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Parameterization of perennial bioenergy crops in Version 5 of the Community Land Model

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U.S. DEPARTMENT OF ENERGY BATTELLE

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Source: https://cabbi.bio/about/cabbi-facilities/

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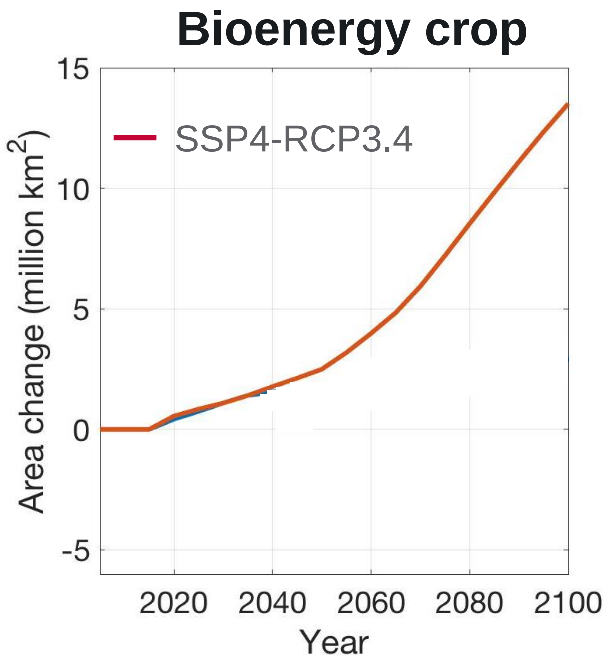
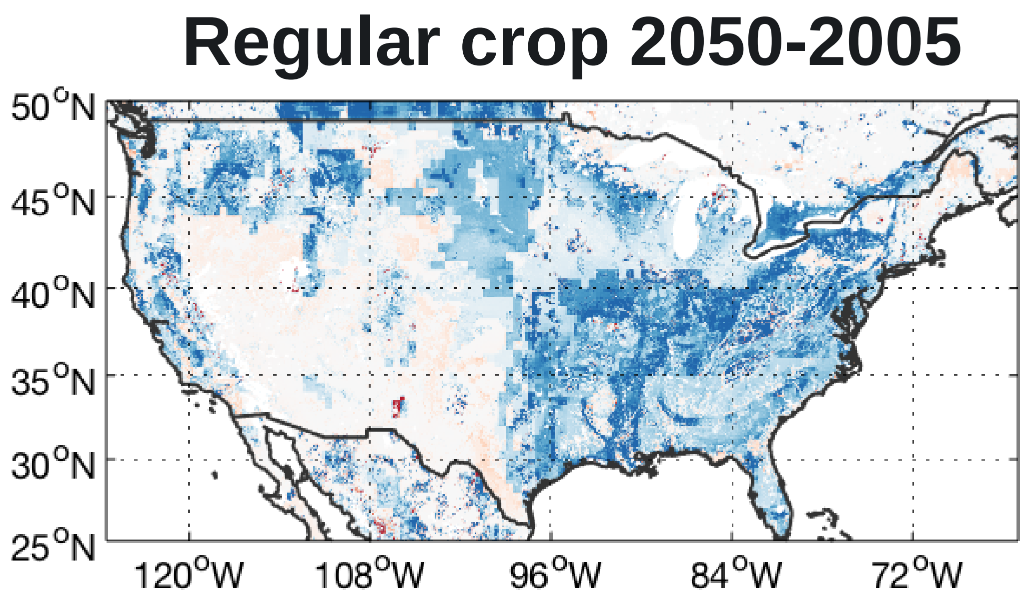
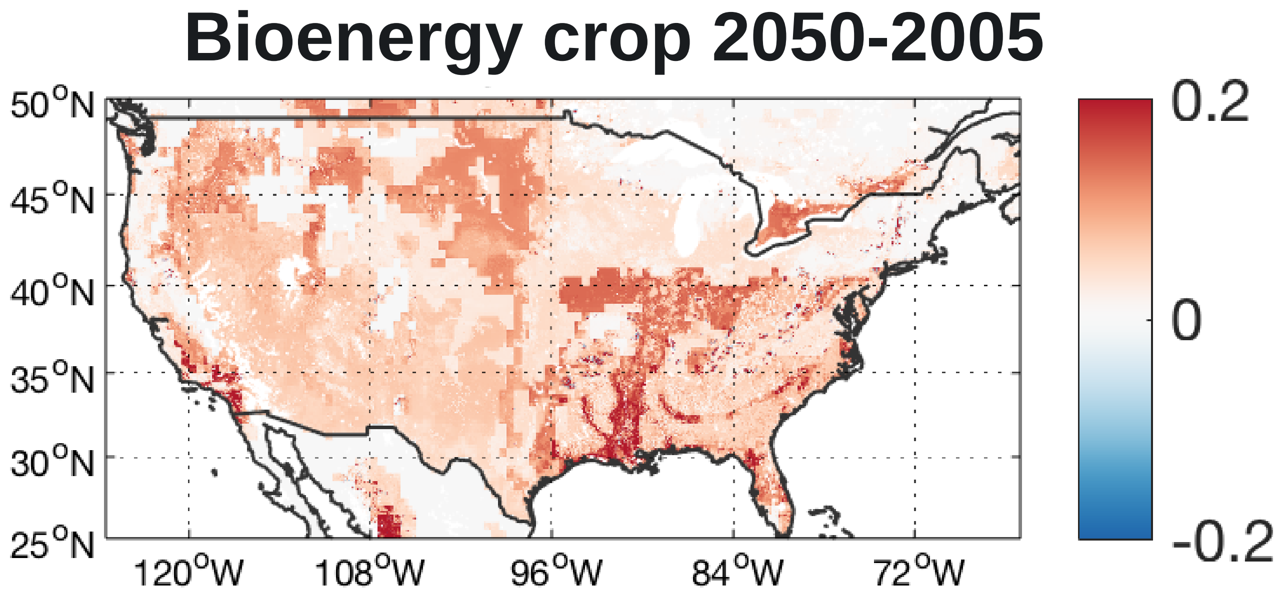
Motivation

- **Biomass energy** is major renewable and sustainable energy source to replace fossil fuels and mitigate climate changes.
- Plantation areas of bioenergy crops are projected to **expand** in future land use change scenarios.







Changes in regular and bioenergy crop fractions between year 2050 and 2005 in the SSP4-RCP3.4
(with high biofuel mitigation)

Motivation

- While traditional crops can be used as biofuel feedstocks, they may have unfavored consequence.
- Perennial grasses such as ***Switchgrass* and *Miscanthus*** are better alternatives.

Traditional crops:

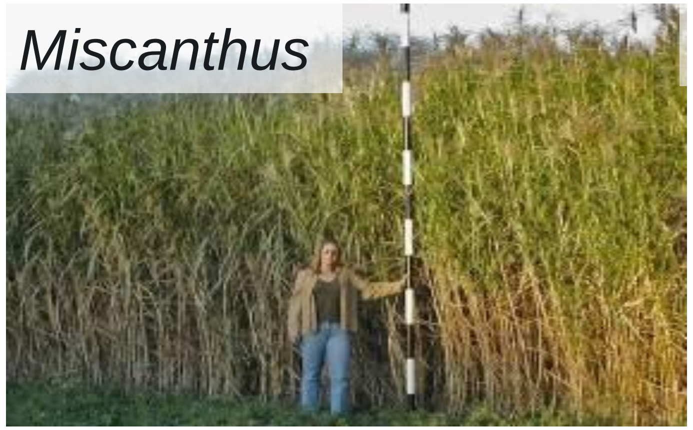
- High demands for fertilization and irrigation
- Jeopardize food security and environmental sustainability

Source: https://www.wideopenspaces.com/7-food-plot-crops-will-create-feeding-frenzy/

Source: https://research.umn.edu/inquiry/post/researchers-set-sights-uprooting-land-based-invasive-species

Perennial grasses:

- Less demands for nutrients and water
- High productivity



Source: https://research.umn.edu/inquiry/post/researchers-set-sights-uprooting-land-based-invasive-species

Credit: Rob Mitchell

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Objective

- We aim to **explicitly represent perennial bioenergy crops** in land model:
    - While ESMs are effective tools to study mitigation effects of land use change, representations of key bioenergy crops are missing in ESMs.
    - Developing representations of the key bioenergy crops in ESMs will help quantify their biogeophysical and biogeochemical effects.

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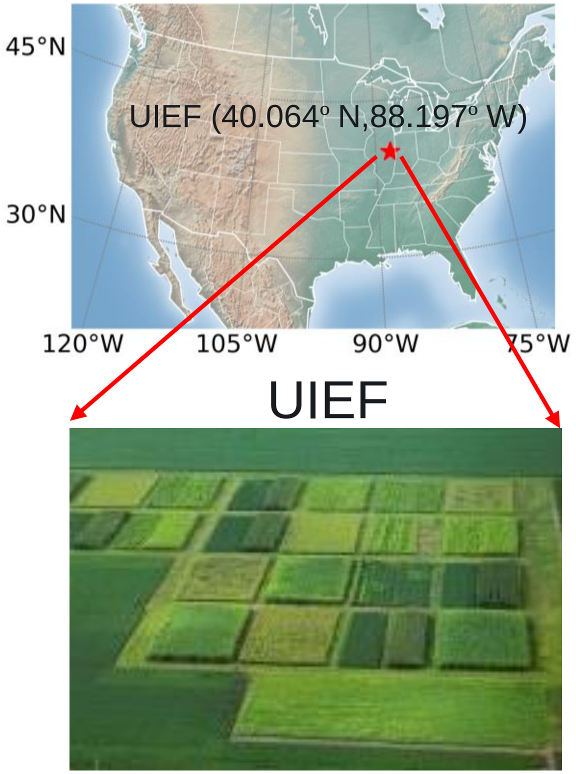
Site description

- University of Illinois Energy Farm (UIEF) in central Illinois.
- Three experimental plots (each 4 ha in size, 200 Ｘ 200 m) :
  1. Maize-soybean rotation; 2. Switchgrass; 3. Miscanthus;
- Three plot-level measurements over **2009-2013**:
  - Meteorological data: rain, incoming radiation, relative humility, temperature, etc.
  - Carbon fluxes: gross primary production (GPP), net ecosystem exchange (NEE), etc.
  - Energy fluxes: latent heat, etc.
  - Water fluxes: evapotranspiration, runoff, etc.



