1 S1 Appendix

2 **GRASSMIND 2.0 – grassland model**

3

4 **1 Overview and general concept**

5 The grassland model GRASSMIND is designed to simulate grasslands and combines 6 biogeochemical cycles with biodiversity [1]. The model includes additional submodels that 7 allow for analyzing plant-soil feedbacks and effects of management and climate change. A 8 first conceptual model description (GRASSMIND 1.0) has been described earlier [1]. Since 9 then, progress in the model development has been made in terms of modelling the nitrogen 10 demand of plants and nitrogen relocation, as well as the coupling with soil models.

11

12 GRASSMIND 2.0 is an individual-based and process-oriented model that follows the a gap 13 approach typically applied in forest models [2-5]. Grassland is simulated on an area of size A (m²), which is a composite of regularly ordered, quadratic patches of a = 1 m² in size and 14 15 described by their location within the area A (S1.1 Fig). Individual plants interact and 16 compete for resources on one patch without assignment of explicit spatial locations to each 17 plant (S1.1 Fig). Intra- and interspecific competition for resources and their resulting uptake 18 influence the productivity of plants. Aboveground resources include light and space and 19 belowground resources comprise soil water and nitrogen. Resource supply is assumed to be 20 homogenous within each patch, but can differ between patches.

21

For simulating soil resource dynamics, GRASSMIND is coupled with two soil models: (i)
 CANDY [6] and (ii) CENTURY [7]. This study uses the soil model CENTURY. The monthly
 time step of CENTURY is matched with daily dynamics of GRASSMIND by updating soil
 water processes and carbon-nitrogen decomposition at the beginning of each month (while
 accumulating daily soil water uptake by plants and daily litter fall of plant leaves and roots).

27

28 Biogeochemical cycles include the carbon, nitrogen and water fluxes in the grassland 29 ecosystem. The growth of single plants is modeled based on a carbon balance of gross 30 primary production (GPP) and respiration. Adding leaf and root turnover and demographic process (like seed ingrowth and plant mortality), the carbon cycle is extended to the plant 31 32 community and is closed via litter decomposition and soil carbon processes for the grassland 33 ecosystem. The nitrogen cycle is modeled in close connection to the carbon cycle by 34 assuming CN ratios for plants (green and senescent leaves and roots) and soil pools. The 35 water cycle includes as main processes interception, evaporation, water infiltration and percolation in soil as well as plant transpiration. 36

- 38 **Biodiversity** is integrated in the model by either simulating single species or plant functional
- 39 types (aggregated species with similar functional behavior; PFT). Species or PFT can differ in
- 40 traits which determine their demographic rates, growth and behavior in competition with other
- 41 plants. Plants of the same species or PFT do not differ in their traits, but can have different
- 42 ages or sizes. The geometry of an individual plant is described by the aboveground shoot
- 43 (here, leaves) and belowground root system (root branches).
- 44
- 45 The **processes** included in the grassland model are modeled according to a specific schedule
- 46 (S1.1 Fig):
- 47 (A) recruitment and emergence of plant seedlings (1,2)
- 48 (B) plant senescence and mortality (3-5)
- 49 (C) gross production (incl. shading and competition for soil water and nitrogen, 6-10,13)
- 50 (D) plant respiration (for maintenance and growth, 11)
- 51 (E) net production and allocation for plant growth (12,14)
- 52 (F) management (15)
- 53

54 The grassland model runs at daily time steps ($\Delta t = 1$). For the purpose of shading and 55 crowding mortality, the aboveground space is discretized into vertical height layers of 56 constant width Δh (S1.1 Table).

57

58 Table S1.1. Overview of general input parameter for GRASSMIND.

Description	Parameter	Unit	Value	
Time step	Δt	d	1	
Simulation area	A	m ²	1 100	
Patch area	a	m ²	1	
Width of height layers	Δh	m	0.01	

59

60



62

63 Fig S1.1. Overview of main processes in GRASSMIND.

Numbers in brackets within each box show the serial order of their calculation within one time step Δt . Grey frames that underlie these boxes group them according to the main processes and their corresponding chapters. Rhombuses indicate climatic input parameters with the following abbreviations: *PET* – potential evapotranspiration, *PPFD* – photoactive photon flux density. Spatial scale of a process is marked by different colors (green = patch, yellow = individual plant).

70

71 **2 The geometry of an individual**

72

73 Each individual plant is characterized by the following state variables (organic dry matter in

- 74 g_{ODM}):
- 75 (1) above ground shoot biomass B_{shoot}
- 76 (2) belowground root biomass B_{root}
- 77 (3) reproduction biomass B_{rep}
- 78

79 The aboveground shoot biomass is divided into biomass of fresh green leaves B_{shoot}^{green} and

80 biomass of senescent yellow leaves B_{shoot}^{sen} . Further state variables, which describe the

81 geometry of an individual, can be derived from allometric relationships with species-specific

82 attributes (S1.2 Fig).

