Modelling symbiotic biological nitrogen fixation in grain legumes globally by LPJ-GUESS

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Table S1. A list of parameters for the daily carbon allocation (Eqs. 1-7) for soybean and faba bean.

Parameter	Description	Soybean	Faba bean	Reference
a_{veg} (Eq.1)	Regression intercept, vegetative phase	-0.06	-0.06	Irmak et al. (2013)
b_{veg} (Eq.1)	Regression slope, vegetative phase	3.29	3.29	Irmak et al. (2013)
a_{rep} (Eq.1)	Regression intercept, reproductive phase	0.71	0.71	Irmak et al. (2013)
b_{rep} (Eq.1)	Regression slope, reproductive phase	1.31	1.31	Irmak et al. (2013)
$fphu_{anthesis}$ (Eq.1)	The threshold of fphu when anthesis starts	0.34	0.34	Irmak et al. (2013)
T_b	Base temperature for heat sum requirement	10°C	4°C	Irmak et al. (2013); Etemadi et al. (2018)
f_1 (Eq.3)	a_1	0	0	
	b_1	1	1	
	c_1	8.93	9.59	
	d_1	1.41	1.46	
f_2 (Eq.4)	a_2	0.67	0.75	
	b_2	0	0	
	c_2	30.78	7.69	
	d_2	1.73	1.38	
f_3 (Eq.5)	a_3	0.56	0.59	
	b_3	0	0	
	c_3	3.74	5.53	
	d_3	0.53	0.51	

Table S2. Literature-based soybean and faba bean sites used for model testing: Geographic location; Available years; BNF trial and its managements; Variables used for evaluation; Measured plant traits of the studied sites.

Geographic location	Crop[a]	Lon	Lat	Years	BNF trials	Managements involved[b]	Variables evaluated[c]	SLA[d]	Grain C:N ratio	Reference
Illinois (U.S.A.)	S	-88.2	40.0	2001/08	Elevated CO_2	W: Rf F: 0	Y, SB, LB,LAI	47	-	Morgan et al., 2005 Ainsworth et al., 2007
Kisumu (Kenya)	S	34.4	0.1	2004/14	Conservation tillage	W: Rf F: 0	Y	-	7.0	Sommer et al., 2018 Nyawira et al., 2021
Kisumu (Kenya)	S	34.4	0.1	2007	Conservation tillage	W: Rf F: 0	Y, GN, BNF, Nsoil, %Ndfa	-	7.0	Kihara et al., 2011
Florida (U.S.A.)	S	-82.4	29.6	1976,78/79, 1981,84/85	Irrigation	W: Rf & Irri F: 0	Y, GN, SB, SN, LB, LN	55	6.5	DeVries et al., 1989a,1989b Boote et al., 2008
Lugo (Spain)	S	-3.3	43.0	1991,1993, 1995,1998	Sowing date & Legume variety	W: Rf & Irri F: 0	Y	50	-	Sau et al., 1999
Zavalla (Argentina)	S	-60.9	-33.0	2013	Legume variety	W: Rf & Irri F: 0	Y, GN, SN, BNF, Nsoil, %Ndfa	-	7.5	Santachiara et al., 2017
Zavalla Argentina	S	-60.9	-33.0	2015/16	N-fertilizer	W: Rf F: 0 & 600	Y, GN, SN, BNF, Nsoil, %Ndfa	-	7.5	Santachiara et al., 2018
Chiang Mai (Thailand)	S	98.6	18.5	1989	Irrigation	W: Irri F: 0 & 50	Y, GN, SN, BNF, Nsoil, %Ndfa	-	6.0	Guafa et al., 1993
Iowa (U.S.A.)	S	-93.8	42.0	2016	N-fertilizer	W: Rf F: 0 & 135	Y, GN, SN, BNF, Nsoil, %Ndfa	-	10.0	Córdova et al., 2019
Wuhan (China)	S	114.3	30.3	1995/97	N-fertilizer	W: Rf F: 25 & 75	Y, GN, SN, BNF, Nsoil, %Ndfa	56	6.5	Gan et al., 2002 Gan et al., 2003
Mullaley (Australia)	S	150.0	-31.2	1991	N-fertilizer	W: Irri F: 56 & 260	Y, GN, SN, BNF, Nsoil, %Ndfa	-	8.0	Herridge and Peoples, 2002
Niigata (Japan)	S	138.9	37.9	2001	Inoculation	W: Rf F: 100	Y, GN, SN, BNF, Nsoil, %Ndfa	-	10.5	Tewari et al., 2004
Suwon (Korea)	S	127.0	37.3	2002	N-fertilizer	W: Rf F: 0 & 30	Y, GN, SN, BNF, Nsoil, %Ndfa	-	5.5	Park et al., 2005