Source: http://news.aces.illinois.edu/news/lower-nitrogen-losses-perennial-biofuel-crops

UIEF

Source: https://cabbi.bio/about/cabbi-facilities/

Source: https://www.critex.fr/critex-tools/wp1-soil-atmosphere-exchanges/task-1-2-flux-tower-ad-ir-scintillometry/

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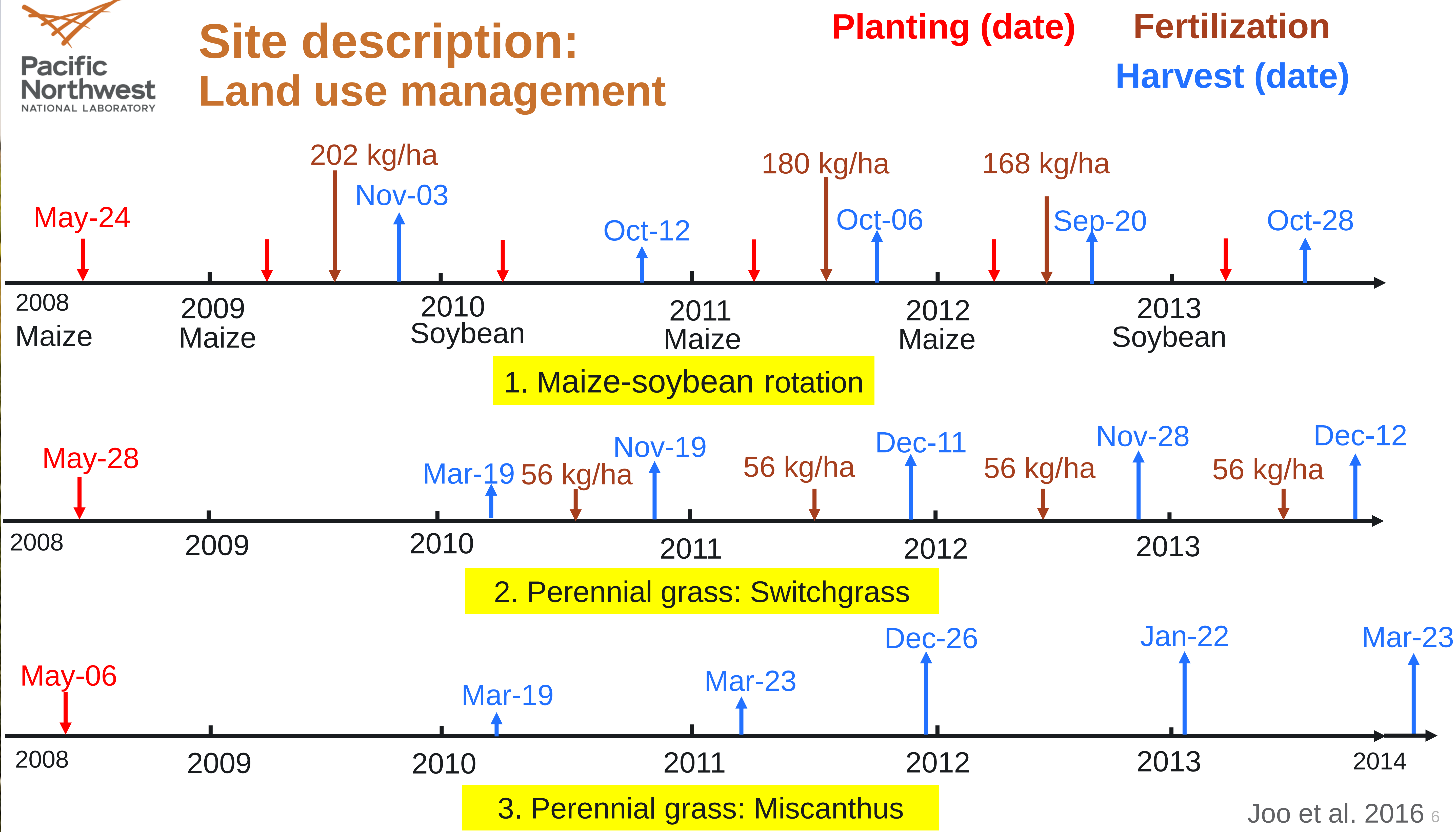
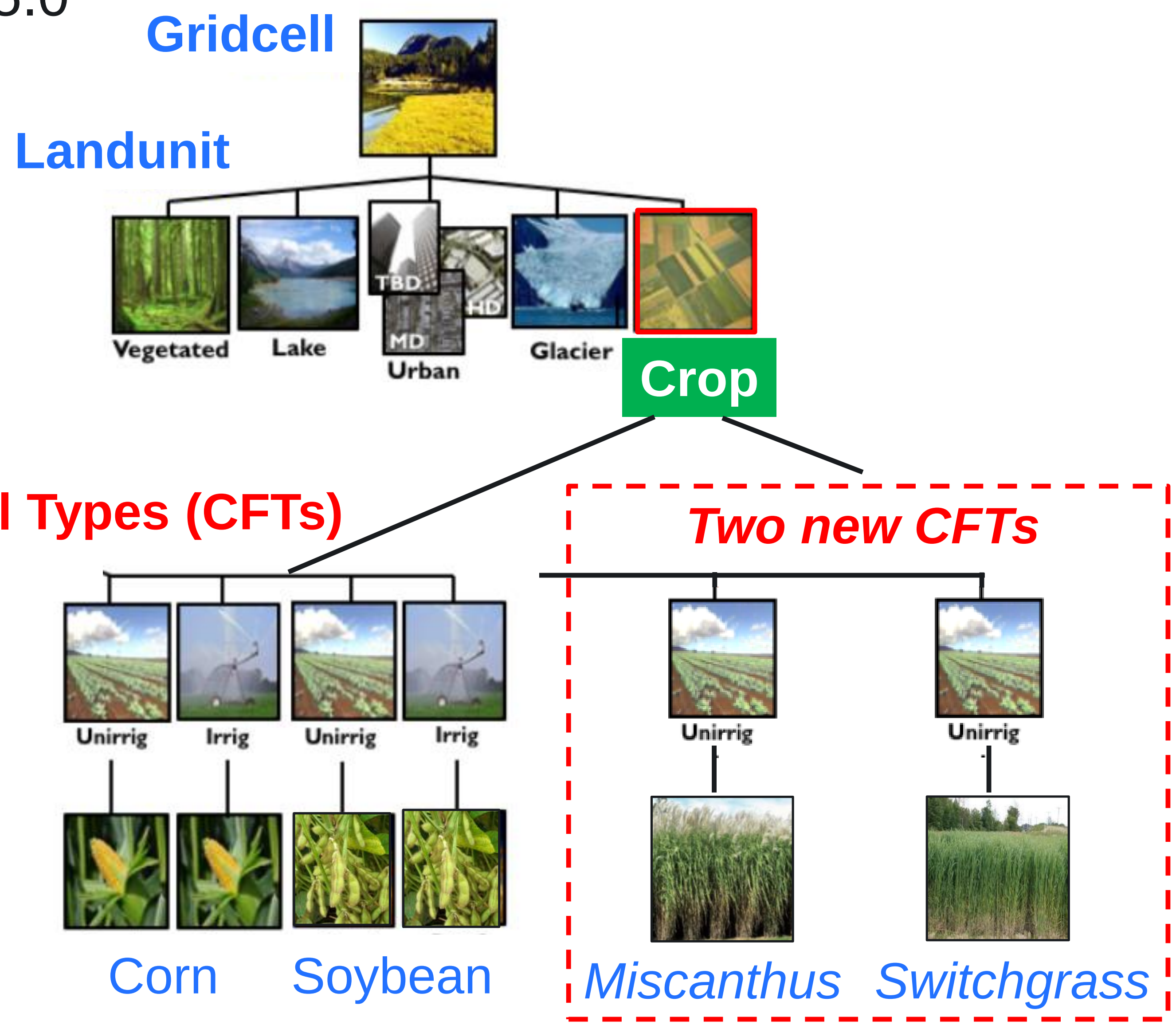
Site description:
Land use management



Joo et al. 2016

Method: model improvement

- Community Land Model version 5 (CLM5.0)
- Add two bioenergy crops to CLM5.0



Configuration of the CLM subgrid hierarchy

Source: CLM5.0 Technical notes

Method: parametrization

	Parameters	Description	Units	Corn	Soybean	Switchgrass	Miscanthus
Photosynthesis capacity	s_vcad	Slope of the relationship between leaf N per unit area and Vcmax25top	umol CO_2/s/gN	26.48	42.96	40.96	59.23
	i_vcad	Intercept of the relationship between leaf N per unit area and Vcmax25top	umol $CO_2/m^2/s$	3.21	4.71	6.42	14.71
	slatop	Specific Leaf Area (SLA) at top of canopy, projected area basis	m^2/gC	0.05	0.035	0.042	0.052
Crop phenology	laimx	Maximum Leaf Area Index	-	5	6	6.5	10
	hybgdd	Growing Degree Days for maturity	-	1700	1900	2850	3000
	mxmat	Maximum number of days to maturity	days	165	150	210	210
Carbon cost of nitrogen uptake	kc_nonmyc	Constant relating root C to non-mycorrhizal root active uptake cost	gC/m^3	7.2	0.72	0.72	0.72
	kn_nonmyc	Constant relating soil layer Nitrogen content to non-mycorrhizal root active uptake cost	gC/m^2	0.12	0.012	0.012	0.012
	FUN_fracfixers	The maximum fraction of assimilated carbon that can be used to pay for N fixation	fraction	0	1.0	0.25	0.25
	fun_cn_flex_c	Parameter linking leafCN content and N cost to FUN C expenditure	-	5	5	100	500
Allocation	fleafi	Leaf Allocation coefficient parameter fraction used in CNAllocation	-	0.6	0.85	0.7	0.9
	arooti	Root Allocation coefficient parameter used in CNAllocation (initial)	-	0.1	0.2	0.14	0.13
	arootf	Root Allocation coefficient parameter used in CNAllocation (final)	-	0.05	0.2	0.09	0.08
Decomposition	rf_l3s2_bgc	Respiration fraction from litter 3 to SOM 2	-	0.5	0.5	0.25	0.2
	rf_s2s3_bgc	Respiration fraction for SOM 2 to SOM 3	-	0.55	0.55	0.55	0.2
	rf_s2s1_bgc	Respiration fraction SOM 2 to SOM 1	-	0.55	0.55	0.55	0.2

