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Integrating socio-environmental models: vegetation, agriculture, and landform dynamics

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Abstract: How did landscapes evolve as agriculture emerged thousands of year ago? How do we ensure sustainable food production and still maintain environmental quality? Integrated socio-environmental models help provide answers to these two seemingly distant, yet related questions. For practical purposes, in this paper we use the terms socio-ecological and socio-environmental systems, with acronym SES as synonyms. The Mediterranean Landscape Dynamics (MedLand) project aims to develop experimental SES models made possible by recent advances in computation while exercising interdisciplinary collaboration. In this paper, we exemplify one aspect of this integration by discussing the development of a vegetation model, which at the outset provides the future links to agent-based models of societal dynamics and process-based models of landform evolution. While designing a vegetation model specific to the needs of the MedLand SES workbench, we preserve those aspects of vegetation dynamics that yield a generic model applicable to other systems. We model vegetation using an individual-based (or gap-model) approach with detailed biological interaction of plants with fire. For this purpose, we use components of existing models of Mediterranean vegetation dynamics. As part of the integration challenge, we discuss spatial and temporal scales, resolution, and future prospects for integration analysis based on sensitivity of integrated model to coupling parameters.

***Keywords**:* model integration, socio-environmental, socio-ecological, vegetation, agriculture.

1 INTRODUCTION

How did landscapes evolve as agriculture emerged thousands of year ago? How do we ensure sustainable food production and still maintain environmental quality? Integrated socio-environmental models help provide answers to these two seemingly distant, yet related questions. During the last several decades, increased recognition of the co-evolutionary nature of human and the environment have led to the development of theories and models on integration of human and natural systems. Significantly, these efforts have resulted in a paradigm shift from one of separately using social and ecological sciences, to one of an integrative science.

To identify this new paradigm, and its body of research, the term socio-ecological systems (SES) has been widely used and have permeated numerous publications (e.g.,Young et al., 2006). An alternative term, socio-environmental systems (with the same acronym, SES), has been employed as a synonym and is gaining recent acceptance (Mooney, 2016; Turner et al., 2016). For practicality, in this paper, we will use these terms indistinctly, with the acronym SES, and suggest that it would be of benefit to have future conversations among practitioners to elucidate possible differences in these terms. Importantly, we recognize that in our study we are investigating interactions of human and natural systems that transcend ecological theories and have environmental science implications beyond ecosystem science, or not yet formulated as ecosystem theory. These implications include, for instance, the profound transformation of topography, occurring as agroecosystems evolved and became part of the built environment, with drastic impacts on watersheds and drainage networks.

For nearly three decades, the US National Science Foundation has supported research bridging the natural and social sciences, leading to the Dynamics of Coupled Natural and Human Systems (CNH) initiative, which has been a standing program during the last ten years (Baerwald et al., 2016). CNH systems models have resulted in integration of a variety of models, which are then used, for instance, to formulate system synthesis (Acevedo et al., 2008) and experiments for theoretical understanding of long-term dynamics (Barton et al., 2012). Specifically, the Mediterranean Landscape Dynamics (MedLand) project aims to develop experimental SES models made possible by recent advances in computation (Barton et al., 2016). Beyond computational tools, at the heart of model integration we emphasize best interdisciplinary research practices, by integrating the epistemological and methodological traditions of the individual disciplines (Acevedo et al., 2018).

In this paper, we exemplify one aspect of SES model integration by discussing the development of a vegetation dynamics model, which at the outset provides for links to agent-based models (ABM) of societal dynamics and process-based models of landform evolution of the MedLand Modeling Laboratory (MML). Besides direct human actions on the landform model and their corresponding feedback, the vegetation model responds to human actions taken by the ABM as well as terrain changes elicited in the landform model. Therefore, focusing this paper on the vegetation model provides more insight in conceptualizing and understanding model integration in the MML (Figure 1). Not depicted in this figure is a climate model that provides synthetic weather series to all three models.

