Ecological Modelling 306 (2015) 326–333

Contents lists available at ScienceDirect

Ecological Modelling

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

An open-source spatio-dynamic wetland model of plant community responses to hydrological pressures

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ARTICLE INFO

Article history:
Available online 5 December 2014

Keywords:
Semiarid wetlands
Remote sensing
Irrigated agriculture
Plant communities
Spatio-dynamic modelling
Open source software

ABSTRACT

Semiarid Mediterranean saline wetlands are semi-terrestrial ecosystems, which yearly undergo dry periods of several months, and shelter a rich, endemic and sensitive biota. In the last decades, the expansion of agricultural irrigated areas in semiarid Mediterranean catchments has led to altered inputs of water and nutrients to lowland wetlands. Hydrological alterations have affected characteristic plant communities, resulting in the replacement of valuable halophilic salt marsh and salt steppe plant communities by more generalist and opportunistic taxa, such as *Phragmites australis* (reed beds). A spatio-dynamic model and library were developed that aimed to explain the spatial distribution of three characteristic wetland plant communities in a semiarid Mediterranean wetland site in response to hydrological pressures from the catchment. Wetland plant communities and watershed irrigated agricultural areas were mapped by means of remote sensing at several dates between 1984 and 2008 and were partly used as forcing inputs and validation data. A dynamic model was initially developed using Stella software and then converted into R language by means of the StellaR software. Spatial dimension was added including neighbourhood and spatial flow algorithms representing the dispersion of plant communities. The conversion between plant communities was caused by the increase in water inflows from the watershed, mediated by spatial parameters, such as the distance to ephemeral rivers and the flow accumulation map within the wetland site. Results of the model were in agreement with remote sensing data, showing that in 2008 salt steppe had lost a half of its original area, whereas salt marsh and reed beds expanded extensively. The model developed in this study is available online as an R library, including all necessary input data sets and maps and documentation to run it. The model library offers a flexible tool that suits the needs of both advanced modellers and neophytes. Free and open source software and online code sharing repositories are proposed as modelling tools for future research.

1. Introduction

Semiarid Mediterranean saline wetlands are unique and endangered ecosystems which shelter high biodiversity. These are highly complex ecosystems in which the distribution of plant communities is mainly determined by spatial environmental gradients of water availability and salinity (Álvarez Rogel et al., 2001, 2006). During the last decades, land use changes in Murcia province and the associated hydrological changes at watershed scale have caused a rise in water tables of aquifers and have increased the levels of groundwater, flooding periods and soil water content in the wetlands (Álvarez Rogel et al., 2007). Characteristic plant communities, especially salt steppe, are negatively affected by these pressures to the wetland, while opportunistic invasive species, such as *Phragmites australis* (reed beds), are favoured (Chambers et al., 1999; Burdick and Konisky, 2003; Maheu-giroux and Blois, 2005). These changes are relevant from a biodiversity and conservation perspective since salt steppe is considered to be of priority interest

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http://dx.doi.org/10.1016/j.ecolmodel.2014.11.024
0304-3800/

according to the European Habitat Directive (Council of Europe, 1992).

A proper management of protected areas, such as wetlands, should aim at decreasing the influences on them from external anthropogenic pressures (Chape et al., 2005; Martínez-Fernández et al., 2014a). However, the failure to perceive that wetlands are not standalone elements in the landscape and to understand or express the complexity of spatial relationships among hydrology and wetland vegetation, has led to an extensive loss of the most characteristic wetland habitats during the last decades (Turner et al., 2000; Cools et al., 2013; Martínez-López et al., 2014a). In this regard, tools are needed to design effective management actions and evaluate potential scenarios. To this end, modelling the physical environment of wetlands is essential for assessing the relationships among pressures and species responses in these threatened ecosystems (Zhou et al., 2008).