Method: land management practice

- **Planting**: no annual planting
- **Harvest**: late harvest in winter
- **Fertilization**: little fertilizer for switchgrass and no fertilizer for Miscanthus
- **Irrigation**: no irrigation
- 70% of **Above-ground biomass** → “grain_to_food” at harvest, to represent harvest for lignocellulosic biofuel crops

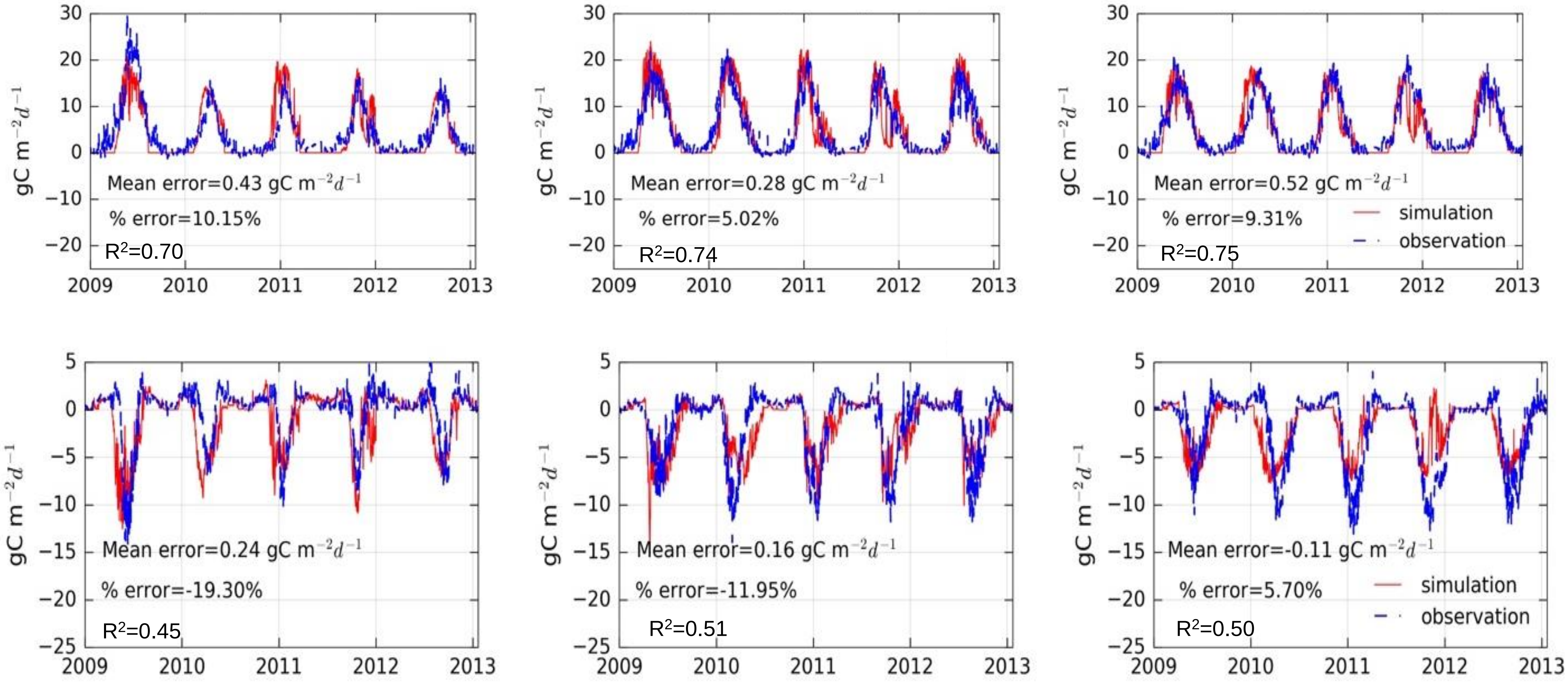
Model configuration at three single points

Single-point simulation results: model evaluation

Maize-soybean rotation | Switchgrass | Miscanthus

GPP

NEE



- All R^2 are greater than 0.5 and all relative errors are less than 20%.
- Simulated carbon fluxes match measurements well.

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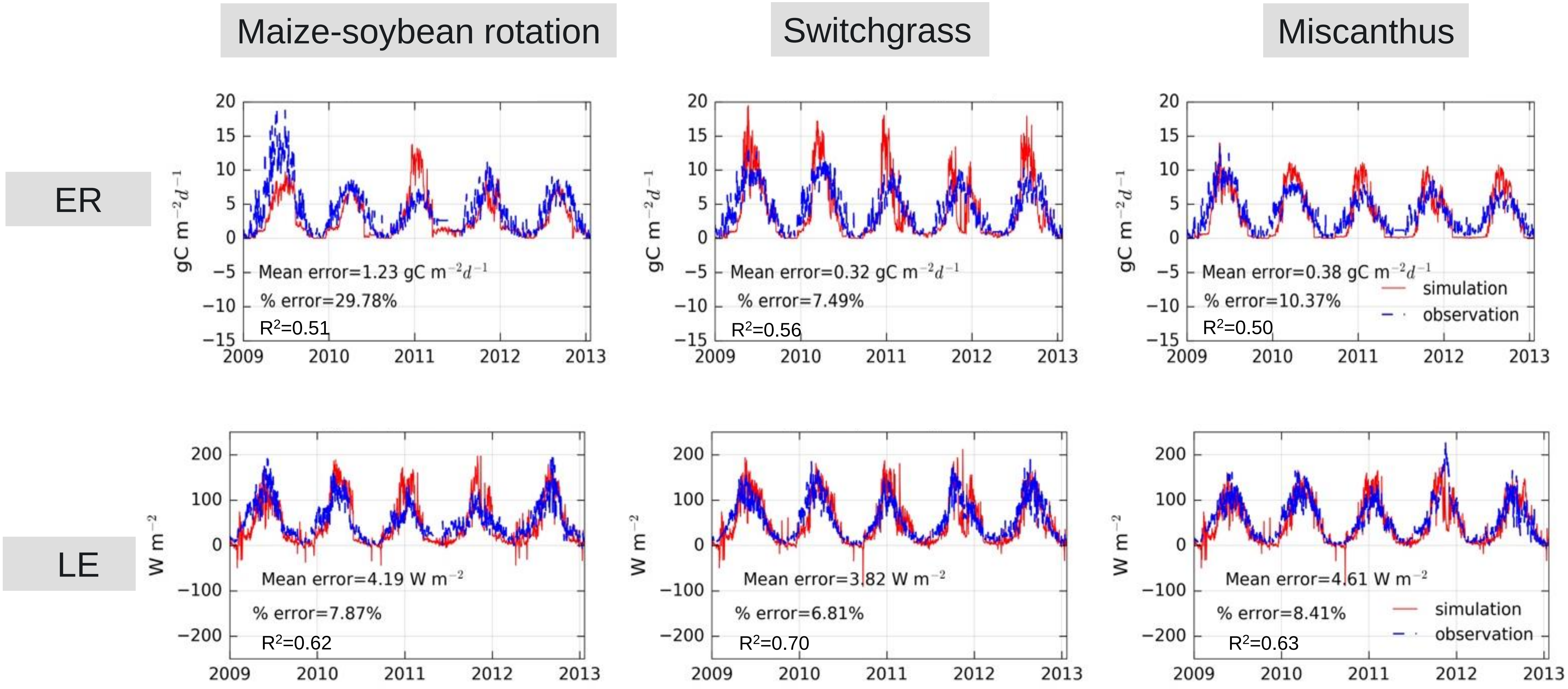
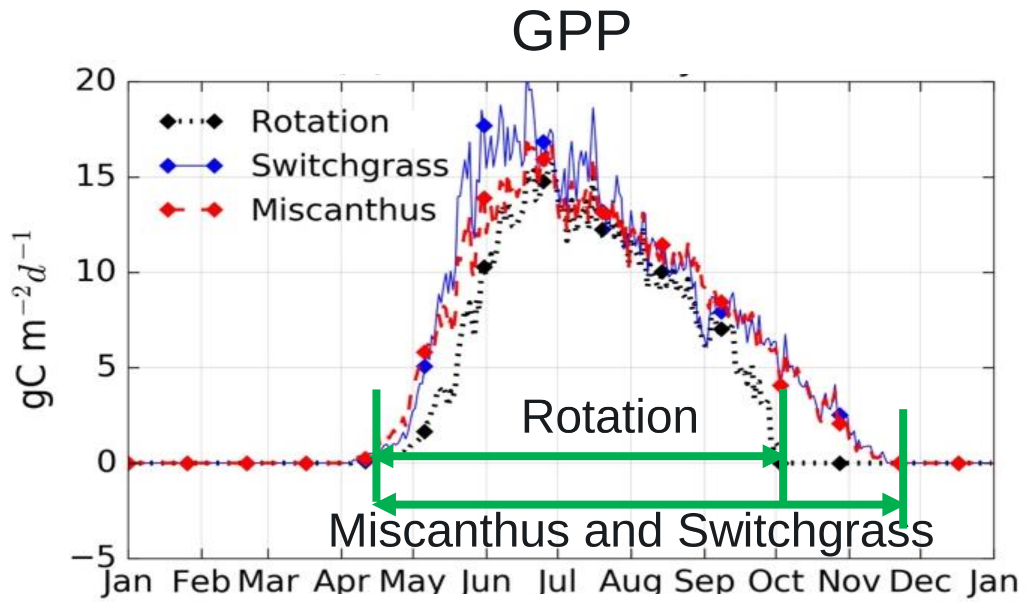
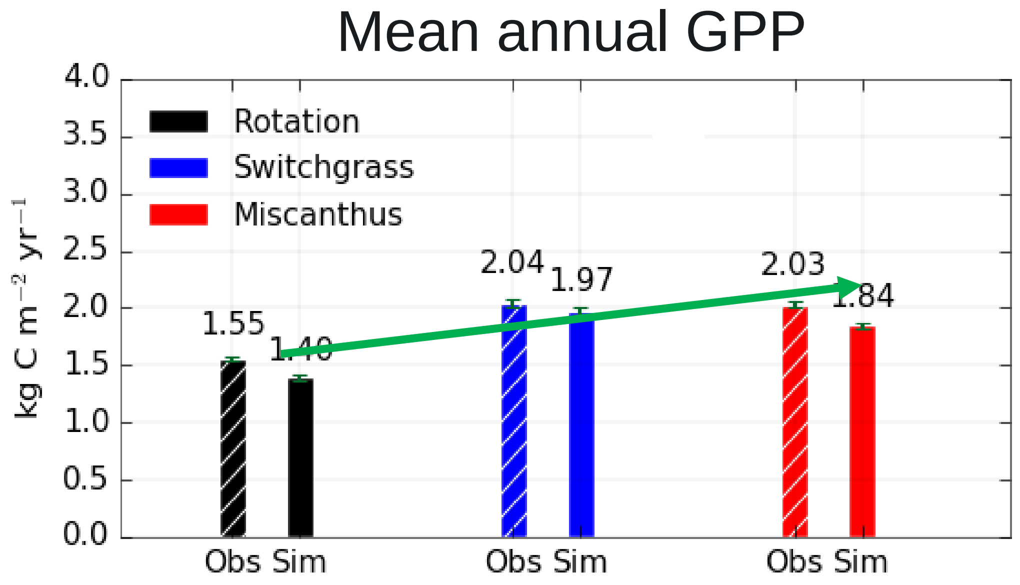
Single-point simulation results: model evaluation

