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**HYDROPHYSICAL  
PROCESSES**

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## **Patuxent Landscape Model: 2. Model Development – Nutrients, Plants, and Detritus<sup>1</sup>**

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**Abstract**—We developed a spatially explicit, process-based model of the Patuxent river watershed in Maryland, and its subwatersheds to integrate data and knowledge over several spatial, temporal and complexity scales, and to serve as an aid to regional management. The model was developed using the Library of Hydro-Ecological Modules (LHEM, <http://giee.uvm.edu/LHEM>). In this paper we continue the description of the LHEM modules focusing on nutrient cycling, vegetation growth, decomposition, and other processes, both locally and spatially. The modular approach takes advantage of the Spatial Modeling Environment [1] that allows integration of various Stella models and C++ user code, and embeds local simulation models into a spatial context. Local ecosystem dynamics are replicated across a grid of cells that compose the rasterized landscape.

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### NUTRIENT MODULES

#### *State Variables*

As in GEM, the nutrients considered in the LHEM are nitrogen and phosphorus. Various nitrogen forms,  $\text{NO}_2^-$ ,  $\text{NO}_3^-$ , and  $\text{NH}_4^+$  are aggregated into one variable representing all forms of nitrogen that are directly available for plant uptake. Available inorganic phosphorus is simulated as orthophosphate. There are two nutrient modules currently available. The distinction appears in the conceptualization of nutrients in the vertical dimension. In terrestrial ecosystems nutrients on the surface are no longer necessarily associated with surface water, and therefore need not be in the dissolved form as in GEM. Since most of the time most of the cells have no surface water,  $n_{SW}$  ( $n = \text{N}$  or  $\text{P}$ ) represents the dry deposition of nitrogen or phosphorus on the surface. Over dry periods  $n_{SW}$  continues to accumulate with incoming fluxes from air deposition or mineralization of organic material. When rainfall occurs, a certain proportion of the accumulated  $n_{SW}$  becomes dissolved and therefore is made available for horizontal fluxing and infiltration.

The first nutrient module closely follows the hydrologic fluxes and considers nutrients on the surface ( $n_{SW}$ ), in the unsaturated storage ( $n_{UW}$ ) and in the saturated layer ( $n_S$ ),  $n = \text{N}$  or  $\text{P}$ .

The second nutrient module is designed to accommodate for the aggregation of surface and shallow subsur-

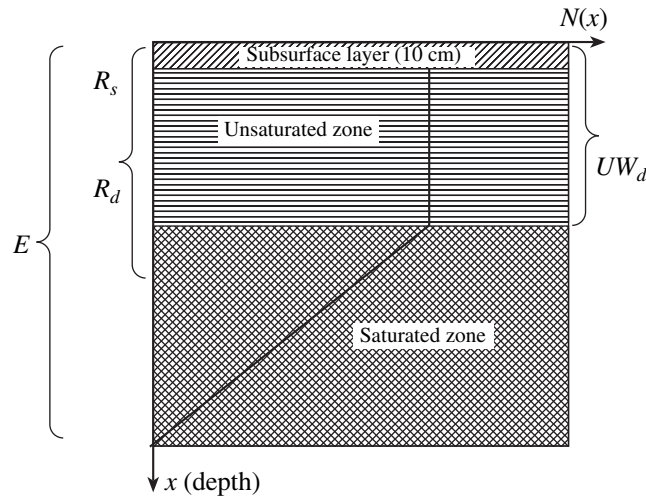
face flows in the hydrologic sector. A proportion of nitrogen and phosphorus stored in the upper soil layer is made available for fast horizontal fluxing along with nutrients on the land surface. The depth of this layer is a soil dependent parameter. In most cases we have assumed this layer to be 10 cm thick, following a similar formalization in the CNS model [2], where this upper soil layer was also assumed to be exposed to direct surface runoff. Therefore the spatial allocation of nutrient variables does not quite match that of the water. This is in attempt to minimize the number of variables, since even in this case measurements that may be used for calibration are fairly scarce. However the price that we pay for this aggregated representation is more complexity in the formalization of processes, because we have to compensate for the spatial aggregation assumed.

