A Coupled ABM-GIS model of small-scale farming

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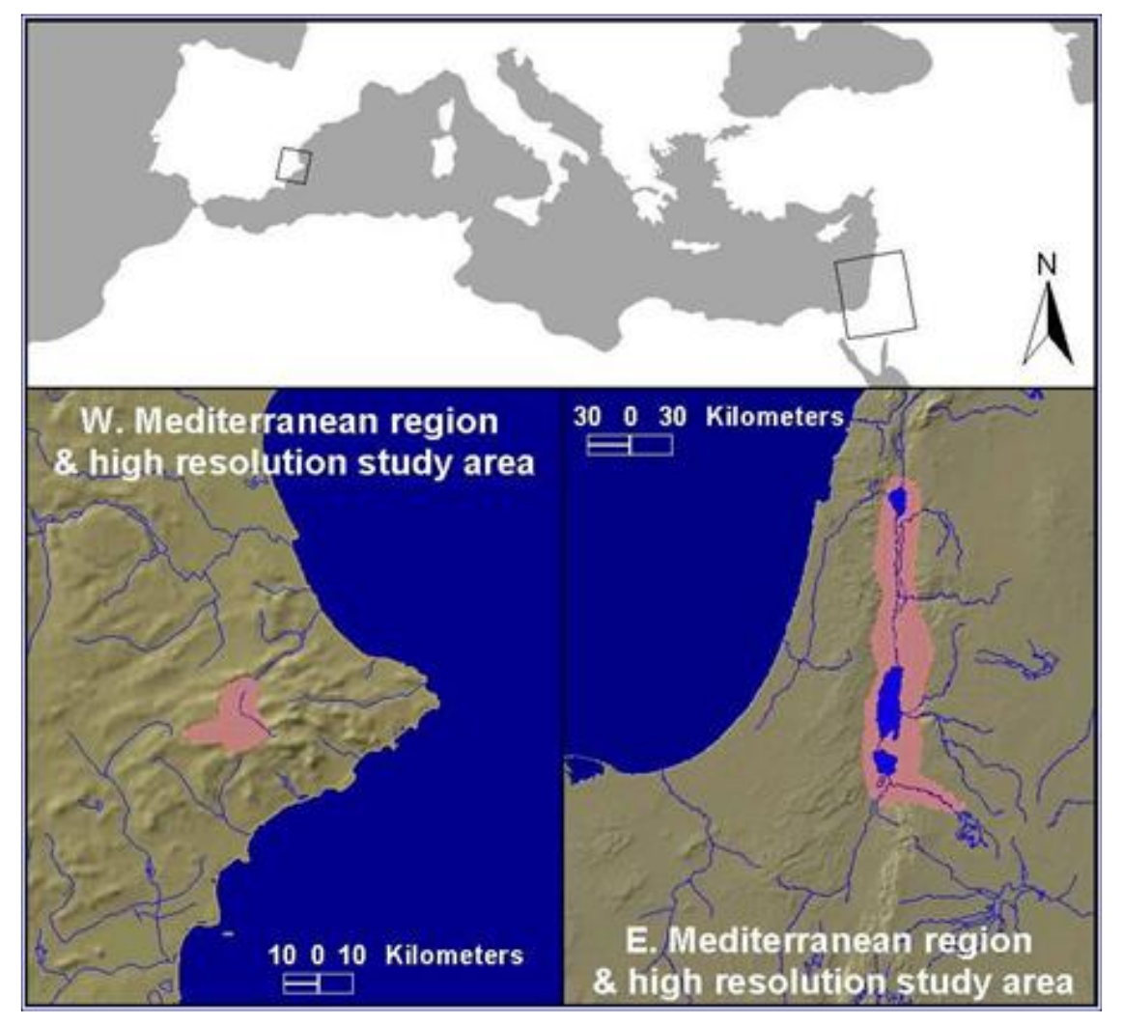
The MedLand Project