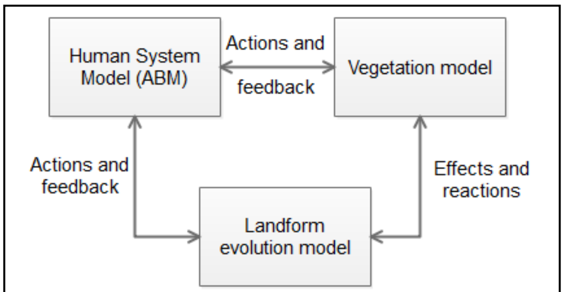

Figure 1 Vegetation model interactions with ABM and landform models

While designing a vegetation model specific to the needs of the MedLand MML, we preserve those aspects of vegetation dynamics that yield a generic model applicable to other systems. As part of the integration challenge, we discuss model couplings to address spatial and temporal scale changes, trade-offs between ecological model fidelity and relevance to human-decision making, and future prospects for integration analysis based on sensitivity of integrated model to coupling parameters.

2 VEGETATION MODEL: DESIGN AND INTEGRATION

SES numerical experiments in the MML help to infer what happened to the vegetation and landforms when people started clearing land in Mediterranean landscapes ~10,000 to 5,000 years ago (~10-5kya) to grow crops and graze animals. These simulations have been performed using a deterministic vegetation successional model that modifies vegetation state of a cell within a grid following a one-directional sequence from bare land, grass, shrub, to woodland over a 50-year period (Ullah, 2013). The vegetation state links with the ABM, via conversion to usable biomass (grazing fodder, firewood, and cereal yields), and with the landform evolution model (LEM), via conversion to a “cover” factor for protection against erosion (Figure 1).

This integration has allowed new insights in agro pastoral productivity, long-term sustainability of alternative land-use strategies, and identifying signatures of human driven landscape dynamics (Barton et al., 2016). The interactions between the agent and landform models are modelled and implemented using the concept of Knowledge Interchange Broker (KIB) (Sarjoughian, 2006; Sarjoughian et al., 2015). The KIB separately models bi-directional data transformations (arbitrary aggregation and disaggregation functions) with well-formed timing and control regime.

2.1 Vegetation model requirements

A revised MedLand vegetation model (MVM), the subject of this paper, is under development with the purpose of accounting for more detailed human interactions with the vegetation, particularly land clearing by fire. Besides, enhancing ecological realism, a more detailed vegetation model provides variables relevant to human decision-making and finer grain land cover for influencing landform change (Table 1). Thus, we focus on integration questions while developing MVM structure and functionality. The MVM must capture the essential of vegetation dynamics resulting from agro-pastoral complex processes (Figure 2), in order to provide a model mapping that allow the integration approach depicted in Figure 1.

The MVM processes are represented on a spatially explicit framework such as raster-based maps or the grid employed by the MML. For each cell, the MML input includes land use actions such as burning vegetation to clear land and using grazing animals to fertilize fields. Its output, state of the vegetation for a cell, contains detailed plant community variables (e.g., biomass, basal area, density) as well as times elapsed since significant events (last fire, cultivation, and left fallow), and fuel load potential for fire events (Table 1).

Table 1 MVM states

Variable	Type/Unit
Under cultivation (Cultivated or Natural)	Categorical
Biomass plant species *i*	Kg/ha
Basal area plant species *i*	Kg/ha
Density of plant species *i*	Stems/ha
Time since last fire	Years
Time under cultivation	Years
Time since land was fallow (time since last cultivation cycle)	Years
Dry biomass (fuel load) wood (available for wood gathering)	Kg/m^2
Dry biomass (fuel load) non-woody (not valued for wood gathering)	Kg/m^2

The MVM will respond to a climate and weather driver, thus modulating vegetation dynamics according to annual rainfall. Our intent is for the MVM to track fuel load dynamics, so that we can simulate fire related processes, dry biomass, broken down by wood and leaf area, taking into account vegetation composition by species. While keeping this level of taxonomical detail in a vegetation model yields a more computationally complex model, it provides important scientific advantages. On one hand, it allows to examine details of relevant agro-pastoral impacts, such as grazing and gathering of deadwood. Additionally, provides plant species information that relate to the archaeological proxy records (artefacts, pollen, charcoal, and phytoliths) offering an opportunity for comparison to the plant community that may have been present thousands of years ago (Vidal-Matutano et al., 2015; Zurro et al., 2016).

