Modeling Soil Quality Issues Related to Sustainable Switchgrass and Poplar Production

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U.S. DEPARTMENT OF ENERGY

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Outline

- *Introduction*
  - *What sustainability issues?*
  - *Three science questions related to sustainable production*
- *Model development and approach to the questions*
- *Results - answers to science questions indicated by model-based experiments*
  - *Predicted baseline comparisons for switchgrass and poplar*
  - *"Hypothesis testing" (qualitative forecasts)*
- *Wrap up*

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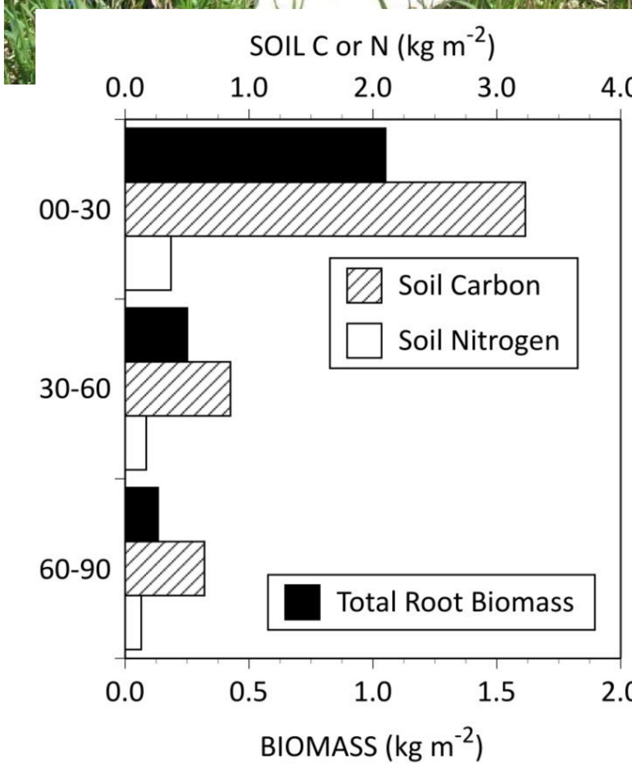
What are the soil quality issues linked to sustainable production?

Lots of issues, but only three are considered here:

- *Can soil organic matter be maintained or increased for the long-term benefit of soil carbon sequestration?*
- *Could bioenergy crops eventually become less productive due to disruptions of carbon and nitrogen cycling?*
- *How might nitrogen management and/or nitrogen cycling impose long-term constraints on production?*

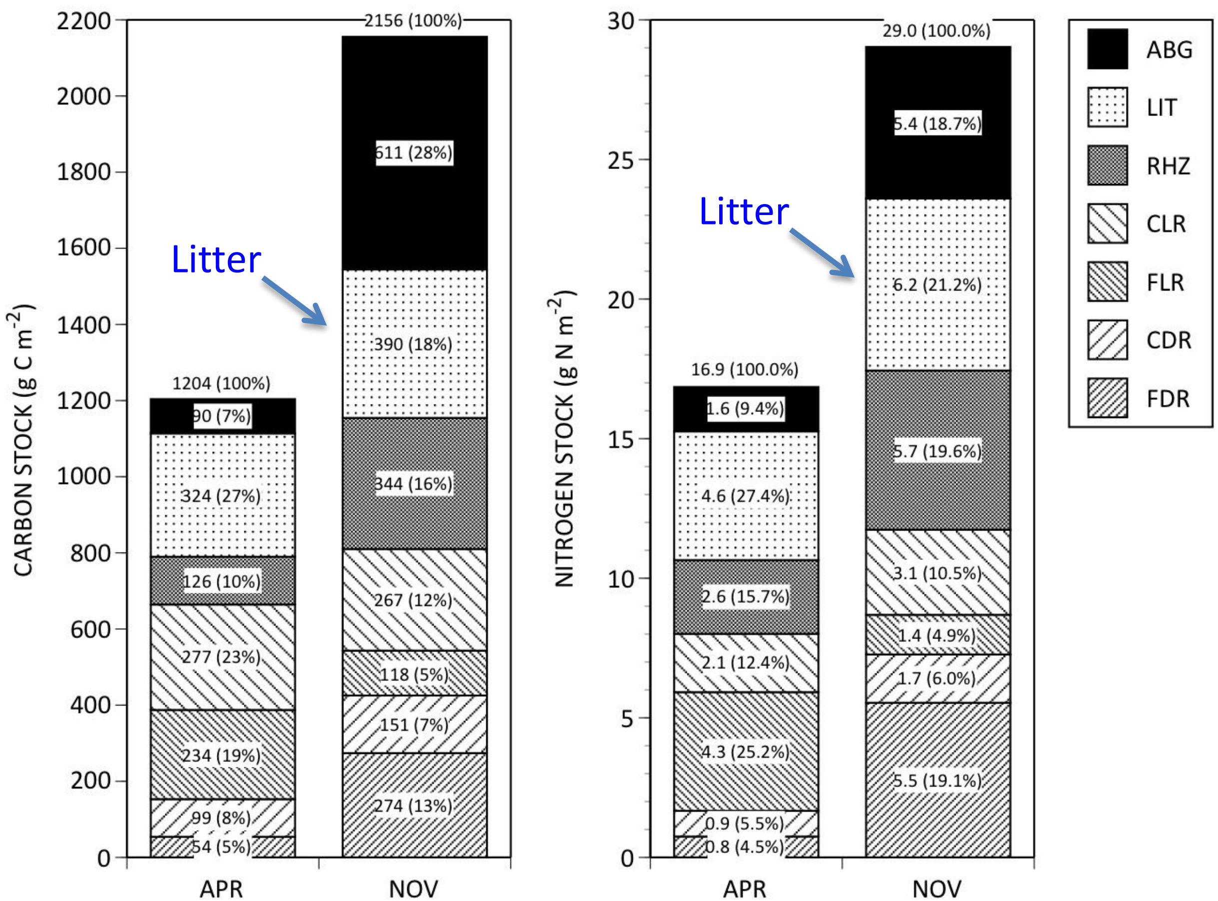
Q1: What are the characteristics of newly stored carbon under bioenergy crops?

