OVERVIEW

Purpose

The MML (MedLand Modeling Laboratory) is a combination of a DEVS-Suite (Kim et al., 2009) agent-based model of subsistence agropastoralism (referred to as AP-SiM in other MedLanD publications) with a GRASS GIS (GRASS Development Team, 2012) Landscape Dynamics Model (referred to as LandDyn in other MedLanD publications), connected by a third overarching custom software architecture, referred to as the Interaction Module, or IM. The MML simulates non-irrigated subsistence cereal farming and site-tethered pastoralism, and its connection to surface process dynamics (i.e., erosion and deposition, vegetation growth, and soil fertility) at a regional spatial extent and at an annual temporal scale. The IM acts as both an interpreter and a messenger between the social and natural halves of the MML and also serves as a manager for the coupled agent/landscape simulations by explicitly modeling the interactions between AP-Sim and LandDyn. Using the IM to model interactions within a hybrid model also provides the researcher with the ability to manage a number of disparities between the agent and environment subsystem models that are inherent to this kind of coupled modeling platform, including disparities of timing, structure, scale, and resolution (Mayer and Sarjoughian, 2007).

The agent-based component of the hybrid model (AP-Sim) is based on ethnographic data for village-based subsistence agropastoralism in the Mediterranean region (Watson, 1979; Kramer, 1980, 1982; Gibbon, 1981; Thomson and Bahhady, 1983; Thomson et al., 1986; Thomson, 1987; Kamp, 1987, 2000; Shoup, 1990; Nablusi et al., 1993; Nordblom et al., 1995; Hirata et al., 1998; Khresat et al., 1998, 2008; Corbeels et al., 2000; Al-Jaloudy, 2006). It consists of two agent types: villages and households. Villages represent a collection of households and are responsible for sending information received from the IM to the appropriate households. Household agents represent a family of agropastoralists acting as a cohesive unit. Household agents farm wheat and barley, collect wood and raise sheep and goats to acquire food, which they require for survival and growth.

The number of people contained within a household strongly influences what it can do. The maximum amount of land that can be planted and subsequently harvested is based on the percentage of each household that is available to do work. The desired amount of farmed land is also based on population, since the number of plots to be farmed by a household in a given year is based on the kilocalorie needs of that household and agricultural yield expectations based on the average yield of the previous year. The amount of grazed land is dependent on the number of sheep and goats possessed by a household. Households consume most of the farmed wheat and barley directly and use the rest as supplemental fodder for the goats and sheep. Sheep and goats also need to graze wild vegetation to round out their diet, and they provide households with additional kilocalories derived from meat and milk products. The yearly consumed kilocalorie need of each household is thus translated to a yearly gross farming kilocalorie need as the sum of wheat and barley kilocalories that will be directly consumed with those that will be used as supplemental fodder. There is no allowance for storage in the simulation.

Household birth and death rates change based on household need/kilocalorie yield ratios. If a household fails to meet its energy requirements (if a household is within

10% of requirements, requirements are considered met), the probability that a household member will die increases and the probability of a new household member being born decreases. Likewise, if a household exceeds its energy needs, death rates decrease and birth rates increase.

The IM is responsible for all data interchange between the DEVS-Suite-based AP-Sim and GRASS-based LandDyn. At the beginning of each simulated year a household agent calculates the amount of land it needs based on the previous year's average return and limits the amount of land requested by enuring that the population of a household is large enough to maintain the amount of requested land. The amount of land for grazing is also calculated based upon the previous year's average fodder return. The number of cells, or amount of land needed for each subsistence activity per household is then sent to R.Land.Assess as one simultaneous, large request string.

R.land.assess (RLA) is a python based GRASS script which sorts and processes the subsistence requests from each of the households. Within RLA each of the households' requests are treated in a random order. The potential return of all of the land surrounding a village is calculated and then sorted from best to worst. Then the simulation advances through the ordered list and assigns farms to each of the households in a randomly generated order. Once each household has been assigned the number of farms it has asked for, or no more farms exist, RLA then performs the same operation for grazing patches, ordering each of them by their yield and assigning them to each of the households according to the households' requests.

Once a household agent had received information about its agricultural and pastoral returns for the year and land, households evaluate their population for the next year. Next the IM then relays these decisions as impacts at specific locations, and executes LandDyn scripts that appropriately modify land cover and soil fertility values, calculate the amount of erosion and deposition. This information is then used to update the digital topographic map, as well as the map of soil depths. The newly updated maps of soil fertility, soil depth,land-cover, and topography are all then used by the agents to make new subsistence plans for the next year, creating a dynamic simulation of the consequences of yearly household-based subsistence decisions in a low-level Mediterranean agropastoral socio-natural system.

