Available online at www.sciencedirect.com
ScienceDirect
Agricultural and Forest Meteorology 139 (2006) 399–412
AGRICULTURAL AND FOREST METEOROLOGY
www.elsevier.com/locate/agrformet

Agro-climatic suitability mapping for crop production in the Bolivian Altiplano: A case study for quinoa

Sam Geerts [a,*], Dirk Raes [a], Magali Garcia [b], Carmen Del Castillo [b], Wouter Buytaert [a]

[a] K.U.Leuven University, Division of Soil and Water Management, Celestijnenlaan 200 E, B-3001 Leuven, Belgium
[b] Universidad Mayor de San Andres, Facultad de Agronomia, La Paz, Bolivia

Received 1 March 2006; received in revised form 25 August 2006; accepted 25 August 2006

Abstract

An agro-climatic suitability library for crop production was generated by using climatic data sets from 20 to 33 years for 41 meteorological stations in the Bolivian Altiplano. Four agro-climatic indicators for the region were obtained by validated calculation procedures. The reference evapotranspiration, the length of the rainy season, the severity of intra-seasonal dry spells and the monthly frost risks were determined for each of the stations. To get a geographical coverage, the point data were subsequently entered in a GIS environment and interpolated using ordinary kriging, with or without incorporating anisotropy. The presented case study focuses on quinoa (*Chenopodium quinoa* Willd.), an important crop in the region that is cultivated during the short and irregular rainfall season and that is well adapted to the frequent occurrence of drought and frost. The GIS library was used to mark zones where deficit irrigation could improve quinoa production. With a data query, zones were delimited where the irrigation can be useful to stretch the length of the growing season beyond the limits of the rainy season and/or to mitigate intra-seasonal dry spells. Determined net irrigation requirements were used to assess the vulnerability of the delineated zones. Two regions with a high vulnerability, a severe drought risk and an acceptable frost risk are the eastern region of the Altiplano and the inter-salt depression region in the south. Together, they account for around one-third of the Altiplano area. In 1 year out of 2, irrigation in these regions can strongly improve crop production. The use of irrigation in other regions of the Altiplano will be less beneficial either because the irrigation requirements are low (region around Lake Titicaca), or because the frost risk is too high (the dry west, the south-west, and the region in between Lake Poopo and the Uyuni salt depression). Apart from the presented application, a general view on the climatic system of the Altiplano could be deduced from the library.

The proposed routine in this study yielded a straightforward method to deal with large sets of detailed climatic information and to link them with practical agricultural advice. By redefining query limits and incorporating other data, the GIS library can be used for impact assessments of other agricultural practices and for studying the effects of climate change and of the El Niño Southern Oscillation on quinoa production in the delineated zones.

Keywords: Quinoa; Agro-climatology; Suitability mapping; Deficit irrigation; Bolivia; Altiplano

1. Introduction

The Bolivian Altiplano is a high plateau of about 200,000 km^2 situated for 75% between 3600 and 4300 m a.s.l. It ranges from Lake Titicaca in the north to the Uyuni salt depression (Salar de Uyuni) in the south and is bounded to the west and east by mountain chains (the Andean Cordillera Occidental and Oriental). Notwithstanding the extreme temperatures, a short and irregular rainfall season and unfavorable soil conditions, the Altiplano is a very important agricultural zone

* Corresponding author. Tel.: +32 16 32 97 54; fax: +32 16 32 97 60.
E-mail address: sam.geerts@biw.kuleuven.be (S. Geerts).

0168-1923/$ – see front matter
doi:10.1016/j.agrformet.2006.08.018

Nomenclature

AI	aridity index
AI_{is}	intra-seasonal aridity index
E_0	reference evapotranspiration
GIS	geographical information system
IDM	intra-seasonal drought mitigation
I_n	net irrigation requirements
ITCZ	inter-tropical convergence zone
K_c	crop coefficient
LRS	length of the rainy season
MBE	mean bias error
P	precipitation
PE	probability of exceedance
RMSE	root mean squared error
$S.E._g$	geographical standard error
SGS	stretching of the growing season beyond the limits of the rainy season
SV	semi-variogram
TAW	totally available soil water
T_{dew}	dewpoint temperature
T_{max}	maximum temperature
T_{min}	minimum temperature

in Bolivia. It is home to over a quarter of the rural population of the country (Vacher, 1998).

The planning and management of sustainable methods for drought mitigation and production increase require detailed agro-climatic information that is summarized in a conceivable way (Hoogenboom, 2000; Smith, 2000). In this paper, a GIS-based suitability mapping for crop production in the Bolivian Altiplano is performed. As a case study it focuses on quinoa production. The pseudo cereal quinoa (*Chenopodium quinoa* Willd.) is a traditional Andean crop with high nutritional value that can grow under unfavorable soil and climatic conditions (Jacobsen and Mujica, 2001). Quinoa is produced on 37,000 ha in the Bolivian Altiplano (Barrientos and Jacobsen, 2004). It is an important economic activity in the region.

Although quinoa is a suitable crop, the average yield over the past 10 years was only 0.6 Mg ha^{-1} (INE, 2003). Droughts, low temperatures, soil salinity and low input farming are the main reasons for the relatively low yields for rainfed quinoa. Given the scarcity of water resources in the region, full irrigation is not an option. Deficit irrigation however could reduce the problem of droughts during the optimal sowing period and crop sensitive stages. Deficit irrigation (English, 1990; Pereira et al., 2002) aims at obtaining maximum water productivity and at stabilizing yields rather than at obtaining maximum yields (Zhang and Oweis, 1999). Garcia (2003) indicated that deficit irrigation would indeed be an option to significantly increase the yield of quinoa in the region and to stabilize it at a sustainable level of 65% of its maximum yield.

Different meteorological indicators that determine the region's suitability for crop production are studied with a specific focus on quinoa. The following four indicators were considered: (i) reference evapotranspiration (E_0), (ii) the length of the rainy season (LRS), (iii) intra-season dry spells and (iv) frost risk. The E_0 expresses the evaporative demand of the atmosphere independently of crop type, crop development and management practices (Allen et al., 1998). The LRS strongly determines the success or failure of rainfed crops. Because rainfall in the Altiplano is likely to occur in delimited small episodes of rain separated by periods of drought (Garreaud et al., 2003), a study of intra-seasonal dry spells is essential (Fox and Rockström, 2000). Next to drought, frost is one of the major growth limiting factors in the Altiplano (Carrasco et al., 1997; Hijmans, 1999; François et al., 1999; Jacobsen et al., 2003). The net irrigation water requirement (I_n), with which the importance of the irrigation introduction can be assessed, is determined for quinoa in the different locations of the Altiplano.

In this study, a procedure is elaborated to obtain a GIS library with a compressed summary of the important agro-climatic information for the production of quinoa in the Bolivian Altiplano. Within this library, data queries can be performed. As an example, regions are marked where deficit irrigation of quinoa might be considered to improve crop production, with frost risk as a restrictive factor and irrigation water requirement as a vulnerability index. Knowing the common varieties and production systems of quinoa in the region, this paper gives guidelines where research on, and (micro-) investment in deficit irrigation for quinoa might be valuable.

2. Materials and methods

2.1. Derived climatic indicators

Climatic data from 41 climatic stations from the 3 departments of the Altiplano were used in the analysis. Daily rainfall and maximum and minimum air temperature were obtained from Servicio Nacional de Meteorologia y Hidrologia (SENAMHI). Additional monthly absolute minimum and maximum temperature data were provided by Hijmans et al. (2003) for those