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Supplement of

A sub-canopy structure for simulating oil palm in the Community Land Model (CLM-Palm): phenology, allocation and yield

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Supplementary materials

Description of the oil palm phenology in CLM-Palm

The following sections describe the life cycle of each phytomer as well as the planting, stem and root turnover, and rotation (replanting) for the whole plant. Nitrogen retranslocation is implemented for each phytomer during its senescence. Summary of new phenological parameters introduced for the palm PFT is in Table A1 in the Appendix.

1. Planting and leaf initiation

Planting is implemented in the similar way as in the CLM4.5 crop phenology except that GDD_{15} (growing degree-days with 15 °C base temperature) is tracked since planting and an option of transplanting is enabled. An initial phytomer emergence threshold (GDD_{init}) is prescribed for attaining the first leaf initiation after planting (Table A1). When GDD_{init} is zero, it implies transplanting from nursery instead of seed sowing in the field. Oil palm seedlings usually grow in nursery for 1-2 year before being transplanted into the field. Therefore, in this study GDD_{init} is set to zero and the first new phytomer is assumed to initiate immediately after transplanting in the field. An initial total leaf area index (LAI) of 0.15 is assigned to the existing expanded phytomers, whose leaf sizes are restricted to be within 10% of the maximum phytomer LAI ($PLAI_{max}$) (Table A2).

The oil palm phytomers initiate as leaf primordia in the apical bud and then appear as leaves on the stem successively according to relatively stable intervening periods, termed plastochron (the duration in terms of heat unit (GDD) between successive leaf initiation events) and phyllochron (the rate of leaf emergence from the apical bud). Here for simplicity, the phyllochron is assumed equal to the plastochron. As the apical buds in palms usually do not start to accumulate dry mass immediately after physiological initiation but wait until several phyllochrons before expansion (Navarro et al., 2008), we define leaf initiation as the

start of active accumulation of leaf C in this model, so that the phenological steps and C and N allocation process can be at the same pace.

A parameter *phyllochron* is prescribed with an initial value of 130 degree-days at planting with reference to GDD_{15} and it increases linearly to 1.5 times at 10-year old (Huth et al., 2014). Given GDD_{init} and *phyllochron*, a heat unit index H_p^{init} for triggering leaf initiation can be calculated for each new phytomer when a preceding phytomer initiates:

$$\begin{aligned} H_1^{init} &= GDD_{init} \\ H_{p+1}^{init} &= H_p^{init} + \textit{phyllochron} \end{aligned} \quad \text{Eq. S1}$$

where subscripts p and $p+1$ refer to successive phytomers and 1 refers to the first new phytomer initiated after planting.

As the GDD accumulates since planting, new phytomers will be turned on in sequence when $GDD_{15} > H_p^{init}$, and will enter the 7-step life cycle one by one. The timing of later phenological steps for each new phytomer is determined at the time of initiation by adding the length of a corresponding phase period (Table A1). Each newly initiated phytomer is assigned a negative rank of $-N$ and remains packed in the bud until the next phase of leaf expansion is triggered. The oldest unexpanded phytomer (spear leaf), right before expansion, has a rank of -1 . The GDD period between leaf initiation and expansion is used to calculate the number of bud phytomers that have already initiated before transplanting, i.e. $N = \frac{GDD_{exp}}{\textit{phyllochron}}$.

2. Leaf expansion

During the phase from initiation to leaf expansion, leaf C already starts to build-up in the bud or spear leaf but it remains photosynthetically inactive. The thermal threshold for leaf expansion is calculated by $H_p^{exp} = H_p^{init} + GDD_{exp}$. Only when $GDD_{15} > H_p^{exp}$ for a phytomer ranked -1 , the leaf starts to expand and becomes photosynthetically active. Its rank

changes to a positive value of 1, while the ranks of other phytomers all increase by 1 at the same time. The expansion phase lasts for roughly 5-6 phyllochrons until leaf maturity (Legros et al., 2009).

Hereafter, the pre-expansion and post-expansion growth periods, distinguished by negative and positive ranks, are treated separately so as to differentiate non-photosynthetic and photosynthetic increases in leaf C. The following post-expansion phases and their thresholds are determined with reference to H_p^{exp} .

3. Leaf maturity

Another phenological step is added for the timing of leaf maturing so as to control the period of post-expansion leaf growth for each phytomer. An oil palm leaf usually reaches maturity well before fruit-fill starts on the same phytomer. Therefore, we set the parameter $GDD_{L.mat}$ to be smaller than $GDD_{F.fill}$ (Table A1) so that post-expansion leaf growth continues for 2-3 months (5-6 phyllochrons) and stops around 6 months before fruit-fill. The phenological threshold $H_p^{L.mat}$ is calculated as $H_p^{L.mat} = H_p^{exp} + GDD_{L.mat}$.