83



84

85 Fig S1.2. Geometry of a single plant in GRASSMIND.

86 State variables that correspond with the geometrical characteristics of an individual plant and

87 that can be derived from the aboveground shoot and belowground root biomass.

88

89 2.1 The aboveground shoot

We model the aboveground shoot of an individual plant encased by a cylinder. The volume of the encasing cylinder $V_{cylinder}$ [m³] is related to the shoot biomass:

92

93
$$V_{cylinder} = \frac{B_{shoot}}{f_s}$$
 (1)

where the species-specific correction factor f_s [g_{ODM}/m³] accounts for free space within the cylinder not filled with biomass. A species-specific constant parameter *hw* defines the ratio between plant height *h* [m] and width *w* [m] of the assumed cylinder.

97

98 The space an individual plant occupies on a patch is determined by the ground area $cov [m^2]$ 99 of the encasing cylinder. To calculate a patch's *vegetation cover CC* (the area occupied by all 100 individuals relative to the patch area), it is necessary to take leaf overtopping or overlapping

- 101 among individual plants into account. For this, each plant cover is corrected by a species-
- 102 specific overlapping factor f_o (unitless). This factor accounts for overlapping in an implicit

manner since the individuals do not have spatially explicit positions within the patch. The
 corrected covers of all plants on the patch are summed up and normalized by the patch area:

106
$$CC = \frac{1}{a} \cdot \sum_{all individuals} (cov \cdot f_o)$$
 (2)

107

108 The leaf area of the aboveground shoot is obtained by multiplying the plant's biomass B_{shoot} 109 with the constant parameter of *specific leaf area SLA* [m²/g_{ODM}]. This includes the assumption

110 that all leaves have the same *SLA*, leading to the overall plant leaf area index $L \, [m^2/m^2]$:

111

112
$$L = \frac{B_{shoot} \cdot SLA}{cov}$$
(3)

113

114 By using only the green shoot biomass B_{shoot}^{green} instead of B_{shoot} in equation (3), we obtain 115 the green leaf area index L_{green} which is especially important for photosynthesis (see section 116 3.5).

117

118

119 **2.2 The belowground root**

120 We assume a species-specific allometric relationship between an individual's aboveground 121 shoot biomass B_{shoot} and belowground root biomass B_{root} – determined by the parameters *sr* 122 (defining the species-specific *shoot-root ratio* of a plant in terms of biomass):

123

$$124 \qquad B_{shoot} = sr \cdot B_{root} \tag{4}$$

125

The individual's ability to access and compete for soil nitrogen and water resources strongly depends on its root system. In addition to root biomass, the root system's vertical distribution in soil is also considered. Shallow and highly branched root systems are beneficial for nutrient uptake as most nutrients occur predominantly in the upper soil layers. In contrast, deeper root systems strongly increase the individual's access to soil water resources, particularly during drought periods.

132

To calculate the rooting depth $depth_{root}$ [m], which is required for water uptake, we adapt the power-law approach [8] which functionally relates rooting depths to the aboveground ellipsoidal canopy volume. Using the same relationship for the volume of an individual's aboveground shoot cylinder (equation 1) and including the *shoot-root ratio* (equation 4) leads to:

139
$$depth_{root} = r_1 \cdot \left(\frac{sr}{f_s} \cdot B_{root}\right)^{r_2}$$
 (5)

140 where the species-specific parameters r_1 and r_2 define the dependence of the rooting depth on 141 plant biomass. Each individual has its own rooting system, irrespective of whether the 142 individual plant has been recruited via generative or vegetative reproduction. The total 143 branching root length $length_{root}$ [m], which is important for nitrogen uptake, is related to 144 root biomass via the species-specific parameter *specific root length SRL* [m/g_{ODM}]:

145

$$146 \quad length_{root} = B_{root} \cdot SRL \tag{6}$$

- 147
- 148

1493 Model processes

In the following, we describe the details of the modeled processes important within the life
cycle of an individual plant. These have already been introduced in brief (see chapter 1, S1.1
Fig).

153

154 **3.1 Recruitment**

155

156 **3.1.1 Reproduction**

157 We distinguish three different sources of species-specific recruitment of plants:

- seed rain from a surrounding meta-community
- local reproduction of plants
- sowing of seeds
- 161

162 Seed rain from a surrounding meta-community is modeled by a constant species-specific seed 163 input rate N_{seed}^{meta} (in [1/m²/d], starting pre-defined at t_{meta}) while sowing throws N_{seed}^{sow} seeds 164 (in [1/m²]) to the patch only at time t_{sow} .