State Variables & Scales

AGENT VARIABLES

Village Information
- -Location
- -Number of households
- -Number of residents per household and total village population

Resources
- -amount of wheat and barley yield belonging to each household
- -amount of calories supplied by sheep and goats belonging to each household

Households

- -Probability of birth and death
- -the amount of labor that the household can provide
- -total amount of kcal per year needed
- -the amount of wood required for each household
- -the population of each household

ENVIRONMENT MODEL

- - Yearly, elevation map, cost surface maps for each village, map of the region's landcover, friction, kfactor constant map, map of soil depth
- -climate specific variables, either constant values for r factor, precipitation, and the number of rain days, or the location of a .csv file from which to read these variables.
- -Parameters exclusively used for running Landscape Evol, the soil density, infiltration, stream transport, load exponent, amount of smoothing, and cutoffs.
- -soil depth minimum and maxium
- -soil recovery rate
- -impact upon fertility if the land is farmed

INTERACTION MODEL

- -Start Date, End Date, map naming conventions

SYSTEM SETTINGS

- -Location of the APSIM package
- -Location of GRASS 6.4 & Python as well as the grass ".rc6" file
- -Turn WorldWind visualization on/off
- -Adjust which log files are kept from the household, the village, and the interaction model

Process Overview and Scheduling

Each iteration of the simulation is designed to simulate a year for the agropastoral agents. The simulation year begins with households sending their agropastoral needs to the interaction model. The r.land.assess script is run and agricultural and pastoral yields are returned to the agents. The agents then evaluate their caloric returns. If they have met their return needs, then their birth and death rates may be adjusted (according to user selected values). Next, the population is adjusted, and agents await the beginning of a new year. After agents have received their returns, the landcover and landscape are updated using python based grass scripts.

Design Concepts

Emergence (a summary of emergent phenomena from the interaction of the agents)

As the simulation progresses, several phenomena may emerge from the interaction of agropastoral households and their environment, and from natural landscape processes.
- Soil characteristics such as fertility and depth are greatly affected by the farming choices of households and natural erosion and deposition.
-Households in the simulation may increase or decrease in population or may be eliminated from the simulation if they are unable to procure enough annual resources.
-Landcover values are reduced resulting in a reduction from wooded areas to areas with little landcover or grasses.

Adaptation (how the agents adapt their behavior to their and their environments current state)

Farmers in the simulation adapt to the changing conditions of the landscape around them, by choosing new areas to farm or put their livestock to pasture. The amount of land needed for farming and to feed sheep and goat herds is re-evaluated each year. After each year, households calculate the average return from agricultural and ovicaprid patches and attempt to meet their annual caloric needs assuming that each patch will return an average agricultural or pastoral return.

Fitness/Objectives (a summary of the agents' goals)

The main goal of households is to achieve their annual caloric needs. The population of each household determines the amount of calories needed. Each year, the households attempt to plant enough crops, and provide enough pastoral land, to meet their needs. If they are unable to meet their needs, the probability of a member of the household dying increases. Conversely, if a household is able to exceed their caloric needs, the probability that the household gains an additional member increases. Ultimately, the goal of the households is to increase their population and prevent the complete loss of all household members.

Prediction (how the agents predict the consequences of their decisions)

Agents predict their agricultural and pastoral returns based upon the returns from the previous year. Households compute average returns by reference to the total number of patches used for an economic activity, and the return for the activity. Agents use this number to estimate how many patches they will need to fulfill their current subsistence needs.

Sensing (environmental variables perceived by the agents, which might include their own variables)

Households are aware of their current population. This variable greatly influences their subsistence behaviors. It influences the agent’s estimation of their caloric needs as well as determining the maximum amount of patches that can be used to harvest grains by reference to the number of people available for agropastoral labor.

Agents are also able to sense the conditions of the environment around them. Agents make decisions based upon a suite of environmental factors that are used to make choices about which patches to cultivate. This includes the depth of the soil, the slope, and the landcover. These variables are all included in a numerical evaluation that agents use to choose their land. They are also able to sense if another household has laid claim to a particular patch of land, which prohibits households from farming a plot that another household is using.

Interactions

Agents do not interact with one another per se. Instead, their main interaction is with the environment around them. Their subsistence choices, land used for farming, land used for sheep and goats, and the respective amounts of that land, greatly effects the soil, and landcover of the land around them. In turn, the landcover is changed based upon their impacts, and subsequent decisions from the agents are affected by the changes that have occurred on the landscape.