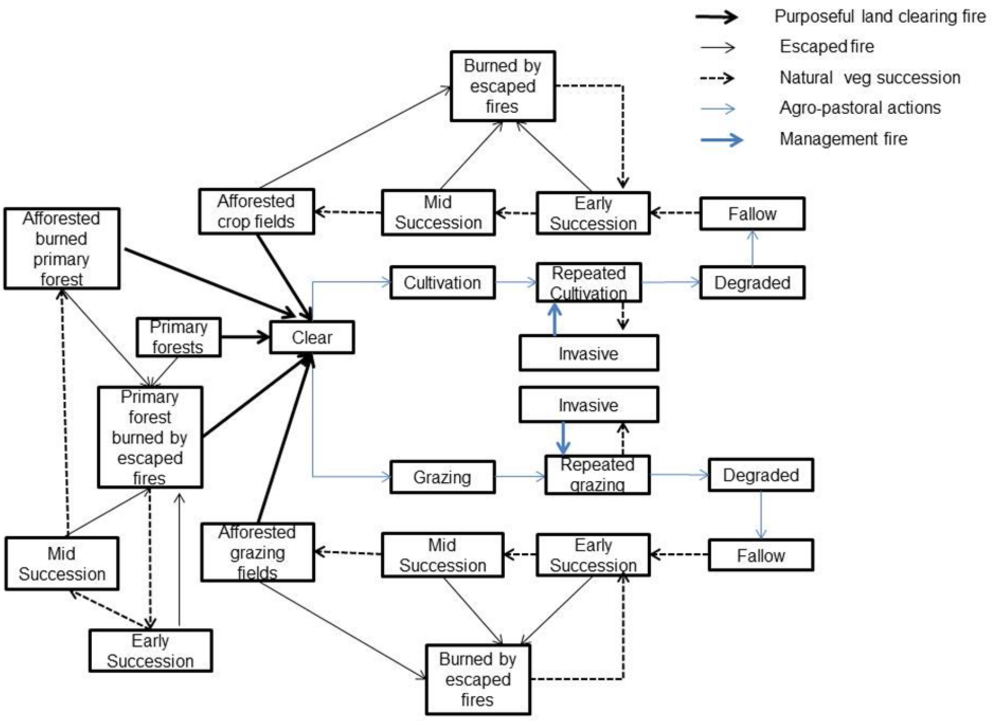

Figure 2 MVM conceptual interactions: land cover and land use types and processes

MVM development has focused on the MedLand study area near Navarrés, Spain, where vegetation today is a mosaic of cultivated areas, fallow areas, sparse shrubs on hillsides and slopes, and patches of woodland resulting from secondary succession. The landforms includes valleys, steep slopes, ridges, and highly eroded gullies ("barrancos"). Terraces are ubiquitous, many under active cultivation, and some abandoned.

We surveyed vegetation in the study area at two levels: 1) site level, locally around some of the archeological survey sites, 2) landscape, at representative terrain conditions (ridge, slope, and valley).

During the survey, vegetation types and species were noted and selected for modeling: *Cistus albidus*, *Pinus halepensis*, *Ulex parviflorus*, *Juniperus oxycedrus*, *Thymus vulgaris*, *Quercus coccifera*, *Brachypodium retusum*, *Pistacia lentiscus*, *Erica multiflora*, and *Rhamnus lycioides*.

2.2 Modeling approach

A major SES model integration challenge faced by MVM development is how to represent Mediterranean vegetation dynamics with acceptable ecological fidelity while capturing the essential attributes that would matter to humans making decisions on the landscape ~10-5kya. There are various approaches to model Mediterranean vegetation with ecological detail and focusing on fire. Some of these are based on vital attributes and life stage mechanisms (Moore and Noble, 1990), for Mediterranean species (Lloret et al., 2003; Pausas, 1999b) and used to implement the spatially-explicit landscape model FATELAND (Pausas, 2006; Pausas and Ramos, 2004). In this model different species can coexist and compete in a landscape cell which represents a refinement over previous implementations where a cell is completely dominated by one species (Pausas, 2003). Mediterranean vegetation models from Israel have emphasized coarser vegetation types and interaction with management practices (Carmel et al., 2001; Koniak and Noy-Meir, 2009) provide further insights for MVM development.