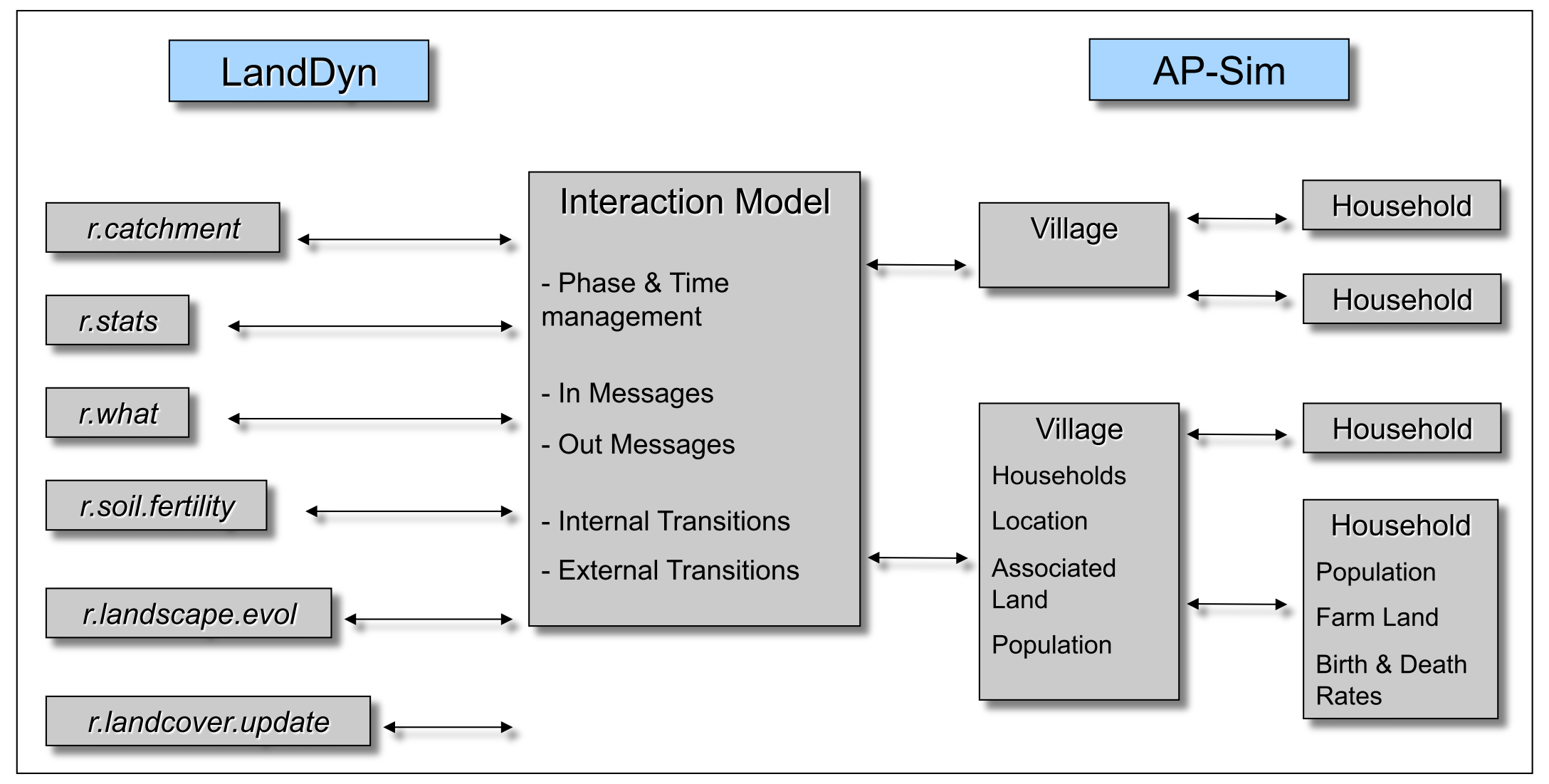
The Mediterranean Landscape Dynamics (MedLanD) project aims to understand the long-term effects of human-environment interaction in the Mediterranean Basin. The project is developing a modeling laboratory for studying the long-term consequences of human landuse decisions on regional landscapes, and currently has project areas in eastern Spain, northern Jordan, and south-central Jordan. Models of socioecosystems often lack the capacity to successfully capture the dynamics of human-environment interaction. We are achieving this goal by coupling agent-based human-action simulations—constructed in a Java implementation of the Discrete Event System Specification (DEVS) modeling formalism (Mayer and Sarjoughian 2007)—with landscape dynamics simulations—constructed in the GRASS GIS environment (GRASS Development Team 2009)—via a third bridging model in the platform-independent Java scripting environment. The strength of this approach is that it independently uses the strengths of each extant modeling environment to achieve a unified result, and does so while avoiding having to “reinvent the wheel” by attempting to code an agent-based model that also does geospatial calculations or by trying to implement a true agent-based approach in a GIS. Both are approaches that would inevitably result in slower-running, overly complicated models that would likely produce less accurate results. On the other hand, our modular approach yields a robust modeling environment that allows simulation at centennial time-scales to finish on the order of hours, rather than days while at the same time producing accurate results. It balances calculation time with accuracy by using the built-in features of GRASS GIS to execute necessary geospatial operations while allowing DEVS Java to calculate all landuse decision making algorithms and rectify any agent request disputes. Although these two environments are in essence “unaware” of each other, the flow of information, simulation parameters, and output data between the two are independently managed via the bridging model, which also manages the timing of all processes in the simulation.