Seibersdorf (Austria)	S	16.5	48.0	1984	Non-nodulation	W: Irri F: 33 & 100	Y, GN, SN, BNF, Nsoil, %Ndfa	-	7.5	Zapata et al., 1987
Rio (Brazil)	S	-43.7	-22.8	1984	Inoculation	W: Irri F: 0 & 60	Y,BNF	-	-	Neves et al., 1985
Dourados (Brazil)	S	-54.8	-22.3	2001/02	N-balance	W: Rf F: 0	Y, GN, SN, BNF, Nsoil, %Ndfa	50	7.0	Alves et al., 2006
Mokwa (Nigeria)	S	6.1	9.8	1994/95	Inoculation	W: Rf F: 20	Y, GN, SN, BNF, Nsoil, %Ndfa	-	6.5	Sanginga et al., 1997
Murewa (Zimbabwe)	S	31.6	-17.8	2003/05	Nutrients	W: Rf F: 122 (M)	Y, GN, SN, BNF, Nsoil, %Ndfa	-	9.0	Zingore et al., 2008
Jabalpur (Inida)	S	78.4	22.8	1973/2005	Nutrients	W: Rf F: 0 & 20	Y, SN, BNF, Nsoil, %Ndfa	-	-	Singh et al., 2012
Cordoba (Spain)	F	-4.8	37.9	1986/88	N-fertilizer	W: Irri F: 0 & 300	Y, GN, LB,LN, SN	55	11.0	Mínguez et al., 1993 Boote et al., 2002
Alberta (Canada)	F	113.6	53.7	2008/09	Legume variety	W: Rf F: 10	Y, GN, SN, BNF, Nsoil, %Ndfa	-	8.0	Williams et al., 2014
Swift (Canada)	F	107.7	50.4	2008/10	Legume variety	W: Rf F: 9.5	Y, GN, SN, BNF, Nsoil, %Ndfa	-	13.0	Hossain et al., 2016
Mininera (Australia)	F	142.9	-37.6	2008	Inoculation	W: Rf F: 0	Y, SN, BNF, Nsoil, %Ndfa	-	-	Denton et al., 2017
Rutherglen (Australia)	F	146.5	-36.1	2008	Inoculation	W: Rf F: 0	Y, SN, BNF, Nsoil, %Ndfa	-	-	Denton et al., 2017
Culcairn (Australia)	F	147.0	-35.6	2010	Inoculation	W: Rf F: 0	Y, GN, SN, BNF, Nsoil, %Ndfa	-	11.0	Denton et al., 2017
Sicily (Italy)	F	13.5	37.5	2001/08	Conservation tillage	W: Irri F: 8	Y, SN, BNF, Nsoil, %Ndfa	-	-	Ruisi et al., 2012 Giambalvo et al., 2012

a Legume crop types: S is soybean; F is faba bean; **b** Management involved in trials: W is water management, in which Rf and Irri represents rain-fed and irrigated crops, respectively; F is N application rate in the unit of kg N ha^{-1}; M denotes the N-fertilizer was applied as manure; **c** Measured variables used for evaluation in this study: Y - yield; SB - shoot biomass; LB - leaf biomass; LAI - leaf area index; GN - grain N mass; SN - shoot N mass; LN - leaf N mass; BNF - biologically N fixation; Nsoil - plant N uptake from soil; %Ndfa - the proportion of plant N derived from the atmosphere (i.e., BNF); **d** SLA (specific leaf area) taken from trials: the unit is m^2 kg^{-1} C;