165

166 In contrast, local recruitment by mother plants is dependent on their fitness. In its current 167 version, GRASSMIND does not explicitly distinguish between vegetative and generative 168 reproduction. Here, we assume that the single seed biomass produced via generative 169 reproduction equals the biomass investment also required for vegetative reproduction (e.g. rhizomes or stolones). The number of locally recruited seedlings N_{seed}^{local} (in [1/m²/d]) 170 produced by a reproductive mother plant is dependent on the mother plant's net production 171 172 NPP allocated to its reproduction pool B_{rep} (see section 3.13) and the species-specific seed 173 biomass B_{seed} [godmministic godmministic godministic goddinistic goddinistic

174
$$N_{seed}^{local} = \frac{B_{rep}}{B_{seed}}$$
 (7)

175 The total number of potentially germinating seeds N_{seed} [1/m²/d] is then determined by:

176				
177	$N_{seed} = N_{seed}^{meta} + N_{seed}^{sow} + N_{seed}^{local} $ $\tag{8}$			
178				
179	3.1.2 Emergence of new seedlings			
180	Only a limited number \widehat{N}_{seed} of potential seedlings can germinate successfully within the			
181	same patch:			
182				
183	$\widehat{N}_{seed} = N_{seed} \cdot germ_{\%} \tag{9}$			
184	where germ% denotes the germination rate (unitless). In the current version of GRASSMIND,			
185	environmental conditions are not explicitly considered for the germination process, so the			
186	germination rate can be interpreted as a constant species-specific success rate.			
187				
188	The successfully germinated seedlings emerge dependent on an emergence time t_{em} [d] since			
189	seed rain and have an initial height h_{min} [m] (further geometrical properties can be derived			
190	from h_{min}).			
191				
192	At the time of emergence, seeds could additionally fail to establish in terms of limited space.			
193	If the emergence of all potentially germinating seeds would increase total vegetation cover			
194	CC above a patch's area (i.e. > 100%), only those seeds (for each species) proportional to the			
195	remaining free space on the patch will establish successfully (see also section 3.3.3). All seeds			
196	that failed to emerge are directly transferred to the litter pool.			
197				
198	3.3 Mortality			
199				
200	3.3.1 Senescence of leaves and root branches			
201	All plants are subject to tissue turnover as a result of partial yellowing of leaves and the death			
202	of root branches. The transfer rate from green to yellow (senescent) shoot biomass B_{shoot}^{sen} is			
203	defined by the reciprocal value of the leaf life span LLS [d].			
204				
205	Senescent shoot leaves remain attached to an individual's shoot geometry and thus can still			
206	shade other leaves, but do not photosynthesize any longer. The transfer of senescent shoot			
207	biomass into the surface litter pool occurs either (a) if an entire plant dies or (b) at the turn of			
208	the year.			
209				
210	Equivalent to leaf senescence, the transfer rate of root branches into dead root biomass is			
211	defined by the reciprocal value of the root life span <i>RLS</i> [d]. Dead root parts do not remain			
212	within an individual's root system and geometry and are immediately transferred to the soil			

- 213 litter pool.

215 **3.3.2 Base mortality**

A base mortality is modeled using a daily constant rate m_b [1/d]. The value of this rate is a pre-defined parameter and allows differentiating dependent on the individual plant age (e.g. seedlings versus mature plants):

219

$$220 mtextbf{m}_{b} = \begin{cases} 0 & , age = 0 \\ m_{seed} & , 0 < age < age_{rep} \\ m_{basic} & , age_{rep} \leq age < life \\ 1 & , age \geq life \end{cases}$$
(10)

221

A basic mortality rate m_{basic} is used for mature plants, whereas a special mortality rate m_{seed} is used for seedlings. Plants enter the mature plant state as soon as they start to reproduce (determined by the parameter age_{rep}). Based on the species-specific lifespan *life* [yr] and current age of plants, the rate m_b can be set to one (meaning that plants immediately die). For annual species thus m_b equals one, if the *age* [yr] of an annual plant exceeds one year. For biannuals and perennials m_b is set to two years or larger, respectively. Dying plants are directly transferred to the litter pool (i.e. to surface and soil litter pools for decomposition).

229

230 **3.3.3 Crowding mortality**

Due to space limitations only a finite number of plants are able to survive on a patch. There are different possibilities to define an indicator of limited space at which crowding mortality can be triggered.