- *Is newly stored carbon mostly labile or stable?*
- *Labile and stable soil carbon have different mean residence times that impact maintenance of soil organic matter.*
- *Most of the root biomass and soil carbon is found in the surface 30 cm of mineral soil where it is vulnerable to disturbance.*



Q2: How might surface litter collection (residue removal) disrupt soil C and N?

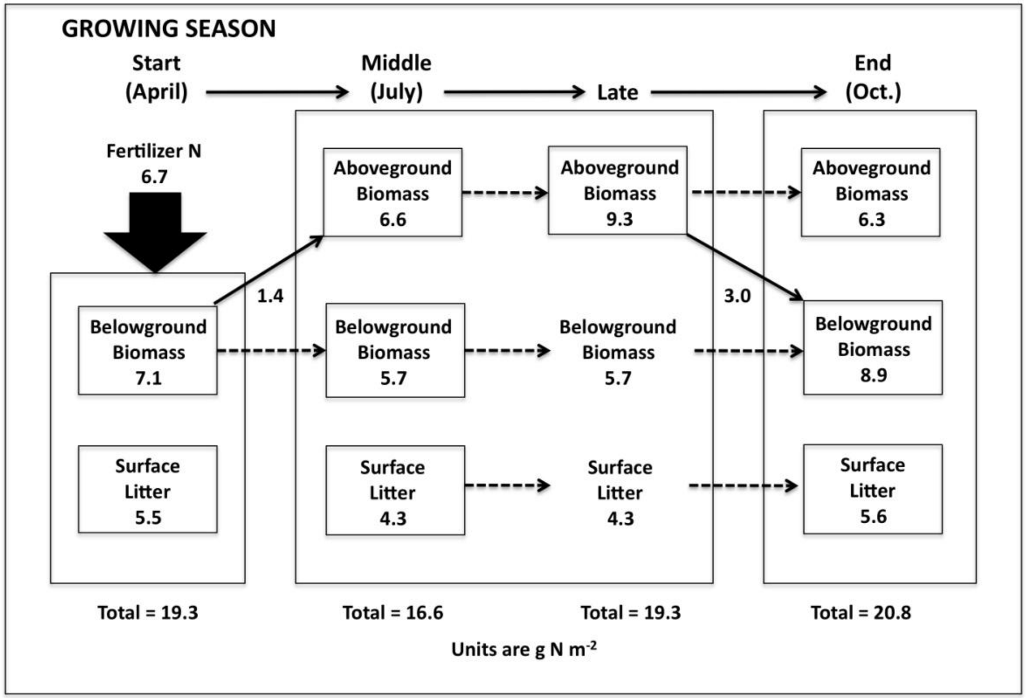
- *Surface litter in switchgrass fields at Milan contains remarkably large amounts of carbon and nitrogen*
- *End of season surface litter biomass is 50 to 70% of aboveground biomass*
- *Other studies report similar findings*



