$) were considered as adequate for crop yield estimation, and only these grids were considered for further study. A similar approach was used by (Huang et al., 2014). Afterwards, a regression of the selected NDVI grids and the precipitation was developed. The satellite precipitation data was used for the regression. For this analysis, the NDVI grids were compared to the same spatial location of satellite precipitation data.

4. Results

4.1 Validation of Chirps satellite precipitation data

The mean annual gauged precipitation and CHIRPS satellite data product (Fig. R1) shows the relevance of the application of satellite data in the studied region. The RMSE and ME (Fig. R5) shows the locations where satellite data overestimates or underestimates the gauged precipitation. Generally, the precipitation is under/overestimated in a range of -10 to +10 mm per month [6] (Fig. R5b). However Charazani [6] present a large bias of 40.7 mm/month. As well, most of the stations present a RMSE between 15 to 30 mm/month, Charazani [6] had a RMSE of 58 mm/month

4.2 NDVI simulation of crop yield

Figure R6 presents the locations where NDVI simulates the crop yield with a correlation larger than 0.6 (spearman correlation, p = 0.001). The NDVI grids that better simulates the quinoa crop are shown in Fig. R6a, and the NDVI that better simulates the potato crop are shown in Fig. R6b. We can see that NDVI can simulate the proper production of the crop land area in La Paz, Oruro, and Potosi.

4.3 NDVI association with precipitation

Only the NDVI grids with larger correlation of 0.6 with crop yield were considered for the climate regression. The results for stepwise linear regression between NDVI and accumulated precipitation were statistically significant at the 0.01 level. The analysis was firstly applied with the NDVI that best simulates the quinoa yield and afterwards with the NDVI that best simulates the potato yield. In La Paz, the mean correlation coefficient resulting from the regression of the NDVI that best simulates the quinoa and accumulated precipitation is 0.7 in La Paz, and above 0.6 in Oruro and Potosi. The regression of the NDVI that best estimates the potato yield and the accumulated precipitation shows a mean correlation coefficient of 0.7 in La Paz, 0.6 in Oruro, and 0.5 in Potosi.

5. Discussion

We employed a satellite product dataset and tested it for accuracy as well as performance to similar (but with coarser resolution) datasets available for our region. Using this dataset, it was shown that during El Nino years the crop yield reduces, and as a consequence the socio-economic vulnerability of the farmers increases. Furthermore, it was found that NDVI can be related to crop yield and therefore, NDVI could be used to target specific hot spots depending on NDVIs availability at a local scale. As a consequence, ENSO forecasts as well as possible magnitudes of crop deficits could be established by the authorities, including identification of possible hotspots of crop deficits during the growing season. Our approach therefore, can not only help for determining the magnitude of assistance needed for farmers at the local level but also enable a pro-active approach to disaster risk management against droughts. This may include not only economic related instruments such as insurance but also risk reduction instruments such as irrigation needs. In fact, early warning based financing is gaining increasing attraction in some real world settings as it has several advantages. However, it should be acknowledged that large challenges still remains (French and Mechler, 2017). Drought severity could be measured via shifts from normal conditions of climatic parameters such as precipitation. As in our case, we not only provided shifts but the difference in risk for El Nino and neutral/moderate years. However, one of the main challenges of drought risk analysis is data-scarcity, e.g., low density or not evenly distributed stations for hydro-meteorological data networks, poor data quality due to missing data, and restricted use of data between government agencies or other institutions. As it was shown here, ENSO warm phase related characteristics are especially important in the context of extreme drought events and should therefore be incorporated within early warning systems as standard practice. Despite these challenges for development of drought risk assessment, applications have been successful in the past. There are numerous cases in many countries around the globe. As in our case, particularly in the mid-latitudes weather patterns are strongly influenced by ENSO. Monitoring and predicting ENSO can therefore significantly contribute to reduce the risk of disasters.

6. Conclusions

This study is a first attempt to provide an agricultural drought risk assessment in relation to the ENSO phenomenon for the Bolivian Altiplano. Given the large differences in risk, and corresponding strategies to lessen the impacts could be implemented in the

Bolivian Altiplano. In doing so, we introduced and tested a satellite product that was used for estimating crop risk. The ENSO impact on crop production was evaluated by studying the relation of crop yield, vegetation and climate variables, considering that El Nino generally drives a drought event. Our study provides valuable information for drought risk reduction, primarily by providing information of the hotspots where crop yield is more affected for droughts. Moreover, we showed that ENSO phases are strongly related to crop yield, and with this information the prediction of ENSO could be used to define risks in terms of decrease in crop yields in the studied region. While overall good fit among climate, ENSO, and crop yield variables were found, it is important to consider other parameters, such as evapotranspiration and soil moisture in improved models. With such information also agricultural models could be set up and risk management plans with better accuracy determined.