Stochasticity

The amount of stochasticity in the model is stochastic. Most of the variables can be changed in the GUI which accepts user inputs for all of the variables used in the simulation. Additionally, the population of each household is controlled by a death rate and a birth rate. The rates are largely affected by subsistence returns, and can never be zero. Users determine a minimum and maximum death rate shared by all of the households. First choice for yearly land acquisition is varied randomly as is the ownership of land in between two separate villages.

Collectives (whether the agents are grouped socially)

The agents themselves represent Neolithic agropastoral households. Households contain a population of individuals, but these individuals have no properties of their own. Each household belongs to a village. Villages serve to represent a starting location for the calculation of distance to resources and relay information to the interaction model.

Observation (how data are gathered from the model)

Data is gathered from the output of maps and data files. Data files are saved inside of the mapset generated for the model run and includes household and village level data on population, as well as subsistence expectations and returns. Maps for the environmental impacts and factors for each year of the simulation are recorded in the mapset created for the simulation. Statistical analyses of landscape variables, such as erosion and deposition, can also be recorded in text output file.

DETAILS

Initialization

Model initialization is first begun using a GUI meant to help users set a wide variety of variables ranging from the maps used in the simulation to caloric yields of wheat and barley. Once all of the variables have been entered by the user, the GUI module checks to make sure that all appropriate fields have been filled in and attempts to make sure that the values are in agreement with the program's design and within proper ranges.

All input variables are saved in one class file, entitled InitParameters, which can be accessed by the Interaction Model, as well as the agents. Agents are initialized with the variables set in the GUI, and they in turn notify villages of their existence and their population. Villages are initialized with a location set in the GUI and they in turn update the village's total population.

Within the interaction model, initialization centers upon the creation and organization of landscape maps. Maps selected in the GUI are copied from the user's permanent mapset directory, to the mapset created for the model run in progress. These maps include the elevation maps, the soil maps, the friction map, the fertility map, the landcover map, and a fertility map.

Input

The model requires a great amount of input and these inputs are managed by a GUI created exclusively for the simulation. The GUI will not allow the model to run until each of the variables has an appropriate value. It checks to make sure that some landscape or agent variables are within an appropriate range, that maps are provided for the location being modeled, and that all files are in appropriate locations. Below is a list of all of the input variables.

AGENT VARIABLES

Village Information
- -Location
- -Number of households
- -Number of residents per household

Resources
- -Labor Required for harvest
- -Total calories required
- -Ratio of Ovicaprid Per Person
- -Herd composition, ratio of sheep to goats

-Ovicaprid Density Scalar adjusts the ratio in relation to a sustainable amount of sheep and goat per cell.
-percent of fodder needs that comes from farmer's barley.
-proportion of milk producing and meat yielding animals.
-the amount of fodder required for sheep and the amount required for goats in kg.
-the amount of kcal that is provided by each sheep or goat.
-decide if sheep and goats will get some of their caloric requirements from feeding on the remaining stubble in agricultural fields.
-the amount of wood needed per capita
-the intensity of wood collection per area

Households
-Probability of birth and death
-minimum and maximum probabilities for birth and death
-percent of population providing labor
-total amount of kcal per year needed
-amount of labor provided per person
-maximum cost distance agents will look for land

ENVIRONMENT MODEL

-Grass Database
-Mapset, DEM, landcover map, friction, kfactor constant map
-climate specific variables, either constant values for r factor, precipitation, and the number of rain days, or the location of a .csv file from which to read these variables.
-Parameters exclusively used for running Landscape Evol, the soil density, infiltration, stream transport, load exponent, amount of smoothing, and cutoffs.
-soil depth minimum and maximum
-soil recovery rate
-impact upon fertility if the land is farmed

INTERACTION MODEL

-Start Date, End Date, map naming conventions

SYSTEM SETTINGS

-Location of the APSIM package
-Location of GRASS 6.4 & Python as well as the grass ".rc6" file
-Turn WorldWind visualization on/off
-Adjust which log files are kept from the household, the village, and the interaction model
-Keep or get rid of temporary raster maps

Submodels

Choosing the number of farmed plots

To determine the number of wheat plots (N_W) needed in the coming year, households use the following decision rules:

$$N_w = \frac{(P_h \cdot F_w) + (P_h \cdot F_w \cdot p_s)}{\mu_w \cdot E}$$

Where, P_h is the current population of the household, F_W is the total amount of wheat needed for subsistence purposes [kg/pers.] (i.e., the "food wheat" needed per person), p_s is the "seeding proportion" needed needed for reseeding the next years' crop [percentage of crop], μ_W is the average amount [kg/ha] of wheat that was grown on the plots owned by the household in the previous year, and *E* is unit-less "expectation" scalar that determines how conservative farmers are when predicting the amount of land they will need (as the value of *E* increases, farmers will try to plant more and more above the minimum needed to survive). Thus, the number of wheat plots is determined as the total amount of wheat needed by the household plus the extra wheat needed as seed crop, all divided by the amount of wheat expected to be produced from a typical plot.