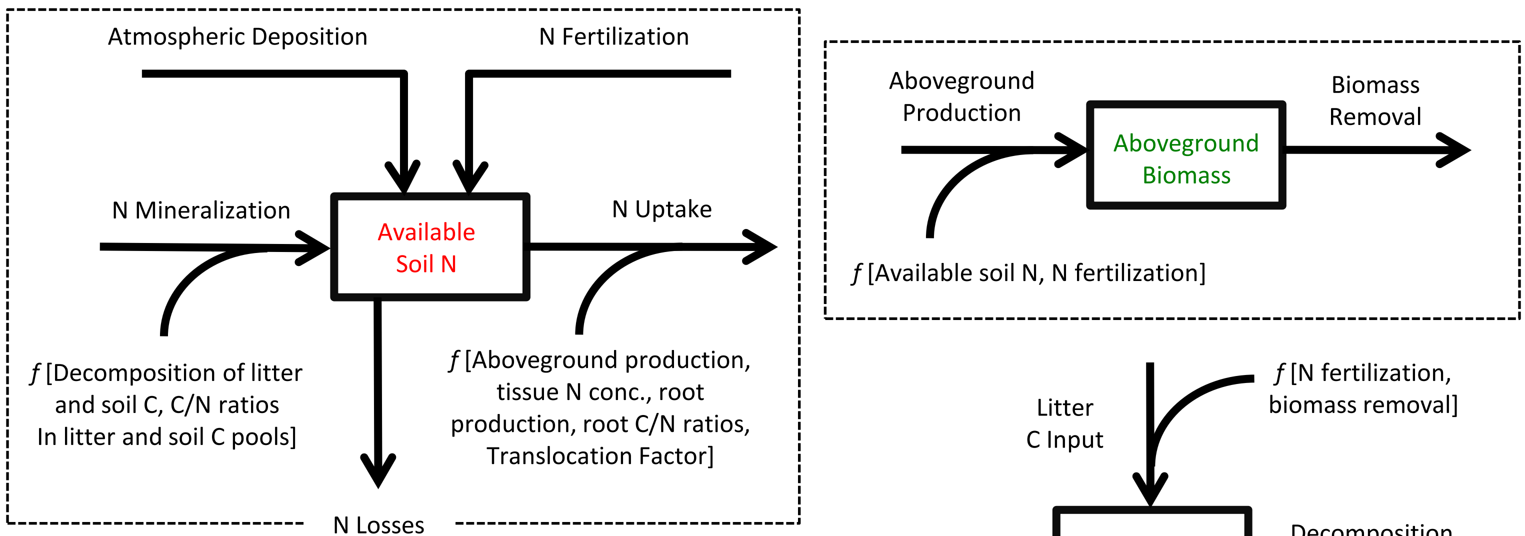
Q3: How does fertilization impact soil C and N cycling and biomass production?

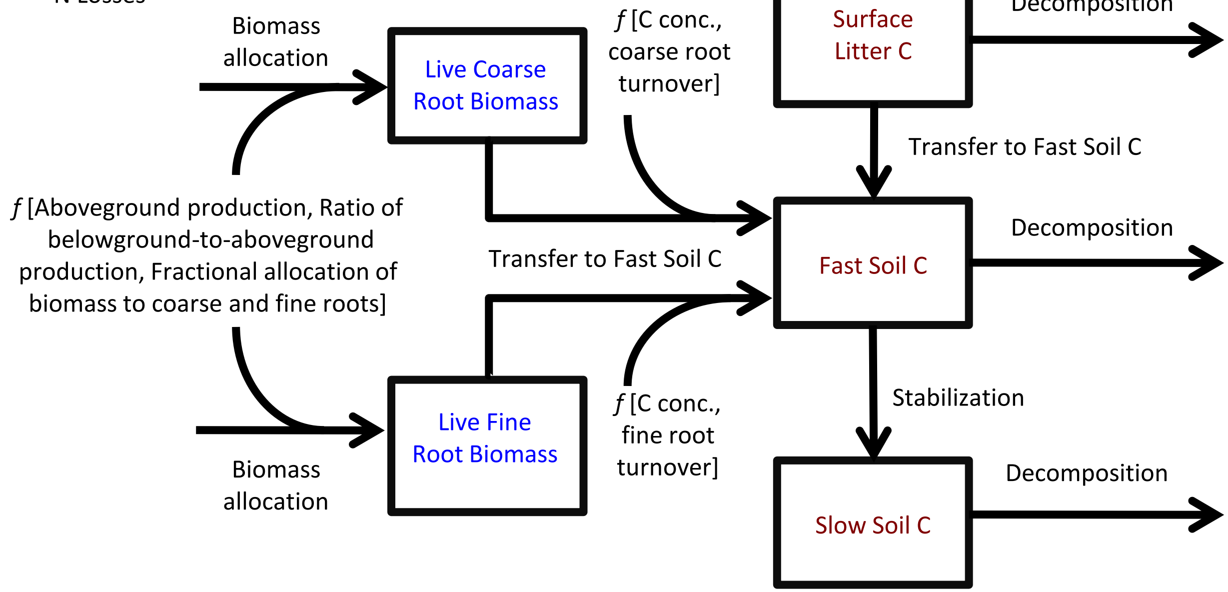
- *Some studies indicate soil carbon sequestration under perennial grasses and SRWC (especially on marginal soils).*
- *Excessive N fertilization can lead to water quality problems*

Nitrogen additions at 6.7 g N m^{-2} are balanced by end-of-season N removals by harvesting at Milan, TN; however, nitrogen leaching is evident at higher levels of N fertilization