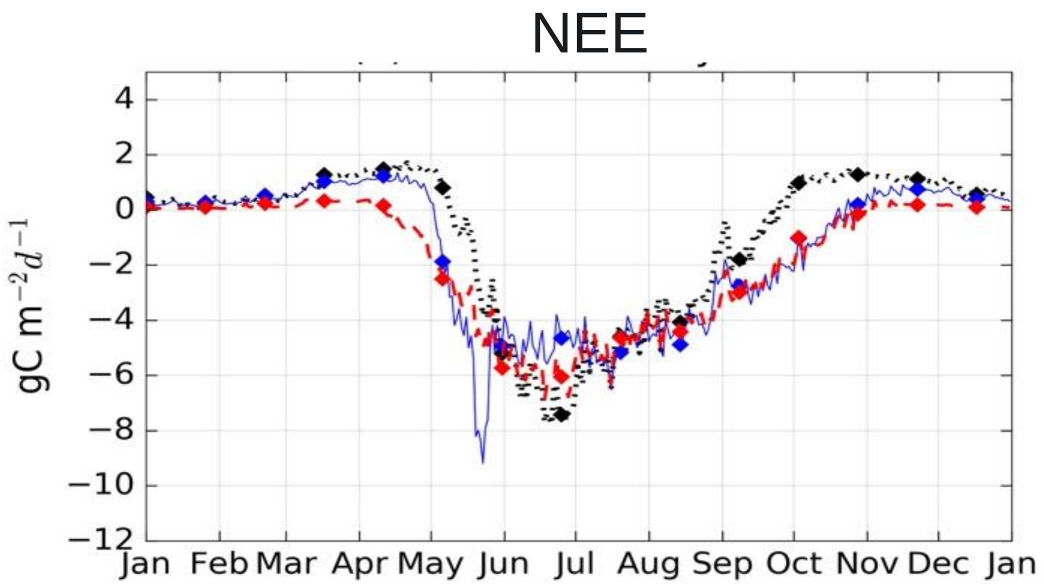


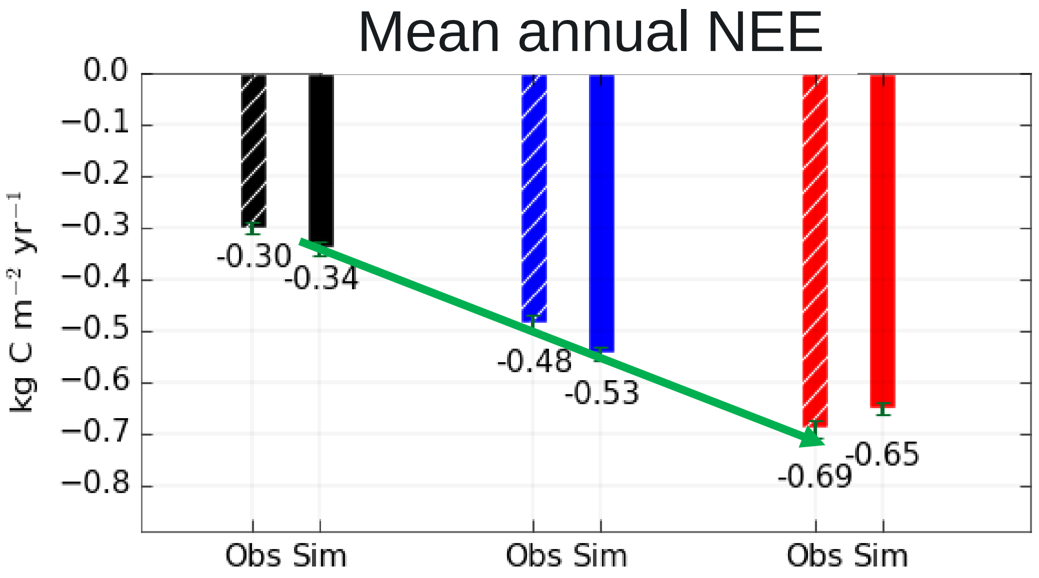
- Simulated energy fluxes match measurements well.