We decided to develop the MVM as an individual based or gap-model that operates on the landscape following Acevedo et al. (1995) but combined with species parameters adapted and modified from FATELAND. Species-specific parameters include those listed in Table 2.

Terrain parameters include potential reduction of light due to terrain position, carrying capacity or maximum vegetation basal area, and potential of a fire occurring at the location during one year.

Table 2 Biological parameters

Species specific parameter
Maximum age, diameter, and height
Height vs. Diameter allometry coefficients
Maximum growth coefficients
Leaf-area vs diameter allometry coefficient
Mortality rate and enhancement due to slow growth
Number of seeds contributed to the seed bank
Reproductive age
Probability of germination of seeds in the seed bank
Probability of seed survival upon fire
Lifeform type (woody or non-woody)
Light tolerance
Resprouting capacity
Survival probability
Flammability

2.3 Integration methods

Our approach is to develop the MVM with high biological fidelity while designing it such that can be integrated with the ABM and LEM at various levels of spatial and temporal resolution, as well as ecological detail according to the type of experiments formulated in the MML (Figure 3). This is accomplished by including the capability to support input/output coupling, using the KIB model, thus allowing systematic integration with other standalone models. A KIB model has a variety of data transformations, each of which can be independently defined in terms of time and execution order. For simplicity, we define a “coupler”, as a relationship, represented by a trapezoid block in the diagram of Figure 3, as an element that transforms model outputs into the inputs of another model with fidelity and resolution that are relevant for the simulation of the integrated models. As shown by Figure 3, a KIB model can have a collection of couplers supported by data type (agro-pastoral, ecological and landform) conversions and scaling, in conjunction with time and frequency scaling. These interactions can be executed under a sequential or other control regime. Besides integration to the MML, and consonant with the theme of the A2 session of the 9th International Congress of iEMS, these model couplers, would facilitate integrating this model to other models on an open platform.

Several types of couplers are of interest to exemplify how the vegetation model allows examining integration methods. A spatial scale coupler adapts the spatial extent and resolution; e.g., a reclassification of a digital elevation model (DEM) to reduce the number of calculation cells and thus perform the simulation faster over the same spatial extent. For instance, depending on level

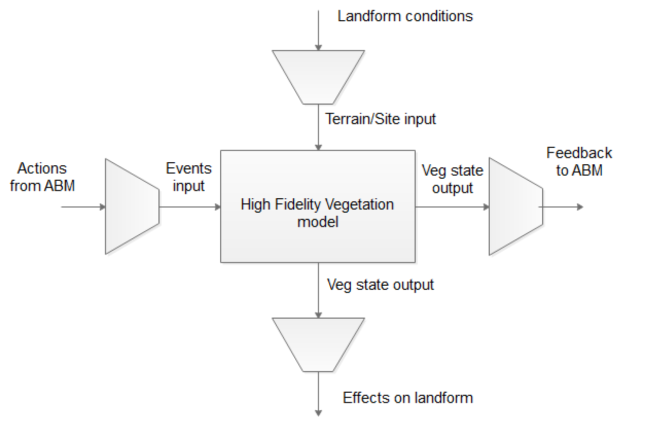

Figure 3 Integration couplers (trapezoid blocks)

of analysis, we perform simulations based on 1.00 ha cells for large area simulations or 0.01 ha cells for limited area simulations.

Fine detail of the timing of events can have substantial impact on the trajectory of a vegetation model. For instance, the timing of torrential rainfall after fire can have profound consequences on Mediterranean plant community development post-fire (De Luis et al., 2003). Temporal scale couplers change simulation time interval and resolution of timing of events; e.g., from days, months and seasons to annual events, so that a simulation proceeds on a 1-year time scale.