4. Fruit filling

Fruit-fill starts on a phytomer when GDD_{15} exceeds a heat unit index $H_p^{F.fill}$. This threshold is calculated by $H_p^{F.fill} = H_p^{exp} + GDD_{F.fill}$. At this point, the phytomer enters reproductive growth. Growth allocation increases gradually for the fruit component while leaf C and LAI remain constant on the mature phytomer until senescence. Due to the fact that most inflorescences on the initial phytomers within 2 years after planting are male (Corley and Tinker, 2003), another threshold GDD_{min} is used to control the beginning of first fruiting on the palm. Only when $GDD_{15} > GDD_{min}$, the mature phytomers are allowed to start fruit-filling.

5. Fruit harvest and output

Fruit harvest occurs at one time step when a phytomer reaches fruit maturity, measured by a heat unit index $H_p^{F.mat} = H_p^{exp} + GDD_{F.mat}$. Since GDD build-up is weather dependent and phyllochron increases through aging, the harvest interval is not constant. New variables track the flow of fruit C and N harvested from each phytomer to PFT-level crop yield output pools. The fruit C and N outputs are isolated and are not involved in any further processes such as respiration and decomposition, although their fate is largely uncertain.

6. Litter fall

For oil palm, leaf litter-fall is performed in two phases: senescence and pruning. Senescence is simulated as a gradual reduction in photosynthetic leaf C and N on the bottom phytomers when $GDD_{15} > H_p^{L.sen}$, where $H_p^{L.sen} = H_p^{exp} + GDD_{L.sen}$. These phytomers are allowed to stay on the palm until pruning is triggered. Their senescence rates are calculated as the inverse of the remaining time until the end of a phytomer's life cycle (GDD_{end}). Leaf C removed during this phase is not put into the litter pool immediately but saved in a temporary pool $C_{leaf}^{senescent}$ until pruning, while the photosynthetic LAI of senescent phytomers are updated at every time step. The reason to do this is that each oil palm frond is a big leaf attached tightly to the stem and its leaflets do not fall to the ground during senescence unless the whole frond is pruned. Thus, the dynamics of soil litter pool and decomposition process could be represented better with this function. Nitrogen from senescent phytomers is remobilized to a separate N retranslocation pool that contributes to photosynthetic N demand of other phytomers and avoids supplying excessive amount of N to the litter. The proportion of N remobilized from senescent leaves before pruning is adjusted by the length of senescent period ($GDD_{end} - GDD_{L.sen}$) with a given pruning frequency, and the rest N goes to the litter pool.

Pruning is conducted at one time step if the number of expanded phytomers (including senescent ones) exceeds the maximum number allowed on a palm ($mxlivenp$). All senescent phytomers are subject to pruning at the time of harvest and their remaining C and N together with the temporary $C_{leaf}^{senescent}$ pool are moved to the litter pool immediately. The frequency and intensity of pruning is determined through the combination of $mxlivenp$, $GDD_{L.sen}$ and $phyllochron$. A larger $mxlivenp$ gives lower pruning frequency and a smaller $GDD_{L.sen}$ results in more senescent leaves being pruned at one time. Besides, since $phyllochron$ increases by age, the rate of phytomer emergence decreases and thus pruning frequency also decreases when the plantation becomes older.

7. Stem, roots and rotation

Unlike other crops, the oil palm stem is represented by two separate pools for live and dead stem tissues (Fig. 1a). Although the stem of oil palm is not truly woody, field observations have found that the stem section below the lowest phytomer only contains less than 6% of live tissues in the core of trunk for transporting assimilates to the roots (van Kraalingen et al., 1989). This is similar to the stem of most woody trees that largely consists of functionally dead lignified xylem. Therefore, conversion from live to dead stem for oil palm follows the CLM stem turnover function for trees, except that the turnover rate is slightly adjusted to be the inverse of leaf longevity (in seconds), such that when a leaf is dead the stem section below it will mostly become dead. Leaf longevity is around 1.6 years measured from leaf expansion to the end of senescence. The oil palm fine-root turnover follows the CLM scheme for trees and crops which also uses a turnover rate as the inverse of leaf longevity. When the maximum plantation age (usually 25 years) of oil palm is reached and a new rotation cycle starts, the whole PFT is turned off and all C and N of the leaves, stem and roots go to litter. Existing fruit C and N of mature phytomers go to the fruit output pools. The PFT is then replanted in the next year and enters new phenological cycles.