In this case only  $n_{SW}$  (mineral N or P on the surface), and  $n_S$  (mineral N or P in the sediment) are considered. The phosphorus cycle in both modules, features another variable  $P_{SS}$ , which is the phosphorus deposited in the sediment in particulate form, no longer available for plants uptake, and effectively removed from the phosphorus cycle. The input variables in this module are the hydrologic fluxes defined by the hydrologic modules as well as Net Primary Productivity and Root Depth calculated in the Plant dynamics modules.

#### *Loading*

There are five major sources of nutrients in the system: atmospheric deposition, fertilizer application, septic leakage, discharges from sewage treatment

<sup>1</sup> The text was submitted by the authors in English.



**Fig. 1.** Calculations of nutrients in the sediment available for root uptake. A linear decline in nutrient concentrations is assumed. *E* is the elevation, *R<sub>d</sub>* is the root zone depth, *R<sub>s</sub>* is the depth of the subsurface layer associated with the surface water flow, *UW<sub>d</sub>* is the depth of the unsaturated layer.

plants and natural decomposition of organic material. The atmospheric loading consists of dry and wet deposition. In most cases only the wet deposition is reported. To account for dry deposition we may assume that it is in proportion to wet deposition with a coefficient *D<sub>d</sub>* that may be different for different localities.

The fertilizer loading can be defined by the amount and application time. In most cases it occurs once or twice during the crop growth season and depends upon the crop, soil type and agricultural practices adopted in the area. One common way to estimate the amount of nitrogen fertilizers applied is to assume the pounds per bushel rule, when the amount of fertilizer applied per area in pounds is equal to the crop yield in bushels expected for the type of soil in the area [3]. Both atmospheric deposition and fertilizers contribute to the above ground storage of nutrients *n<sub>SW</sub>*.

The amount of nutrients discharged from sewage treatment operations is usually a point timeseries that may be fed directly into the model for those cells where the discharge occurs. In most cases it will contribute to *n<sub>SW</sub>*, but in some cases, depending upon the engineering of particular discharges may also go to *n<sub>UW</sub>* or *n<sub>S</sub>*. The leakage from septic tanks is a non-point source of pollution that may be estimated based on the amount of nutrients produced per individual per time period. For example, the amount of nitrogen is 4.8 kg/individual/year = 0.0132 kg/individual/day [4]. According to other sources this may vary: 3.5–5 kg/individual/year [5].

The natural decomposition of dead organic material also contributes to nutrient loading. It occurs both on the surface and in the soil. If *D<sub>min</sub>* is the total amount of

mineralized detritus, then we assume that *gD<sub>min</sub>* is channeled to the surface storage of nutrients, whereas  $(1 - g)D_{min}$  goes to the subsurface storage.  $0 < g < 1$  is the separation parameter, that is hard to measure and usually has to be calibrated.

*Plant Uptake*

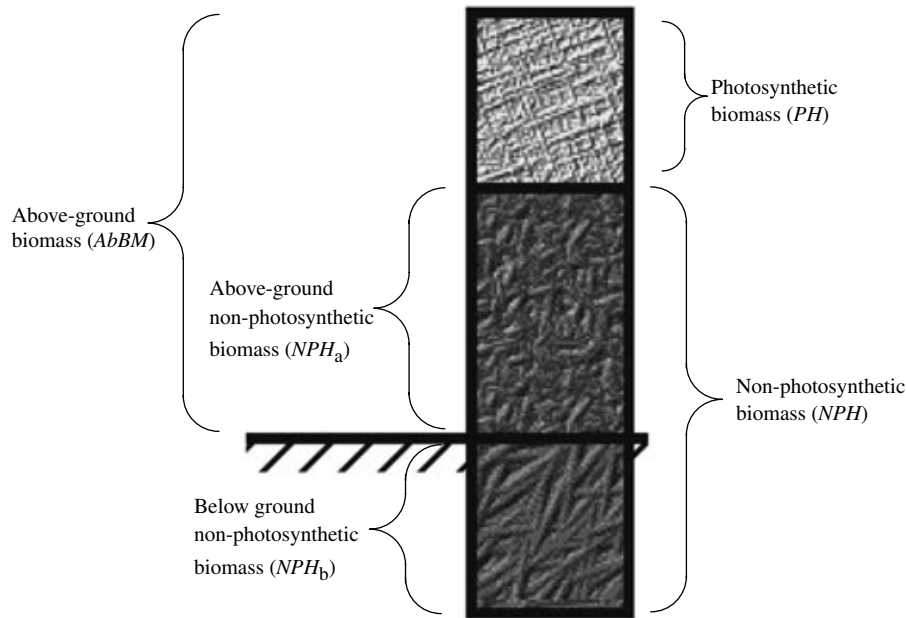
The amount of nutrients used for plant growth is in proportion to the net primary production. The nutrients in the surface storage are assumed to be available for plant uptake only when there is water to dissolve them. This water is taken to be surface water (*SW*), plus water contained in the 10 cm subsurface layer (*R<sub>s</sub>* in Fig1).