In the model, barley is used only as supplemental fodder for ovicaprids. To determine the number of barley plots (N_b) needed in the coming year, households use the following decision rules:

$$N_b = \frac{(P_h \cdot P_{oc} \cdot DM_{tot} \cdot p_b) + (P_h \cdot P_{oc} \cdot DM_{tot} \cdot p_b \cdot p_s)}{\mu_b \cdot E}$$

Where, P_h is the current population of the household, P_{oc} is the number of ovicaprids per person (determined by the modeler – should be based on the importance of pastoral products in the diet), DM_{tot} is the total amount [kg] of digestible matter needed by the average animal in the herd (the actual amount will vary based on the goat/sheep ratio, breed characteristics, and herd profile, as entered by the modeler), p_b is the proportion of the total diet of a herd animal that will be provided by supplemental barley foddering [percentage], p_s is the same "seeding proportion" used in the previous equation, μ_b is the average amount [kg] of barley that was grown on the plots owned by the household in the previous year, and *E* is the same "expectation" scalar used in the first equation. Thus, the number of barley plots is determined as the total amount of barley needed as supplemental fodder by the herd owned by the household plus the extra barley needed as seed crop, all divided by the amount of barley expected to be produced from a typical plot.

Choosing the amount of grazing land

To determine the number of grazing patches (N_g) needed in the coming year, households use the following decision rules:

$$N_g = \frac{(P_h \cdot P_{oc} \cdot DM_{tot}) - (DM_{stub} + (P_h \cdot P_{oc} \cdot DM_{tot} \cdot p_b))}{\mu_g}$$

Where, P_h, P_{oc}, DM_{tot}, and p_b are as in Equation 4.2 above, DM_{stub} is the amount of digestible matter [kg] provided by grazing the stubble of the wheat and barley fields owned by the household, and μ_w is the average amount [kg] of digestible matter that was grazed from all the patches exploited by the household in the previous year. Thus, the number of grazing patches is determined as the total amount of digestible matter needed by the herd minus the amounts of digestible matter obtained from stubble-grazing on wheat/barley fields and that obtained as supplemental barley fodder, all divided by the amount of digestible matter expected to be produced from a typical grazing patch.

Choosing the amount of firewood gathering patches

The number of firewood gathering plots (N_{fw}) needed in a given year is determined by the following algorithm:

$$N_{fw} = \frac{(P_h \cdot F_{tot}) - F_{clear}}{W_i \cdot RC_m}$$

Where, P_h is the current population of the household, F_{tot} is the total amount [kg] of firewood needed per person per year, F_{tot} is the amount of firewood obtained during any new agricultural field clearances that occurred that year [kg], W_i is the intensity at which people gather wood [kg/m^2], and RC_m is the number of raster cells per square meter (i.e., a conversion factor to scale the impacts to the current raster resolution). Thus, the number of firewood gathering patches is determined as the total amount of firewood needed by the household minus the amount they obtained during field clearances, all divided by the amount of firewood that will be gathered from each firewood gathering patch. It is important to note that firewood gathering differs from other activities in that there is no “average return” from the cells, but instead a “gathering intensity” that is determined by the modeler.

Choosing the location of farm plots

For farming plots, households want relatively level land that has deep fertile soil, but which is not too far away from the village. Thus, farming value (*FV*) of potential plots are evaluated using the following equation:

$$FV = SV \cdot \left(\frac{(F + F_w) \cdot (SD + SD_w)}{F_w + SD_w} \right) - \left(\left(D_w \cdot \frac{D}{D_{max}} \right) + LC_{dval} \right)$$

