

SI Text 1: Global evaluation of nutrient enabled version land surface model ORCHIDEE-CNP v1.2 (r5986)

Sun et al.

Correspondence to: Daniel S. Goll (dsgoll123@gmail.com)

Abstract. Here, model modifications for the global version of ORCHIDEE-CNP (revision 5986) since the last published revision (r4630) are described. For complete description of nutrient cycles see Goll et al. (2017, 2018), for general model description see Krinner et al. (2005), and for plant allocation see Zaehle and Friend (2010), Naudts et al. (2015). For code access see main manuscript.

5 1 Modifications

The representation of the nitrogen and phosphorus cycles is described in detail in Goll et al. (2017) with some modification related to soils in Goll et al. (2018). Here we report only model modifications related to the nutrient cycles since the last published revision (r4630). If not stated otherwise, we use the parameterization of ORCHIDEE trunk version revision 4695. We use a similar nomenclature as in earlier publications (Naudts et al., 2015; Goll et al., 2017, 2018).

10 1.1 Photosynthetic capacity

In ORCHIDEE-CNP (r4630) (Goll et al., 2017) the photosynthetic capacity on leaf level is a function of leaf nitrogen concentration using an empirical relationship (Kattge et al., 2009). There is evidence that leaf phosphorus concentration affects photosynthesis characteristics (Walker et al., 2015). Therefore, we exchanged the original empirical relationship with a new one which links leaf nitrogen and phosphorus concentration ($P_{leaf}^*, N_{leaf}^*; \times 10^{-3} \text{ g(N,P)g}^{-1}(\text{Dryweight})$) and maximum
15 carboxylation capacity ($V_{cmax}; \mu\text{mol}(\text{CO}_2)\text{m}^{-2}\text{s}^{-1}$) and maximum rate of electron transport ($J_{max}; \mu\text{mol}(\text{CO}_2)\text{m}^{-2}\text{s}^{-1}$) of photosynthesis based on a compilation of measurements on 451 plant species (Ellsworth et al. in preparation). The coefficient relating maintenance respiration to tissue nitrogen concentration ($c_{r,maint}$) had to be re-calibrated to the relationship between new leaf nitrogen and V_{cmax} (Table 1).

1.2 Stoichiometry

20 In ORCHIDEE-CNP (r4630) (Goll et al., 2017), narrow plant functional type (PFT)-specific ranges for leaf phosphorus to nitrogen concentration ($pn_{leaf,min} - pn_{leaf,max}$) are used. Here, we use a wide range for leaf phosphorus to nitrogen concentration which is common to all PFTs (Table 1). A globally uniform range facilitates the evaluation of the model as the predicted gradient in leaf phosphorus to nitrogen concentration along latitudes is independent of the prescribed land cover. The range of

leaf phosphorus to nitrogen concentration chosen here is in line with the validity of the leaf nutrient - photosynthetic capacity relationship (Ellsworth et al. in preparation).

As a consequence of the wide range in leaf phosphorus to nitrogen concentration, the coefficients in the function for the plasticity of the leaf phosphorus to nitrogen concentration had to be recalibrated (replacing eq.11 in Goll et al. (2017)):

$$5 \quad D_{leaf,np} = \begin{cases} D_{max}(1 - \exp[-(1.3 \frac{1/pn_{leaf} - 1/pn_{leaf,min}}{1/pn_{leaf,max} - 1/pn_{leaf,min}})^{7.1}]) & \text{for } P_{labile} < G_P \\ D_{max} \exp[-(1.3 \frac{1/pn_{leaf} - 1/pn_{leaf,min}}{1/pn_{leaf,max} - 1/pn_{leaf,min}})^{7.1}] & \text{otherwise} \end{cases} \quad (1)$$

where D_{max} [] is the maximum change in phosphorus to nitrogen ratio of new biomass relative to the stoichiometry of existing biomass (Goll et al., 2017), P_{labile} [g(P)m⁻²] the size of plant labile phosphorus pool, G_P [g(P)m⁻²t⁻¹] phosphorus allocated to growth.