One important kind of coupler, a model fidelity coupler, allows changing model output fidelity or grain. For instance regarding ecological fidelity, we can aggregate fine-grain or high fidelity biomass by species into coarse-grain totals for the cell or summarize proportion of each vegetation type in a cell within a grid. Vegetation fidelity of the output influence how other models respond to the MVM output; e.g., the calculation of erosion potential for each cell, e.g., RUSLE’s C factor, and agent perceived forest resource abundance. In MVM, a fidelity model coupler, allows aggregating or representing species by plant functional types based on traits of responses to fire (Pausas, 1999a). Two major traits are selected: re-sprouting from surviving tissue, and fire-stimulated recruitment. The presence or absence of these two traits yields four functional types (see Table 2). Resprouter and fire-intolerant (type 1), resprouter and fire-tolerant (type 2), non-resprouter and fire-tolerant (type 3), and non-resprouter and fire-intolerant (type 4).

Another example of fidelity coupler applies to the landform model. The MVM responds to changes produced by the LEM, by using terrain conditions, including elevation, slope, aspect, soil depth. In other models we have used derived functions such flow accumulation and compound topographic index (Goetz, 2014). In the MVM, a landform fidelity coupler translates DEM values into a discrete set of simplified terrain types that are relevant to vegetation dynamics, such as valley, slope, and ridge.

A particular type of model coupler is a metrics coupler, expressing relevant metrics or statistics of the model output. For example, calculation of landscape fragmentation metrics to express an entire map as a set of numbers summarizing the quality or characteristics of the spatial arrangement of the landscape from the point of view of an organism. We have applied this method for habitat analysis (Thapa et al., 2014) and plan to make it part of the MVM.

Vegetation dynamics using individual-based models or gap-models (as the MVM) are suitable for transformation using a meta-model coupler such as a transition model (Acevedo et al., 2001a; Acevedo et al., 2001b; Acevedo et al., 1995; Urban et al., 1999). These models are sufficiently generic to be parameterized to a site accounting for differing species composition and terrain. Once parameterized, the meta-model can replace the individual-based MVM for simulating large areas with reasonable computation times, since the meta-model runs faster than the original model. Within the vegetated-natural category (not the cultivated land category), land cover change is dominated by ecological succession and modeled using transition parameters of a semi-Markov process estimated from detailed individual based gap-model simulations (Acevedo et al., 2001b; Monticino et al., 2002). Semi-Markov model parameters are transition probabilities and probability density functions of holding times among patches. This coupling procedure is based on running a gap model (Acevedo et al., 2001a) based on individual plants or trees, and their interactions at a multitude of terrain or environmental conditions. These conditions are determined by a factorial combination of categorical values of relief, soil and other environmental parameters. Using pre-defined vegetation types, we determine the probabilities of transitions among these classes from the results of those multiple runs (Acevedo et al., 2001b).

Table 3 Functional types (from Pausas 1999)

		Sprouting ability	
		Yes, resprouter	No, non-resprouter
Fire Stimulated recruitment	Yes, fire-tolerant (fire resistant)	Type 2, Resprouter and fire-tolerant. Examples: *Thymus vulgaris, Anthyllis cytisoides*	Type 3, Non-Resprouter and fire-tolerant. Examples: *Cistus sp.*, *Pinus halepensis*, *Ulex parviflorus*
	No, fire-intolerant, (fire sensitive)	Type 1, Resprouter and fire-intolerant. Examples: *Quercus ilex*, *Pistacia lentiscus, Brachypodium retisum Erica sp.*	Type 4, Non-Resprouter and fire-intolerant. Examples: *Juniperus phoenicea*

2.4 Integration analysis

As demonstrated in the previous section, there is a variety of model interactions that can be captured as couplers (within a KIB model), which allow adapting scale and level of detail among models under timing and control regimes. Interaction modeling affords a systematic parametric analysis approach to examine the effect of models on each other. To be more specific, conduct analyses of the sensitivity of the response of the entire model to the variation of the coupler parameters. For example, what are the percent changes in mature woodland abundance calculated by the MML to percent changes in the interval values employed in a scale coupler reclassifying the LEM to three terrain types for input to the MVM? Sensitivity analysis has been employed in the MML, but the higher ecological fidelity of the MVM affords improved examination of model integration. Explicitly quantifying the effect of model coupling on the resultant integrated response is of great value for sharing models on open platforms.

