Ecological Modelling 363 (2017) 31–47

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Research paper

Spatially explicit modelling of agricultural dynamics in semi-arid environments

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ARTICLE INFO

Article history:
Received 9 May 2017
Received in revised form 3 August 2017
Accepted 29 August 2017
Available online 5 September 2017

Keywords:
Agricultural detection and classification
Agricultural expansion
Agent-based modelling
Land-use land-cover changes
Water resource management
Decision support system

ABSTRACT

This paper describes a software package called Spatially Explicit Agricultural Dynamics (SEAD), which investigates agricultural spatial and temporal land-use changes. SEAD is an agent-based model whose rules are set to mimic the human decision making processes regarding agricultural land expansion. Model calibration is based on remotely sensed data. Detection of agricultural lands was executed using intra- and inter-annual Landsat images, with an overall accuracy of 86%. An analysis regarding the correlation of agricultural spread with water availability, irrigation infrastructure, road infrastructure, soil type, and geographical variables was conducted. These data, along with interviews with agricultural experts examining farmers' decision-making processes, were translated into rules that were used to model agricultural expansion. The SEAD results show that agricultural expansion in the north-western Negev (Israel) is highly dependent on water availability, which in turn is sensitive to forecasted climate change scenarios. While the spatial expansion patterns are mostly influenced by irrigation and road infrastructure positioning and placement, they vary in their infrastructural costs and agricultural settlement clustering and connectivity, thus affecting landscape fragmentation, travel time, and social/ecological connectivity. SEAD, being highly encapsulated and object-oriented in nature, can be reused in different settings.

1. Introduction

One of human beings' most vital needs is a stable supply of food and water. Agriculture is the world's largest freshwater user, impacting the water cycle especially in arid and semi-arid regions, through the diversion of surface water and the extraction of groundwater. This is exacerbated by increases in the standard of living, and crop yield reductions resulting from land overuse and degradation (Nellemann, 2009). In order to provide the agricultural sector with the appropriate amount of water that will guarantee its sustainability, it is important to understand the rules that govern agricultural land-use land-cover change (LULCC). This can be achieved by investigating past dynamics in agricultural lands, connecting these changes to the drivers and extrapolating future change according to forecasted future reality. Remote sensing (RS) is a first-choice tool for analyzing historical land-use dynamics.

Historically, agricultural output increases were achieved mainly by increasing the cultivated area, since the "green revolution" and markedly since the 1960s, agricultural yield intensification has propelled agricultural production per cultivated unit area, thus promoting world food production while curbing agricultural expansion (Lambin et al., 2003). However, as some research show, agricultural intensification cannot fully compensate for the growth in demand, and there are ample examples for agricultural expansion in areas that were previously untouched natural habitats, such as forests, grasslands, and other natural vegetation areas (Brink and Eva, 2009; Lambin et al., 2003; Meyfroidt et al., 2013; Teferi et al., 2013). Using global agricultural statistics data can aid in revealing the intensification-land sparing causal chain. The overall results show that over the last four decades, there has been a global increase in agricultural cultivated areas, rather than land sparing (Rudel et al., 2009).

The aim of this work is to understand spatial and temporal land-use changes in agricultural lands by examining the human decision-making processes and the physical environment's changes that ensue in response. This is done by using RS technology and Agent Based (AB) and Cellular Automata (CA) techniques. In particular, it examines whether changes in the amounts and distribution of water available for agricultural use and other factors, such as climate, geographical, pedological, and topographical properties, population growth, policies, and infrastructure (the road system, irrigation piping), have affected the spread of agricultural lands

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http://dx.doi.org/10.1016/j.ecolmodel.2017.08.025
0304-3800/

into rural frontier areas within the semi-arid to arid region of the north-western Negev Desert, Israel.

AB and CA modelling approaches have been extensively used to describe LULCC, with a major focus on the dynamics of human settlement patterns and urbanization processes (Batty, 1997; Benenson and Torrens, 2004; Clarke et al., 1997; Portugali et al., 1994; Sanders et al., 1997; Torrens, 2003). Less attention has been paid to the dynamics of the spatial expansion of agricultural land.

Berger (2001) developed a spatially explicit multi-agent model that assesses individual farm-households innovation adoption choices. Schreinemachers et al. (2009) studied the diffusion of greenhouse agriculture within the farm household level, applying econometrics and AB modelling. Similar work was done by Schreinemachers and Berger (2011) introducing the MP-MAS model simulating an agricultural farm decision-making system, in order to examine how market dynamics, economic constraints, technology and environmental changes and policy interventions affect heterogeneous farm households. Happe et al. (2006) constructed the AgriPoliS AB agricultural land-use model examining how policy changes cause and affect structural changes using empirical data on individual farms. The model of Bert et al. (2011) is similar to the AgriPoliS model and focuses on agricultural land tenure, interactions between big/small farms, and preferred crop type.