The amount of water in the subsurface layer is

$$S = \begin{cases} UW R_s / UW_d, & \text{if } R_s < UW_d, \\ UW + S(R_s - UW_d) / (E - UW_d), & \text{if } R_s > UW_d, \end{cases}$$

where *UW* is the water in the unsaturated storage, *S* is saturated water, *R<sub>s</sub>* is the depth of the subsurface layer (*R<sub>s</sub>* = 10 cm), *UW<sub>d</sub>* is the unsaturated layer depth and *E* is elevation at the given locality. The total amount of water available to dissolve the nutrients is *SW* + *S<sub>r</sub>*, and the concentration of nutrients is *n<sub>SW</sub>* / (*SW* + *S<sub>r</sub>*). The amount of nutrients available for plant uptake is then equal to the total amount of nutrients on the surface, when surface water is present, or is represented by only a part of *n<sub>SW</sub>* that is estimated to be in the subsurface storage:

$$n_{A_{SW}} = \begin{cases} n_{C_{SW}}(SW + S_r) = n - SW, & \text{if } SW > 0, \\ n_{C_{SW}}(1 - n_{D_d})S_r, & \text{if } SW = 0. \end{cases}$$



**Fig. 2.** Major plant components considered in the plant module. Plant biomass is assumed to consist of the photosynthetic (*PH*) and the non-photosynthetic (*NPH*) biomass. The ratio between above ground non-photosynthetic biomass (*NPH<sub>a</sub>*) and below ground non-photosynthetic biomass (*NPH<sub>b</sub>*) is assumed to be constant.

The coefficient  $n_{D_d}$  is used to separate between the amount of nutrients that are dissolved and further infiltrated into groundwater and the nutrients that are retained in the subsurface layer ( $R_s$ ).

Then for the uptake of nutrients from the surface we may assume the rate:

$$n_{SW_{up}} = \min(n_{A_{SW}}, n_{U_{SW}NPP}),$$

where *NPP* is the net primary production of plants calculated in the plants module, and  $n_{U_{SW}}$  is the parameter for nutrient requirements of photosynthesis.

The description of nutrients uptake from the sediment (both unsaturated plus saturated zone is more complicated, since we need to parameterize the gradual decrease of nutrient concentration with depth (Fig. 1), also taking into account the depth of the root zone. Assuming that the concentration of nutrients is the same throughout the unsaturated zone and then decreases to zero at the bottom of the elevation considered, we may write that

$$n_S = \int_{R_s}^E N(x)dx,$$

where  $N(x)$  is the vertical distribution of nutrients in the sediment in Fig. 2. Then the amount of nutrients available for uptake in the root zone  $R_d$  is

$$n_S(y) = \int_{R_s}^y N(x)dx.$$

Therefore the amount of nutrients available for plant uptake in the sediment is

$$n_{A_y} = \begin{cases} 0, & \text{if } R_d \leq R_s, \\ \frac{n_S(2E - UW_d - R_d)(R_d - R_s)}{(E - R_d)(E - UW_d)}, & \text{if } R_d > R_s \geq UW_s, \\ \frac{n_S}{E + UW_d - 2R} \left( 2(UW_d - R_s) + \frac{(2E - UW_d - R_s)(R_d - UW_d)}{E - UW_d} \right) & \text{otherwise.} \end{cases}$$

Here  $R_d$  is the root depth calculated in the plants module. The uptake of nutrients from the sediment is then similar to the one calculated for the surface:

$n_{SD_{up}} = \min(n_{A_S}, n_{U_S}NPP)$ , where  $n_{U_S}$  is the uptake parameter for the sediment storage of nutrients. In all the above formulas  $n = N$  or  $P$  for nitrogen or phosphorus, respectively.

