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Suitability evaluation system for the production and sourcing of agricultural commodities

Isabel Jaisli*, Patrick Laube, Sonja Trachsel, Pascal Ochsner, Sarah Schuhmacher

Institute of Natural Resource Sciences, Zurich University of Applied Sciences, Waedenswil, Switzerland

ABSTRACT

This article presents CONSUS (Connecting for Sustainable Sourcing), a modular GIS-based decision-support system for producing and sourcing agricultural commodities. The system extends the classic FAO land evaluation approaches in three specific dimensions: (i) the sustainability dimension: the extended suitability analysis reaches beyond purely biophysical suitability and integrates ecological, economic and social suitability; (ii) the value chain dimension: the focus of suitability analysis includes further upstream activities relevant for product trading; (iii) the spatio-temporal dimension: the inclusion of an adaptive global crop cycle model and scale-specific suitability modules allow for multi-scale suitability evaluation that considers cropping seasons; The system was implemented as a flexible tool set, featuring knowledge databases, GIS toolboxes, and supporting data processing modules. CONSUS emerged from a series of third party funded applied research projects. Two of these serve in this article as case studies illustrating the capabilities of the system: one global case study on the sourcing of hazelnuts, and one regional case study on suitability of soybean production in Rwanda.

1. Introduction

The reality of the food business from production to trade and consumption currently faces enormous changes. Increasing pressure on land, growing populations, changing environmental conditions due to climate change, increasing global trade, and changing food patterns are calling for new strategies and fast adaptations in the agricultural market. The identification of suitable production opportunities under the changing conditions is becoming an increasingly important but complex task for both farmers and agribusinesses. The need for land use planning due to changing needs and pressures, as well as increasing competition between different uses for the same land, led to the development of the ‘Framework for land evaluation’ (FAO, 1976). The method describes the process of matching crop requirements with land qualities to identify the suitability of production at a given location. A key element of the method is the classification of land suitability, which is defined as the land’s fitness for a certain crop or use.

Since its first description land evaluation has been applied in a variety of studies (Alabi et al., 2012; Verdoodt and Van Ranst, 2006; Zolekar and Bhagat, 2015) and has been further developed to account for changing needs as well as benefiting from advancements in spatial data availability and computing power (Elsheikh et al., 2013; FAO, 2007; Rossiter, 1996). New and increasingly accessible information sources, capturing the biophysical but crucially also the socio-economic properties of potential production sites, offer previously unseen opportunities for inclusive decision support systems for agricultural production and sourcing. Geographic Information Systems (GIS) combined with database technology offer an efficient and effective way of integrating the vast and heterogeneous data sources required to cover the multiple information dimensions included in current interpretations of the FAO framework. This article builds upon the theory of land evaluation and suitability assessment, as well as previous work on their implementation in software applications in GIS and spatial-decision support systems (SDSS).

1.1. Land suitability

As initially pointed out by the FAO (1976) and later echoed by the same organization (FAO, 2007) biophysical and socio-economic factors are both crucial in defining suitable and sustainable agricultural land use. Thus, on the one hand, the land evaluation system proposed in this article includes **biophysical factors** such as climate, landscape and soil. An important step forward in biophysical land evaluation was contributed by Sys et al. (1991), providing alternative methodologies for the matching of multiple land qualities and their respective crop requirements as well as a comprehensive catalogue of specific crop requirements. The majority of land evaluation studies are limited to the assessment of biophysical factors, due to the availability of data as well

* Corresponding author.
E-mail address: jais@zhaw.ch (I. Jaisli).

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as their direct and predictable effect on crop productivity.

On the other hand **socio-economic factors** are also important to include in a land evaluation system, as the sustainability of the production of a crop depends on its compatibility with an existing farming system (Dal Belo Leite et al., 2015). The compatibility of a farming system with new land use depends on economic, political, legal, and cultural circumstances (Mandryk et al., 2015), on prevailing risks and opportunities farms are facing (Heumann et al., 2013), and on their endowment with different livelihood assets, such as human, social, financial, physical and natural capital (Nijbroek and Andelman, 2015; Pretty, 2008). Thus, a wide range of factors – on the global, regional and local levels – influence the socio-economic suitability of the production of a certain crop.

Several studies have shown that the integration of socio-economic factors into land evaluation is crucial because biophysical and socio-economic suitability can differ (He et al., 2013), and sustainable agricultural production depends on the suitability of both aspects. Land evaluation studies offering broader and more detailed socio-economic information provide decision-makers with a better basis for planning (Alabi et al., 2012). So far, suitability evaluations including socio-economic factors have been applied on the regional or local level (e.g. Alabi et al., 2012; Ayorinde et al., 2015). But from a global sustainable sourcing perspective, land evaluation including both socio-economic as well as biophysical site characteristics is needed. The insights gained on the global scale can then be sharpened in a more detailed land evaluation on the regional level using regional data.