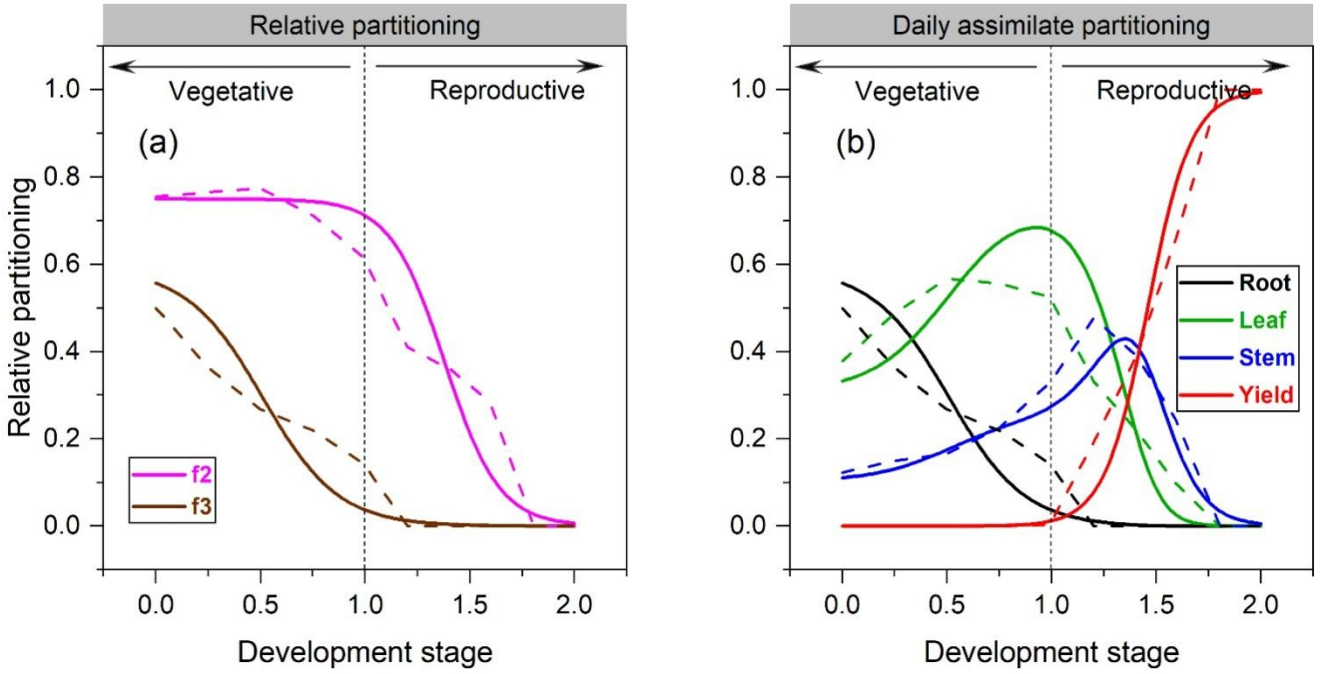

Figure S1. The organ's relative allocation (a) and assimilate partitioning (b) to root, leaf, stem and yield for faba bean. Solid lines represent the fitted Richards functions in this study and dashed lines are the allocation scheme from Penning de Vries et al. (1989). f_2 in Fig.1a denotes leaf relative allocation to shoot vegetative organs (Eq.4), whereas f_3 is root relative allocation to vegetative organs (Eq.5).