Here, *SV* is a slope modification value (0°-10°, *SV*=1; 11°-20°, *SV*=0.75; 21°-60°, *SV*=0.25; 60°-90°, *SV*=0) that makes lower slopes more valuable than higher ones, *F* is the current soil fertility value [percentage] (scaled 0-1), *Fw* is a weighting factor for soil fertility in the decision algorithm, *SD* is the current soil depth [m] (scaled 0-1), and *SDw* is a weighting factor for soil depth in the decision algorithm. The maximum soil depth needed for full yields is 1m (Carter et al., 1985; Christensen and McElyea, 1988; Rhoton and Lindbo, 1997; Sadras and Calvino, 2001; Wong and Asseng, 2007), so for depths greater than 1m, *SD* is set to 1. *D* is the least-cost distance of the current cell from the center of the village, *Dw* is the least cost distance weight in the decision algorithm, and *Dmax* is the maximum calculated least cost distance value on the least cost map. Finally, *LCdval* is a land-cover "devaluation" coefficient such that degree of devaluation of vegetation other than wheat/barley grassland is set according to a "graphing function" (a sequential series of boolean-separated linear regressions that approximate the results of a more complex regression function) parameterized by breakpoints entered by the modeler. Adjusting *LCdval* preferences farm plots with certain land-cover values, and essentially sets the fallow-cycle of the system (e.g., forest-fallow, bush-fallow, short-fallow, intensive agriculture, sensu Boserup [1965]). Thus, the left side of the equations estimates the general suitability of a plot of land for farming, and the right side estimates the costs to the agent if they were to farm that plot, and the equation balances to an estimate of the total "value" of a particular plot of land to agents from a particular village. This equation selects for deep fertile plots, but scales the attractiveness of such plots based on their slope, and reduces their value based on their distance from the village along the least-cost route and the amount of vegetation currently on the plot. It is also important to note that in the current simulations, agricultural plots are not tenured. Every year, agents simply farm the "best" land parcels available to them, and thus, agents are free to drop a parcel of previously farmed land if the perceive that another parcel of land would is better.

Choosing grazing patches

Once all of the households have chosen agricultural plots, they must decide on locations for grazing. For pastoralism, slope and soil attributes are unimportant when deciding upon grazing locations, but households do prefer grazing patches that have abundant fodder but which are not too far from the village (Oba, 2012). Thus, the grazing value (*GV*) of potential grazing patches is evaluated according to the following equation:

$$GV = \frac{\left(DM_w \cdot DM\right) + \left(D_w \cdot \left(1 - \frac{D}{D_{max}}\right)\right)}{DM_w + D_w}$$

Here, *LC* is current the land-cover value of a particular patch, which is proxy for the amount of available digestible matter (fodder) available in the patch, and *LCw* is the weight of the land-cover value in the decision algorithm. *D* is the least-cost distance of the current cell from the village [sec], *Dw* is the least cost distance weight in the decision algorithm, and *Dmax* is the maximum calculated least cost distance value on the least cost map. In Mediterranean environments, slightly immature grassy open oak and pine woodland produces the largest amount of digestible matter, and digestible matter actually decreases as these woodlands mature into denser oak forests (Al-Jaloudy, 2006). To account for this, any *LC* value above 40 (which corresponds to these open grassy woodlands) are rescaled by a boolean function in descending order (e.g., 41 is changed to 39, 42 to 38, etc.) before being rescaled from 0-1 and entered into the equation. This equation favors patches of land with high fodder production, but scales their attractiveness according to their distance from the village along the route of least accumulated costs. Thus grazing patches that have large amounts of edible vegetation, but which are very far from the village are less attractive to agents than are grazing patches that have less edible vegetation, but which are very close to the village. The actual number of cells chosen depends upon the total number of ovicaprids being herded, and the stocking rates of these animals on the landscape. In our models, the total number of ovicaprids herded is linked to the village population by a ratio of animals to people determined *a priori* by the modeler at the start of each model run. This ratio stays constant during each simulation. Stocking rates are also determined by the modeler at the start of each model run, as is the ratio of goats to sheep (which determine the amount of fodder needed and the total kilocalorie output from the herd, based on its size in any given year).

Choosing firewood gathering patches

Finally, households must meet their requirement for firewood. If households clear a plot of land for farming, they acquire and amount of wood equal to a proportion of the standing biomass of the plot, determined from the land-cover value of that plot at the time of clearance. Any additional firewood needed by the household must be gathered from other parts of the landscape. The wood value (*WV*) of landscape patches is calculated by the following equation:

$$WV = \frac{LC + \left(D_w \cdot \left(1 - \frac{D}{D_{max}}\right)\right)}{1 + D_w}$$

Here, *LC* is the land-cover of a particular patch, *D* is the least-cost distance of the current cell from the village [sec], *Dw* is the least cost distance weight in the decision algorithm, and *Dmax* is the maximum calculated least cost distance value on the least cost map [sec]. Land-cover values between 9 and 50 are rescaled from 0-1 before being input into the equation. Land-cover values below 9 (which equates to grass and shrubs) are deemed to not produce large enough pieces of woody material to make firewood gathering efficient, and so are set to 0. Typically, D_W should be set higher than 1 ($D_W = 3$ by default) because ethnographic research shows that distance is the primary concern when gathering firewood (Tabuti et al., 2003). Thus, the equation favors firewood gathering on those patches with the most amount of woody material suitable for firewood and are also closest to the village. The amount of wood actually gathered depends on two things: the total amount of wood need per person, and the intensity of wood gathering.