Overview of model structure

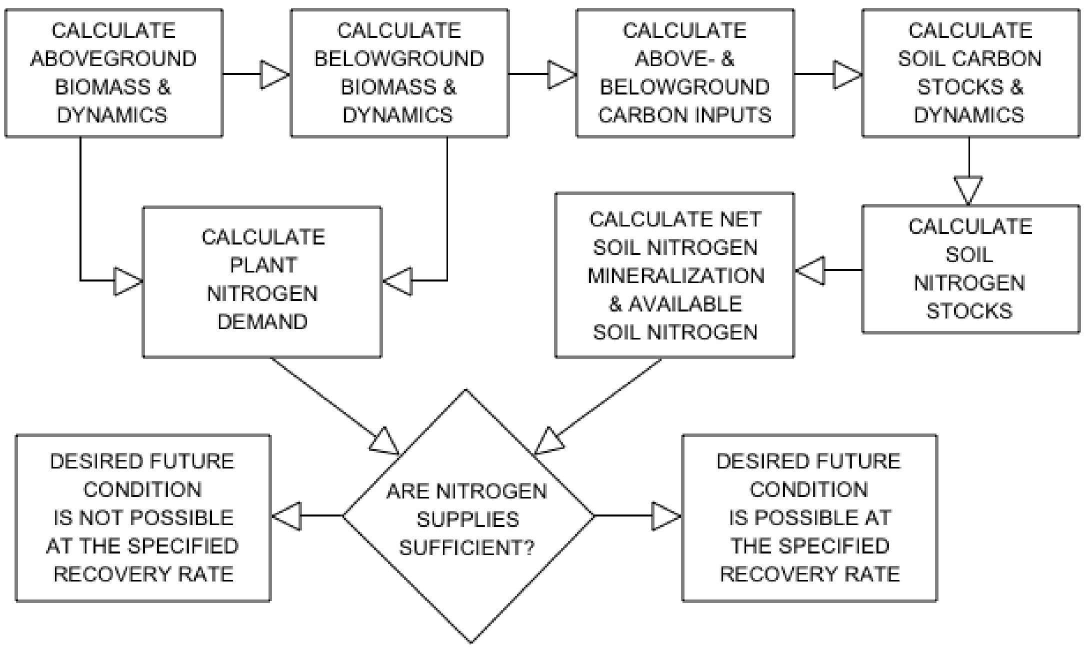




- *Modeling platform is Stella® by isee systems http:/www.iseesystems.com/*
- *Stochastic parameterization yields predictions with uncertainty limits*
- *Variability about particular parameter values is not well known*

SWGM and RSPM are "research models"

- *These models have fluidity – easily and frequently changed*
- *Useful for asking "what-if" questions and summarizing data*
- *Carbon and nitrogen dynamics are linked*



Using data from field trials for SWGM

- *UT Research and Education Center at Milan, TN*
- *Primary field site*
- *Field campaigns in 2007 and 2008*
- *Four to five year old switchgrass*
- *Useful for understanding site-specific relationships between yield, tissue chemistry, and fertilization*

Approach to the science questions

- *Starting assumption is that switchgrass or hybrid poplar is grown on marginal soils in the southeastern US*
- *Initial conditions were set based on prior studies in TN and SC*