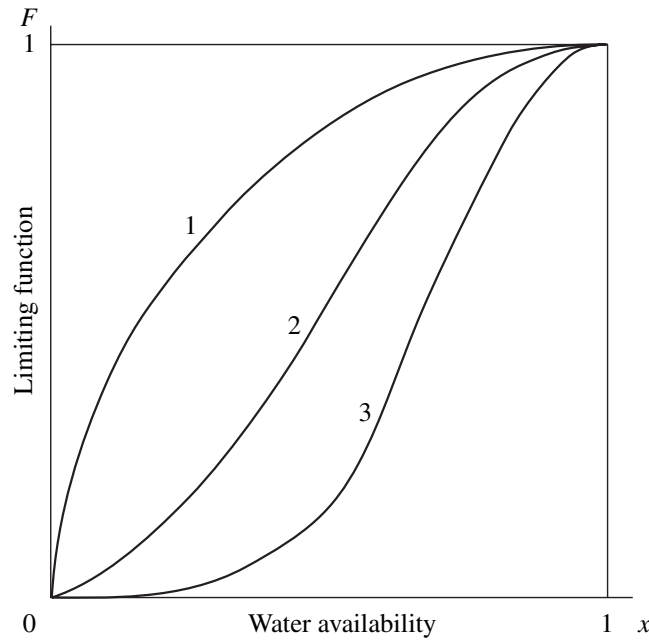


Fig. 3. General form of limitation function used for water availability. (1)  $m = 0.5$ ; (2)  $m = 2.0$ ; (3)  $m = 5.0$ .

*Vertical Transport*

Nutrients are dissolved in water and carried with hydrologic flows, both in the vertical and horizontal dimensions. The downflow from  $n_{SW}$  to  $n_S$  is associated with the infiltration of water from the surface into the sediment:

$$N = n_{C_{SW}}(n_{D_d}(UW_p + S_p + SW_S)),$$

where  $n_{C_{SW}}$  is the nutrient concentration on the surface,  $n_{D_d}$  is the separation coefficient discussed above,  $UW_p$  and  $S_p$  are the amount of rainfall infiltrated into unsaturated storage and saturated storage respectively, and  $SW_S$  is the flow from surface water into the saturated storage. The reverse process occurs when saturated water hits the surface and flows out:

$$N_{up} = n_{C_S}S_{SW},$$

where  $n_{C_S}$  is the nutrient concentration in the sediment,  $n_{C_S} = n_S/(S + SW)$ , and  $S_{SW}$  is the flow from saturated storage to the surface. Both  $S_{SW}$  and  $SW_S$  flows are calculated in the hydrologic module.

*Sorption*

At higher concentrations,  $PO_4$  becomes adsorbed by organic material and metal ions in the soil. The rate of sorption is controlled by the amount of organic material in the soil. At lower concentrations of soluble  $PO_4$  in the sediment,  $P_{SS}$  becomes available again and returns back into the nutrient cycle.

*Spatial Implementation*

The horizontal spatial fluxes of nutrients are closely tied to the hydrologic flows. Therefore they are described together with the hydrologic flows on the surface (SWTRANS1 and SWTRANS2), and in the ground (GWTRANS).

PLANTS

*State Variables*

In the plant module we simulate the growth of higher vegetation. It will be the macrophytes in an aquatic environment, trees in forests, crops in agricultural habitats, grasses and shrubs in grasslands. The plant biomass ( $kg/m^2$ ) is assumed to consist of the photosynthetic ( $PH$ ) and the non-photosynthetic ( $NPH$ ) components. In addition to that we distinguish between the above ground and the below ground biomass (Fig. 2).

Another state variable ( $B_t$ ) is employed to track the so-called biological time in the module. Biological time is the sum of effective daily average temperatures over the life span of the plant (growing degree-days). The temperature is called effective if it exceeds a certain value ( $5^\circ C$  in our case). These are the temperatures that are most suitable for the physiological development of the plant. Therefore the total of such temperatures is a good indicator of the plant life stage and may be used to trigger certain processes such as sprouting and appearance of reproductive organs.

The module imports temperature and solar radiation data from the physical module, nutrient availability from the nutrient modules, and water availability from the hydrologic module.

### Temperature Limitation

There are a great variety of functions that can be used to represent the temperature ( $T$ ) limitation  $L_t$  on growth processes [6]. In most cases a bell-shaped curve is described, which has a range of optimal temperatures where the limitation is negligible ( $L_t = 1$ ) whereas at other temperatures the growth slows down or stops completely ( $L_t > 0$ ).