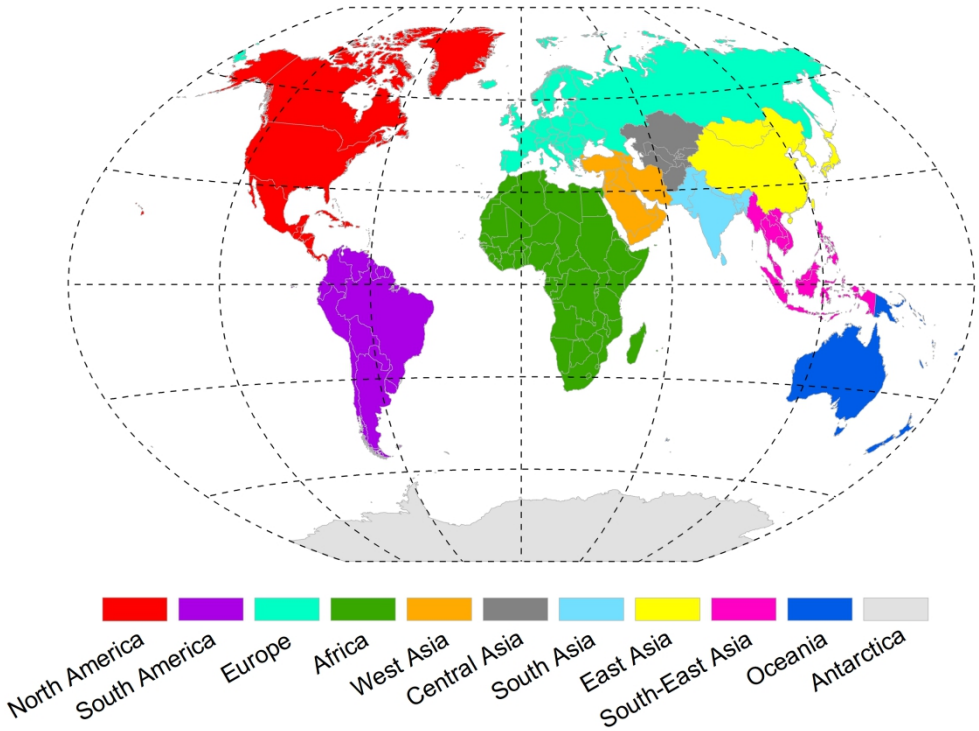

Figure S2. A global division of geographical regions to compare the modelled BNF rates with the literature-reviewed findings from Peoples et al. (2009) on continent level (see Sect. 2.4.2).