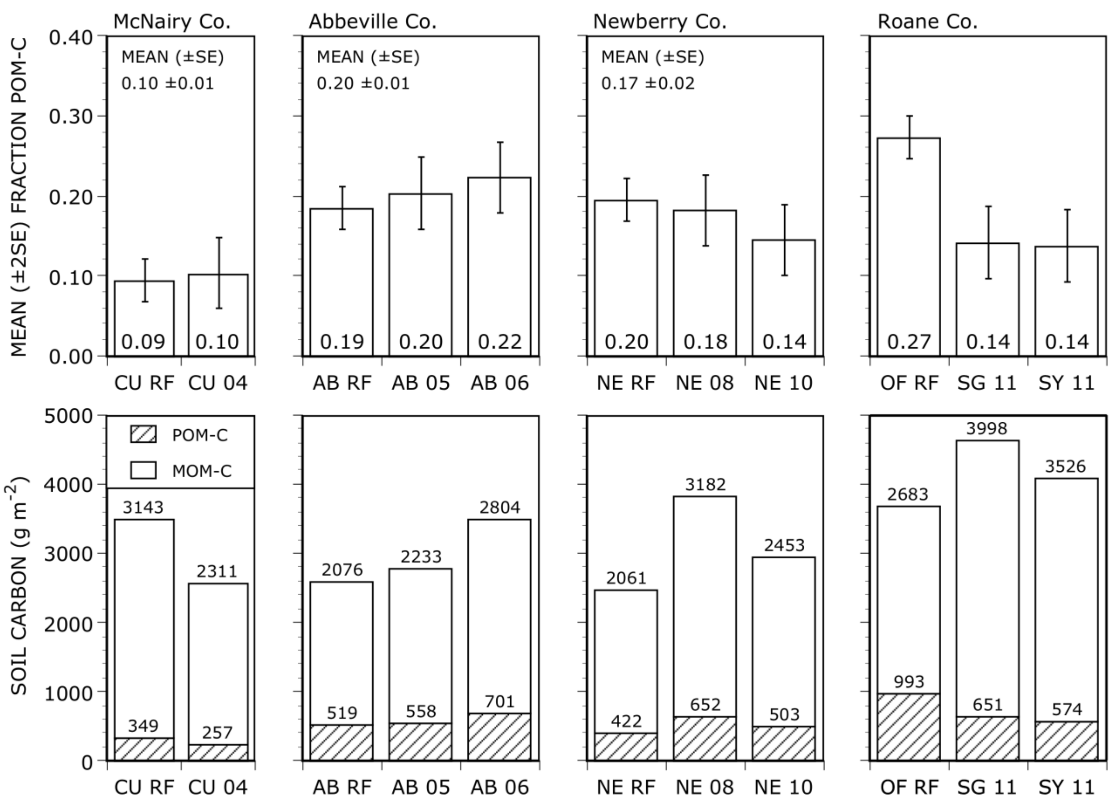


FIGURE 2 - GARTEN

- *Objective was to undertake a comparison of switchgrass and hybrid poplar growing on abandoned agricultural land and answer the three questions*

What is the same and what is different?

- *Site to site differences were controlled for the comparison*
- *A comparative study necessitates predictions that are normalized for differences in N fertilization (e.g. biomass production per unit N input or soil C stored per unit N input)*

Property	Units	RSPM	SWGM
Bioenergy crop	…	Poplar	Switchgrass
Initial soil C	kg m^{-2}	2.5	2.5
Fraction of initial soil C in the fast pool	…	0.2	0.2
Harvest interval	…	Every 7 years	Annually
Fertilization	g N m^{-2} yr^{-1}	10	6.7
Slow soil C/N ratio	…	15	15
Fast soil C/N ratio (based on root inputs)	…	100	100
Atmospheric N deposition	g N m^{-2} yr^{-1}	0.5	0.5
Mean annual temperature	°C	15.4	15.4

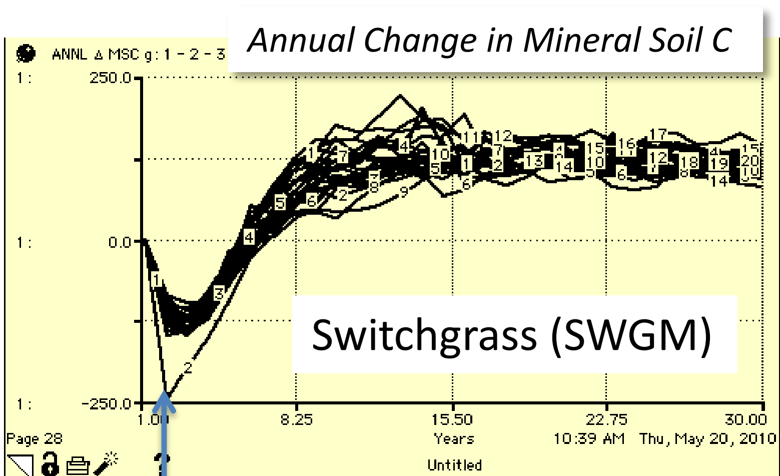
Checkpoints for the switchgrass model

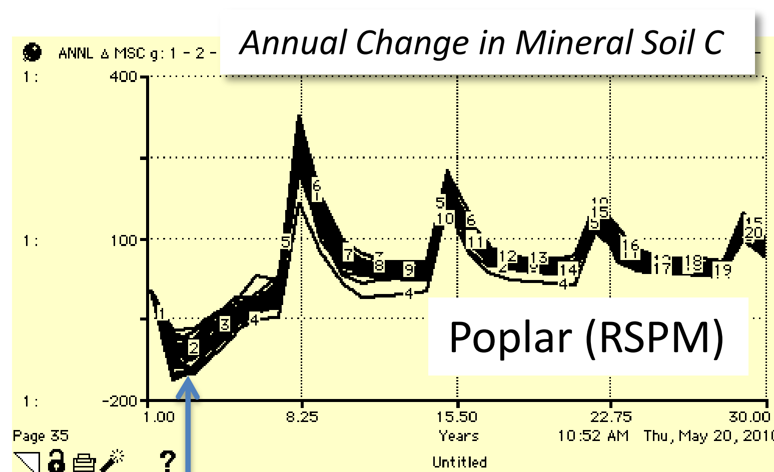
- *SWGM is parameterized to yield predictions that match calibration data from 4 year old field trials at Milan*