Single-point simulation results: carbon budget



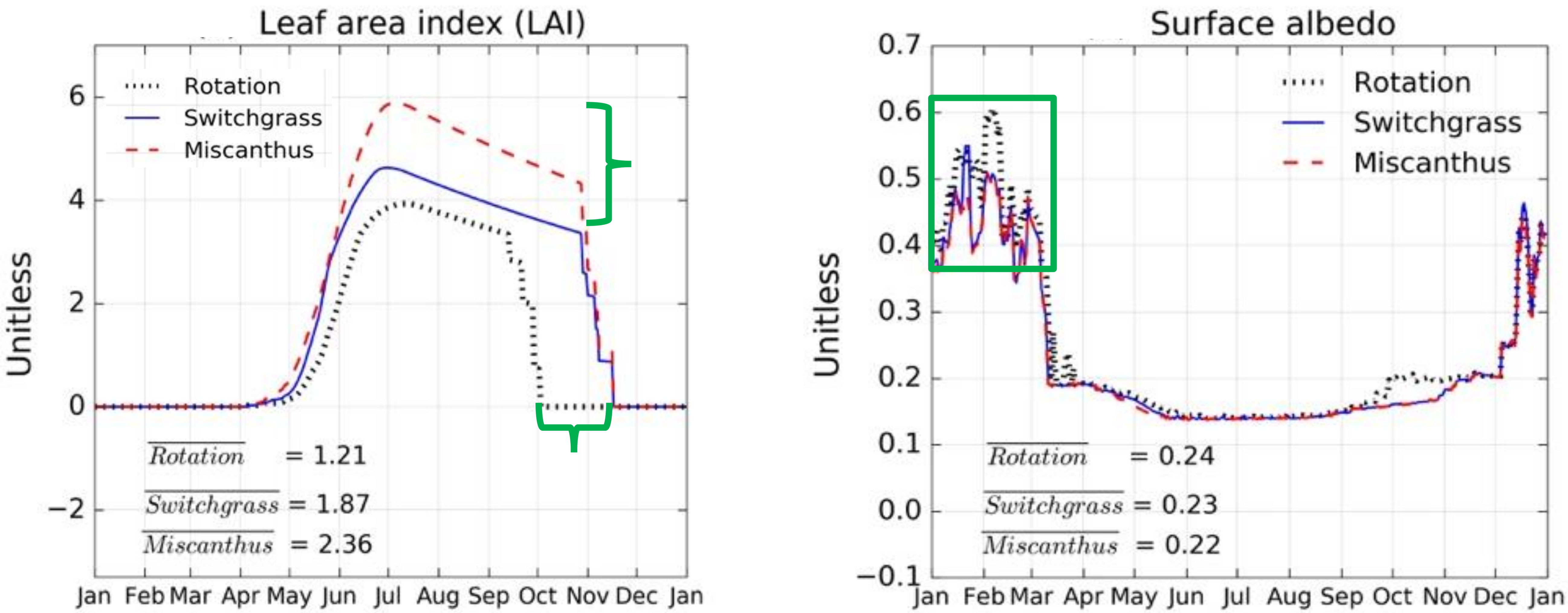






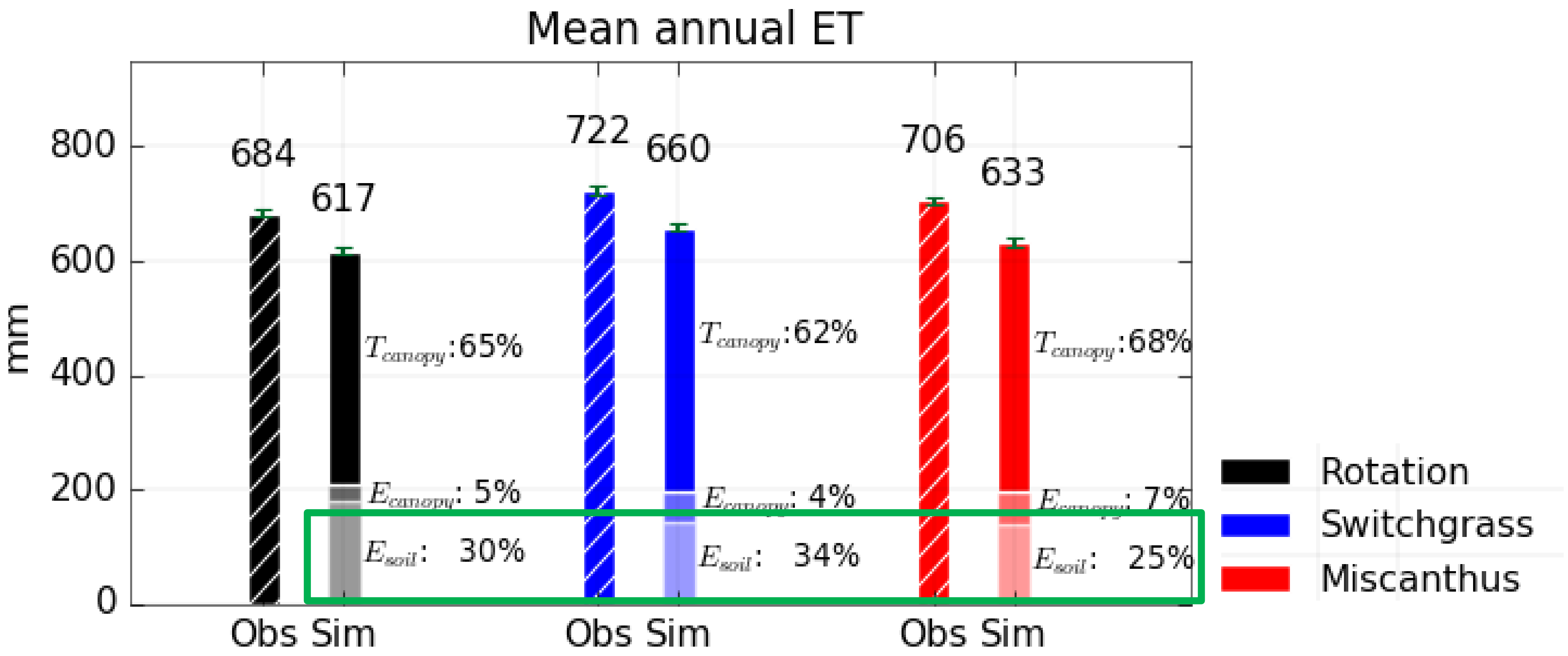
- Bioenergy crops have **longer growing season** and are **more productive** than traditional crops.
- Miscanthus and switchgrass are **larger net carbon sinks**.

Single-point simulation results: energy budget



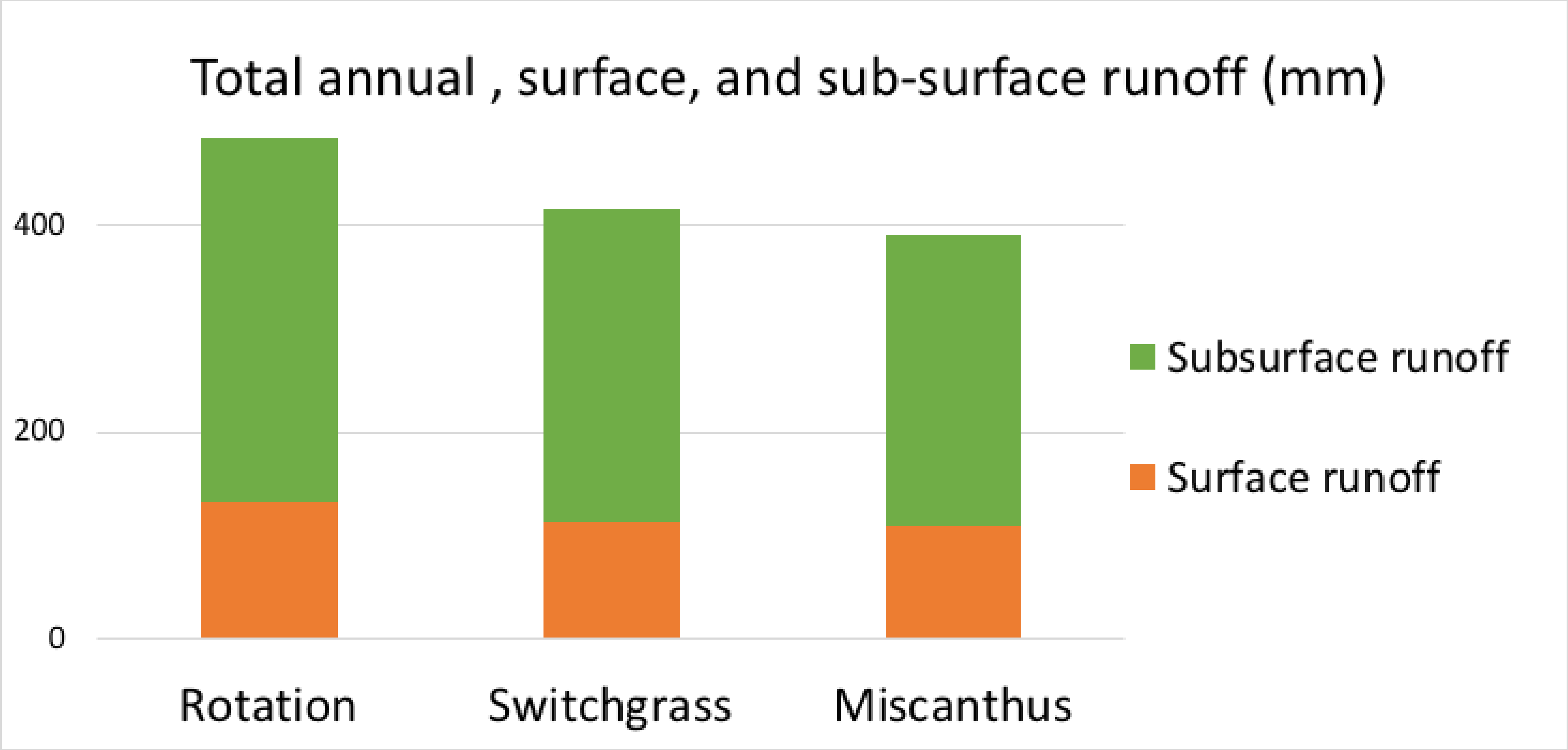
- Average LAI for bioenergy crops is larger due to their **longer growing season and higher productivity**.
- Average albedo for perennial crops is lower due to **higher above-ground biomass during winter that covers snow**.

Single-point simulation results: water budget



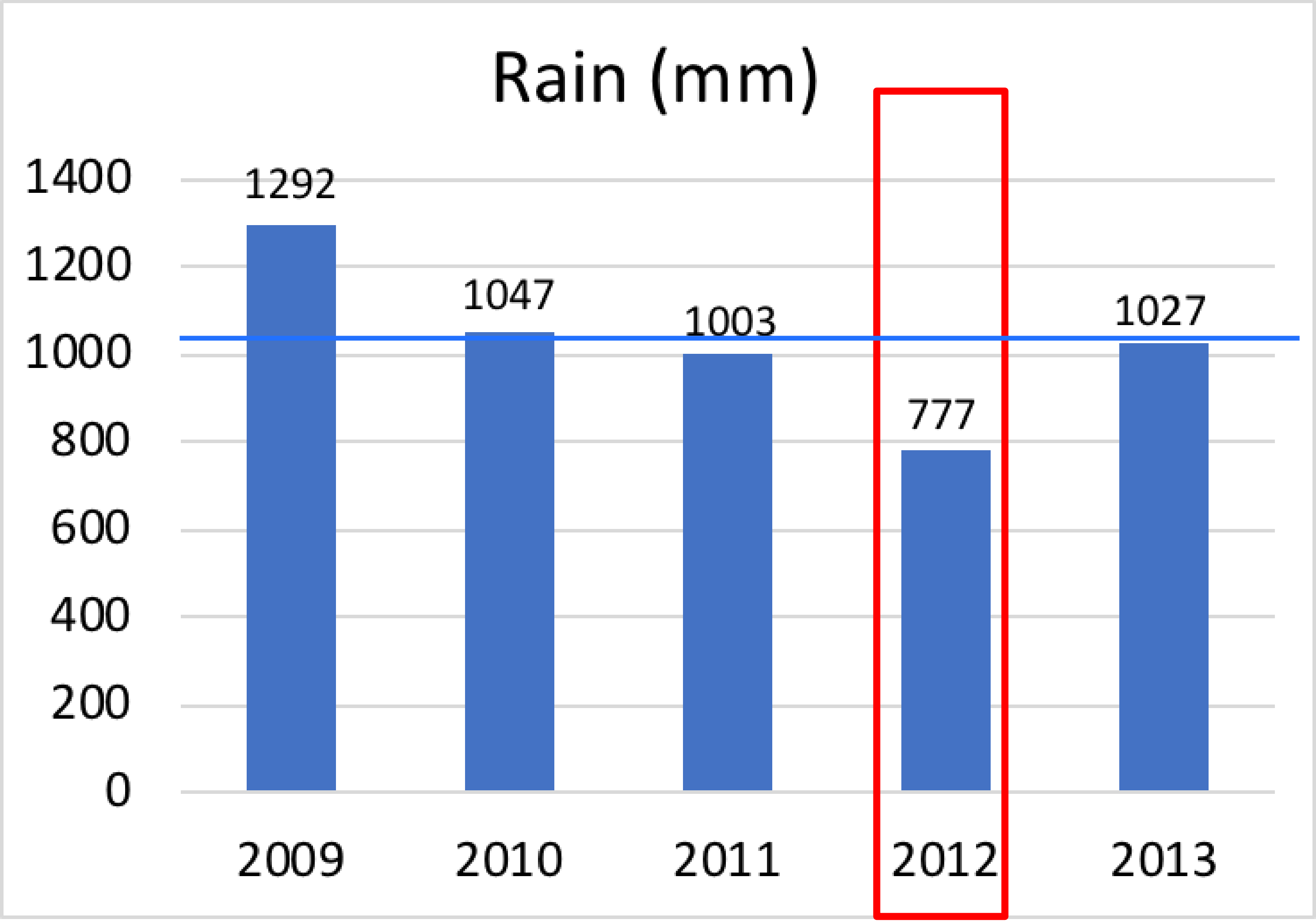
- Miscanthus and switchgrass have higher annual ET owing to their **perennial nature and larger LAI**.
- Miscanthus has **largest LAI** which effectively covers the soil, resulting in the **smallest contribution of soil evaporation** to total ET.

