Supplementary Material for "Modelling Herbivory Impacts on Vegetation Structure and Productivity"

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The Coupling Loop in Detail

At present, LPJ-GUESS cannot model daily or monthly leaf growth and regrowth, which is needed by Madingley. Growth seasonality dynamics are incorporated through a phenology factor f_{ph}, which equals 1 for evergreens, but varies between 0 to 1 for deciduous plants, reflecting environmental and climatic conditions throughout the year. Following the approach of Kautz et al. (2018), an individual's daily leaf biomass is estimated by multiplying its annual potential leaf biomass with the phenology factor. We estimate monthly leaf carbon values by averaging daily leaf carbon masses. These estimates are either accounted towards an evergreen or a deciduous leaf carbon mass pool per grid cell. Herbaceous PFTs are accounted towards the deciduous leaf carbon stock. This approach is identical to the "offline" coupled version of the model system presented in Krause et al. (2022).

The monthly leaf carbon sums are captured on a grid cell level and then passed to Madingley through the file exchange interface. In case of evergreen stock mass, only one third is passed on. This is due to different assumptions in the two models regarding the vegetation stock: The original Madingley model is calibrated with a monthly regrowing vegetation stock for both deciduous and evergreen leaves. In contrast, LPJ-GUESS regrows its PFT age-cohorts at the start of each year. Giving herbivores access to the complete evergreen leaf stock would cause unrealistically high damage to the evergreen PFTs at the start of each year – also due to the seasonality of deciduous trees, which leads to only evergreens being available as nutrition source. Furthermore, evergreen PFTs in LPJ-GUESS have a 3-year leaf lifespan. This results in damage to evergreen leaves persisting three times longer than damage to deciduous PFTs. Our feedback allocation method partially compensates for the higher risk of growing long-lived leaves and the lack of defence mechanisms, which long-lived tree species typically invest more into (Coley and Aide 1991). The impact of passing only one-third of the evergreen leaf biomass, as opposed to 10% or 100%, is further explored in a sensitivity study discussed later in this study. The formulations for aggregating the individual leaf carbon masses m_i in LPJ-GUESS into an evergreen leaf carbon mass per grid cell m_e (respectively m_d for deciduous and grasses) can be summarized as the following:

$$m_e = \sum_i m_i * {}^1/_3 \quad \Big| \forall\, i \; in \text{ evergreen individuals}$$

$$m_d = \sum_i m_i * f_{ph} \quad \Big| \forall\ i\ in \text{ deciduous individuals}$$

After receiving the vegetation data from LPJ-GUESS, Madingley runs its ecological processes, which result in a reduction of the leaf biomass by the herbivores and omnivores. This reduction of the leaf biomass $m_{r,e}$ and $m_{r,d}$ is recorded and returned to LPJ-GUESS. Subsequentially, LPJ-GUESS determines the corresponding amount of biomass to be removed based on the input from Madingley. The defoliation method used to calculate this biomass removal follows a similar approach to the methods described by Kautz et al. (2018). The reduction is calculated as separate evergreen and deciduous herbivory reduction fractions f_e and f_d :

$$f_e = \frac{m_{r,e}}{3 * m_e} \quad , \quad f_d = \frac{m_{r,d}}{m_d}$$

which is then weighted with f_{ph} and applied to every age-cohort's maximum annual leaf carbon mass. This assures that a PFT age-cohort that did not contribute to the original leaf biomass that was supplied to herbivores and omnivores is not damaged by herbivory. This would be an issue e.g. early in the season when f_{ph} is still zero for some age-cohorts. The new individual's leaf carbon mass is then therefore calculated for evergreen or deciduous PFTs like the following:

$$m_{i,new} = m_i - m_i * f_e \quad \Big| \forall\ i\ in \text{ evergeen individuals}$$

$$m_{i,new} = m_i - m_i * f_d * f_{ph} \quad \Big| \forall\ i\ in \text{ deciduous individuals}$$

We assume that the animals will digest all the biomass they have eaten within one timestep. Since Madingley does not yet have a coupled carbon-nitrogen cycle, we here simplify the impacts of herbivory on the nitrogen cycle by adding all eaten leaf nitrogen mass directly towards the litter pool in LPJ-GUESS at the time of the defoliation event, given that animal faeces and carcasses are enriched in nitrogen. Analogously, all leaf carbon mass removed gets accounted towards the carbon litter pool. This latter assumption results in an overestimation of carbon remaining in the system, since animals respire carbon during growth. However, we concentrate our initial analysis here on impacts of herbivory on photosynthesis and growth and will quantify impacts of plant-animal interactions on total ecosystem carbon and nitrogen cycling in a future analysis with an updated version of Madingley which incorporates the animal stoichiometry and explicit C and N cycling (in prep.).