Calculating farming returns

Wheat and barley returns (*WR* and *BR*, respectively) are measured in terms of kilograms of harvested grain, which is calculated according to the following equations:

$$WR = \frac{(PR_w \cdot SV \cdot Max_w)}{RC_{ha}}$$

$$BR = \frac{(PR_b \cdot SV \cdot Max_b)}{RC_{ha}}$$

Where PR_W and PR_b are the potential wheat and barley production rates of a particular plot (scaled from 0 to 1), Max_W and Max_b are the maximum wheat and barley yields possible under ideal conditions [kg/ha], *SV* is the slope modification value, and RC_{ha} is the number of raster cells per hectare (in the model, the size for an individual farm plot is the same as the starting raster cell resolution). As suggested by Rhoton and Lindbo (1997) and Christensen and McElyea (1988), PR_W and PR_b are calculated as the average of three regressions against precipitation, soil depth, and soil fertility:

$$PR_w = \frac{(((0.51 \cdot \ln(P)) + 1.03) \cdot ((0.28 \cdot \ln(SD)) + 0.87) \cdot ((0.19 \cdot \ln(F)) + 1))}{3}$$

$$PR_b = \frac{\left(\left((0.48 \cdot \ln(P)\right)+1.51\right) \cdot \left(\left(0.34 \cdot \ln(SD)\right)+1.09\right) \cdot \left(\left(0.18 \cdot \ln(F)\right)+0.98\right)}{3}$$

Where P is the amount of annual precipitation (in meters), F is the current soil fertility value [percentage] (scaled 0-1), SD is the current soil depth [m]. The particular regression coefficients in Equations 4.10 and 4.11 derive from data presented by various authors. The regressive relationship between wheat/barley yield and precipitation was determined from data presented by Araus et al. (1997a), (1997b b), Pswarayi (2008), and Merah et al. (2000). The regressive relationship between wheat/barley yields and soil depth was determined from data presented by Wong and Asseng (2007) and Carter et al. (1985), and the relationship derived from these data also generally agrees with those presented by Sadras and Calvino (2001) (although data from Sadras and Calvino were not used to determine the regression). And finally, the regressive relationship between wheat/barley yield and soil fertility was determined from data presented by Barzegar et al. (2002) and Quiroga et al. (2006).

Calculating grazing returns

Grazing returns (GR) are measured in kilograms of digestible matter, and are calculated according to a different logic than wheat and barley returns:

$$GR = \left(\frac{DM}{RC_{ha}}\right) \cdot G_i$$

Where DM is the amount of sustainably available "digestible matter" (edible biomass) in a patch [kg/ha], RC_{ha} is the number of raster cells per hectare (again, grazing patches are constrained to be the size of the current raster resolution), and G_i is a "grazing impact factor" (unit-less multiplier, allowing for "unsustainable" grazing practices). The value of DM for each cell is calculated by a "graphing function" (a sequential series of boolean-separated linear regressions that approximate the results of a more complex regression function):

$$if: 50 \geq LC \geq 40,\ DM = 800-(10 \cdot LC),$$

$$elif: 40 > LC \geq 27,\ DM = (27.27 \cdot LC)-663.64,$$

$$elif: 27 > LC \geq 4,\ DM = (2.27 \cdot LC)+38.64,$$

$$elif: 4 > LC \geq 1,\ DM = (12.5 \cdot LC),\ else: DM = 0$$

Where, LC is the land-cover value in the 50-year succession regime of the model (coded 0-50).

Calculating wood gathering returns

Because wood is typically gathered at a set density at each patch (Karanth et al., 2006), firewood gathering returns (*FR*) are measured in kilograms of wood, and will be the same at each patch:

$$FR = W_i \cdot RC_m$$

Where W_i is the intensity at which people gather wood [kg/m^2], and RC_m is the number of raster cells per square meter (i.e., a conversion factor to scale the impacts to the current raster resolution).

Vegetation Regrowth

The actual rate of regrowth (V_r) in a patch (and thus the actual timing of the succession) depends upon the soil depth and fertility of that patch, and is calculated by taking the average of two power regressions via the following formula:

$$V_r = \frac{((-0.000118528 \cdot F^2)+(0.0215056 \cdot F)+0.0237987) + ((-0.000118528 \cdot SD^2)+(0.0215056 \cdot SD)+0.0237987)}{2}$$

Where F is the current soil fertility [percentage fertility] of the patch and SD is the current soil depth [m] of the patch. the resulting regrowth rate scales between 0 and 1[9] according to a power law so that regrowth slows exponentially as the average of soil depth and fertility approach 0. The actual rate of regrowth (V_r) is in units of "succession amount per year", so that values of V_r less than one mean that vegetation recuperates at some fraction of the "ideal" possible yearly rate.