Here, we chose an indicator M_C which is defined by the reciprocal of vegetation cover *CC* on a patch:

236

$$237 \qquad M_C = \frac{1}{cc} \tag{11}$$

238

239 If vegetation cover *CC* exceeds a patch's area, the indicator $M_{\rm C}$ drops below one. Note that 240 vegetation cover also includes species-specific overlapping factors $f_{\rm O}$.

241

Crowding mortality occurs earliest in the subsequent time step. If space is limited ($M_C < 1$), a specific number of plants N_{crowd} [1/d] die stochastically (without any species- or size-specific advantages) so that the factor M_C exceeds the threshold of one again:

245

$$246 N_{crowd} = N \cdot (1 - M_c) (12)$$

247

Dying plants are directly transferred to the litter pool (i.e. to surface and soil litter pools fordecomposition).

251 **3.4 Light intensity**

An increasing number of plants on a patch (which can differ in their plant height) results in shading among the individuals. Therefore, the global radiation I_0 [µmol_{photons}/m²/s] on top of the highest individual is increasingly attenuated down to the bottom of the patch. To calculate vertical light conditions on a patch, the aboveground space is divided into horizontal layers of constant width Δh [m]. For each individual, its height *h* [m] determines the highest layer l_{max} which is covered by its shoot:

258

$$l_{max} = \left[\frac{h}{\Delta h}\right] \tag{13}$$

260

Since the leaf area *L* is assumed to be uniformly distributed in vertical direction within an individual's encasing cylinder, the plant's contribution of leaf area index \hat{L}_i [m²/m²] is also assumed to be uniformly distributed among the height layers *i*=1,...,*l*_{max}:

264

265
$$\hat{L}_{i} = \begin{cases} \frac{L \cdot cov}{h} \cdot \Delta h &, 0 \le i \le l_{max} \\ 0 &, i > l_{max} \end{cases}$$
(14)

where *cov* is the ground area of the individual's encasing shoot cylinder. Summing up these leaf area contributions for all individuals on a patch results in the patch-based community leaf area index LAI_i [m²/m²] for each height layer *i*:

269

270
$$LAI_i = \frac{1}{a} \cdot \sum_{all individuals} k \cdot \hat{L}_i$$
 (15)

where k denotes the species-specific light extinction coefficient and a is the area size of the patch. The light extinction coefficient is a species-specific constant parameter and includes the assumption of similar leaf angles of an individual's shoot.

274

To determine the irradiance I_S [µmol_{photon}/m²/s] at the top of an individual, the patch-based leaf area indices LAI_i of all height layers above the plant's height are summed up. Light attenuation through these height layers is then calculated using the approach of Monsi and Saeki [9]:

279

$$280 I_S = I_0 \cdot e^{-(\sum_{i>l_{max}} LAI_i)} (16)$$

where I_0 [µmol_{photon}/m²/s] is the incoming photosynthetic photon flux density (*PPFD*) above canopy modeled as a daily average from sunrise to sunset.

283

By the calculation of the light climate within grasslands, competition for light between individuals is considered. Species that grow higher receive more light but also affect the light which is received by smaller plants via shading (S1.3 Fig). Note that not only green but also standing senescent shoot leaves contribute to shading. To reduce the effect of shading (compared to competition between plants for belowground resources) we weight the patchbased leaf area indices LAI_i each by a factor (here 1/9, which equals a subdivision of a 1 m² patch into 9 sub-patches of homogeneous leaf area distribution). Self-shading within a single plant is included at a later stage (equation 19 and 20).

292







Fig S1.3. Light competition between individual species of different plant heights. Aboveground space is divided into height layers of width Δh . Each plant's leaf area is uniformly distributed among the respective covered height layers. The height layers marked in grey are shaded by plant A and B. Here, plant B is higher than plant A (vertical black arrows) and receives the unreduced incoming irradiance I_0 . Plant A is shaded by those parts of plant B's leaf area that are higher than A, and hence receive the reduced irradiance I_S (equation 16).

301

302 3.5 Gross primary production

303 Gross biomass production of a plant is modeled via photosynthesis. Following the approach 304 of Thornley and Johnson [10], we calculate the gross photosynthetic rate for a single leaf 305 using a saturation function:

306

$$307 \quad P_{leaf} = \frac{\alpha \cdot I_{leaf} \cdot p_{max}}{\alpha \cdot I_{leaf} + p_{max}} \tag{17}$$

308

309 Here, α is the species-specific initial slope of the light response curve [μ mol_{CO2}/ μ mol_{photon}], 310 p_{max} is the species-specific maximum gross photosynthetic rate [μ mol_{CO2}/m²/s], and I_{leaf} is the 311 incoming irradiance on the leaf surface [μ mol_{photon}/m²/s]. The latter is derived by correcting 312 the incoming irradiance I_S at the top of an individual:

314
$$I_{leaf} = \frac{k}{1-m} \cdot I_S \tag{18}$$

315 where k is the species-specific light extinction coefficient and m the transmission coefficient.