Litter Transfer Sensitivity Study

In addition to the sensitivity experiments presented in the main manuscript, we conducted an ensemble of simulations in which only 10% of the consumed carbon and nitrogen were transferred to the litter pools (see Figure S1). While Hedge's d indicates the largest effect size in the rainforest site, the most pronounced changes in average carbon and nitrogen pool sizes occur in the boreal ecosystem. This originates from the low variance in the boreal litter pool time series, which amplifies the significance of even small changes. Although litter pool sizes are substantially affected by the reduced transfer rate, the resulting changes in animal biomass densities remain minor (with d values < 0.5). Leaf carbon mass shows a modest negative effect in both the rainforest and boreal ecosystems (for both: d = -1.1), while the savanna ecosystem exhibits a negligible response (d = 0.4). Overall, the impact of altering litter transfer is comparatively smaller than the effects observed from the other two model modifications discussed in the manuscript.

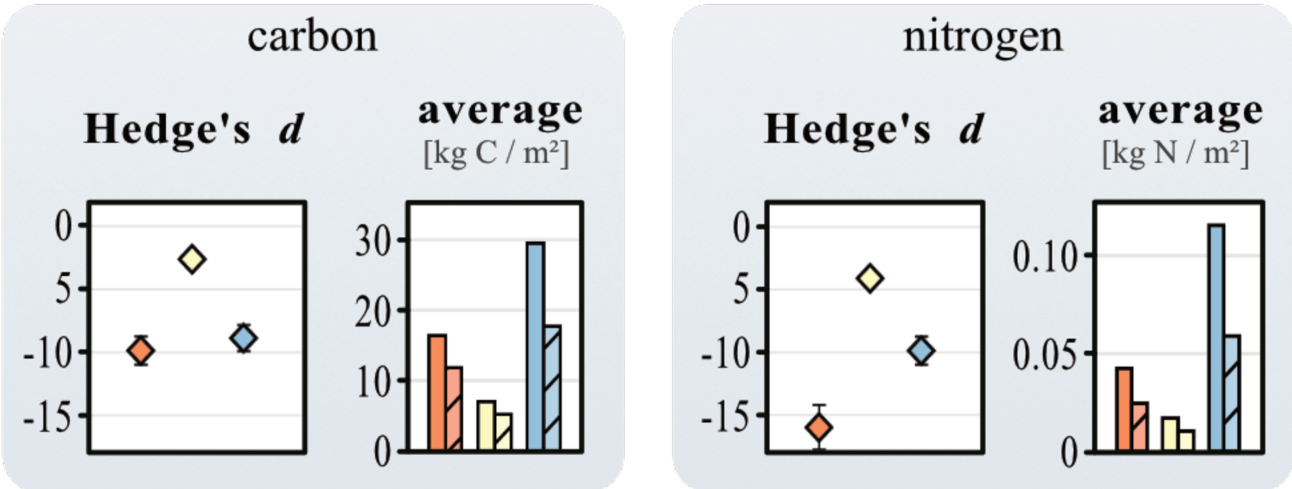

Figure S1: Effect size (Hedge's *d*), as well as average responses of carbon an nitrogen litter when transferring 10% of eaten carbon/nitrogen to the corresponding litter pool (instead of 100%). The analysis was carried out during the simulation years 1900–1980. Both panels show data from three model domains: orange – AF1 rainforest, yellow – AF3 savanna, and blue – EU2 boreal forest, each comprising 25 grid cells. Solid bars show data from simulations with the baseline 100% transfer assumption, while hatched bars show data from simulations with the 10% transfer modification.