Single-point simulation results: water budget



- Higher ET of bioenergy crops → **reduced** mean annual, surface, and sub-surface **runoff**
- Implications for soil erosion and groundwater pollution

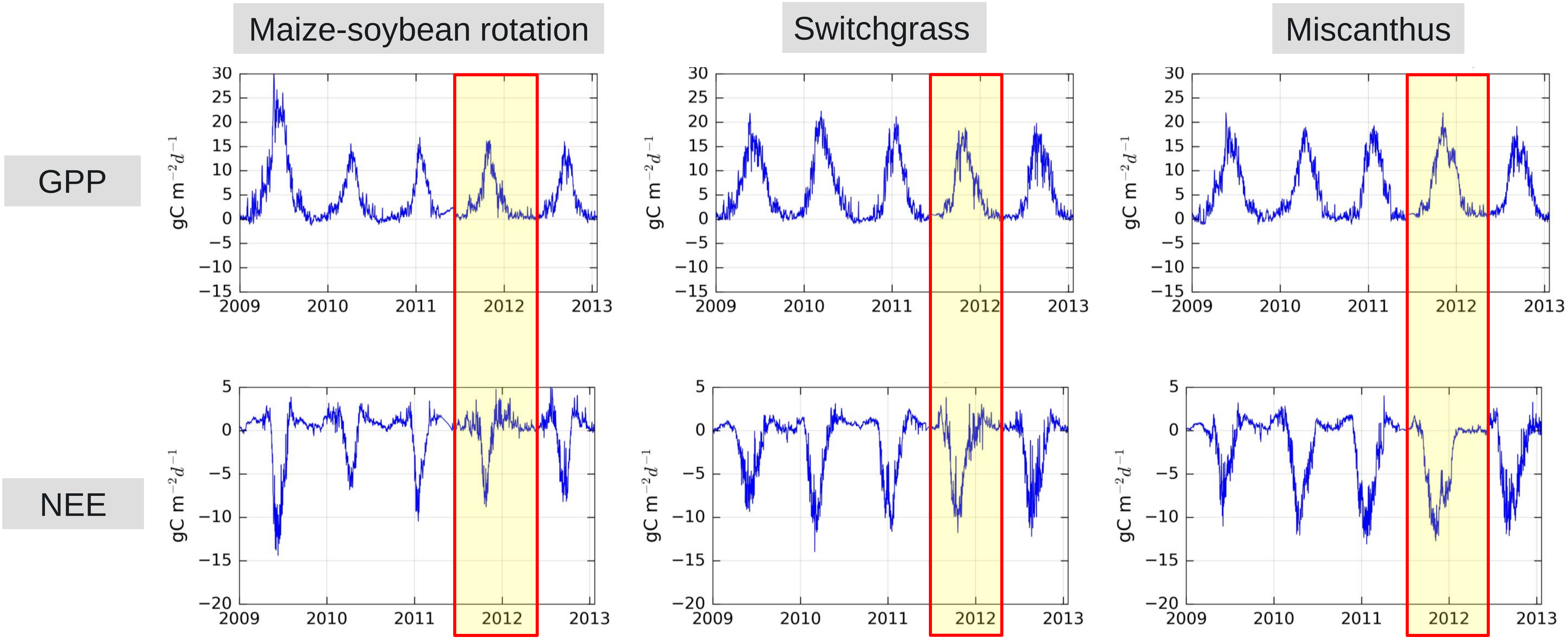
Single-point simulation results: inter-annual variability



Historical mean annual rainfall: 1042 mm

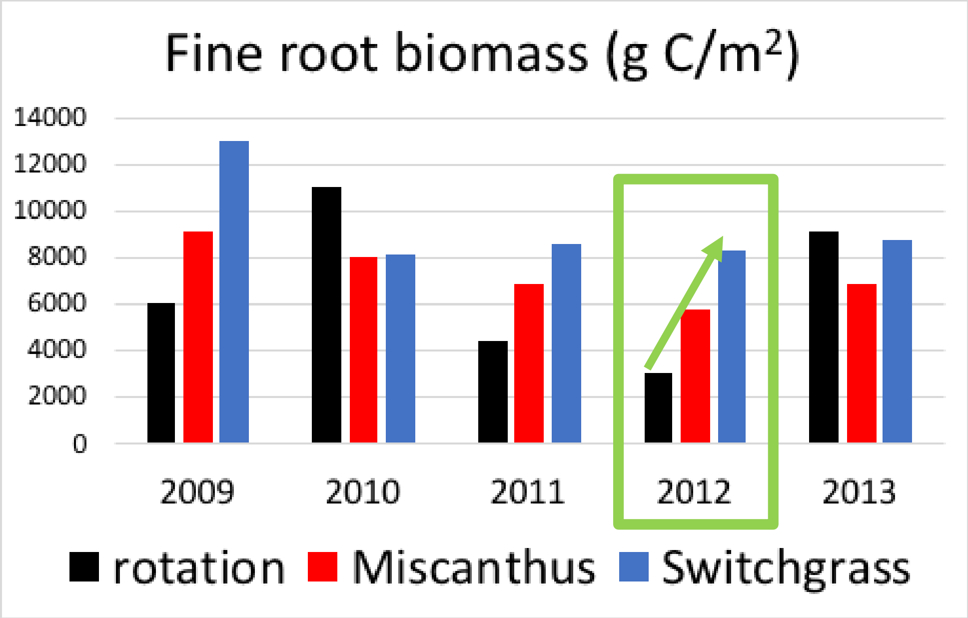
- 2012 is the most severe drought year in the Midwestern USA in the last 100 years.

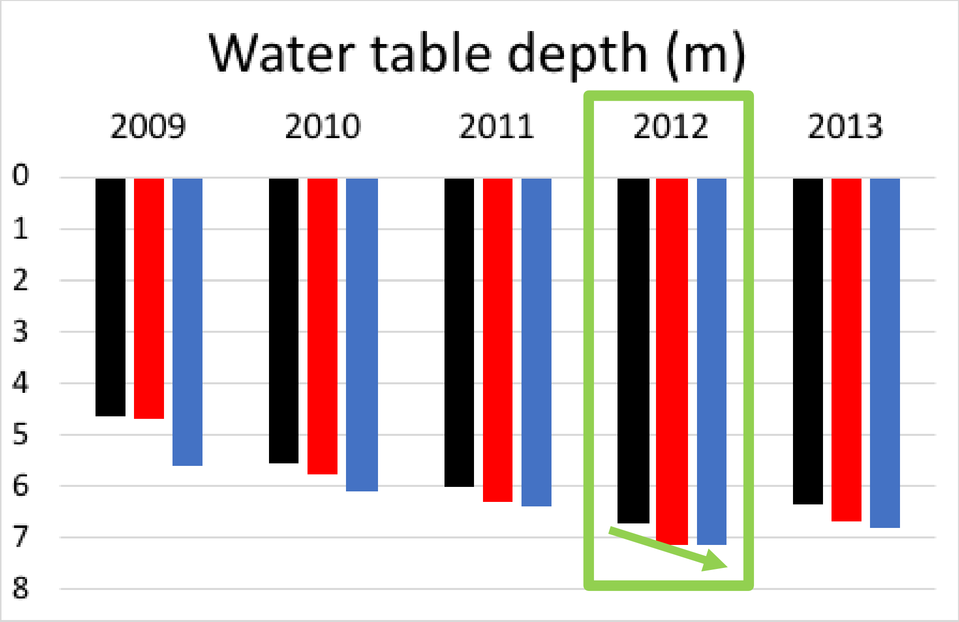
Single-point simulation results: inter-annual variability

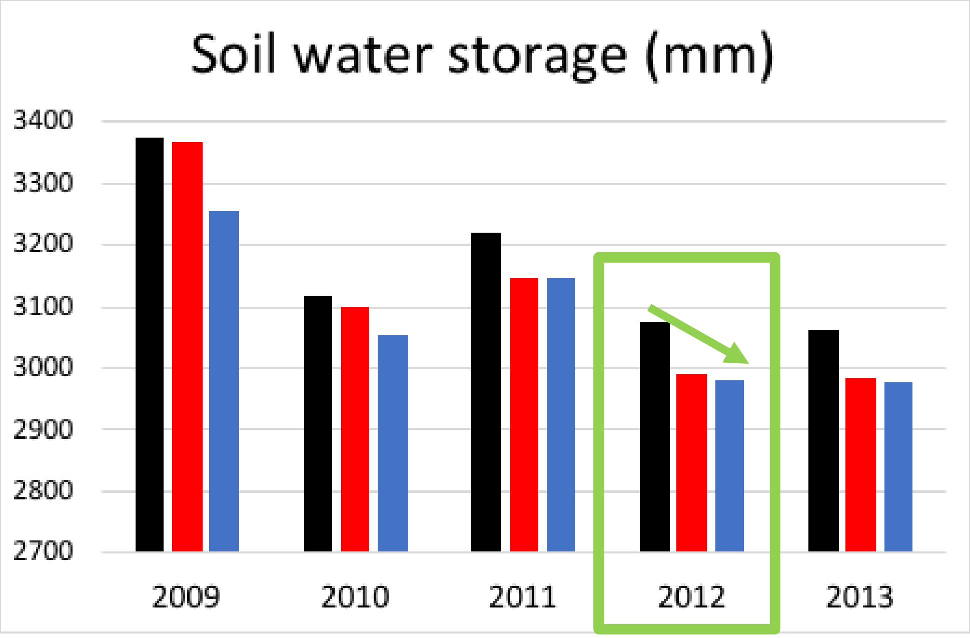


- Perennial grasses can maintain similar high productivity and large CO_2 fixation as the other years in 2012 during drought → **why?**