System property	Field data	Model prediction
Aboveground biomass	2092 ±131 g m^{-2} yr^{-1}	2036 ±74 g m^{-2} yr^{-1}
Live coarse root biomass	963 g m^{-2}	995 ± 44 g m^{-2}
Live fine root biomass	513 ±36 g m^{-2}	512 ±25 g m^{-2}
Surface litter carbon	429 ±25 g C m^{-2}	406 ± 14 g C m^{-2}
Root/shoot ratio	0.78	0.79 ±0.06

Other indicators of model performance

Predictions in mature plantations			
Variable	Poplar	Switchgrass	Comment
Heterotrophic soil respiration (g m^{-2} yr^{-1})	592 ±22	1087 ±55	Somewhat high for switchgrass
Rate of net soil N mineralization (yr^{-1})	0.063 ±0.002	0.069 ±0.003	High, but acceptable based on literature review
Annual change in mineral SOC (g m^{-2} yr^{-1})	41 ±1.5	106 ±3.1	Similar to rates reported in field studies

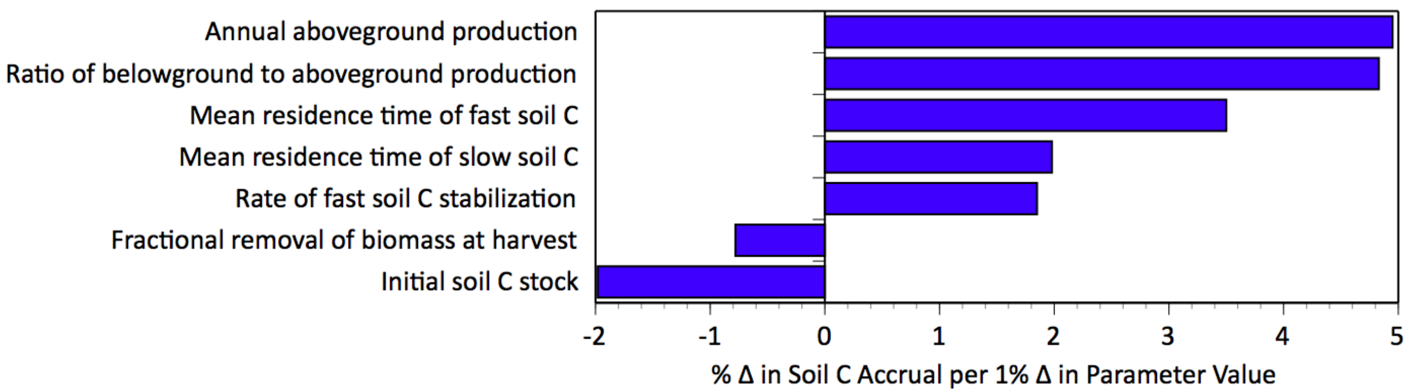


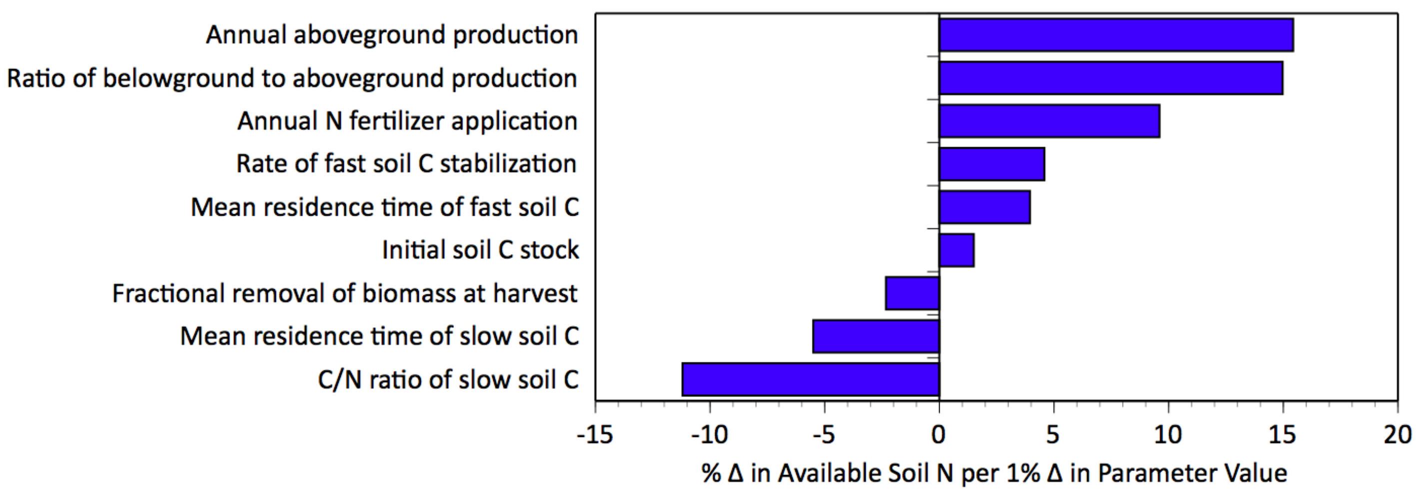


Both SWGM and RSPM predict initial declines in soil C stocks

Sensitivity analysis of switchgrass model

- *What parameters affect soil C accrual and available soil N the most?*
- *An index >0 is positively associated with soil C accrual or N availability (indices <0 are negatively correlated with soil C accrual or N availability)*