1.2. GIS-based multi-criteria evaluation and spatial decision support systems in agriculture

Geographic information systems (GIS) are an established tool for integrating heterogeneous spatial information through the metaphor of space, or more precisely through a shared geographic reference system (Longley et al., 2011; Worboys and Duckham, 2004). Land evaluation has been a signature GIS application for decades (Chen et al., 2010), and has been applied in a multitude of academic and applied research areas. The typical procedure of choice for formalizing spatial decision problems is the so-called multi-criteria evaluation method (Carver, 1991). Multi-criteria evaluation (MCE) operationalizes a set of suitability criteria through appropriate spatial variables and combines those variables into a spatially explicit suitability assessment, in the most simple case a suitability map (Malczewski, 2006, 1999) or in more complex spatial decision support systems, SDSS (Mendas and Delali, 2012).

Since its peak decade around 2000, MCE has seen a constant stream of applied suitability studies in agricultural applications. Many of them are based on the FAO framework, with minor to major adjustments accounting for technological advancements and improved data sources. Recent methodological progress includes sensitivity studies and the inclusion of expert systems (Elsheikh et al., 2013), a significant increase in the breadth of considered criteria (Mendas and Delali, 2012), as well as the integration of previously unavailable input data through the use of remote sensing, e.g. soil moisture and soil depth data (Zolekar and Bhagat, 2015). Multi-criteria suitability evaluation has furthermore proved to be an application field for the conceptually elegant but in practice rather complex fuzzy set theory, allowing for gradual memberships instead of mere discrete suitability class boundaries (Elsheikh et al., 2013; Qiu et al., 2014; Sharififar et al., 2016).

Clearly, technological progress and better data sources have lifted classic land evaluation to a new level. However, most studies still focus on the biophysical aspects of the sourcing problem and neglect the equally important socio-economic properties of the targeted areas. Furthermore, most GIS-based SDSSs for agricultural production are tailored to very specific regional application scenarios, resulting in tools with limited transfer potential to other areas or even other scales and which mostly neglect limitations that become relevant in the trading and transporting of goods.

1.3. Scope and objectives

The main focus of this research project is to develop a flexible tool for assessing the spatially explicit production and sourcing potentials of crops, considering not only the biophysical suitability of potential sites but also socio-economic suitability aspects and considerations of environmental protection. By including not only production criteria, but also trade and compliance issues, CONSUS goes beyond the mere identification of production opportunities and considers limitations within the entire supply chain. In detail, the contributions of this article are threefold:

- Section 2 presents our extension of the FAO suitability framework, adopting a holistic suitability perspective covering both biophysical and socio-economic suitabilities.
- Section 3 describes a flexible tool set implementing the suitability evaluation process, linking GIS-workflows in toolboxes to knowledge sources developed and managed in databases.
- Section 4 puts the concept and its implementation to the test through two application case studies covering both the global and the regional scale: a search for suitable sites for hazelnuts (*Corylus avellana* L.) worldwide and for soybeans (*Glycine max* L. Merrill.) in Rwanda.

2. The CONSUS suitability model

CONSUS is designed as a decision support system for agribusinesses and for rural developments and is implemented in a GIS. It is designed to evaluate the suitability and sustainability of (crop) production and sourcing opportunities. Current land use, biophysical criteria, such as soil and climate, and other factors influencing trade and business compliance are considered, as well as agricultural systems and other socio-economic conditions. Results help identify suitable sites for selected crops and existing restraints in production, as well as the overall sustainability impacts.

Through its design as a flexible multi-modular and multi-scale sequential framework, CONSUS allows for application in a variety of contexts and scales. The overall model contains five core modules (Fig. 1) to assess several suitability aspects of crop production at, and sourcing from selected sites. On the one hand CONSUS examines the suitability of a certain crop by matching biophysical site characteristics with crop requirements. On the other hand, CONSUS integrates business and compliance perspectives with land use and infrastructure preliminaries, with the aim of assessing the socio-economic suitability of crops under consideration. The selection of modules used in a specific case depends on the case-specific questions, data availability, and project scale. When searching globally for suitable areas for a certain crop, coarse global data sets can be used. When, by contrast, the focus is narrowed down to finding specific production sites in a given country, regional or even local data with much finer granularities can be used.

2.1. Suitability evaluation process

The suitability assessment in CONSUS is based on the theory of land evaluation (FAO, 2007, 1976; Sys et al., 1991). It is built on the core element of matching crop requirements with site qualities to assess the land's fitness for a selected crop. This general approach is used in both the biophysical and socio-economic assessment of crop suitability, with adaptations explained in Sections 2.2 and 2.3.

The suitability evaluation in CONSUS consists of the following four steps (Fig. 1):

(1) Niche description: The description of crop requirements is based on the socio-environmental niche concept (Heumann et al., 2013; Ojiem et al., 2006). Niche in this context describes the region as a