Single-point simulation results: inter-annual variability







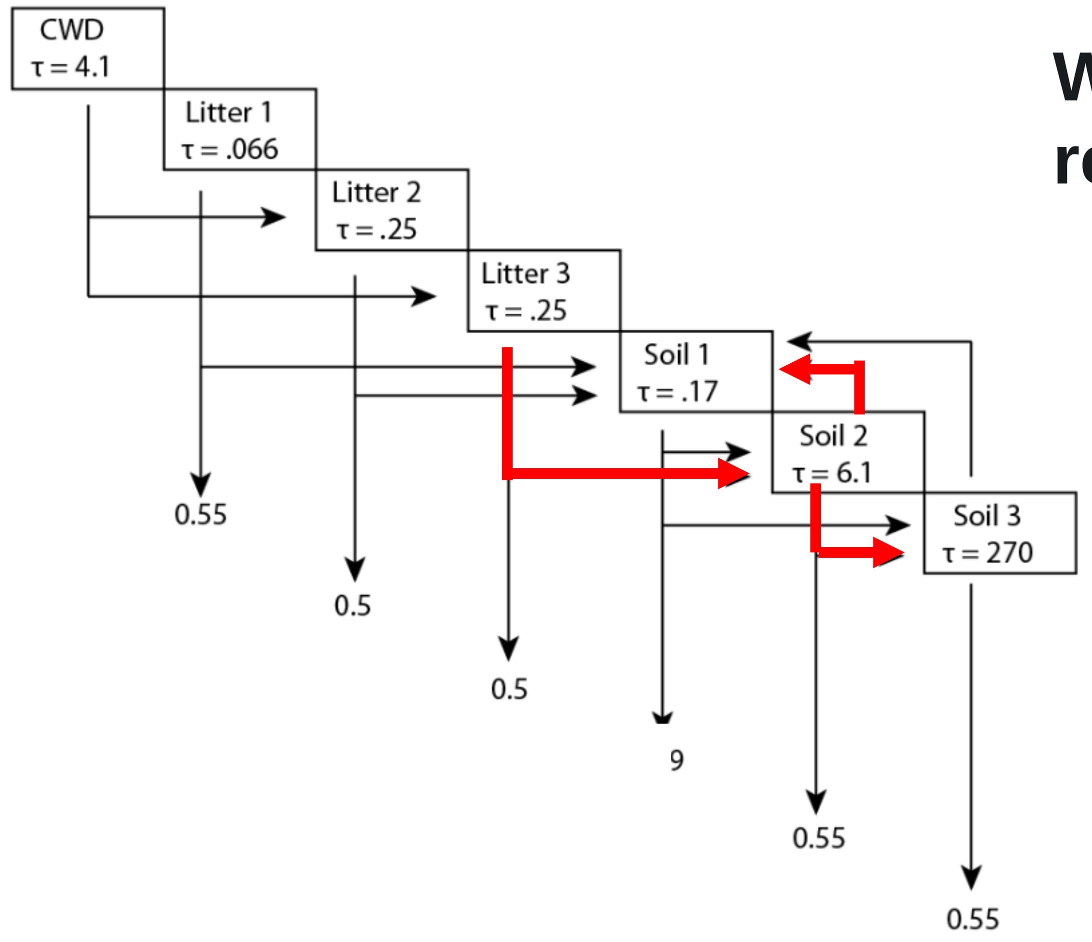
Bioenergy crops have more extensive **rooting system** under drought condition

→ Enhanced ability to access **soil moisture in deep soil layers**

→ High yield and carbon uptake under drought stress

Model structure discussion

Century Soil C pool structure

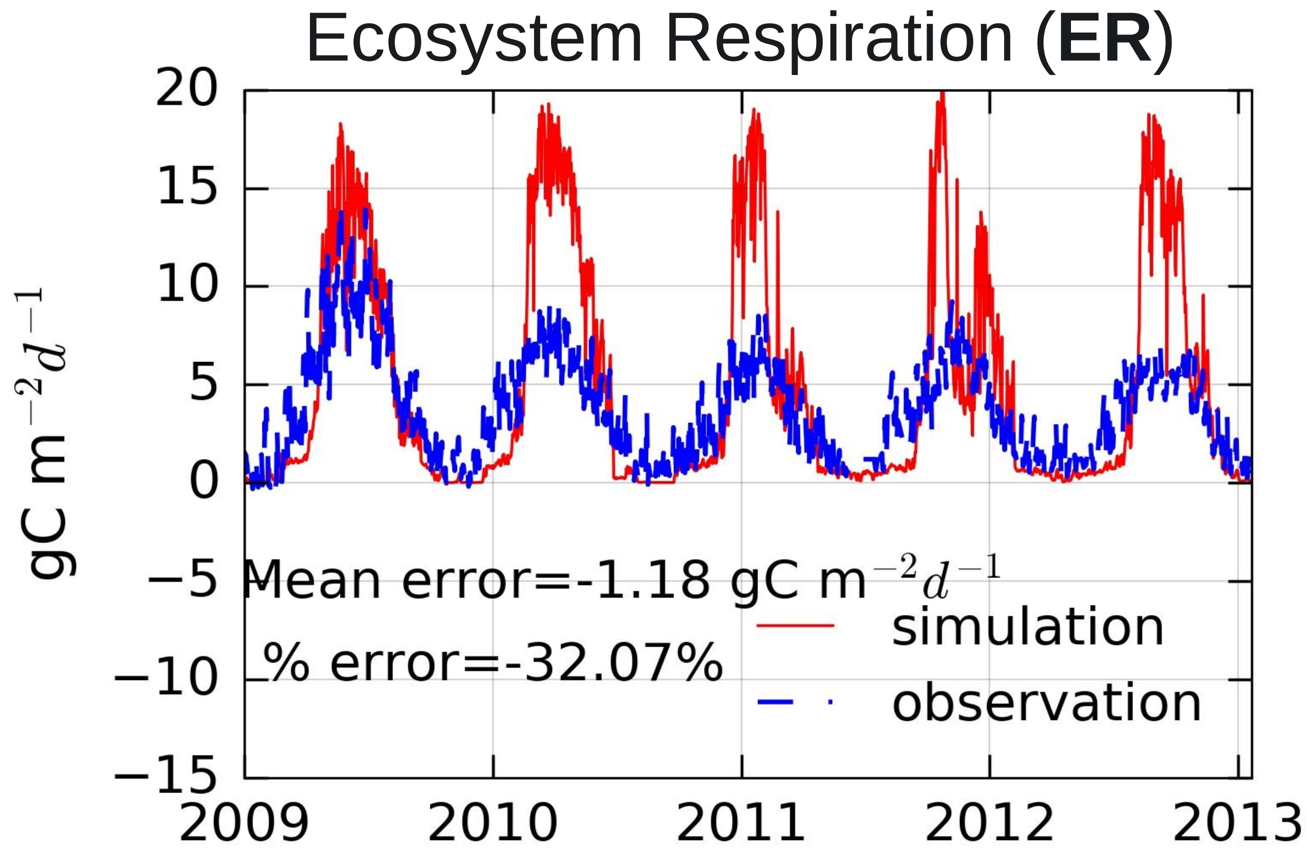


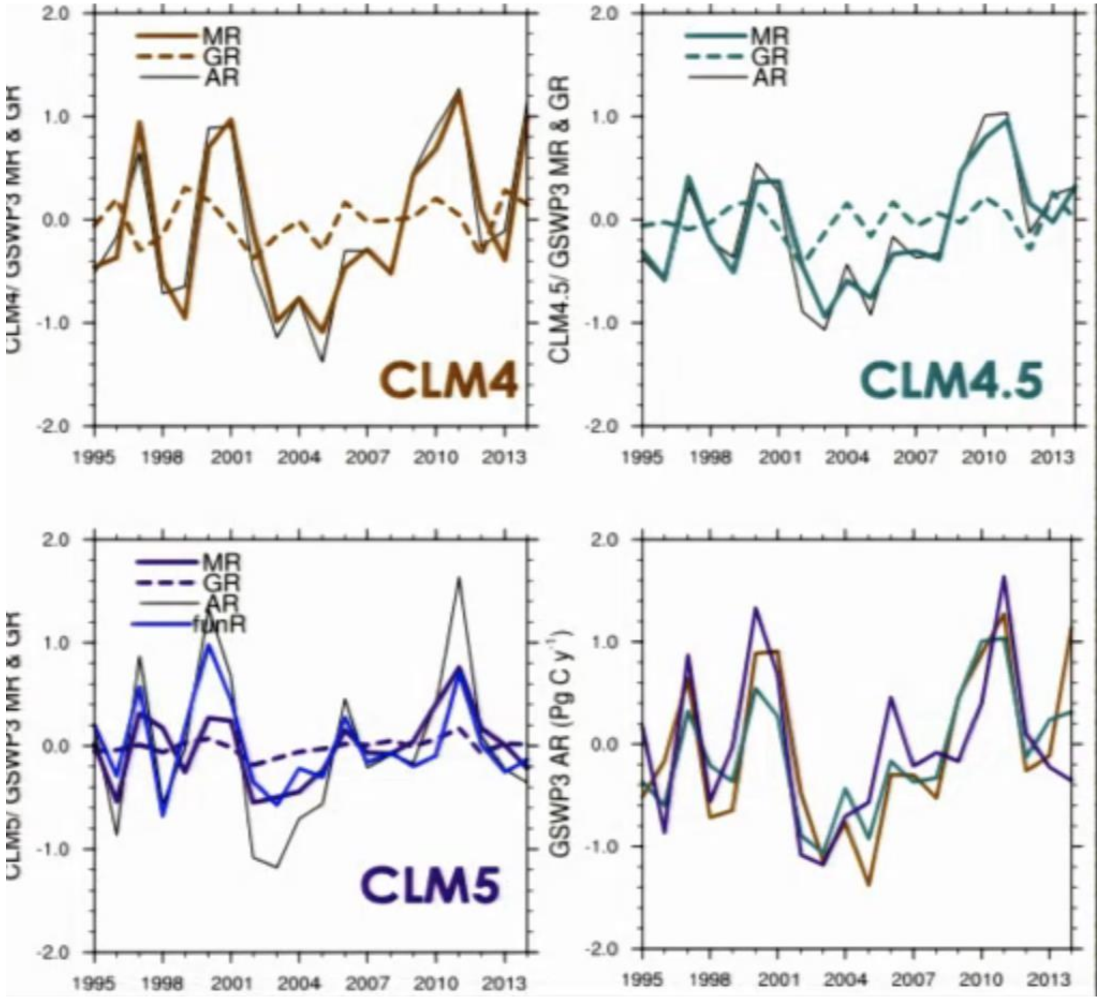
Pool structure, transitions, respired fractions (numbers at end of arrows), and turnover times (numbers in boxes) for the **Century-like soil C decomposition model**.