Our DEVS Java agent-based Agropastoral Simulation (AP-Sim) model, emulates non-irrigated subsistence cereal farming and non-mobile foddered pastoralism. Our GRASS GIS Landscape Dynamics (LandDyn) model simulates surface process dynamics (e.g., erosion and deposition) at regional spatial scales and at decadal to centennial temporal scales using a modification of the USPED erosion-deposition equations (Warren, Mitasova et al. 2005; Barton, Ullah et al. n.d.), and simulates simple vegetation succession dynamics based on field data from Southern Spain (Bonet and Pausas 2004). The bridging Interaction Model (IM), acts as both an interpreter and messenger between the two models, and also serves as a manager for coupled agent/landscape simulations. It explicitly models the interactions between AP-Sim and LandDyn (Mayer and Sarjoughian 2007). Using the IM to model interactions within a hybrid model also provides the modeler with the capability to manage a number of disparities inherent to this kind of hybrid model. The disparities between the agent and environment sub-system models may include timing, structure, software implementation, scale, resolution, data visualization, and user base.



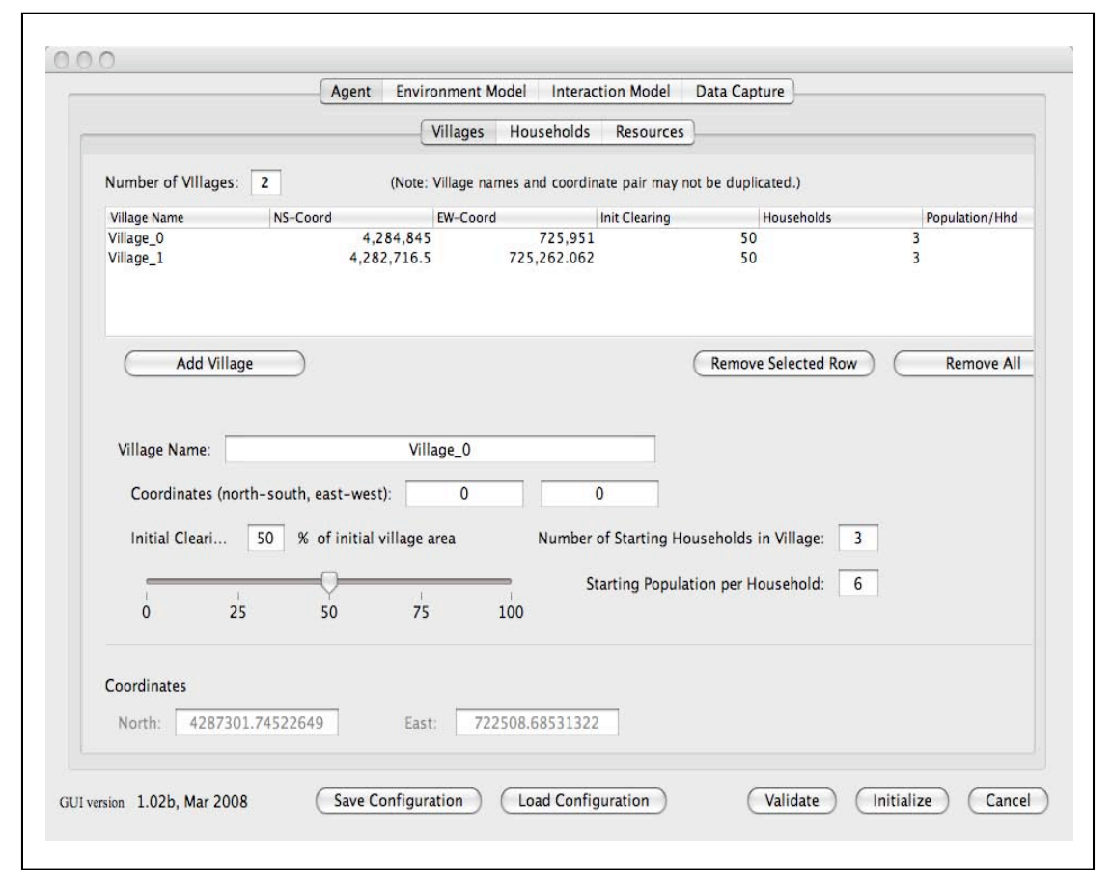
A Hybrid Model

Researchers are now beginning to integrate GIS capabilities into their agent-based models in order to better integrate landscape dynamics. However, the marriage of two intricate modeling tools is not easily implemented. Our model approach utilizes two separate, publicly available, existing modeling platforms, the DEVS Java Suite (for AP-Sim), and GRASS GIS (for LandDyn). To facilitate the interaction of these platforms a third interaction model was developed.



The Interaction Model

The Interaction Model is responsible for the interchange between the DEVS Java-based AP-Sim and GRASS-based LandDyn. All communication and interaction between the two is handled in this model as well as the timing of some discrete landscape or agent events. It creates a new GRASS mapset for each execution of the model, and creates agents and villages based upon input parameters from the model initialization interface. The GRASS toolkit is accessed by the interaction model via a simple Java package entitled GRAVA. GRAVA is a partial mapping of the GRASS Software development environment to Java. It provides methods to implement all standard GRASS modules as well as the specific LandDyn add-on GRASS routines. Currently, GRAVA only provide enough functionality to execute specific landscape dynamics routines, but can be easily expanded. The GRAVA