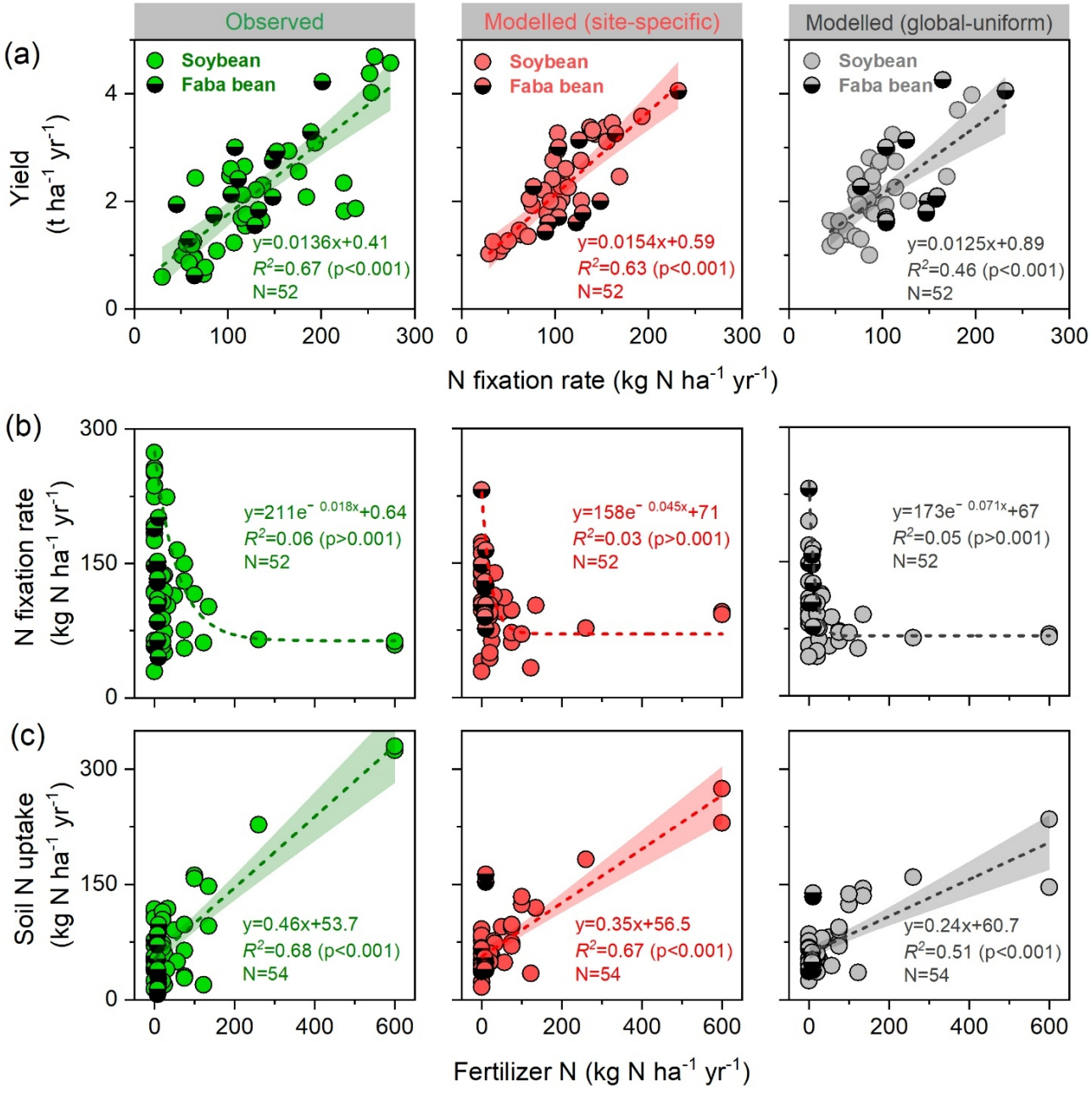

Figure S3. Comparison of modelled and observed yield and N fixation rate (a) and the response of BNF (b) and soil N uptake (c) to N-fertilizer addition across all field trials. The shaded areas represent the 95% confidence interval in linear regression.