This behavior is provided by a function described by Lassiter and Kearns [7]:

$$L_t = \exp(s_1(T - T_{opt})) \left( \frac{T_{max} - T}{T_{max} - T_{opt}} \right)^{s_1(T_{max} - T_{opt})},$$

Here  $T_{opt}$  is the optimal temperature,  $T_{max}$  is the maximal temperature after which the growth stops,  $s_1$  is the curvature parameter that regulates the form of the curve.

Another function [8] that is more complex, but offers more flexibility in defining the shape of the temperature limitation curve is:

$$L_t = \begin{cases} f_0^{(1 - T/T_{max})^*}, & \text{if } T < T_{opt}, \\ f_m \left( \frac{T_{max} - T}{T_{max} - T_{opt}} \right)^{s_1}, & \text{otherwise,} \end{cases}$$

where the additional parameters are  $f_0$  - the value of the function at zero temperature ( $L_t(0) = f_0$ ); and  $f_m$  - the value of the function at maximal temperature ( $L_t(T_{max}) = f_m$ ).

### Light Limitation

Another factor that limits photosynthesis is the availability of light. The light limitation ( $L_i$ ) is defined as:

$$L_i = \frac{I}{I_s} \exp\left(1 - \frac{I}{I_s}\right),$$

where  $I$  is the incoming solar radiation, and  $I_s$  is the saturation level for irradiation.

### Water Limitation

If there is too much or too little water the process of plant growth slows down. To account for the deficit of water the function  $W_0$  (Fig. 3) is used.

$$W_0 = \sin(W_a \pi / 2)^m,$$

where  $W_a$  is the available water,  $m$  is the water deficit tolerance coefficient. When the tolerance is high ( $m < 1$ ) the plant can grow fast enough even under low water availability. When tolerance is low ( $m \gg 1$ ) the plant growth declines whenever water availability becomes below 1.

As with inadequate water availability, excess water may also be detrimental to plant growth. Certain plants require that a proportion of the root zone be above the water table to ensure that there is no limitation. Other plants grow well as long as they are covered by surface water to a certain level, but then if there is more water their growth becomes inhibited. The function  $W_1$  is to take into account both conditions. The coefficient  $k$  - the tolerance to high water stage represents the tolerance to surface water stage when it is negative, and represents the requirement of a proportion of the root zone to be above the water table when it is positive:

$$W_1 = \begin{cases} 1/(1 + \exp(SW + k)), & \\ \text{if } k < 0 \cup SW > -k, & \\ \min(1, UW/R_d/k), & \text{if } k > 0 \cup R_d > 0, \\ 1 & \text{otherwise.} \end{cases}$$

here  $SW$  is the surface water,  $UW$  is the water in the unsaturated storage, and  $R_d$  is the root depth. As the surface water stage exceeds the tolerance level, (or the unsaturated depth becomes less than  $< R_d k$ ),  $W_1$  becomes smaller than 1 and limits the plant growth.

The overall water limitation ( $0 < L_w < 1$ ) is then calculated as

$$L_w = \min(W_0, W_1).$$

### Nutrient Limitation

The standard Michaelis-Menten equation is assumed to calculate the uptake ( $f_n$ ) of each individual nutrient:

$$f_n = S_n / (S_n + C_n),$$

where  $S_n$  is the nutrient ambient concentration,  $C_n$  is the half-saturation coefficient;  $n = N$  for nitrogen or P for