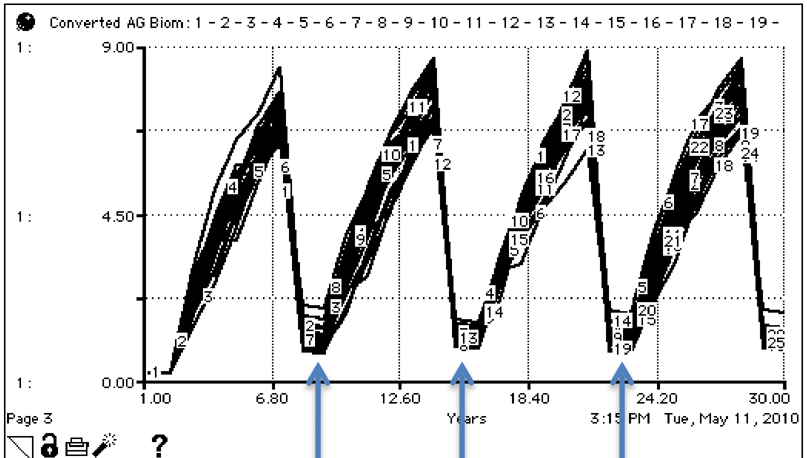




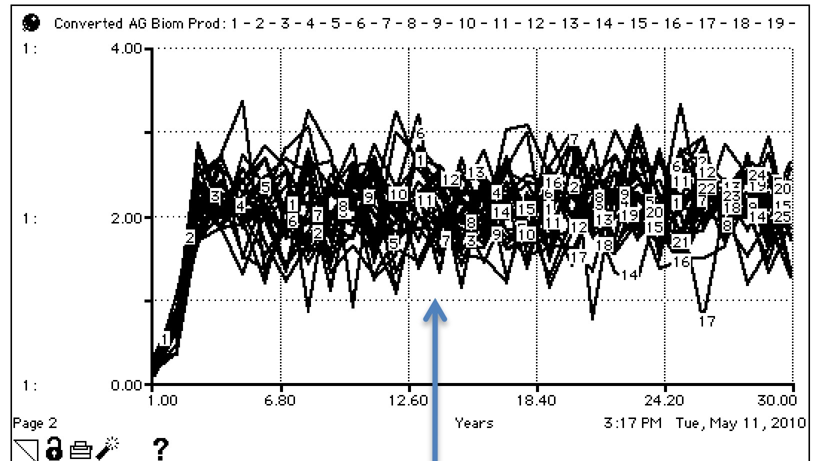
Predicted time history of aboveground production in poplar and switchgrass

- *Differences in biomass dynamics require comparisons of cumulative measures over time (e.g., cumulative production)*

Poplar Aboveground Biomass (kg m^{-2})



Switchgrass Aboveground Biomass (kg m^{-2})



