

# 1 **Modelling of productive sanitation systems, Niger**

2 *Research report*

3 Louise Karlberg, 2010-01-04

## 4 **Summary**

5 A model of a productive sanitation system with urine fertilised millet, and a non-fertilised  
6 millet crop grown in Niger, was used to predict yields under three different climate scenarios.  
7 Results indicate that urine fertilisation causes large yield improvements (on average 60%)  
8 also under a changing climate. The uncertainties in these estimates are large due to the lack of  
9 measured data from the field.

## 10 **Model description**

11 A physically based transient ecosystems model, the CoupModel (Jansson & Karlberg, 2001)  
12 was used in this study. Like many other large ecosystems models, the CoupModel is a  
13 simulation package containing several modules for estimating water, energy, carbon and  
14 nitrogen processes in the ecosystem. This model has the advantage that it includes a number  
15 of both detailed and simple modules for soil physical and biological properties, hydrology,  
16 micrometeorology and of crop growth. In addition, transpiration and growth are simulated  
17 concurrently, hence accounting for feedback mechanisms between the plant and the  
18 environment. The CoupModel can be used to estimate the uncertainty in the analysis by  
19 allowing a number of parameters to vary according to pre-specified ranges. Table 2 and 3  
20 contain the most important equations and variables for this study respectively.

## 21 **Measured data and parameterisation procedure**

22 The parameters used in the study are listed in table 4-6. The soil data and many of the plant  
23 physical characteristics were based on a study of pearl millet conducted on a farmer's field in  
24 Niger (Rockström et al., 1998). The relative allocation of biomass to leaves, stems, roots and  
25 grain were taken from recent field measurements (*ref to Linus data*), as well as some other  
26 plant characteristics and the fertilisation schedule for the urine fertilised treatment. Average  
27 grain yields for millet from 2000-2008 from Niger ( $0.45 \text{ ton ha}^{-1}$ ) (FAOStat, 2010), was used  
28 to calibrate crop growth by changing soil nutrient content.

29  
30 Hourly climate data (wind speed, air temperature, cloudiness, dew point temperature, and  
31 precipitation) from Maradi, Niger, July to November 2009 (NCDC, 2009), was used to  
32 represent a normal cropping season. During this period the precipitation was 460 mm which is  
33 close to the average of 470 mm for the region (Climate Charts, 2010). Two climate change  
34 scenarios were created, one wet and one dry, by changing the precipitation data by +/- 10%,  
35 and increasing the air temperature by 2 °C.

36  
37 Two variables, the critical threshold for soil moisture stress on water uptake,  $\Psi_c$ , and the  
38 specific leaf area,  $p_{l,sp}$ , were allowed to vary randomly within a pre-specified range in 1000  
39 model iterations to get an estimate of the uncertainty of the simulated values (Table 5).

40  
41 The water balance in the simulation showed a good correspondence with Rockström et al.  
42 (1998) (data now shown).

43 **Results and discussion**

44 Simulated average millet yields under conventional management and normal climate was 0.65  
 45 ton ha<sup>-1</sup> (Table 1), which thus is slightly higher than the average yield for the country (see  
 46 above). Crop growth is limited by both water and nutrients, and is very sensitive to changes in  
 47 all parameters that influence the availability of these resources, such as  $\Psi_c$ . The range selected  
 48 for this parameter (Table 5) caused simulated yield levels to be higher than the original  
 49 calibration. Urine fertilisation causes a yield increase of around 60% (Table 1), which is also  
 50 seen in the field experiment. Compared with the control treatment, the variability in the  
 51 results was larger.

52  
 53 A changed climate has less impact on yields than fertilisation (Table 1), and the yield  
 54 improvements for the urine treatment compared with control remained the same also for a  
 55 changed climate. The highest yields were predicted for the current climate (normal year). A  
 56 higher temperature in combination with less precipitation caused the largest yield reductions  
 57 due to a combination of temperature and water stress on crop growth. However, these  
 58 reductions are likely to be underestimated since the distribution of the precipitation remained  
 59 unaltered in the simulations, while in reality a more uneven distribution is expected, causing  
 60 longer dry-spells and concurrent damage to the crops.