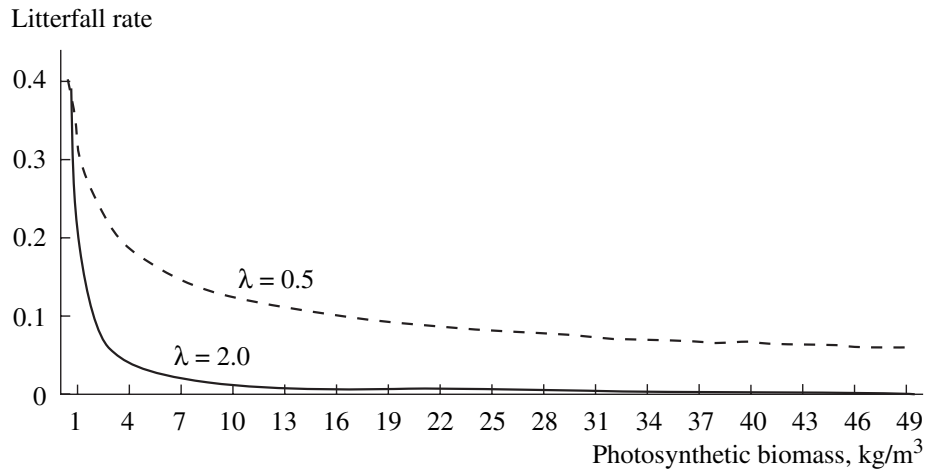


Fig. 4. Litterfall function. As the remaining photosynthetic biomass  $PH$  decreases the rate of litterfall increases.

phosphorus. The Liebig principle of limiting factors is driving the overall nutrient limitation:

$$L_n = \min(f_N, f_P).$$

*Net Primary Production*

The four limiting functions for light, temperature, moisture and nutrient availability are assumed to be multiplicative. The net primary production ( $F_{NPP}$ ) is then calculated as

$$F_{NPP} = \alpha_{npp} L_t L_i L_w L_n PH (1 - PH/PH_M),$$

where  $\alpha_{npp}$  is the photosynthesis rate (1/day), and  $PH_M$  is the maximal photosynthetic biomass for the given type of plant.

*Planting*

Some types of plants, such as agricultural crops, are planted at a certain time,  $t_p$ . During planting, a given amount of biomass is introduced into the system and then starts to grow. If seeds are planted, then the biomass introduced is non-photosynthetic. This biomass remains inactive until the biological time  $B_t$  becomes larger than a certain threshold,  $B_{st}$ . After that, the translocation process described below starts to channel the biomass from the non-photosynthetic (NPH) to the photosynthetic (PH) storage. As PH appears, photosynthesis begins and the plant starts to grow.

*Translocation*

We describe the distribution of new biomass among the model compartments based on the following two proportions:

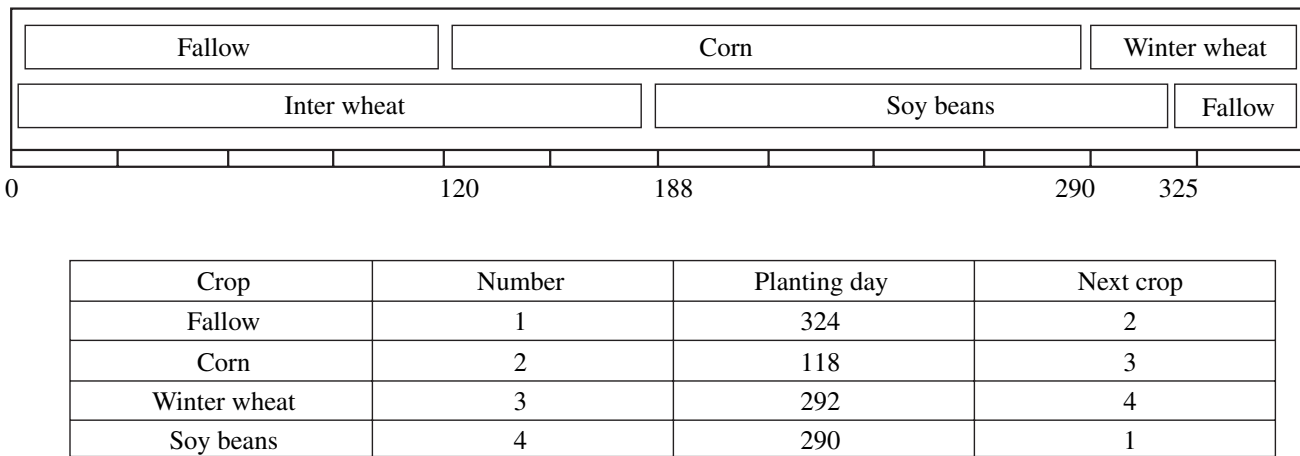
$\alpha^* = \max(\alpha) = \max(PH/BM_a)$  is the maximum ratio of photosynthetic biomass to above ground biomass ( $BM_a$ ); and

$\beta = NPH_a/NPH_b$  is the ratio of above ground non-photosynthetic biomass ( $NPH_a$ ) to below ground non-photosynthetic biomass ( $NPH_b$ ), which is assumed to be constant.