package is capable of utilizing older GRASS scripts written in the Unix shell-scripting language as well as newer platform-independent Python scripts. The IM uses GRAVA functionality to invoke scripts that plot the location of each village in projected space, query a series of environmental maps to provide villages with information, and modify these maps based on agent impacts. As a model cycle begins, the IM mainly acts to relay environmental information. When a household requires information, it sends a coordinate to the IM which caches all of the information requests from agents. The IM then utilizes a GRASS module, *r.stats,* to request information about each specific coordinate and the output from those queries is written to a text file by the GRASS module. Next the IM reads and parses the file, ultimately sending the requested information back to each household. After agents have formalized their farming plans based on the calculation of farming returns, the IM then relays these decisions as impacts at specific locations, and executes LandDyn scripts that appropriately modify land cover and soil fertility values. Farming a plot changes the landcover value and the soil fertility of the plot, while also allowing natural regrowth and revitalization of unaffected plots. The IM then executes the core LandDyn script *r.landscape.evol* that calculates the amount of erosion and deposition and creates a new elevation map to be used as input into the next model cycle.



Number of Villages: 2 (Note: Village names and coordinate pair may not be duplicated.)

Village Name	NS-Coord	EW-Coord	Init Clearing	Households	Population/Hhd
Village_0	4,284,845	725,951	50	3	
Village_1	4,282,716.5	725,262.062	50	3	

Village Name: Village_0

Coordinates (north-south, east-west): 0 0

Initial Cleari... 50 % of initial village area

Number of Starting Households in Village: 3

Starting Population per Household: 6

Coordinates

North: 4287301.74522649 East: 722508.68531322

GUI version 1.02b, Mar 2008

AP-Sim

The agent-based component of the hybrid model is made up of two agent types, villages and households. Villages represent a collection of households and contain information about the location and area of the village. Moreover, villages are responsible for sending information to the appropriate households from the interaction model. At the beginning of each simulation year, agent's must decide upon a farm plan consisting of the plots that will be farmed, and the plots that will be released to the rest of the village. Potential plots are evaluated using the following equation:

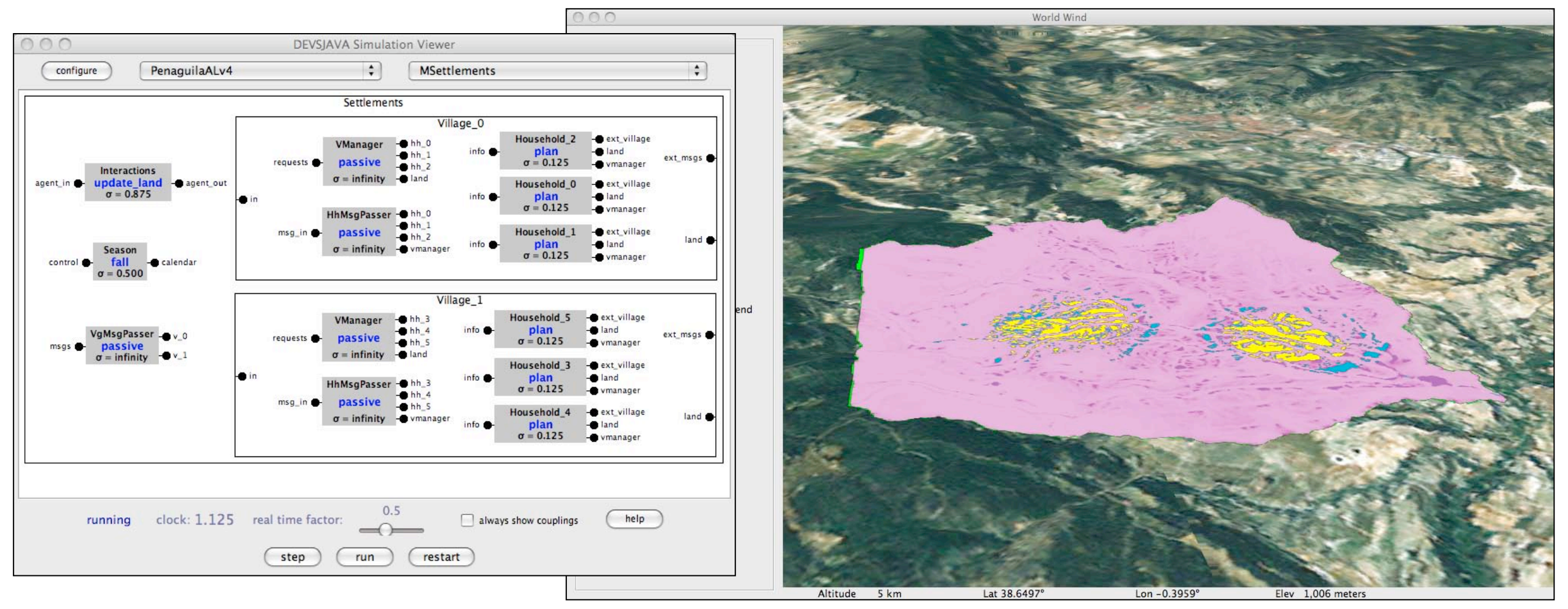
1. $$LandValue = P_{max} \cdot SV \cdot \frac{(F \cdot SD)}{(F_{max} \cdot SD_{max}) - (D \cdot D_w)}$$

Where P_{max} is a constant that represents the maximum amount of energy that can be possible produced from any one plot, SV is a slope devaluation value (lower slopes are more valuable), F is the soil fertility value, F_{max} is the maximum fertility (100), SD is the soil depth, SD_{max} is the maximum soil depth need for full yields (1 meter), D is the distance devaluation, and D_w is the distance weight. Once the households valuate their land, they send a request to farm it through the village. The village is responsible for managing these plans, ensuring that households do not farm on identical plots of land, and enqueuing plots of land that have been released to the agents within the village.