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 62  
 63 **Table 1. Predicted yield (ton ha<sup>-1</sup>) for different management and climates.**

Treatment	Climate	Average	STDV
No urine	Normal	0.65	0.08
	+2 °C and +10% prec	0.63	0.06
	+2 °C and -10% prec	0.56	0.11
2,500 l Urine	Normal	0.76	0.12
	+2 °C and +10% prec	0.73	0.08
	+2 °C and -10% prec	0.64	0.18
5,000 l Urine	Normal	0.85	0.16
	+2 °C and +10% prec	0.83	0.10
	+2 °C and -10% prec	0.74	0.28
7,500 l Urine	Normal	0.94	0.21
	+2 °C and +10% prec	0.92	0.12
	+2 °C and -10% prec	0.86	0.40
10,000 l Urine	Normal	1.02	0.25
	+2 °C and +10% prec	1.02	0.15
	+2 °C and -10% prec	0.93	0.43

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 65  
 66 Since the current water, carbon or nutrient balances are unknown in this study, the simulation  
 67 could not be validated and thus the uncertainty of the results is high. The assessment should  
 68 be regarded as a first attempt to estimate the impact on yields of a changed climate under  
 69 conventional management and urine fertilised crops. In order to improve the simulation, data  
 70 describing the field water, carbon nutrient balances is therefore needed. However, this study  
 71 indicates the potential for models to address the impacts of management not only under the  
 72 conditions during the season when field data was collected, but also for other climates and  
 73 soil types. Moreover, the models can give an insight on key processes determining crop  
 74 growth, such as nutrient limitation and water stress.

75 **References**

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111 **Tables**

112 **Table 2. List of equations.**

Equation	Definition	No.
<i>Plant growth*</i>		
$P_V = V_m \cdot \frac{c_i - \Gamma^*}{K_c(1 + O/K_o) + c_i}$	$C_3$ Rubisco (carboxylation) limited rate of photosynthesis (mol m <sup>-2</sup> s <sup>-1</sup> )	(1)
$P_V = V_m$	$C_4$	
$V_m = V_{max} f(T_l) f(CN_{leaf}) f(E_{ta} / E_{tp})$	Catalytic capacity of Rubisco at saturating levels of Ribulose biphosphate (RuBP) and intercellular partial pressure of CO <sub>2</sub> (mol m <sup>-2</sup> s <sup>-1</sup> )	(2)
$V_{max} = V_{cmax} (1 - e^{-k_m A_l}) \frac{1}{k_{rn}}$	Maximum rate of carboxylation for the bulk canopy per leaf area, $V_{max}$ , RuBP regeneration (light)	(3)
$P_J = J_m \cdot \frac{c_i - \Gamma^*}{c_i + 2\Gamma^*}$	$C_3$ limited rate of photosynthesis (mol m <sup>-2</sup> s <sup>-1</sup> )	(4)
$P_J = J_m$	$C_4$	
$J_m = \min(\varepsilon R_{s,pl}, 0.25 \cdot J_{max} \cdot f(T_l) \cdot f(E_{ta} / E_{tp}))$	Electron transport rate (mol m <sup>-2</sup> s <sup>-1</sup> )	(5)
$J_{max} = V_{max} \cdot 2.1$	Maximum electron transport rate for the bulk canopy per leaf area, $J_{max}$	(6)
$P_S = 0.5 \cdot V_m$	$C_3$ Metabolism of end product (TPU) limited rate of photosynthesis (mol m <sup>-2</sup> s <sup>-1</sup> )	(7)
$P_S = \frac{2 \cdot 10^4 \cdot V_m c_i}{P_{atm}}$	$C_4$	
$f(T_l) = \begin{cases} 0 & T_l < p_{mn} \\ (T_l - p_{mn}) / (p_{o1} - p_{mn}) & p_{mn} \leq T_l \leq p_{o1} \\ 1 & p_{o1} < T_l < p_{o2} \\ 1 - (T_l - p_{o2}) / (p_{mx} - p_{o2}) & p_{o2} \leq T_l \leq p_{mx} \\ 0 & T_l > p_{mx} \end{cases}$	Response function for leaf temperature (-)	(8)
$f(CN_l) = \begin{cases} 1 & CN_{leaf} < P_{CN,Opt} \\ 1 + \frac{CN_{leaf} - P_{CN,Opt}}{P_{CN,Opt} - P_{CN,Th}} & P_{CN,Opt} \leq CN_{leaf} \leq P_{CN,Th} \\ 0 & CN_{leaf} > P_{CN,Th} \end{cases}$	Response function for leaf carbon nitrogen ratio (-)	(9)
$f(E_{ta} / E_{tp}) = \frac{E_{ta}}{E_{tp}}$	Response function for soil moisture (-)	(10)
$\beta_{vj} P_P^2 - P_P (P_V + P_J) + P_V P_J = 0$	Quadratic equations for smoothing the transition between assimilation rates (Collatz et al., 1991). The equations are solved for their smaller roots.	(11)
$\beta_{ps} P^2 - P (P_P + P_S) + P_P P_S = 0$		
where $P_P$ is an intermediate variable equal to the minimum of $P_V$ and $P_J$ .		
$P = \frac{c_a - c_i}{P_{atm}} \cdot (g_{sc} + g_{bc} + g_{ac})$	Supply of carbon for photosynthesis (mol m <sup>-2</sup> s <sup>-1</sup> )	(12)