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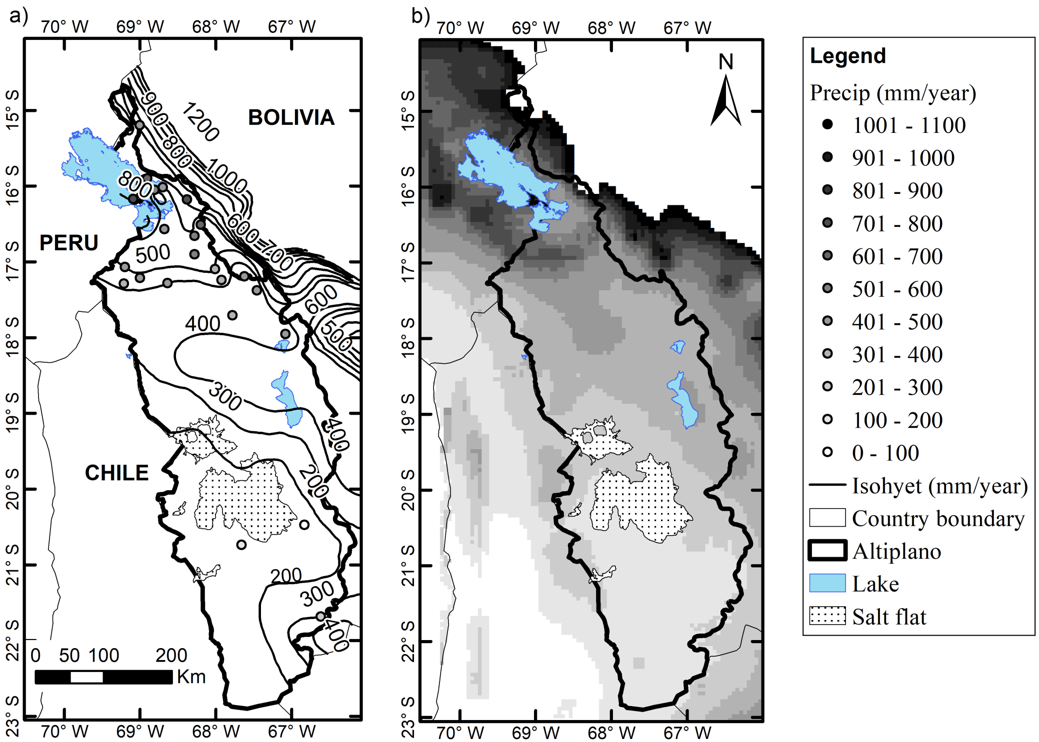

Fig. 1. R1. Map of mean annual precipitation (July 1981- June 2016) of (a) gauged data* and isohyets** and (b) CHIRPS satellite product. Source: *SENAMHI, **Ministry of Rural Development and Land of Bolivia.