Using these two ratios we can calculate most of the other model fluxes and compartments. The above ground non-photosynthetic biomass is  $NPH_a = \beta NPH / (1 + \beta)$ , and the below ground component is  $NPH_b = NPH / (1 + \beta)$ . When there is more photosynthetic biomass produced than transferred into the non-photosynthetic storage, then  $\alpha > \alpha^*$ . During periods that are unfavorable for photosynthetic production, may become small,  $\alpha < \alpha^*$ . However at all times the plant is assumed to try and maximize photosynthetic biomass,  $\alpha = \alpha^*$ . The two processes that are employed for this purpose are Transup and Transdown. Transup describes the translocation of material from the non-photosynthetic storage (roots, branches) into the photosynthetic parts of the plant (leaves), and dominates at the start of the growth period or during periods unfavorable for growth when stored assimilates are used to maintain plant growth. Reciprocally the Transdown dominates during periods of effective photosynthesis, when more assimilates are produced than currently needed and a portion can be channeled into storage in the non-photosynthetic parts of the plant. In both cases the plant tries to maintain the proportion between the photosynthetic and non-photosynthetic parts as close to  $\alpha^*$  as possible.

The above ground biomass  $BM_a = PH + NPH_a = PH + \beta NPH / (1 + \beta)$ .

Therefore  $\alpha = PH / [PH + \beta NPH / (1 + \beta)]$ , and the translocation mechanism should operate in such a way that  $\alpha > \alpha^*$ . This condition is altered for certain plants



**Fig. 5.** Diagram of crop rotation most commonly implemented in Maryland. A user code modifies the Habitat Map used in the model according to this rotation. As a result the modules get different sets of habitat dependent parameters at different times of the year.

that grow reproductive organs (such as crops). As soon as the reproduction process comes into play, the plant changes the translocation patterns and growth of the reproductive organs becomes a priority. Since we do not have a special variable to account for these organs we assume that they are part of the non-photosynthetic storage and when biological time exceeds the threshold for reproduction, the translocation is altered in favor of the NPH stock.

The proportion of the newly produced photosynthetic material that is translocated into the non-photosynthetic storage is then described as:

$$T_{PH} = \begin{cases} \cos((\pi/2)\alpha^*/\alpha), & \text{if } \alpha > \alpha^*, \\ 1 - 1/B_r, & \text{if } B_r > b_r, \\ 0 & \text{otherwise,} \end{cases}$$

where  $b_r$  is the biological time threshold after which reproductive organs start to develop. The reverse process of translocation from the non-photosynthetic storage to generate photosynthetic biomass, Transup, occurs at the beginning of the vegetation period and is also triggered by the biological time counter  $B_r$ .

*Mortality, Litterfall and Harvest*

These three flows occur at different times but they all decrease the plant biomass. Mortality is a natural process of decay of certain plant parts that is assumed to occur at a constant rate as a proportion of the photosynthetic and non-photosynthetic biomasses. Deciduous plants shed their leaves (PH biomass) in the fall. The process is triggered by changes in day length: once day length becomes smaller than a certain threshold value, the litterfall process starts. The litterfall process

starts slow and then accelerates as less photosynthetic biomass is left:

$$F_L = \begin{cases} 0, & \text{if } d_1 \cap D \geq D(t-1), \\ PH, & \text{if } PH < p_{\min}, \\ \lambda(PH_{\max}/PH)^a & \text{otherwise.} \end{cases}$$

Here the first condition only allows litterfall to occur in fall when the day length  $D$  is decreasing and becomes less than the threshold value  $d_1$ . The second condition clears the foliage completely after a certain minimal biomass  $p_{\min}$  is reached. The third condition is the gradual litterfall that starts when the day length requirement is reached;  $\lambda$  is the litterfall rate and  $n$  is the intensity ( $n = 3$ );  $PH_{\max}$  is the maximal biomass reached during the season. It serves as a reference point from which to decrease the photosynthetic biomass (Fig. 4).

The harvest is another process that removes plant biomass. At harvest time,  $t_H$ , certain proportions of  $PH$  and  $NPH$  are taken out of the system. Right after harvest occurs, a certain portion,  $\rho$ , of the biomass left, is made available for the mortality flows that quickly channel the living biomass into the dead organic pool and make it available for decomposition. For seasonal crops,  $\rho = 1$ , and all the biomass remaining after harvest rapidly dies off. For perennial crops,  $\rho \rightarrow 0$ , and there is no additional mortality caused by the harvest.