$$c_b = c_{b,t-1} - \left( P_n + R_{soil} + g_{ac} \left( \frac{c_a - c_b}{p_{atm}} \right) \right) \cdot \frac{\Delta t}{k_{CO2cap}} \quad (13)$$

where  $c_{b,t-1}$  is the carbon concentration in the canopy air space from the previous time step.

$$c_s = c_b - \frac{P_n}{g_{sb}} \cdot p_{atm} \quad (14)$$

$$c_i = c_s - \frac{P_n}{g_{sc}} \cdot p_{atm} \quad (15)$$

$$k_{CO2cap} = \max(d, 4) \cdot a_{mol} \cdot \frac{(T_f - T_{abszero}) \cdot (p_{atm} / p_{atmnorm})}{(T_a - T_{abszero})} \quad (16)$$

$$C_{respleaf} = k_{mrespleaf} \cdot f(T_a) \cdot C_{leaf}$$

where  $P_{leaf}$  is an intermediate variable equal to the amount of assimilates allocated to leaves.

Partial pressure of CO<sub>2</sub> in the canopy air space (Pa)

Partial pressure of CO<sub>2</sub> at the leaf surface (Pa)

Partial pressure of CO<sub>2</sub> in the sub-stomatal cavity (Pa)

Carbon capacity of air (mol air m<sup>-2</sup>), which is the mass of air from ground to displacement height. This factor, together with time,  $t$ , converts the flows (mol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>) into concentrations (mol CO<sub>2</sub> mol air<sup>-1</sup>).

Plant respiration from leaves (gC m<sup>-2</sup> day<sup>-1</sup>)

*Plant abiotic processes*

$$A_l = C_{leaf} \cdot P_{l,sp} \quad (18)$$

$$H_p = p_{hmax} \left( 1 - e^{-P_{h1}(C_{leaf} + C_{stem})} \right) \left( 1 - e^{-P_{h2} \cdot \Delta_{pl}} \right) \quad (19)$$

$$z_r = p_{zroot} \left( \frac{C_{root}}{C_{root} + \frac{P_{zroot}}{P_{incroot}}} \right) \quad (20)$$

$$E_{ta}^* = E_{tp} \int_{z_r}^0 f(\psi(z)) \cdot f(\pi(z)) \cdot r(z) dz \quad (21)$$

$$f(\psi(z)) = \left( \frac{\Psi_c}{\Psi(z)} \right)^{P_1 E_{tp} + P_2} \quad (22)$$

$$E_{ta} = E_{ta}^* + f_{upt} \cdot (E_{tp} - E_{ta}^*) \quad (23)$$

$$\Delta R_n + \rho_a c_p \frac{(e_s - e_a)}{r_a} \quad (24)$$

$$L_v E_{tp} = \frac{\Delta R_n + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma \left( 1 + \frac{r_s}{r_a} \right)}$$

where  $L_v$ ,  $\rho_a$ ,  $c_p$  and  $\gamma$  are constants and  $\Delta$  is the slope of the saturated vapour pressure function.

$$g_l = \frac{R_{is}}{R_{is} + g_{ris}} \cdot \frac{g_{max}}{1 + \frac{e_s - e_a}{g_{vpd}}} \quad (25)$$

$$r_s = \frac{1}{A_l \cdot g_l} \quad (26)$$

$$g_{sc} = \frac{1.6}{r_s} \cdot f(E_{ta}/E_{tp}) \quad (27)$$

Stomatal conductance per leaf area (m s<sup>-1</sup>)

Stomatal resistance (s m<sup>-1</sup>)