Households are single agents which represent a family of agropastoralists acting as a cohesive unit. Household agents farm the land to acquire food, which they require for survival and growth. The number of people represented by a household agent strongly influences what it can do. The amount of land that can be planted and subsequently harvested is based upon the percentage of each household that is available to do work. The amount of farmed land is also based upon population, as the number of plots to be farmed by a household in a given year is based upon the kilocalorie needs of that household. Household consume some wheat/barley directly, and use the rest to feed domestic animals whose meat/milk they will consume. The yearly consumed kilocalorie need of households is thus translated to a yearly gross farming kilocalorie need as the sum of directly consumed wheat and barley with that used for animal fodder. Initial birth and death probabilities are set by the modeler, but are dynamic so that they change based upon household need/crop yield ratios.

Before the model is initialized, a Graphical User Interface (GUI) designed to receive initial parameters is presented. In the GUI, users must choose initial geospatial parameters such as the number and location of villages, the specific maps to be used for the initial model landscape, and the percentage of the landscape around villages that is initially cleared. Modelers must also provide agent values, including the percent of the population which can contribute to household labor, the initial birth and death rate, and percentage of agent investment in wheat, barley, and livestock.

Once the model has begun running, the DEVS simulation viewer allows the modeler to view the interaction of households with villages, and villages with the IM. In this window, messages passed between model components are visibly moved along lines representing network connections. We have also integrated the open source NASA World Wind geographic viewer, so that modelers are also able to view current maps created through the interaction of agents and their landscape. Once the simulation has finished updating the landscape, the resultant GRASS maps are output as PNG files which are auto-imported to be viewed in a World Wind window. The World Wind viewer renders the images on a three dimensional landscape, and allows users to manipulate the view perspective to better understand model images. Moreover, users can select which maps will be rendered using the built in World Wind layer manager



LandDyn

Our landscape evolution model consists of a suite of GRASS scripts that simulate natural landscape processes. Core among these is *r.landscape.evol*, which is a process-based cellular-automata simulation of surface runoff flow, sediment detachment (erosion), sediment transport, and sediment deposition. It is based on well known and broadly applied algorithms that calculate sediment flux at points on the landscape given the supply of sediment at that point and the topographic characteristics of n the vicinity of that point (Braun, Heimsath et al. 2001; Mitasova, Brown et al. 2002; Dietrich, Bellugi et al. 2003; Hancock 2004; Willgoose 2005). These flux calculations also rely on the results of flow accumulation simulation. We use the GRASS module *r.watershed*, which calculates flowpaths, and then simulates discreet flow and accumulation of water at each cell. The sediment flux at each point (raster cell) on the landscape is then transformed into net elevation change through the Unit Stream Powered Erosion Deposition (USPED) equation, itself a three-dimensional modification of the Revised Universal Soil Loss (RUSLE) equation (Warren, Mitasova et al. 2005). In LandDyn, USPED takes the form of :