To obtain the gross photosynthetic rate P_{shoot} [µmol_{CO2}/m²/s] of an entire plant, the single-leaf photosynthesis (equation 17) is integrated over the individual's green leaf area index L_{green} :

319
$$P_{shoot} = \int_0^{L_{green}} P_{leaf}(\tilde{L}) d\tilde{L}$$
(19)

320

318

- 321 leading to:
- 322

323
$$P_{shoot}(I_{leaf}) = \frac{p_{max}}{k} \cdot \ln\left(\frac{\alpha \cdot k \cdot I_{leaf} + p_{max} \cdot (1-m)}{\alpha \cdot k \cdot I_{leaf} \cdot e^{-k \cdot Lgreen} + p_{max} \cdot (1-m)}\right)$$
(20)

324

Multiplying the gross photosynthetic rate (equation 20) by three conversion factors leads to the potential gross primary production GPP_{pot} [g_{ODM}/d] of a plant:

327

328
$$GPP_{pot} = P_{shoot}(I_{leaf}) \cdot \phi_{ODM} \cdot \phi_{day} \cdot \phi_a$$
(21)

329 where $\phi_{ODM} = 0.63 \cdot 44 \cdot 10^{-6}$ [g_{ODM}/µmol_{CO2}], $\phi_{day} = 60 \cdot 60 \cdot length_{day}$ [s/d] with 330 *length_{day}* as the number of hours per day from sunrise to sunset, and $\phi_a = cov$ [m²].

331

332 3.7 Temperature effects

333 Photosynthesis and respiration are sensitive to temperature changes [11]. Gross primary 334 production (equation 21) is reduced for air temperatures T [°C] below a threshold of 10 °C 335 according to Schippers and Kropff ([12], see also [11], S1.4A Fig):

336

337
$$R_{T} = \begin{cases} 0 & ,T \leq -5^{\circ}C \\ 0.02857 \cdot T + 0.142 & ,-5^{\circ}C < T \leq 2^{\circ}C \\ 0.1 \cdot T & ,2^{\circ}C < T \leq 10^{\circ}C \\ 1 & ,10^{\circ}C < T \end{cases}$$
(22)

338

Maintenance respiration r_m increases with air temperature according to Schippers and Kropff ([12], see also [11], S1.4B Fig):

341

$$342 f_T = \begin{cases} 0 & , T \leq 0^{\circ}C \\ 0.033 \cdot T & , 0^{\circ}C < T \leq 15^{\circ}C \\ 2^{\frac{T-25}{10}} & , 15^{\circ}C < T \end{cases}$$
(23)



Fig S1.4. Temperature effects on (A) photosynthesis and (B) respiration of a single plant
in GRASSMIND.

345

349 **3.8 Water competition**

The individual's uptake of water resources from soil is modeled taking into account its demand on the one hand and the soil water available on the other hand. The individual's water demand θ_{demand} [l/d], which is equal to its potential transpiration, is modeled using the water use efficiency concept:

354

355
$$\theta_{demand} = \frac{R_T \cdot GPP_{pot}}{WUE}$$
 (24)

356 where GPP_{pot} [g_{ODM}/d] is the gross primary productivity, R_T (unitless) is the effect of air 357 temperature on GPP and WUE [g_{ODM}/kg_{H2O}] denotes the water use efficiency (assuming 1 358 kg_{H2O} = 1 l_{H2O}).

359

We calculate how much soil water resources are available for an individual plant although competing with other plants on a patch. By coupling GRASSMIND with soil models, the soil is divided into layers of constant width Δs for which information on soil water resources are provided. Using this vertical soil discretization, we calculate for each plant its *rooting zone* described by the soil layer s_{max} [m] (dependent on its current rooting depth):

$$366 \quad s_{max} = \left[\frac{depth_{root}}{\Delta s}\right] \tag{25}$$

367

365

The *rooting zone* represents the composition of the respective soil layers $j=1,...,s_{max}$ in which the individual plant is rooting (S1.5 Fig). To determine the amount of available soil water for the individual plant, we calculate the soil water content θ_W^{plant} [V%], permanent wilting point θ_{PWP}^{plant} [V%] and field capacity θ_{FC}^{plant} [V%] of the plant's *rooting zone* by summing up these variables for all layers in the rooting zone.

- 373
- 374



376 Fig S1.5. Illustration of the rooting zones of two different individuals.

Horizontal dark grey shadow marking the first three soil layers indicates the rooting zone ofindividual A. In this example, the rooting zone of individual B covers nearly the entire soil.