Stomatal conductance of CO<sub>2</sub> (m s<sup>-1</sup>)

where 1.6 is the ratio of the diffusivities of CO<sub>2</sub> and H<sub>2</sub>O in the stomatal pores

$$g_{bc} = \frac{1.4}{r_b} \quad \text{Boundary layer conductance of CO}_2 \text{ (m s}^{-1}\text{)} \quad (28)$$

where 1.4 is the ratio of the diffusivities of CO<sub>2</sub> and H<sub>2</sub>O in the leaf boundary layer

$$r_a = \frac{\ln^2 \left( \frac{z_{ref} - d}{z_0} \right)}{k^2 u} \quad \text{Aerodynamic resistance (s m}^{-1}\text{)} \quad (29)$$

where  $k$  is von Karmans constant.

$$z_0 = z_{0\ factor} \cdot H_p \quad \text{Roughness length (m)} \quad (30)$$

$$d = d_{\ factor} \cdot H_p \quad \text{Displacement height (m)} \quad (31)$$

$$g_{ac} = \frac{1.0}{r_a} \quad \text{Aerodynamic conductance of CO}_2 \text{ (m s}^{-1}\text{)} \quad (32)$$

$$g_{sc} \text{ (mol / m}^2 \text{ / s)} = g_{sc} \text{ (m / s)} \cdot a_{mol} \cdot \frac{(T_f + T_{abszero}) \cdot (P_{atm} / P_{atmnorm})}{(T_a + T_{abszero})} \quad \text{Conversion of conductance from m s}^{-1} \text{ to moles m}^{-2} \text{ s}^{-1}, \text{ which is the unit used in the photosynthesis equations,} \quad (33)$$

$$R_{s,pl} = \left( 1 - e^{-k_m \frac{A_l}{f_{cc}}} \right) \cdot f_{cc} (1 - a_{pl}) R_{is} \quad \text{Plant interception of global radiation (MJ m}^{-2} \text{ day}^{-2}\text{)} \quad (34)$$

$$f_{cc} = p_{cmax} (1 - e^{-p_{ck} A_l}) \quad \text{Surface canopy cover (m}^2 \text{ m}^{-2}\text{)} \quad (35)$$

113 \* The photosynthetic rates are calculated as mole carbon per leaf area per second and  $P$  is thus converted to g  
114 carbon per unit soil area per day.  
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**Table 3. List of variables.**