Modeling Landscape Evolution

Estimating elevation changes due to soil creep

The module implements a diffusion equation for areas near drainage divides, a three-dimensional transport-capacity limited implementation of USPED for hillslopes and gully heads, and a transport-capacity limited reach-average shear stress function for channels.

The diffusion equation used by the MML is well-known and simulates "soil creep" – the movement of soil downslope due to the effect of gravity and particle movement from rainsplash, bioturbation, and other local factors – on portions of the landscape where there is not enough accumulated runoff for overland flow (Culling, 1965, 1963, 1960; Heimsath et al., 2002). The diffusion equation estimates the change in elevation (*dz*) directly:

$$dz = \kappa \cdot \sin(\beta)$$

Where, κ [m/1000yr] is the diffusion coefficient – an empirically-derived constant estimating the base-line soil-creep rate for different climate/vegetation regimes (REFS)), and β is the topographic slope [deg]. Thus, the value of *dz* is determined as a localized adjustment of κ, as scaled by the steepness of the local topography.

Estimating transport-capacity on hillslopes

Sheetwash and rilling/gullying are both hillslope processes, and erosion/deposition deriving from these processes in the MML are estimated using the Unit Stream Powered Erosion Deposition equation (USPED), derived from concepts described by Kirkby (1971), adapted for two dimensional landscapes by Moore and Burch (1986), and operationalized in a GIS environment by Mitasova et al. (1996a). It is an adaptation of the (Revised) Universal Soil Loss Equation (USLE/RUSLE) to scales larger than a farm field, and for and increased suite of overland flow processes[17] (Degani et al., 1979; Flanagan et al., 2003; Mitasova et al., 2001, 1996b; Renard et al., 1997, 1991; Singh and Phadke, 2006; Warren et al., 2005; Wischmeier et al., 1971; Wischmeier, 1976; Wischmeier and Smith, 1978). Although Moore and Burch (1986) referred to this approach as Unit *Stream* Power Erosion/Deposition, this name is somewhat misleading in the context implemented here, as the algorithm focuses on hillslopes, small watersheds, and small channels (i.e., rills and gullies). rather than streams, and is, in fact, *less* applicable to larger streams and rivers (Warren et al., 2005).

The USPED equation estimates the transport capacity (q_S) of flowing water at the cell, which is implemented in the MML as:

$$q_s = R \cdot K \cdot C \cdot A^m \cdot \sin(\beta)^n$$

Where *R* is the rainfall intensity factor for the region [(MJ·mm)/(ha·hr·yr)] , and is computed by an equation that combines monthly precipitation amounts (Renard et al., 1997; Renard and Freimund, 1994). Values of *R* vary from 0 with no theoretical upper limit (although a practical upper range could be said to be between 20 and 30 with values much above 30 highly unlikely under terrestrial conditions). *K* is a soil erosion resistance factor [(ton·ha·hr)/(ha·MJ·mm)] based on the percent of sand, silt, clay, and organic matter in the soil. *K* is scaled from 0 to 1 (i.e., “not erodible” to “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. *A* is the upslope contributing area (flow accumulation per unit cell resolution) and β is again the topographic slope of the cell. The exponents m and n are empirically derived and vary depending upon the process being modeled.

Implementing the USPED algorithm in a GRASS script combines GIS modules for calculating slope, aspect, and upslope accumulated area using map algebra. Input data for the script includes a raster DEM of initial surface topography, soil erodibility (K-factor as a constant for uniform soil or a raster map for variable soil), vegetation cover (C-factor as a constant or raster map), and rainfall intensity (R-factor as a constant only). An underlying bedrock topography DEM is also input to provide a limit on the total depth of unconsolidated sediment that can be eroded

Estimating transport-capacity in streams

For flow in channels, the MML estimates transport capacity as a function of shear stress acting upon the channel bottom (Foster et al., 1972; Howard and Kerby, 1983):

$$q_s = S_e \cdot K_t \cdot (\tau)^a$$

Where S_e is the annual number of storm events, K_t is a unitless transport capacity coefficient relating to the typical size of clasts in the channel (ranging from 0.001 to 0.000001, but typically 0.00001 for gravely, sandy-bottom streams), τ is the shear stress [Pa = kg/m^2], and a is and empirically derived exponent related to the type of transport in the channel (typically 1.5 for bedload, and 2.5 for suspended load).