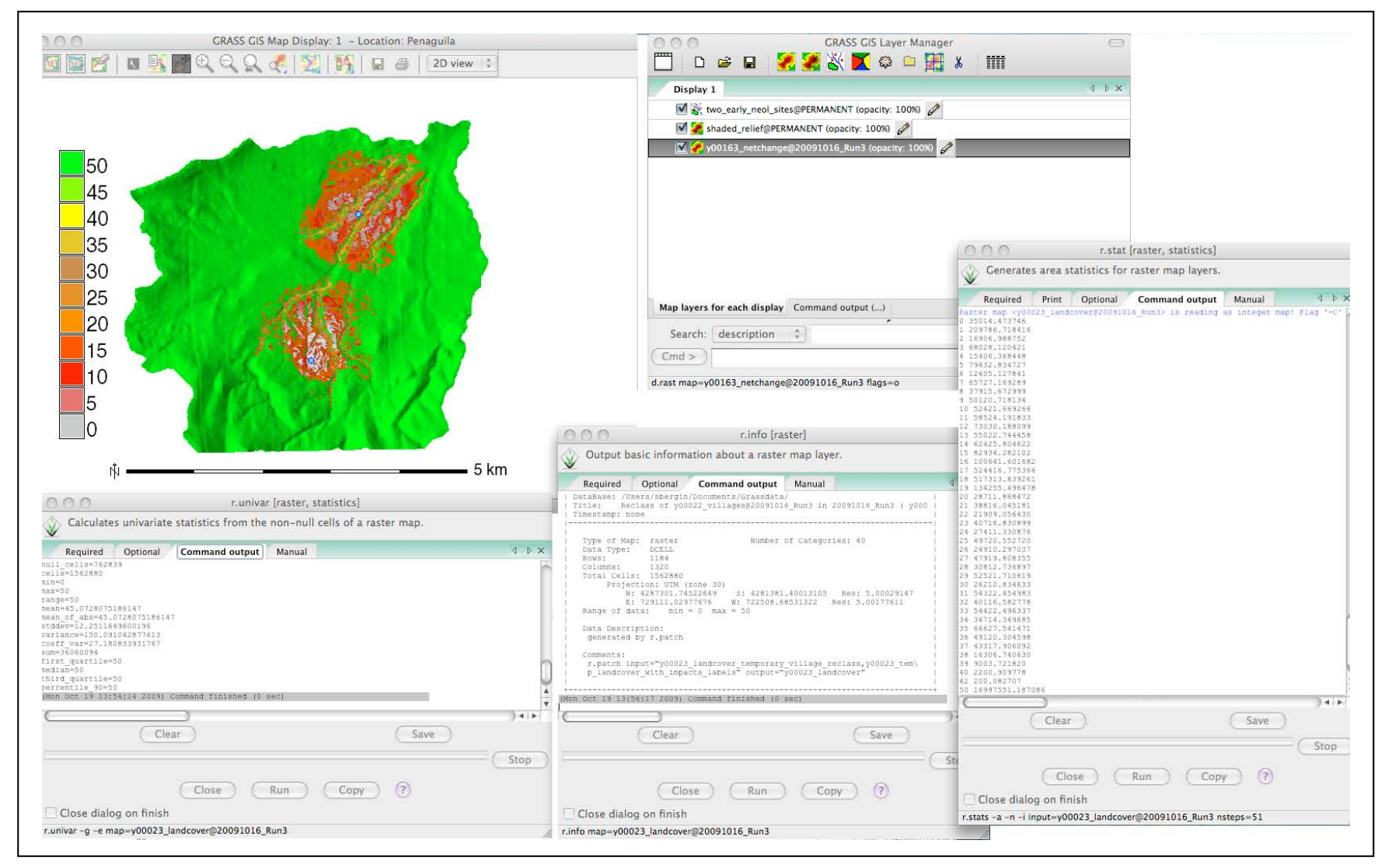
2. $$ED = \frac{\delta(T \cdot q_{sx})}{\delta x} + \frac{\delta(T \cdot q_{sy})}{\delta y}$$

where ED is net erosion or deposition of sediment, q_{sx} and q_{sy} are the terms for sediment transport capacity in x and y directions for a given surface process, and T is the sediment transport factor.

T is derived from a modification of the standard RUSLE equation, which has the form:

3. $$T = R \cdot K \cdot C \cdot P$$

where R is the rainfall intensity factor, and is computed by an equation that combines monthly precipitation amounts and expressed as a map of rainfall intensity for each cell (in tons/ha/mm/hr). These climate data were produced by an Archaeoclimatological model for the region—a method developed by Bryson (Bryson and McEnaney-DeWall 2007), that uses modern weather station data, air and water currents, and known ancient climactic events to retrodict past climatic variables at the location of the input weather stations. K is a unit-less soil erosion resistance factor based on the percent of sand, silt, clay, and organic matter in the soil. This can be represented as a constant throughout the landscape or expressed as a dynamic soil map. K is scaled from 0 (not erodable) to 1 (highly erodible). C is a unit-less vegetation erosion protection factor based on the overall ability of different vegetation to hinder raindrops and surface flow, and to bind soil in place. C , like K, is also scaled from 0 to 1. Typical values of C range from 0.9 for bare ground to 0.005 for erosion resistant forest cover. The ability for LandDyn to accept new C maps at every year is very important, as landcover is what is affected by agent activity. P is a unit-less erosion prevention practices factor that scales from 0 (perfectly protected) to 1 (not protected). It is not used in our current simulations, but could be included in future versions as a map of terraces, check dams, or other erosion control features produced by agents.