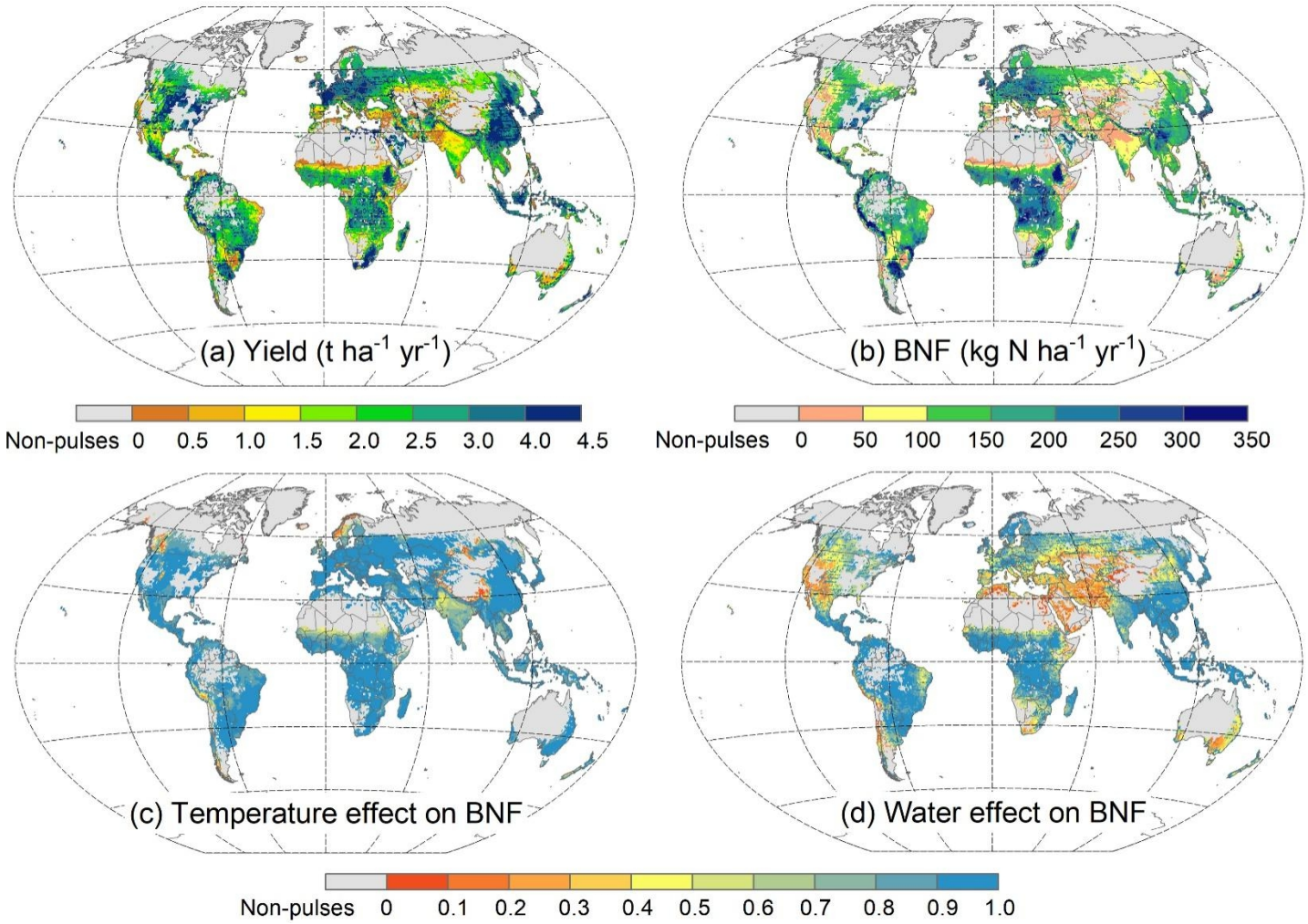

Figure S4. Map of pulses yield (a) and N fixation (b) modelled by LPJ-GUESS, averaged over 1996-2005. The mean soil temperature (f_T, Eq.10) and water limitation (f_W, Eq.11) to N fixation throughout the growing season are presented in (c) and (d), respectively.

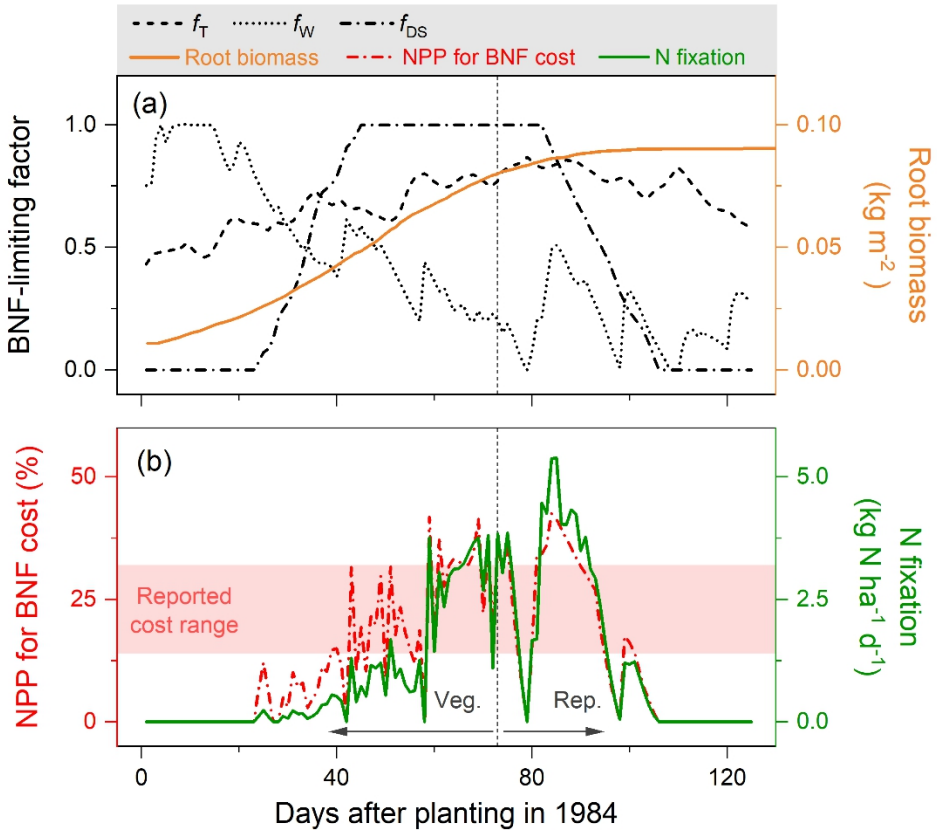

Figure S5. Modelled BNF-limiting factors (a) and daily NPP for N fixation cost (b) in nodulating soybean treatment in the 1984 cropping season at an Austrian site (Zapata et al., 1987). Veg. and Rep. indicate vegetative and reproductive growth phase, respectively. The reported GPP cost range of N fixation was extracted from Table 1 given in Kaschuk et al. (2009), and converted to NPP cost by multiplying by 2.0, assuming GPP=2*NPP.