Further, we disabled the stoichiometric flexibility of sapwood and heartwood biomass which was shown to improve the realism of the simulated response of vegetation to artificially elevated carbon dioxide concentration at two forest sites (Meyerholt and Zaehle, 2015) based on an earlier nitrogen enabled version of ORCHIDEE (Zaehle and Friend, 2010).

1.3 Temperature control on biochemical mineralisation and plant nutrient uptake

The empirical function (f_{temp} ; eq.5 in Goll et al. (2017)) to scale biochemical mineralisation and plant nutrient (nitrogen and phosphorus) uptake according to soil temperature was removed. f_{temp} was originally introduced in the nitrogen enabled version of ORCHIDEE (Zaehle and Friend, 2010) to avoid the accumulation of nitrogen within plants when temperatures are low. This function has proven to be not needed due to the control of nutrient uptake by the respective other nutrient (Goll et al., 2017). It was thus removed.

1.4 Phenology of grasses

In ORCHIDEE, grass senescence is controlled by cold and drought-stress (Krinner et al., 2005). The original module assumes that the turnover of all plant tissue is controlled by leaf senescence with the exception of carbohydrate reserve (i.e., synchronous senescence of leaf, root and stem as an annual grass). This is not in line with observational evidence. A review by Gill and Jackson (2000) estimated that annual root turnover is 53% (100% indicating a synchronous leaf root senescence) in perennial grasses. Belowground parts of grasses can enter a dormant state undergoing significant metabolic changes including decreased respiration (e.g., Shane et al. (2009)). This facilitates the regrowth of a plant following dormancy from the belowground carbon and nutrient reserves. In fact, perennial grasslands with root survival during winter are widespread

Here, we uncouple root senescence from aboveground parts (e.g. leaves) during periods of cold and drought-stress. Instead, root turnover is solely based on root age (Krinner et al., 2005). We implement root dormancy (after leaf senescence completion) by reducing its maintenance respiration by 90% following Table 1 of Shane et al. (2009), and allow root acquisition of soil nutrients as long as root biomass exists (Malyshev and Henry, 2012). It should be noted that complete root senescence (i.e. total loss of root biomass) can still happen for extremely long droughts when maintenance respiration depletes carbohydrate reserves.

1.5 Fire

When biomass is consumed by fire, a part of its nutrients are released into the atmosphere as emissions (Krinner et al., 2005), the rest remains within the biomass residues. In ORCHIDEE-CNP, we apply the emission factors (e_N, e_P) from Akagi et al. (2011) to estimate N and P emitted from different types of biomass during burning, whereas the remaining ($1 - e_N, 1 - e_P$) nutrient in biomass are transferred to the litter pools. In ORCHIDEE we use PFT-specific emission factors distinguishing between tropical forest, temperate forest, boreal forest, and C3 (pasture maintenance) and C4 grassland (savanna) (Table 1).

1.6 Mineral fertilizer and manure

Manure applications are management practices in sustaining agricultural production since thousands of years. More recently, mineral fertilizer application (both N and P) has been the the major causes of the dramatic increase in agricultural productivity in the 20th century. In ORCHIDEE-CNP, both organic (manure) and inorganic (mineral) fertilization which enrich the soil nutrient pools are accounted for.

N and P in mineral fertilizer goes directly into soil mineral pools (i.e. dissolved labile P, ammonia, and nitrate). Mineral N fertilizer is treated as ammonium nitrate for simplicity with half of N as ammonia and half as nitrate. For manure applied to cropland and pasture, we assume a typical slurry application with major part as ammonium contained in the liquid slurry. We assume that 90% of N in manure is in the liquid part of the slurry (like urine), which goes into soil ammonia pool. For the solid part of the slurry, we assume it goes into litter pool with a C:N ratio of 10:1 as suggested by Soussana and Lemaire (2014), and a P:N ratio of 0.2 (a value between the ratio in ruminant manure (0.15-0.18) and monogastric manure (0.24-0.28); see Table SI3 of Lun et al. (2018) for detail).