GRASS GIS Map Display: 1 - Location: Penaguila
2D view
50
45
40
35
30
25
20
15
10
5
0
5 km
GRASS GIS Layer Manager
Display 1
two_early_neol_sites@PERMANENT (opacity: 100%)
shaded_relief@PERMANENT (opacity: 100%)
y00163_netchange@20091016_Run3 (opacity: 100%)
Map layers for each display
Command output (...)
Search: description
Cmd >
d.rast map=y00163_netchange@20091016_Run3 flags=o
r.univar [raster, statistics]
Calculates univariate statistics from the non-null cells of a raster map.
r.info [raster]
Output basic information about a raster map layer.
r.stat [raster, statistics]
Generates area statistics for raster map layers.
Required
Optional
Command output
Manual
Print
Clear
Save
Stop
Close
Run
Copy
Close dialog on finish
r.univar -g -e map=y00023_landcover@20091016_Run3
r.info map=y00023_landcover@20091016_Run3
r.stats -a -n -i input=y00023_landcover@20091016_Run3 nsteps=51

The rates of erosion and deposition are then translated into meters of vertical elevation change at each cell across the landscape. These values are used to create a new digital elevation model and the depth of soil is calculated by subtracting this new elevation data from a map of bedrock elevations. When a cell has been eroded to bedrock, no more erosion can take place, and no vegetation can grow.

LandDyn also includes a simple vegetation succession model, *r.landcover.update*. This script maintains a landcover map where vegetation types are coded as numerical values in a 50 year succession scheme. Our vegetation is coded on a 50 year time-scale such that bare ground will grow back through grass to scrub and eventually to fully matured forest if no human impact has occurred in the meantime (Pardo and Gil 2005). *r.landcover.update* accepts agent impacts from the IM as a map of landcover reduction values, and will modify the landcover map by the amounts specified in this impacts map. Initially, farming reduces the landcover to a certain value with a large reduction value, and then will subsequently maintain that value with a reduction value of 0. Any cells that are unmodified by agents are regenerated as a function of soil-depth, soil-fertility, and time, and will proceed through a simplified Mediterranean succession sequence. The landcover values are then translated into C values based on linear regression of the known relationship between “classic” landcover types and C values in Mediterranean environments. In our case, these known points are for bare land (landcover value 0, C 0.8), climax grassland (landcover value 5, C 0.4), climax shrub/maquis (landcover value 19, C 0.08), and climax Mediterranean woodland (landcover value 50, C 0.005). The C value for the transitional vegetation communities between these points is interpolated.

Finally, a simple soil fertility routine *r.soil.fertility* is used to keep track of the fertility of farmed plots. This routine runs similarly to *r.landcover.update* in that it accepts a map of agent impacts to soil fertility. Fertility is tracked on a linear scale where 0 is completely infertile and 100 is full fertility. Farming a plot will reduce the fertility in that plot by a value of 2 per model year. If agents relinquish a plot, or let it lie fallow (unfarmed), then the soil fertility begins to regenerate by a value of 1 per model year. Currently, fallowing a plot is the only way that agents can increase soil fertility. Artificial increase of soil fertility through direct actions such as manuring, planting of leguminous cover crops, or deep plowing may be integrated in the future.

Future Directions

The continuing effects of agropastoral systems on their surrounding landscapes is a crucial world issue. Modern landscapes have been transformed by a dynamic combination of human landuse decisions and natural landscape processes. The simulation developed by the MedLanD project provides the appropriate modeling laboratory for understanding the exchange between these components. Simulations have begun which will compare long term landscape change from empty landscapes, to those occupied by agropastoral agents.

Forthcoming experiments will include the addition of several influential social and natural features. Tethered pastoralism is a common practice in the Mediterranean which can greatly effect landcover and influence agropastoral returns. Although pastoralism is partly taken into account by household land allocation calculations, subsequent work will focus on pastoral landscape impacts. The addition of terraces to our model will allow direct landscape modification by agents for the purpose of increasing agricultural returns. Additionally, greater social complexity will be incorporated into the model's agents including such factors as storage or social status.

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For further information

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More information about the MedLand project can be found online at http://medland.asu.edu.