Trait	Code	BNE	BINE	BNS	IBS	TeNE	TeBS	TeBE	TrBE	TrIBE	TrBR	C3G	C4G	LSE	LSS
Climate Type	**B**oreal, **Te**mperate, **Tr**opical	B	B	B	B	Te	Te	Te	Tr	Tr	Tr				
Life Form	**t**ree, **l**ow-**s**hrub, **g**rass	t	t	t	t	t	t	t	t	t	t	g	g	ls	ls
Leaf Physiognomy	**N**eedleleaved, **B**roadleaved	N	N	N	B	N	B	B	B	B	B			N	B
Phenology	**E**vergreen, **S**ummergreen, **R**aingreen	E	E	S	S	E	S	E	E	E	R				
Photosynthesis Pathway		C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C3	C4	C3	C3
Light Behaviour	**S**hade **T**olerant, **S**hade **I**ntolerant	ST	SI	ST	SI	ST	ST	ST	ST	SI	ST			SI	SI
Photosynthesis Temperature [°C]	Min to Max Optimum Low to High	-4 to 38 10 to 25				-2 to 38 15 to 25			2 o 55 25 to 30			-5 to 45 10 to 30	6 to 20 45 to 55	-4 to 10 25 to 38	
Survival Temperature [°C]		-31	-31	no limit	-30	-2	-14	-1	15.5			no limit	15.5	-32.5	-40
Leaf Turnover rate [frac/yr]		0.33	0.33	1	1	0.33	1	0.33	0.5	0.5	1	1		0.33	1
Drought Resistance Coefficient (1 = max sensitivity)		0.0001												0.1	0.1
Fire Resistance		0.3			0.1	0.3	0.1	0.3	0.1	0.1	0.3	0.5		0.12	
Respiration Coefficient		1	1	1	1	1	1	1	0.15	0.15	0.15	1	0.15	1	
Minimum forest floor PAR for grass growth/tree establishment (10^6 J m^{-2} day^{-1})		0.35	2.5	0.35	2.5	0.35	0.35	0.35	0.35	2.5	0.35	1	1	1	1

Table S1: The PFT's basic traits alongside a set of selected parameterisations.

Feeding Mode	Reproductive Strategy	Thermoregulation Strategy	Min. Body Mass	Max. Body Mass	Herbivory Assimilation Efficiency	Carnivory Assimilation Efficiency
Herbivore	Iteroparity	Endotherm	1.5 g	5.000 kg	0.8	0
Omnivore	Iteroparity	Endotherm	3 g	200 kg	0.65	0.65
Carnivore	Iteroparity	Endotherm	3 g	400 kg	0	0.8
Herbivore	Iteroparity	Ectotherm	0.0004 g	10 g	0.8	0
Omnivore	Iteroparity	Ectotherm	0.0004 g	20 g	0.65	0.65
Carnivore	Iteroparity	Ectotherm	0.0008 g	20 g	0	0.8
Herbivore	Semelparity	Ectotherm	0.0004 g	1 kg	0.8	0
Omnivore	Semelparity	Ectotherm	0.0004 g	2 kg	0.65	0.65
Carnivore	Semelparity	Ectotherm	0.0008 g	2 kg	0	0.8

Table S2: A detailed overview of all terrestrial Animal Functional Types in Madingley and their key ecological traits.

Figure S2: Ecosystem Net and Gross Primary Production and Evapotranspiration. The Black bars show the offline run, grey bars the online run.

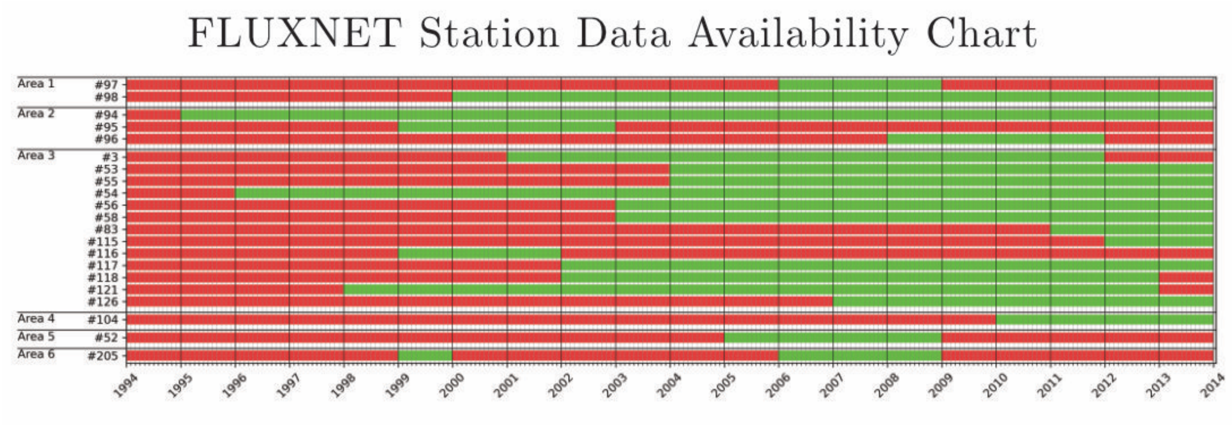

Figure S3: Timeline of available data from FLUXNET stations, which were selected for Figure 7.