Variable	Unit	Eq.
Rubisco (carboxylation) limited rate of photosynthesis, $P_V$	$\text{mol m}^{-2} \text{s}^{-1}$	(1)
RuBP regeneration (light) limited rate of photosynthesis, $P_J$	$\text{mol m}^{-2} \text{s}^{-1}$	(4)
Metabolism of end product (TPU) limited rate of photosynthesis, $P_S$	$\text{mol m}^{-2} \text{s}^{-1}$	(7)
Catalytic capacity of Rubisco at saturating levels of Ribulose biphosphate (RuBP) and intercellular partial pressure of $\text{CO}_2$ , $V_m$	$\text{mol m}^{-2} \text{s}^{-1}$	(2)
Electron transport rate, $J_m$	$\text{mol m}^{-2} \text{s}^{-1}$	(5)
Maximum rate of carboxylation for the bulk canopy per leaf area, $V_{max}$	$\text{mol m}^{-2} \text{s}^{-1}$	(3)
Maximum electron transport rate for the bulk canopy per leaf area, $J_{max}$	$\text{mol m}^{-2} \text{s}^{-1}$	(6)
Response function for leaf temperature, $f(T_l)$	-	(8)
Response function for leaf carbon nitrogen ratio, $f(CN_l)$	-	(9)
Response function for soil moisture, $f(E_{ta}/E_{tp})$	-	(10)
Partial pressure of $\text{CO}_2$ in the canopy air space, $c_b$	Pa	(13)
Partial pressure of $\text{CO}_2$ at the leaf surface, $c_s$	Pa	(14)
Partial pressure of $\text{CO}_2$ in the sub-stomatal cavity, $c_i$	Pa	(15)
Carbon capacity of air, $k_{\text{CO}_2\text{cap}}$	$\text{mol air m}^{-2}$	(16)
Plant respiration from leaves, $C_{res\text{leaf}}$	$\text{gC m}^{-2} \text{day}^{-1}$	(17)
Plant respiration from stem, $C_{res\text{stem}}$	$\text{gC m}^{-2} \text{day}^{-1}$	(17)
Plant respiration from roots, $C_{res\text{root}}$	$\text{gC m}^{-2} \text{day}^{-1}$	(17)
Plant respiration from fruits, $C_{res\text{fruit}}$	$\text{gC m}^{-2} \text{day}^{-1}$	(17)
Leaf temperature, $T_l$	$^{\circ}\text{C}$	
Air temperature, $T_a$	$^{\circ}\text{C}$	
Freezing point, $T_f$	$^{\circ}\text{C}$	
Carbon nitrogen ration in the leaf, $CN_{\text{leaf}}$	$\text{g g}^{-1}$	
Carbon content in leaves, $C_{\text{leaf}}$	$\text{g C m}^{-2}$	
Carbon content in stem, $C_{\text{stem}}$	$\text{g C m}^{-2}$	
Carbon content in roots, $C_{\text{root}}$	$\text{g C m}^{-2}$	
Leaf area index, $A_l$	$\text{m}^2 \text{m}^{-2}$	(18)
Plant height, $H_{pl}$	m	(19)
Root depth, $z_r$	m	(20)
Time that has elapsed since the emergence day of the plant, $\Delta t_{pl}$	days	
Actual transpiration before compensatory uptake, $E_{ta}^*$	$\text{mm day}^{-1}$	(21)
Response function for soil moisture content, $f(\Psi)$	-	(22)
Actual transpiration, $E_{ta}$	$\text{mm day}^{-1}$	(23)
Potential transpiration, $E_{tp}$	$\text{mm day}^{-1}$	(24)
Stomatal conductance per leaf area, $g_l$	$\text{m s}^{-1}$	(25)
Stomatal resistance, $r_s$	$\text{s m}^{-1}$	(26)
Aerodynamic resistance, $r_a$	$\text{s m}^{-1}$	(29)
Stomatal conductance of $\text{CO}_2$ , $g_{sc}$	$\text{m s}^{-1}$	(27)
Boundary layer conductance of $\text{CO}_2$ , $g_{bc}$	$\text{m s}^{-1}$	(28)
Aerodynamic conductance of $\text{CO}_2$ , $g_{ac}$	$\text{m s}^{-1}$	(32)
Roughness length, $z_0$	m	(30)
Displacement height, $d$	m	(31)
Surface canopy cover, $f_{cc}$	$\text{m}^2 \text{m}^{-2}$	(35)
Plant interception of global radiation, $R_{s,pl}$	$\text{MJ m}^{-2} \text{day}^{-2}$	(34)
Net radiation, $R_n$	$\text{MJ m}^{-2} \text{day}^{-2}$	
Incoming short-wave radiation, $R_{is}$	$\text{MJ m}^{-2} \text{day}^{-2}$	
Wind speed, $u$	$\text{m s}^{-1}$	
Vapour pressure deficit, $e_s - e_a$	Pa	

**Table 4. Plant growth properties.**

Property	Value	Unit	Eq.	Source
Maximum Rubisco capacity per leaf area at the top the canopy, $V_{cmax}$	50	$\mu\text{mol m}^{-2} \text{s}^{-1}$	(3)	Massad et al., 2007
Quantum efficiency*, $\varepsilon$	8	$\text{g dw MJ}^{-1}$	(5)	Jones, 1992
Atmospheric pressure at the surface, $p_{atm}$	100	kPa	(7), (33)	model default
Optimum temp. interval, $p_{o1} - p_{o2}$	20-40	$^{\circ}\text{C}$	(8)	assumed
Max temp, $p_{mx}$	60	$^{\circ}\text{C}$	(8)	assumed
Min temp, $p_{mn}$	5	$^{\circ}\text{C}$	(8)	assumed
Optimum carbon nitrogen ratio, $p_{CN,Opt}$	25	-	(9)	model default
Threshold carbon nitrogen ratio, $p_{CN,Th}$	80	-	(9)	model default
Photosynthesis curvature factor, $\beta_{vj}$	0.877	-	(11)	Dai et al., 2004
Photosynthesis curvature factor, $\beta_{ps}$	0.99	-	(11)	Dai et al., 2004
CO <sub>2</sub> concentration atmosphere, $c_a$	386	$\mu\text{mol mol}^{-1}$	(12)	approximate levels 2009
Assimilates to leaf	0.23	-		independent obs.
Assimilates to stem	0.57	-		independent obs.
Assimilates to roots	0.20	-		independent obs.
Biomass leaf to fruit	0.15	-		independent obs.
Biomass stem to fruit	0.25	-		independent obs.
Biomass root to fruit	0.35	-		independent obs.
Maintenance respiration leaf, $k_{mrespleaf}$	0.034	$\text{g g}^{-1}$	(17)	Penning de Vries & van Laar, 1984
Maintenance respiration stem, $k_{mrespstem}$	0.017	$\text{g g}^{-1}$	(17)	Penning de Vries & van Laar, 1984
Maintenance respiration roots, $k_{mresproot}$	0.011	$\text{g g}^{-1}$	(17)	Penning de Vries & van Laar, 1984
Maintenance respiration fruit, $k_{mrespfruit}$	0.011	$\text{g g}^{-1}$	(17)	Penning de Vries & van Laar, 1984