Shear-stress is calculated according to the standard “reach-average” formula:

$$\tau = g_w \cdot \tan(\beta) \cdot R$$

Where g_w is the hydrostatic pressure of water equal to $g \cdot p_w$ (g is the gravitational acceleration constant [9.81 m/s^2], and p_w is the density of water [10000 kg/m^3]), β is the topographic slope [deg], and R [m] is the hydraulic radius of the channel. In a GIS with perfectly square cells, R is best estimated simply as the channel depth (h) [m] .

Estimating erosion/deposition potential from transport-capacity

Both USPED and the reach-average shear stress equation only estimate the transport-capacity (q_s) of flowing water at each cell. In order to determine the net elevation change (dz) predicted by these methods, the MML first must compute erosion/deposition potential (ED_p) at each cell. To do so, it assumes that the system is operating at full transport capacity, and that the divergence of q_s across the cells of a DEM in the downstream direction provides ED_p directly. In a GIS, this is done by finding the divergence in both the x and y directions (i.e., the two cardinal grid directions of a rectangular raster griding system), and summing to find the divergence in the most downstream direction (Mitasova et al., 1996a, 1996b; Warren et al., 2005):

$$ED_p = \frac{\delta q_s \cdot \cos(\alpha)}{\delta x} + \frac{\delta q_s \cdot \sin(\alpha)}{\delta y}$$

Where q_S is the transport capacity as calculated by USPED or the reach- average shear stress equation, and α [deg] is the topographic aspect of a cell.

Converting erosion/deposition potential to net elevation change

Transport capacity, and thus ED_p, is calculated in units of weight per unit area per year ([T/ha.yr] for USPED, and [kg/m^2.yr] for the reach-average shear stress equation). However, in order to iteratively model erosion and deposition across a landscape over time, the calculated values of erosion and deposition must be re- expressed as depth of sediment per cell [m]. This is done by multiplying ED_p by its areal units (hectares for USPED, square meters per cell for reach-average shear-stress equation), and dividing by the unit density of the soil (*p)* [m^3] times the cell resolution (res) [m^2]:

$$dz = \frac{ED_p \cdot u_a}{p \cdot r}$$

Soil density is approximated using the method outlined by Rawls (1983) combining the percentages of sand, silt, clay and organic matter. Like K-factor, soil density can be entered as a single value or a map of spatially varying values[21]. Although soil density is a spatially variable phenomenon.

Implementing landscape evolution

Landscape evolution is change in topography over time. The MML uses the estimated net elevation change (*dz*) in each year to represent these changes. But before implementing them, the we must know which process equation should be used to model net elevation change for each cell of the DEM. In other words, we must know which surface processes govern landscape evolution on each of the different landforms of the input landscape. Processes are not discrete, however, and there is a natural progression from diffusive soil creep (governed by raindrop force and gravity) to hillslope processes such as overland flow and rilling/gullying (governed by the strength of accumulated flow) to stream processes (governed by the strength of accumulated flow and turbulence). It is important to choose the optimal locations on the terrain for the transition between surface process models to ensure smooth transition in estimated net elevation change from one landform to the next. Although transition points vary with overall watershed geometry, area, and topographic relief, and also change during the course of a hydrologic event (e.g., as a function of rainfall intensity and duration during a storm), their general locations can be estimated in a GIS on the basis of upslope accumulated area (*A*) and topographic slope curvature.

Once the location of flow process transition boundaries is determined, it is possible to use this geometry to paste together the *dz* maps produced by each process equation in a geomorphologically appropriate "global *dz*" map. Although the process outlined above ensures that the MML uses realistic transition points between the different process equations, when the final "global *dz*" map is assembled, small linear aberrations in *dz* will be present across process transitions because it is still a "hard" boundary. Furthermore, larger aberrations in *dz* can occur at other points in the landscape when a process equation receives input conditions outside its underlying assumptions, or input numerical data which exceed its mathematical limits. While careful tuning of the equations and smoothing of the input DEM help to reduce the frequency and severity of such aberrations, they nevertheless still occur occasionally due to the abstraction required in the creation of digital topographic models. This is combated by an adaptive "soft-knee" limiter (a type of low-pass smoothing algorithm), that is calibrated to remove abnormal spikes or linear artifacts in the "global *dz*" map, while minimally affecting other areas. The smoothed "global *dz*" map is then can be added to (for deposition) or subtracted from (for erosion) the initial DEM, to create a new DEM after a cycle of land-use and landscape change. This process is iterated at each cycle of the MML to simulate decades to millennia of landscape evolution.

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