Spatial modelling has become an important tool for plant ecology and biodiversity studies (Turner et al., 1995; Moloney and Jeltsch, 2008; Gardner and Engelhardt, 2008). In particular, spatio-dynamic modelling has served as a tool to assess the effects of land use changes on wetland ecosystems and to substantiate and improve wetland restoration measures (Fitz et al., 1996; Hattermann et al., 2006; Fagherazzi et al., 2012). When linked with remote sensing and field studies, spatio-dynamic modelling can help in overcoming some typical limitations of ecological studies, such as the lack of historical data or the difficulty of studying species interactions and their relationships with environmental variables and pressures both in space and time (Damgaard, 2003; Perry and Millington, 2008; Chen et al., 2011). In the last decades there have been important advances in spatio-dynamic modelling, leading to a diversity of models and modelling environments, such as SLAMM (Sea Level Affecting Marshes Model; Park et al., 1986), CELSS (Coastal Ecological Landscape Spatial Simulation model; Costanza et al., 1990), SME (Spatial Modelling Environment; Maxwell and Costanza, 1997), BTELSS (Barataria-Terrebonne Ecological Landscape Spatial Simulation model; Reyes et al., 2000), MOHID (Braunschweig et al., 2004), Simile (Muetzelfeldt and Massheder, 2003), SimuMap (Pullar, 2004), Tarsier (Watson and Rahman, 2004) and TerraME (de Senna Carneiro et al., 2013). However, some of these remain unavailable for the research community and others represent commercial non-open source solutions, which limits their use and development. Furthermore, some key issues still remain open, such as the compatibility between models, the lack of model reusability and transparency and the nature of the targeted end-users or developers communities (Argent et al., 2006; Jørgensen, 2008). To propose a solution, we identified several requirements for modelling tools, as follows: (1) they should allow interoperability between models; (2) they should represent adequately documented software tools that can be useful for non-programmers, and (3) they should be flexible enough that advanced users can fully understand the role of each component and adapt them to case-specific requirements. The challenge is to develop modelling tools which are as general and flexible as possible to suit the needs of both advanced and less skilled modellers (Voinov et al., 2004; Jakeman et al., 2006). Trying to address these challenges, we have used R (R Core Team, 2013) as a modelling environment which meets the above-identified needs with an application for spatio-dynamic ecological modelling of semiarid Mediterranean saline wetlands.

R is an advanced statistical computing system that is freely available for most computing platforms and can be used for modelling. Among other advantages, R offers dynamic modelling, GIS and advanced graphics capabilities by means of multiple libraries (Petzoldt and Rinke, 2007; Pebesma, 2012; Hijmans et al., 2013). R offers the possibility of developing new functions and can easily connect to other free and open source GIS, such as GRASS GIS (GRASS Development Team, 2008), SAGA GIS (Development Team, 2010) or Quantum GIS (Development Team, 2009). Besides, R is used extensively in elementary teaching, for student projects and by researchers including those in companies and it is supported by a worldwide community of users (Ripley, 2001). Modellers need to be aware of the best practices and modelling techniques to improve their own approaches. It is essential that researchers make their models available and adopt common modelling tools and methodologies based on free and open source software tools (FOSS), which are freely accessible and can be iteratively improved by their community of users (Turner et al., 1995; Argent, 2004; Augusiak et al., 2014).

The model developed in this study addresses three plant communities in the Marina del Carmolí wetland in terms of spatio-dynamic interactions and responses to agricultural hydrological pressures from the catchment area over a 24-year period. The specific aims of the study were: (1) to develop an ecological model of a semiarid Mediterranean wetland site; (2) to build a user-friendly, online and documented version of a spatio-dynamic modelling library using R and (3) to test the wetland model by means of empirical and remote sensing data for the period 1984–2008.

2. Background information

Murcia province (SE Spain: 37° N, 1° W) has a semiarid Mediterranean climate with a mean annual temperature of 16 °C and a mean annual rainfall of 339 mm (Esteve et al., 2006). A semiarid Mediterranean saline coastal wetland was studied, which comprises 314 ha (Fig. 1). The Marina del Carmolí wetland is located in a lowland coastal plain, adjacent to the internal shore of the Mar Menor coastal lagoon, which comprises 12,700 ha (Conesa, 1990; Conesa and Jiménez-Cárceles, 2007). The lagoon and its adjacent wetlands are all RAMSAR sites, containing 18 Habitats of Community Interest according to the European Habitat Directive (Council of Europe, 1992). This site is also a Special Protection Area for Birds, a Site of Community Importance and a Special Protection Area for the Mediterranean.

The wetland mainly comprises salt steppe, salt marsh and reed bed areas, which are distributed according to the availability of water and salinity. Salt steppe is located in areas with low water availability and high salinities; reed beds (*P. australis*) are in areas

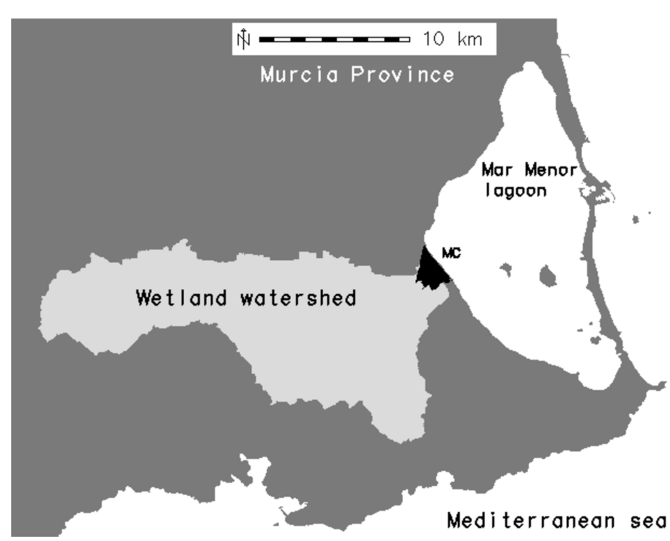

Fig. 1. Location map of the Marina del Carmolí wetland (MC) and its watershed area in Murcia province (SE Spain).