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\* The CoupModel uses absorbed incident solar radiation. All units of quantum efficiency have been transferred to this unit according to Sinclair and Muchow (1999) and Bonhomme (2000).



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**Table 5. Plant physical characteristics, transpiration, resistances to water vapour transfer and radiation properties.**

Property	Value	Unit	Eq.	Source
Leaf mass per unit leaf area, $p_{l,sp}$	15-25	gC m <sup>-2</sup>	(18)	Alagarswamy et al., 1988
Max height, $p_{lmax}$	1.6	m	(19)	independent obs.
Height mass coef, $p_{hl}$	0.003	m <sup>2</sup> day <sup>-1</sup>	(19)	Karlberg et al., 2006, tomato
Height age coef, $p_{h2}$	0.1	days <sup>-1</sup>	(19)	Karlberg et al., 2006, tomato
Root inc depth, $p_{incroot}$	-1	m	(20)	model default
Root lowest depth, $p_{zroot}$	-1.6	m	(20)	Rockström et al., 1998
Crit threshold dry, $\Psi_c$	150-400	- cm water	(22)	Rockström et al., 1998
Demand rel coef, $p_1$	1	1 day <sup>-1</sup>	(22)	Rockström et al., 1998
Non-demand rel coef, $p_2$	2	kg m <sup>-2</sup> day <sup>-1</sup>	(22)	Rockström et al., 1998
Flexibility degree, $f_{upt}$	0.5	-	(22)	Rockström et al., 1998
Lohammar, cond max, $g_{max}$	0.027	m s <sup>-1</sup>	(25)	Rockström et al., 1998
Lohammar, cond ris, $g_{ris}$	20	MJ m <sup>-2</sup> day <sup>-1</sup>	(25)	Rockström et al., 1998
Lohammar, cond vpd, $g_{vpd}$	6000	Pa	(25)	Rockström et al., 1998
Boundary layer resistance, $r_b$	21	s m <sup>-1</sup>	(28)	Collatz et al., 1991
Reference height, $z_{ref}$	2	m	(29)	independent obs.
Roughness coefficient, $z_{ofactor}$	0.1	-	(30)	Rockström et al., 1998
Displacement coefficient, $d_{factor}$	0.66	-	(31)	model default
Plant albedo, $a_{pl}$	25	%	(34)	Oke, 1987; Gustafsson, 2002
Extinction coefficient, $k_{rn}$	0.41	-	(34), (3)	Rockström et al., 1998
Maximum surface coverage, $p_{cmax}$	0.4	m <sup>2</sup> m <sup>-2</sup>	(35)	independent obs
Surface coverage rate, $p_{ck}$	0.5	-	(35)	model default

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**Table 6. Constants for the calculation of photosynthesis.**

Constant	Determination	Unit
CO <sub>2</sub> compensation point in the absence of mitochondrial respiration, $\Gamma^*$	$\Gamma^* = \frac{0.5 \cdot O}{2600 \cdot 0.57^{Q_{10}}}$	Pa
Partial pressure of O <sub>2</sub> in the leaf interior, $O$	$O = 20.5 \cdot 10^3$	Pa
Rubisco Michaelis-Menten constant for CO <sub>2</sub> , $K_c$	$K_c = 30 \cdot 2.1^{Q_{10}}$	Pa
Rubisco Michaelis-Menten constant for O <sub>2</sub> , $K_o$	$K_o = 30000 \cdot 1.2^{Q_{10}}$	Pa
Q <sub>10</sub> temperature coefficient, $Q_{10}$	$Q_{10} = (T_l - 298.16)/10$	-
Absolute zero, $T_{abszero}$	$T_{abszero} = -273.15$	°C
Normal air pressure, $p_{atmnorm}$	$p_{atmnorm} = 1.013 \cdot 10^5$	Pa
Mole air per cubic meter air, $a_{mol}$	$a_{mol} = 44.6$	mol m <sup>-3</sup>

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