- 578 Individual A. In this example, the footnig zone of individual B covers hearly the
- 379

380 Water demand which can actually be fulfilled is determined by:

381

$$382 R_W = \begin{cases} 0 , \theta_W^{plant} < \theta_{PWP}^{plant} \\ \frac{\theta_W^{plant} - \theta_{PWP}^{plant}}{\theta_{MSW} - \theta_{PWP}} & , \theta_{PWP}^{plant} \le \theta_W^{plant} \le \theta_{MSW}^{plant} \\ 1 & , \theta_{MSW}^{plant} \le \theta_W^{plant} \end{cases}$$
(26)

383

384 where the factor R_W (unitless) increases from 0 to 1 (S1.6 Fig, [13]).

385



386

Fig S1.6. Illustration of the reduction factor R_W as a function of available soil water content.

389

390 If soil water content is below the permanent wilting point, the factor R_W is set to zero. If 391 available soil water resources are above the *minimal soil water content* θ_{MSW}^{plant} [V%], the 392 factor R_W is set to one:

$$394 \quad \theta_{MSW}^{plant} = \theta_{PWP}^{plant} + 0.4 \cdot \left(\theta_{FC}^{plant} - \theta_{PWP}^{plant}\right) \tag{27}$$

396 If the soil water content is between the permanent wilting point and the minimal soil water 397 content, soil water uptake is linearly reduced by the factor $R_{\rm W}$. The actual water uptake $\theta_{\rm uptake}$ 398 [l/d] of an individual plant is calculated as follows:

399

$$400 \quad \theta_{uptake} = R_W \cdot \theta_{demand} \tag{28}$$

401

402 For simplicity, roots are assumed to be (vertical) distributed equally among the soil layers (of 403 the plant's *rooting zone*). Soil water uptake of an individual plant (θ_{uptake}) from a single soil 404 layer is then calculated as:

405

406
$$\theta_{uptake}^{j} = \frac{\theta_{uptake}}{s_{max}}$$
 (29)

407 where θ_{uptake}^{j} [l/d/layer] denotes the individual's water uptake from soil layer *j*.

408 Similarly, gross primary productivity of a plant $GPP_{pot} [g_{ODM}/d]$ is reduced according to the 409 limitation factor R_W :

$$410 \quad GPP_W = R_T \cdot GPP_{pot} \cdot R_W \tag{30}$$

411 while $GPP_W[g_{ODM}/d]$ is the reduced gross productivity of a plant due to water stress (R_W) and 412 air temperature effects (R_T , see also section 3.7).

Total soil water uptake (or transpiration) of all plants on a patch can further be restricted by potential evapotranspiration (*PET* in [mm/d]) and permanent wilting point (entire soil). If the sum of transpiration of all plants (sum of θ_{uptake} for all plants on a patch in [mm/d], with 1 $\mu_{H2O}/m^2 = 1 \text{ mm}_{H2O}$) and interception of rainfall by plants on a patch (*RI* in [mm/d]) exceeds the *PET*, then transpiration (or total soil water uptake $\theta_{uptake}^{patch} = \sum_{all \ plants} \theta_{uptake}$ in [mm/d])

418 and gross productivity (GPP_W) of all plants is reduced proportionally by the factor (unitless):

419
$$f_{PET} = \frac{PET - RI}{\sum_{all \ plants} \theta_{uptake}}$$
(31)

420 Interception *RI* [mm/d] of rainfall by plants (before rainfall is percolating into the soil) is
421 thereby calculated in the CENTURY soil model as follows:

422
$$RI = \left(0.0003 \cdot B_{litter}^{surface} + 0.0006 \cdot \sum_{\substack{all \ plants}} B_{shoot}\right) \cdot 0.8$$
(32)

423 where $B_{litter}^{surface}$ [g_{ODM}/patch] is the patch's surface litter pool and B_{shoot} [g_{ODM}] is the plants' 424 aboveground biomass.

425

Further, if total soil water uptake (of all plants) would result in a soil water content (θ_W^{soil} of the entire soil) below the permanent wilting point (θ_{PWP}^{soil} of the entire soil), then total soil water uptake (or transpiration θ_{uptake}^{patch}) and gross productivity (GPP_W) of all plants is reduced by the factor (unitless):

430

431
$$f_{PWP} = \frac{\theta_W^{soil} - \theta_{PWP}^{soil}}{\sum_{all \ plants} \theta_{uptake}}$$
(33)

432

433 **3.9 Nitrogen competition**

434

435 **3.9.1 Nitrogen non-fixing species**

436

437 Nitrogen uptake of a plant is determined dependent on the nitrogen content of the soil (N_{soil} 438 in [g/m²]), the individual's ability to access nitrogen resources (N_{access} in [g/m²/d]) and its 439 nitrogen demand (N_{demand} in [g/m²/d]).