1.7 Recalibration

Several parameters in ORCHIDEE had to be re-calibrated to new model formulations (see above) or are corrected in case of turnover of sapwood for TrEBF and TrDBF to achieve realistic wood growth rates (not shown). We further adjusted the recycling efficiency of nutrients from root ($f_{trans,root}^N, f_{trans,root}^P$) and leaf ($f_{trans,leaf}^N, f_{trans,leaf}^P$) according to global data compilations (Freschet et al., 2010; Vergutz et al., 2012). The new values of vegetation parameter are given in Table 1.

Table 1. Plant functional type (PFT) specific parameters: tropical evergreen broadleaf forest (TrEBF), tropical raingreen broadleaf forest (TrDBF), temperate evergreen needleleaf forest (TeENF), temperate evergreen broadleaf forest (TeEBF), temperate summergreen broadleaf forest (TeDBF), boreal evergreen needleleaf forest (BoENF), boreal summergreen broadleaf forest (BoDBF), boreal summergreen needleleaf forest (BoDNF), C3 grassland (C3grass), C4 grassland (C4grass), C3 cropland (C3crop), and C4 cropland (C4crop). the maximum and minimum ratio between leaf area and sapwood area ($k_{ls,max}$ $k_{ls,min}$), the turnover of tree (τ_{tree}), the coefficient relating maintenance respiration rate to tissue nitrogen concentration ($c_{r,maint}$).

	TrEBF	TrDBF	TeENF	TeEBF	TeDBF	BoENF	BoDBF	BoDNF	C3grass	C4grass	C3crop	C4crop	Source
$cn_{leaf,min}$ [$g(C)g^{-1}(N)$]	12.5	12.5	28.	16.	16.	28.	16.	16.	16.	16.			Zaehle and Friend (2010)
$cn_{leaf,max}$ [$g(C)g^{-1}(N)$]	60.	60.	75.	45.	45.	75.	45.	45.	45.	45.			Zaehle and Friend (2010)
$np_{leaf,min}$ [$g(N)g^{-1}(P)$]	5.	5.	5.	5.	5.	5.	5.	5.	5.	5.			(Ellsworth in review)
$np_{leaf,max}$ [$g(N)g^{-1}(P)$]	30.	30.	30.	30.	30.	30.	30.	30.	30.	30.			(Ellsworth in review)
$c_{r,maint}$ [$\times 10^{-2}$]	2.5	2.5	3.84	3.84	3.84	13.80	13.80	13.80	4.90	13.80	3.84	3.84	calibrated
$k_{ls,max}$ [mm – 2]	4000.	4000.	1600.	1800.	2100.	1500.	3100.	2500.	2.0	1.0	2.5	3.0	calibrated
$k_{ls,min}$ [mm – 2]	1475.	1475.	417.	675.	1600.	400.	2400.	1500.	1.5	.5	1.75	1.5	calibrated
τ_{sapw} [[yr-1]]	0.018	0.018	0.024	0.031	0.042	0.031	0.031	0.042	5.2	1.3	1.3	1.3	this study, Naudts et al. (2015)
τ_{tree} [yr – 1]	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	–	–	–	–	calibrated
$f_{trans,root}^N$ []	.275	.275	.275	.275	.275	.275	.275	.275	.275	.275	.275	.275	Freschet et al. (2010)
$f_{trans,leaf}^N$ []	0.561	0.612	0.627	0.561	0.612	0.627	0.612	0.627	0.746	0.746	0.746	0.746	Vergutz et al. (2012)
$f_{trans,root}^P$ []	.57	.57	.57	.57	.57	.57	.57	.57	.57	.57	.57	.57	Freschet et al. (2010)
$f_{trans,leaf}^P$ []	.65	.65	.65	.65	.65	.65	.65	.65	.65	.65	.65	.65	Vergutz et al. (2012)
e_N [$g(N)g(C)^{01}$]	0.0067	0.0067	0.0045	0.0045	0.0045	0.0086	0.0086	0.0086	0.0056	0.0056	0.0074	0.0074	Akagi et al. (2011)
e_P [$g(P)g(C)^{01}$]	3.69e-06	3.69e-06	0.0	0.0	0.0	0.0	0.0	0.0	3.01e-06	3.01e-06	0.0	0.0	Akagi et al. (2011)

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