*Spatial Implementation and Crop Rotation*

The spatial distribution of plants is fixed; plants do not travel horizontally in the landscape. Therefore the only spatial changes that can occur to the vegetation are connected to human activities, such as crop rota-

tion, or other management practices. The spatial module that takes care of crop rotation is called by CRO-PROT (HAB\_MAP, DAYJUL), where DAYJUL is the Julian day, and HAB\_MAP is the Habitat map of the area. The function scans the whole area and switches land use type from one to another according to the current land use and the Julian day. The sequence of crops is fixed and is determined by the matrix (Fig. 5) where each crop is associated with a certain time interval. For each of the cells ( $i, j$ ) and each of the crops, we perform the operation:

$$\begin{aligned} & \text{If}(\text{TIME} = \text{TIME}_k \ \&\& \ \text{HAB\_MAP}(i, j) \\ & = \text{CROP}_{k-1}) \ \text{HAB\_MAP}(i, j) = \text{CROP}_k, \end{aligned}$$

where  $\text{TIME}_k$  is the planting day for  $\text{CROP}_k$ .

## DETRITUS

### *State Variables*

At present this module serves predominantly to close the nutrient and material cycles in the system, it does not go into all the details of the multi-scale and complex processes of leaching and bacterial decomposition. As biomass dies off, part of it turns into Stable Detritus,  $D_S$ , whereas the rest becomes Labile Detritus,  $D_L$ . The proportions between the two are driven by the lignin content, which is relatively low for the *PH* biomass and is quite high for *NPH* biomass. Labile detritus is decomposed directly, and stable detritus is decomposed either to labile detritus, or becomes Deposited Organic Material (DOM),  $D_{DOM}$ .

### *Decomposition*

Avoiding much of the complexities, we assume the decomposition process as linear. The decay of Stable Detritus is

$$F_{DS} = d_0 DS + d_1 L_{DT} D_S,$$

where  $d_0$  is the flow rate of stable detritus transformation into  $D_{DOM}$ ,  $d_1$  is the flow rate between stable and labile detritus. The latter flow is modified by Vant-Hoff temperature limitation function  $L_{DT} = 2^{(T-20)/10}$ , where  $T$  is the ambient air temperature ( $^{\circ}\text{C}$ ). The decomposition of Labile Detritus and DOM are described similarly as linear functions modified by the Vant-Hoff temperature function.

## CONCLUSIONS

Somewhat in contrast to GEM, in the modular approach we do not intend to design a unique general model. In this case our goal is to offer a framework that can be easily extended and is flexible to be modified. A module that performs best in one case may not

be sufficient in another. The goals and scale of a particular study may require a completely different set of modules that will be invoked and further translated by the SME into a working model. Though STELLA may not be perfect for all models and processes involved, by using it to describe the modules we can provide the transparency that is essential to reimplement modules in different contexts and environments.

There is a certain disparity between the software developer and the researcher views upon models and modules. For a software developer, a module is an entity, a black box, which should be as independent as possible, and should be as easy as possible to combine with other modules. This is especially true for the federation approach to modular modeling and is well demonstrated by the web-based modeling systems. The utility of such applications may be marginal from the research viewpoint.

For a researcher a model is predominantly a tool for understanding the system. By plugging together a number of black boxes, for which specifics and behavior is obscure and hardly understood, we do not significantly increase our knowledge about the system. The results generated are difficult to interpret when there is not enough understanding of the processes that are actually modeled. As noted above this is especially characteristic of ecological and socio-economic systems, which are complex and allow much ambiguity in their formalization. The decomposition of such systems requires careful analysis of spatial and temporal scales of processes considered and is very closely related to specific goals of the model built.

We argue that in this context the modular approach can be useful if the focus is shifted from reusability and “plug-and-play”, to transparency, analysis and hierarchical description of various processes and system components. With the modules being transparent and open for experiment and analysis, the researcher can better understand the specifics of the model formalism that is inherited. It is then easier to decide whether a module is suitable or if it should be modified and tuned to the specific goals of the particular study. It is mostly for this reason that we found the LHEM approach most useful for the PLM development.

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