440

446

441 To calculate N_{demand} [g/m²/d] (here, mainly from the mineral nitrogen pool of nitrate NO₃N), 442 we calculate the amount of nitrogen required for growth of new leaves, new root branches and 443 for seed production. For this, we calculate a preliminary net productivity NPP_{pot} (see section 444 3.11, based on GPP_W already constrained by soil water conditions and air temperature) and 445 divide its carbon content by pre-defined *CN* ratios (of green and brown plant material).

447
$$N_{demand} = alloc_{shoot} \cdot \frac{f_C \cdot NPP_{pot}}{CN_{green}} + \left(alloc_{root} + alloc_{rep}\right) \cdot \frac{f_C \cdot NPP_{pot}}{CN_{brown}}$$
(34)

where $alloc_x$ are allocation rates to different carbon pools of a plant (x = shoot, root and reproduction). CN_{green} and CN_{root} are constant species-specific ratios of carbon to nitrogen contents in the respective pools and f_C denotes the fraction of carbon in organic dry matter (here, we use $f_C = 0.43$).

452 Before plants use the available soil nitrogen, we assume that their demands can be partly 453 fulfilled by nitrogen relocated within the plant from leaves which turn from green to senescent 454 (section 3.14). If demands cannot be fulfilled by relocated nitrogen from senescent leaves, the remaining demand is covered by soil nitrogen resources (for which plants have to competewith each other).

457 The amount of soil nitrogen N_{access} which is potentially available for use by an individual 458 plant is calculated by:

459

$$460 \qquad N_{access} = \sum_{j < s_{max}} F_j \cdot N_j \tag{35}$$

461

462 where N_{access} [g/m²/d] denotes the available nitrogen in soil to which the plant has access and 463 F_j represents a root competition factor. The factor F_j regulates the amount of nitrogen an 464 individual can access by competing with other individuals. F_j is defined as the percentage of 465 root branch lengths of the plant in relation to total root branch length (of all plants per soil 466 layer *j*):

$$468 F_{j} = \frac{\left(\frac{length_{root}}{s_{max}}\right)}{\left(\sum_{\substack{on \ patch\\on \ patch\\with \ j < s_{max}}} \left(\frac{length_{root}}{s_{max}}\right)\right)} (36)$$

469

467

470

We assume that the plant's total root branches $length_{root}$ are distributed equally among the soil layers (in its *rooting zone*, S1.5 Fig). The potential nitrogen uptake N_{uptake} [g/m²/d] is then defined as:

474

$$\begin{array}{ll}
475 \quad N_{uptake} = \min(N_{demand}, N_{access}) \\
476
\end{array} \tag{37}$$

477 Net production of a plant can be reduced due to limitation in available soil nitrogen (see 478 section 3.11). Therefore, we introduce a limitation factor R_N which is calculated by:

480
$$R_N = \frac{N_{uptake}}{N_{demand}} = \min\left(1, \frac{N_{access}}{N_{demand}}\right)$$
(38)

481

479

482

483 **3.9.2 Nitrogen fixing species**

484

485 Symbiotic nitrogen fixation, e.g. by legumes, is modeled using the following assumptions:486

• N-fixing species never compete for nitrogen with other plants. Thus, the limitation factor $R_{\rm N}$ always equals one.

Plants loose carbon for uptake of nitrogen via symbiosis. A specific fraction *rhiz*% of net
 primary production *NPP* is therefore provided to rhizobia which is not available anymore
 for structural growth or recruitment.

492

In GRASSMIND positive effects of nitrogen-fixing species occur as those species do not take
 part in the nitrogen competition process and thus, more nitrogen resources in soil are available
 for N-non-fixing plants. Further, all species contribute to soil nitrogen via decomposition after
 plant death.

497

498 **3.10 Respiration**

499

500 We consider respiratory costs for maintenance of structural tissue (shoot and root biomass) 501 and for growth of plants. Maintenance costs $r_{\text{main}} [g_{\text{ODM}}/d]$ are assumed to be proportional to 502 the green shoot biomass B_{shoot}^{green} and living root biomass B_{root} :

503

504
$$r_{main} = r_m \cdot f_T \cdot \left(B_{shoot}^{green} + B_{root}\right)$$
 (39)

where $r_{\rm m}$ is a constant maintenance respiration rate [1/d] and the factor $f_{\rm T}$ accounts for changing demands for maintenance respiration with varying air temperature (see section 3.7). Growth respiratory costs are modeled by a constant parameter $r_{\rm g}$ (unitless).