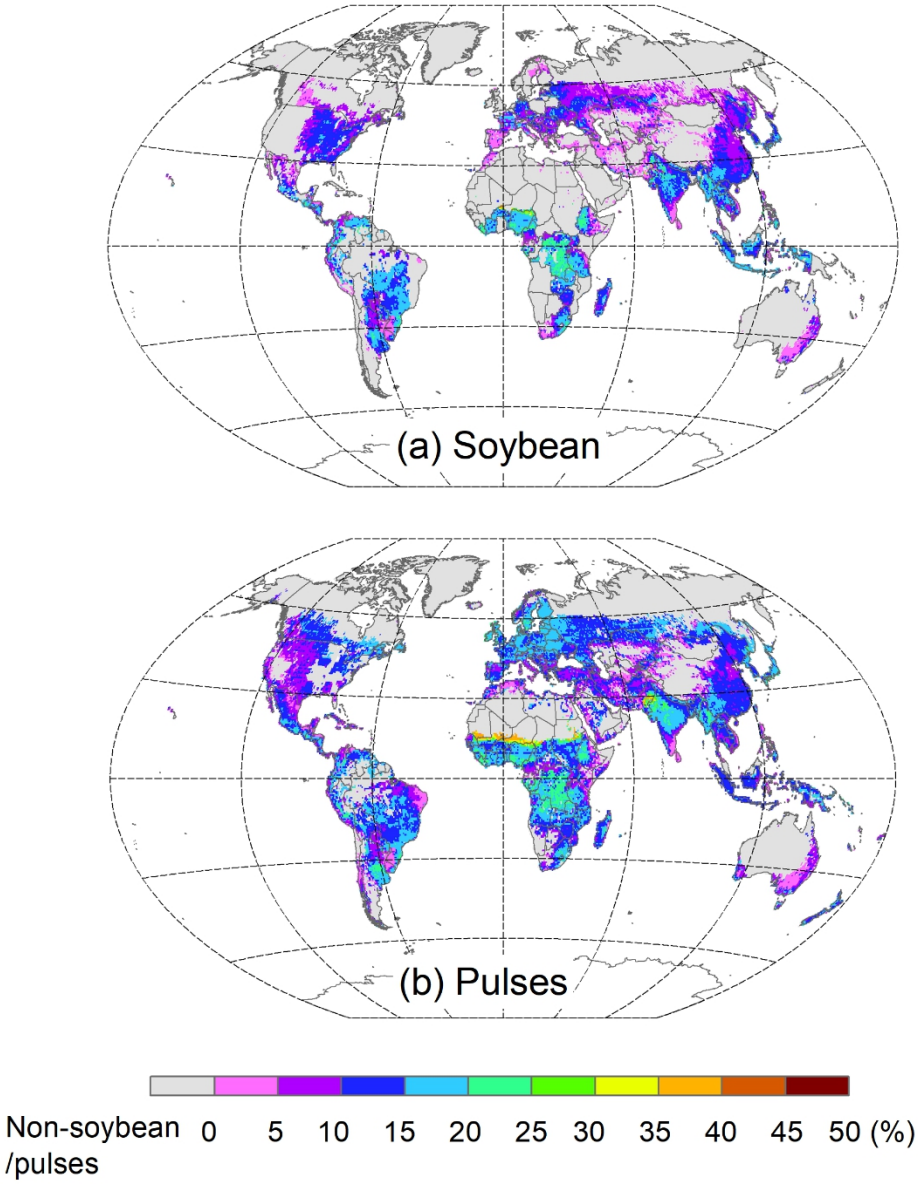

Figure S6. Map of daily NPP used for N fixation cost (%) in soybean (a) and pulses (b) modelled by LPJ-GUESS, averaged over 1996-2005 throughout the growing season. In this study we assumed that at maximum 50% of daily NPP can be used for N fixation (Eq. (13)).

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