Our model, SEAD (spatially explicit agricultural dynamics, available on Github – see "software availability" section), is similar to the abovementioned agricultural land-use models by using: the cellular landscape (elemental cell representing land-use land-cover (LULC)), parcel construction, and farmer agent cultivation decision-making processes. However, whereas the focus in the abovementioned models is on the individual farm level, the focus of SEAD is on the regional level, to examine and forecast macro-changes in the spatial spread of agricultural fields in semi-arid to arid regions, where water is a limited resource. Furthermore, the purpose of our model is to simulate agricultural expansion, whereas other agent-based models only deal with this issue implicitly. We hypothesize that a regional approach, combined with the individual farm approach, is more suitable than the individual farm approach, to better describe and examine agricultural spread. Our model employs modelling of decision-making at multiple scales (individual and agency) introducing both the farmer and a higher level of decision makers (the national-planning-committee), which the other models usually lack. Another unique aspect of our model is that it is calibrated using RS technology to structure and tune the rules of agricultural spread that are later used in an AB and CA modelling framework. Settlements' zoning is an emergent process adhering to the set rules.

In order to examine the spatial and temporal dynamics of agricultural lands, one must first be able to differentiate between imagery depicting agricultural lands and other land-use types. According to the amount of land that is used for agricultural production, it is possible to estimate crop yield and agricultural water demand. Using RS technology, one can look into the past and examine the LULCC dynamics of agricultural lands by comparing images from different periods and applying a change detection technique on the detected agricultural land.

While detection of agricultural lands has been studied by several groups of researchers, only a few have focused on the rapidly changing arid and semi-arid regions. In general, in most semi-arid to arid regions, the precipitation and temperature regimes are out of phase (Bounoua et al., 2009). Precipitation occurs during the winter and early spring when cold temperatures reduce vegetation growth, while vegetation growth is inhibited by the lack of precipitation during the late spring and summer. The phenology of dense, green agricultural lands during summertime creates a clear contrast with the precipitation and temperature signals and makes detection possible. However, abandoned agricultural fields kept fallow that might be re-cultivated in future seasons cannot be easily discriminated from non-cultivated land using only phenological classification techniques (Prishchepov et al., 2012), and thus require a collection of multiple intra- and inter-annual images.

2. Methods

2.1. Study area

The current study is focused in the north-western Negev desert area, Israel, (Fig. 1**A,B**), characterized by a semi-arid to arid climate where average annual precipitation gradually decreases from 350 mm in the north to 150 mm in the south (Evenari et al., 1982). The ratio of precipitation to potential evapotranspiration (P/PET) is about 0.2 (Fig. 1**C**) (Safriel, 2014). This aridity index value is the threshold between semi-arid and arid environments (Fig. 1**C**), that corresponds to the 200-mm rainfall isohyet in the study area, and considered to be the border between rainfed (non-irrigated) and irrigated agriculture (Evenari et al., 1982; Gutterman, 2008). The total size of the study area, including open space for agricultural expansion, is 2126 square km (212,670 ha), out of which 64% is loess, 16% is sandy soil, 5% is brown-red silty sandstone soil, and 15% comprises other soil textures that are less suitable for agriculture.

Israel has insufficient natural water resources to support its growing population, and vast agricultural cultivation within its borders. This lack of water has instigated creative thinking and policy changes for alternative water sources. The two main innovative techniques with which Israel is currently overcoming water shortages are wastewater reclamation systems and desalination facilities (Dreizin et al., 2008; Friedler, 2001; Icekson-Tal et al., 2003; Wintgens et al., 2008). There are two major water sources for the north-western Negev: (1) the "Yarkon-Negev" freshwater pipeline that is used for agricultural and domestic water supply; and (2) Israel's biggest reclamation system, called the Shafdan Project (wastewater carrier), delivering reclaimed domestic and industrial wastewater from the densely populated Tel Aviv metropolis south to the Negev with a special dedicated pipeline (Fig. 2) for unrestricted agricultural usage (Icekson-Tal et al., 2003; Wintgens et al., 2008). The wastewater carrier was added in order to supplement the "Yarkon-Negev" pipeline. Since the inauguration of the wastewater carrier, the amount of fresh water from the Yarkon-Negev pipeline to the north-western Negev has dropped (Fig. 2**)** and been rerouted to mitigate water shortages elsewhere in Israel.

Climate change, population growth, and political consequences have also had significant effects on agricultural land-use and water demand in the north-western Negev. Tremendous changes have occurred since the 1970s in Israel. Demand for food supplies have increased, leading to the vast expansion of agricultural land in the peripheral areas of the state, including the north-western Negev. Furthermore, following the peace agreement with Egypt, the government relocated agricultural settlements from the Sinai Peninsula to the north-western Negev in 1982. Another wave of relocating agricultural settlements within the northern Negev happened after the evacuation of Israeli settlements from the Gaza Strip in 2005.

2.2. Research overview

Looking at the historical remotely sensed images of the study area for the past 40 years, focusing on the agricultural spatial dynamics, along with water availability data, yielded insights regarding the pattern of agricultural spread, and irrigation and road