We modified parameters associated with respiration fractions that fixed across all PFTs.

rf_l3s2_bgc	Respiration fraction from litter 3 to SOM 2
rf_s2s3_bgc	Respiration fraction for SOM 2 to SOM 3
rf_s2s1_bgc	Respiration fraction SOM 2 to SOM 1

Model structure discussion





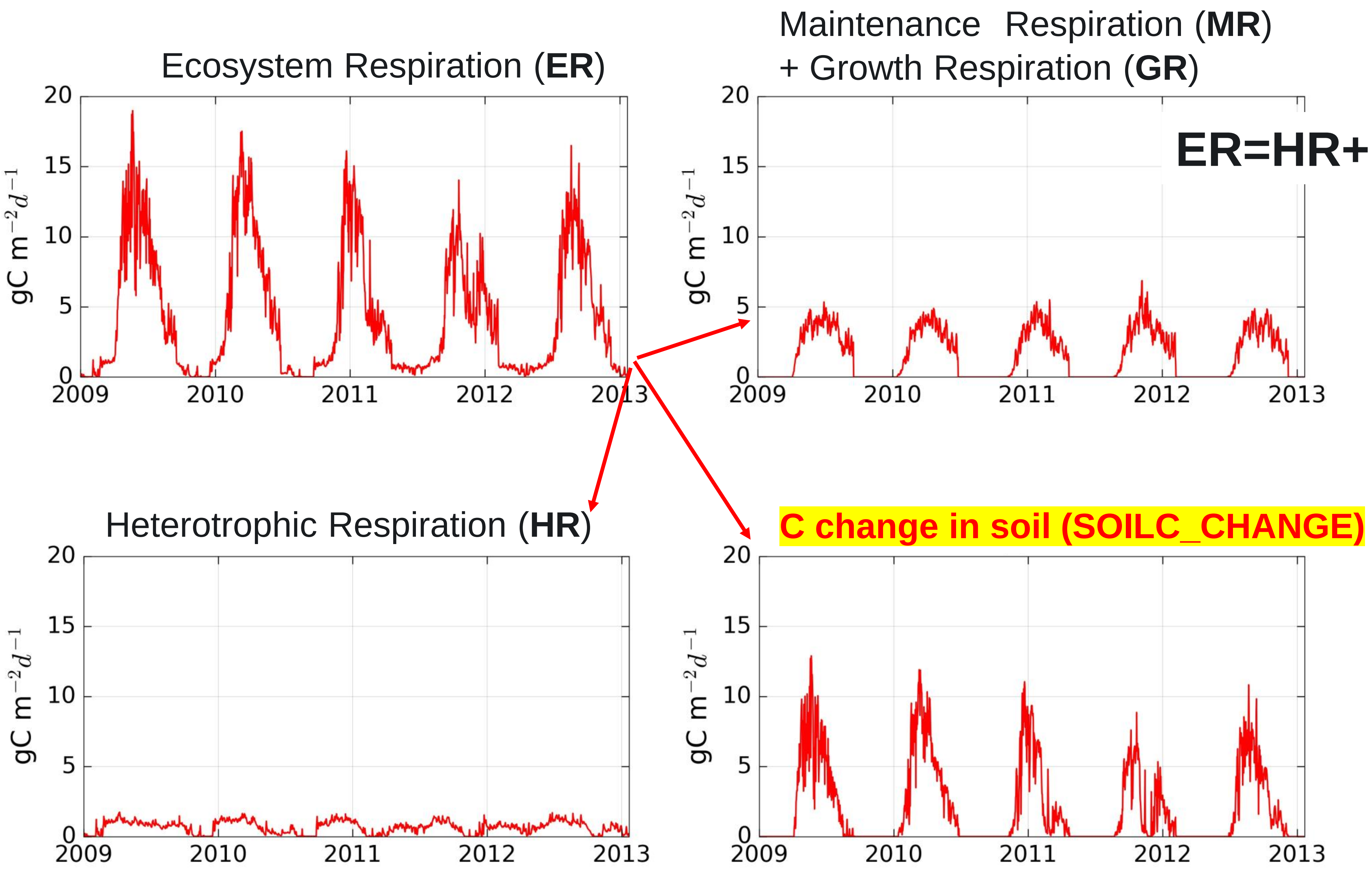
AR component anomalies

Dominated by FUN

Credit: Will Wieder

- **ER for Miscanthus** will be **overestimated** if the respiration fraction parameters in Century model are not modified.

Model structure discussion



ER=HR+MR+GR +SOILC_CHANGE

Old AR

AR in CLM5.0

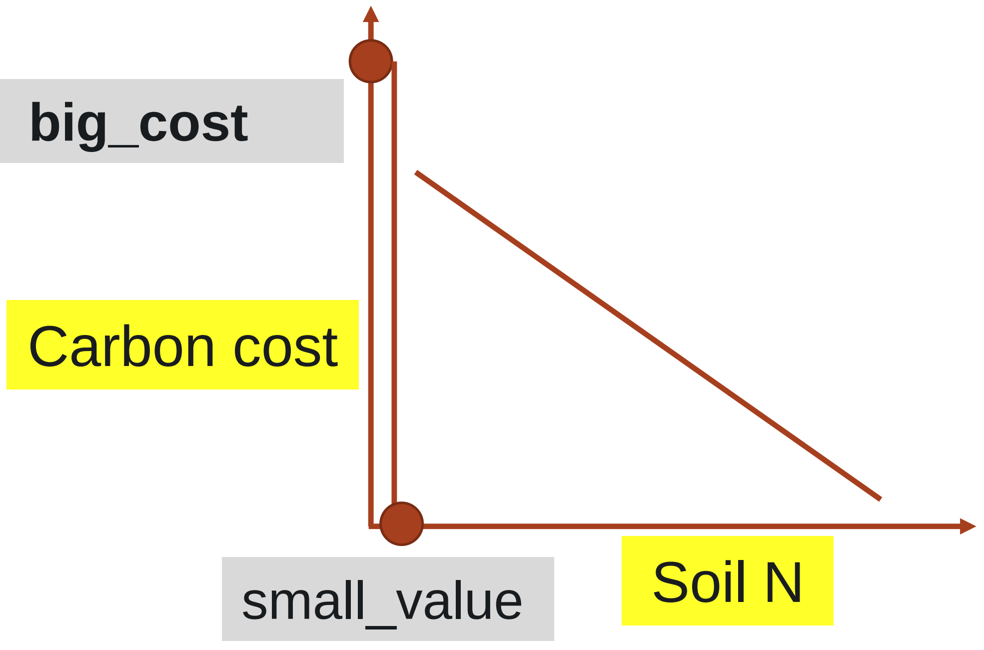
Fixation and Uptake of Nitrogen (FUN) Model

Model structure discussion

FUN: Nitrogen uptake requires the expenditure of energy in the form of carbon.

Nitrogen fluxes ← Calculate ← **big_cost**

Nitrogen fluxes → > Soil nitrogen content → True → Nitrogen fluxes = Soil nitrogen content → Real carbon cost



How to deal with the difference between the initially calculated **big_cost** and **real carbon cost**?

Burned off carbon

AR

- FUN will a **“big cost”** for carbon when soil N is insufficient.
- This big_cost term will be attributed to a burned off term, and eventually tp AR.

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Model structure discussion

The FUN Model

```
! Occasionally, the algorithm will want to extract a high fraction of NPP from a pool (eg leaves) that
! quickly empties. One solution to this is to iterate round all the calculations starting from
! the cost functions. The other is to burn off the extra carbon and hope this doesn't happen very often...

if (npp_to_spend .ge. 0.0000000000001_r8)then
    burned_off_carbon =  burned_off_carbon + npp_to_spend
end if
```

CNFUNMod.F90

Summary

- CLM5 has been parameterized to **represent maize-soybean rotation, Miscanthus, and switchgrass**, and validated against observed fluxes from sites in central Illinois.
- Our results demonstrated that by using more sustainable land management options, the **perennial bioenergy crops could assimilate more carbon** and maintain similar ET levels than typical annual cropping systems.
- **Perennial bioenergy crops** are more **drought-tolerant** than annual crops.
- **Perennial bioenergy crops are promising alternatives to traditional crops under the same climate and environmental conditions** because of their high productivity, large carbon stock, and no requirements for fertilization and irrigation.
- Due to model structure limitation, we need to either modify some parameters associated with decomposition or improve the model structure.
- Future study driven by **future land use change scenarios** is needed to access the climate change mitigation effect of bioenergy crops at **regional scales**.

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Acknowledgement

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Thank you

INTEGRATED Multi-sector Multi-scale Modeling
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