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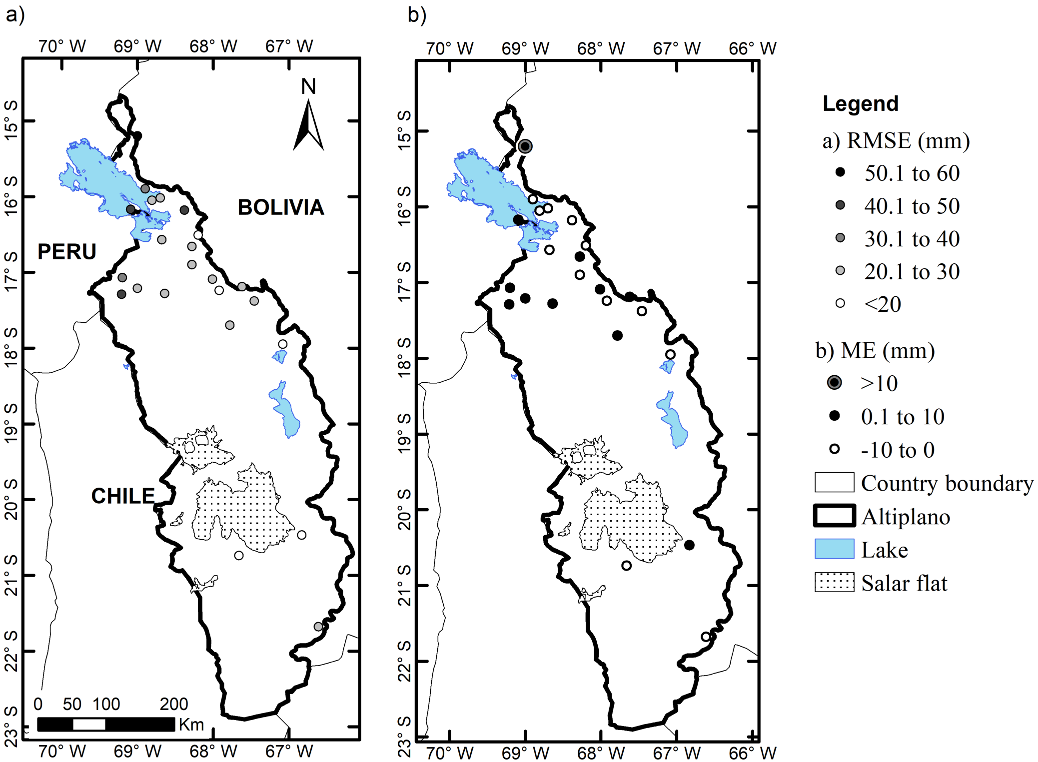

Fig. 2. R5. Map of the Altiplano showing (a) RMSE and (b) ME at the 23 studied locations from July 1981 to June 2016.

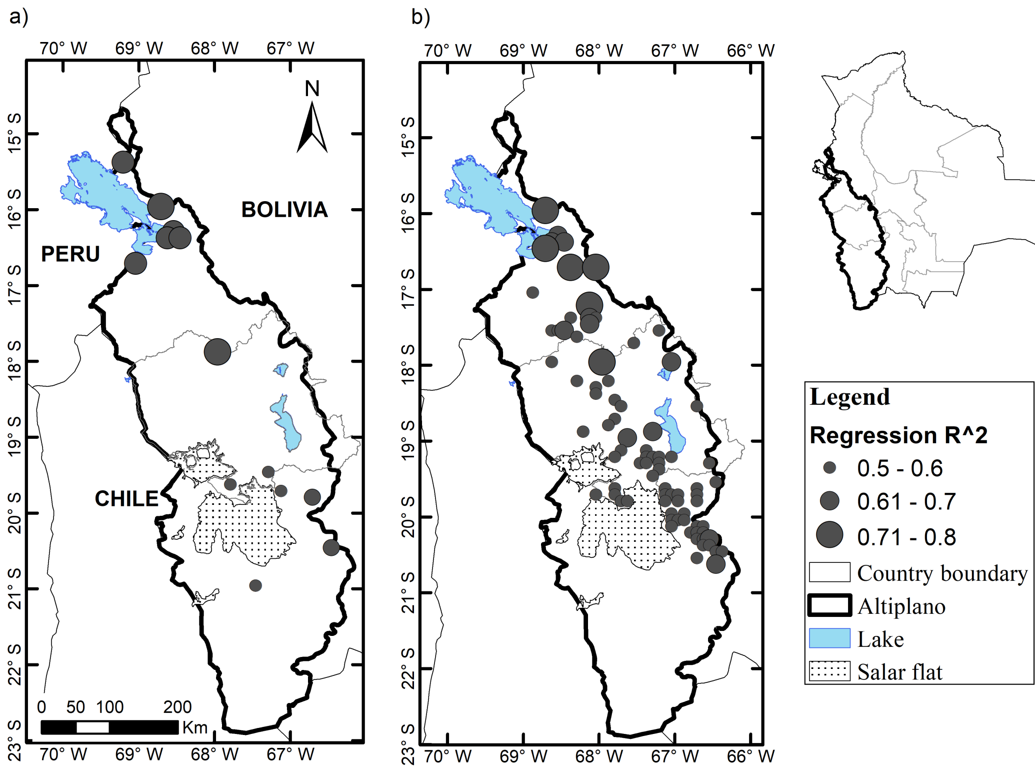

Fig. 3. R6. Correlation coefficient (R2) of the regression of NDVI as the predictand, and precipitation as the predictor for the grids where NDVI better estimate the (a) quinoa and (b) potato yield.

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