3 MODEL DEVELOPMENT: TESTING

Currently, we have developed the skeleton of the MVM using an ecological fidelity coupler (species to functional types) and a landform fidelity coupler (DEM to three terrain types) and tested standalone basic functionality and performance (memory and computation times) using simple surrogate functions to emulate a set of the ABM and LEM model responses. We have integrated the MVM skeleton to the MML, and in order to reduce computation times, begun developing simulations using lower spatial resolution and lower ecological fidelity by a model abstraction of plant response instead of individual plants (Sarjoughian et al., 2017).

The MVM is developed using Python (Python, 2017) and GRASS (GRASS GIS OSGeo, 2017) scripts from Python. Pre-processing and post-processing of input and output files for calibration and testing use R scripts (CRAN, 2017). A preliminary version of this model is available in GitHub. The main program starts importing other modules and then executes the simulation based on two main loops: one for time intervals and one for landscape cells.

The MVM runs either as a standalone Python program or interactively with GRASS. For generic spatial representation, raster maps are computed as Python arrays with standard GIS file formats, allowing exchange with GRASS. For interactive GRASS runs, the MVM runs under two different modalities: 1) the model reads and writes maps to GRASS; 2) registers maps on space-time base of GRASS. When the model runs with GRASS, the maps are given timestamps and space-time series are created. Benchmark tests of run times, indicate that simulations interacting with GRASS, take seven times longer than a Python standalone run. Space-time registration in GRASS means a ten-fold in processing time. Since all maps are given timestamps, a space-time series can be visualized using GRASS or R scripts.

3.1 Species and site parameters

For testing, we use two functional groups (Type 1 and 3) and two life forms (tree and shrub). For each functional group and lifeform, we use one species emblematic of the group. Type 1, Tree - Resprouter and fire-intolerant. Example: *Quercus;* Type 1 Shrub Resprouter and fire-intolerant. Example: *Erica;* Type 3, Tree - Seeder and fire-tolerant. Examples: *Pinus*; Type 3, Shrub Seeder and fire-tolerant. Examples: *Cistus.* Testing is conducted using three terrain types: ridge, slope and valley. Ridge – highland areas where land clearing is less likely. Slope - areas in between ridge and valleys. Valley – relatively flat areas in the river valleys were settlement is expected. The terrain type for each landscape cell is input via a terrain map file. For testing, we use a simple landscape where cells have values 0, 1, and 2 for ridge, slope, and valley respectively.

3.2 Input and output tests

Currently, for testing, a function generates a fire event at random for each cell based on the probability of a fire parameter corresponding to the terrain type of the cell. A file representing a fire map is written to a file at each time step; e.g., a 100-year simulation would produce 100 files, one for each time step. The main program is a time loop. First it reads fire event according to a fire map generated by the ABM, based on fire and current vegetation state variables, calculates an update of the state, which is provided to the ABM and the LEM.

Output consist of files for raster-based maps for each variable of interest at each time step. From these files, using R, we can extract and visualize information of interest to the ABM, as well as the LEM. For example, the basal area total for the cell at time t, or the distribution of diameter for dead and live plants in a cell. We contend that for large area simulations, totals are adequate, but that the distribution of a variable is more human-relevant than a total for agents to make decisions at fine spatial scale.

4 CONCLUSIONS AND RECOMMENDATIONS

Integrating models of human and environment dynamics has become of age. After several decades of research, we have a robust basis of a new paradigm anchored in the co-evolutionary nature of human and the environment. However, there is not yet a clear standard for terminology. For instance, the acronym SES means both socio-ecological and social-environmental; we have use these terms indistinctly to accomplish our research goals. There has not been, to our knowledge, a conversation on potential differences in these terms, and how and when to use either. While good interdisciplinary practice and the technology of integrating existing models from various disciplines has been maturing, we are still in need of developing principles to guide the design of new models that are meant to integrate social and environmental systems.

We have proposed here an example of designing a standalone high-fidelity vegetation model including modular inputs and outputs, foreseeing its use with human decision models and landform models via the KIB modelling approach. Emerging questions from this effort relate to trade-offs of model fidelity and human relevant components, as well as the prospects of parametric analysis of the effect of coupling parameter variations on the integrated CNH model. These methods and questions are of great importance when planning sharing model on an open platform, the theme of the A2 session of the 9th International Congress of iEMS.

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