508

509 3.11 Net primary production

510

511 A plant's gross primary production is used for (a) respiratory costs, (b) growth of an 512 individual's shoot and (c) reproduction. Losses due to respiration (maintenance and 513 growth) lead to the individual's net primary production NPP_{act} [g_{ODM}/d]:

514

515
$$NPP_{act} = R_N \cdot (1 - r_g) \cdot (GPP_{act} - r_{main})$$
 (39)

516 where GPP_{act} [g_{ODM}/d] is the actual gross primary production which can be reduced according

517 to environmental limitations or competition (derived from the potential *GPP*_{pot}):

518

519
$$GPP_{act} = f_{PET} \cdot f_{PWP} \cdot R_W \cdot R_T \cdot GPP_{pot}$$
 (40)

520 where R_W , f_{PET} , f_{PWP} , R_N , and R_T (all ranging in [0,1]) account for reductions due to soil water 521 limitations (R_W , f_{PET} , f_{PWP} , equations 26, 31 and 33), soil nitrogen limitation (R_N , equation 522 38), and temperature effects (R_T , equation 22), respectively.

- 523
- 524

525 **3.13** Allocation of net primary production

527 Net primary production NPP_{act} (equation 39) is allocated to (a) shoot biomass, (b) root 528 biomass and (c) to reproduction as follows:

- 529
- the fraction allocated to the shoot ($alloc_{shoot}$) is a species-specific parameter
- the fraction allocated to the root $(alloc_{root})$ is derived from the fixed species-specific shootroot ratio *sr* (equation 4)

533
$$alloc_{root} = \frac{alloc_{shoot}}{sr}$$
 (41)

- the remaining fraction is allocated to the reproduction pool
- 535

$$536 \qquad alloc_{rep} = 1 - alloc_{shoot} - alloc_{root} \tag{42}$$

537

For seedlings, the fraction allocated to the reproduction pool is zero (when plant age is below age_{rep}). Hence, the fraction allocated to the shoot is adjusted as follows:

541
$$alloc_{shoot} = \frac{sr}{sr+1}$$
 (43)

542

540

543 **3.14 Growth of a plant**

544

Allocation of produced biomass (dependent on the allocation fractions, section 3.13) and senescence (dependent on leaf life span *LLS* and root life span *RLS*, section 3.3.1) result in the following changes in the plant's biomass pools:

548

$$549 \qquad \frac{\Delta B_{shoot}^{sen}}{\Delta t} = \frac{1}{LLS} \cdot B_{shoot}^{green} \tag{44}$$

550
$$\frac{\Delta B_{shoot}^{green}}{\Delta t} = alloc_{shoot} \cdot NPP_{act} - \frac{1}{LLS} \cdot B_{shoot}^{green}$$
(45)

551
$$\frac{\Delta B_{root}}{\Delta t} = alloc_{root} \cdot NPP_{act} - \frac{1}{RLS} \cdot B_{root}$$
(46)

552

553
$$\frac{\Delta B_{rep}}{\Delta t} = alloc_{rep} \cdot NPP_{act}$$
(47)

554

555 Based on the change in the biomass pools B_{shoot} and B_{root} , the new biomass values for the 556 different pools are calculated and the geometrical variables of an individual plant are updated.

557

558 With regard to a plant's biomass pools, the respective nitrogen pools are updated dependent 559 on the species-specific *CN* ratios (of green and brown plant material) and a biomass-to-carbon 560 conversion factor ($f_c = 0.43$). For those shoot biomass parts, which turn from green to

senescent ones (equation 44), leaf nitrogen is relocated and used for nitrogen demands in the subsequent time step (section 3.9.1):

563

564

$$N_{relocated} = \frac{1}{LLS} \cdot B_{shoot}^{green} \cdot f_C \cdot \left(\frac{1}{CN_{green}} - \frac{1}{CN_{brown}}\right)$$
(48)

565

566 3.15 Management

567

568 Management of grasslands is included in GRASSMIND in terms of mowing, irrigation and 569 fertilization. All three events are characterized by the following information:

- dates of management events (i.e. frequency)
- intensity (e.g. cutting height, fertilizer amount, amount of water supply)
- 572

573 In terms of mowing, the height of all plants on a patch greater than the cutting height (e.g. 10 574 cm) is decreased, thus leading to a modified parameter $hw_{modified}$. For the following time 575 steps, increment in aboveground biomass only contributes to height growth until the time step 576 at which the original parameter *hw* is reached again.

- 577
- 578 Fertilizer and water supply by irrigation contribute to soil resources in the upper soil layer.
- 579

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