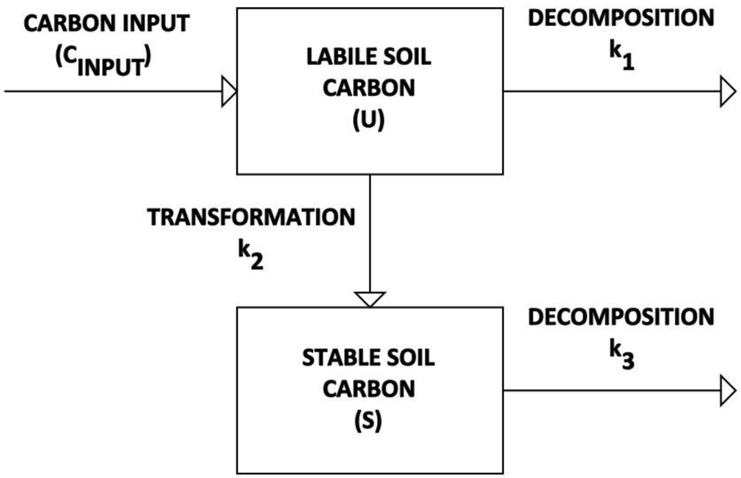
Harvest followed by fallow year

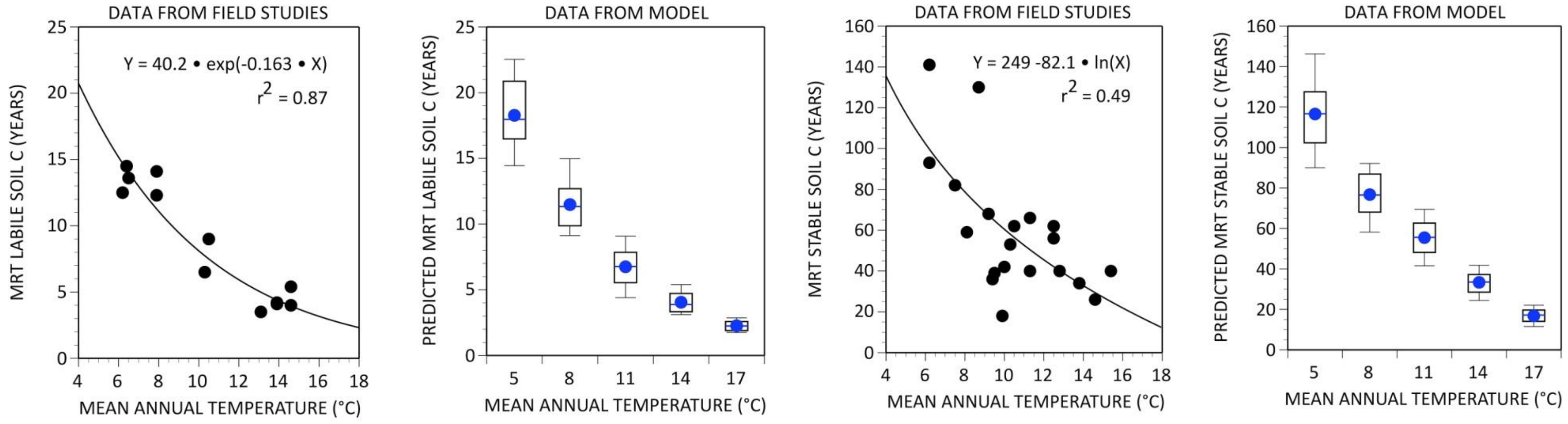
Year-to-year variation in biomass

- *Baseline comparison: after 28 years, cumulative biomass production by switchgrass (58 ±0.5 kg m^{-2}) exceeds biomass production by poplar (30 ±0.25 kg m^{-2})*

Characteristics of newly stored carbon under bioenergy crops

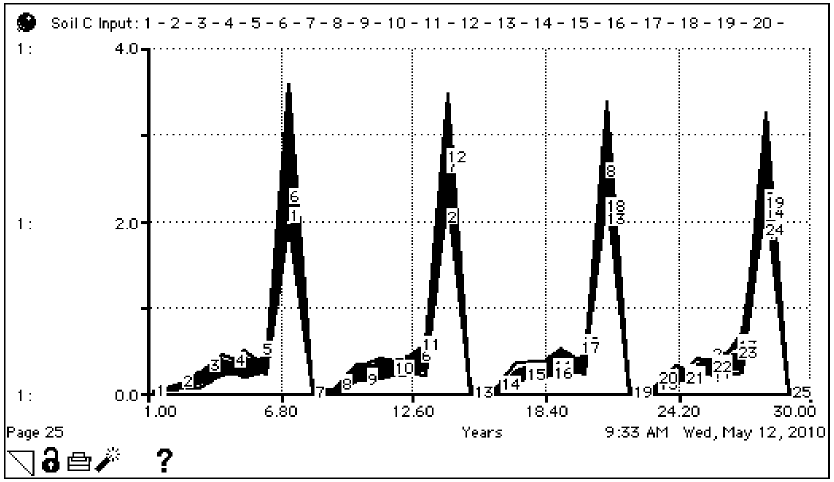
- *Soil carbon is divided into three pools (surface litter, labile soil carbon, and stable soil carbon)*
- *Decomposition is controlled by empirically derived relationships with temperature or root C/N ratios (in the case of labile C)*



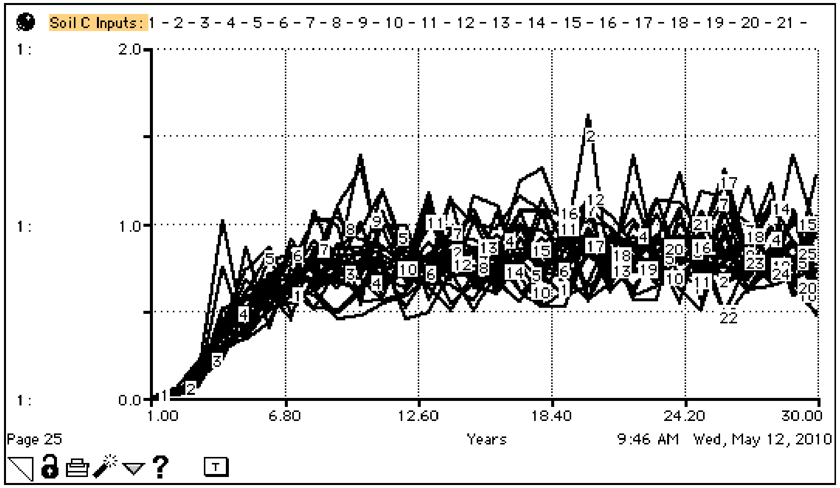


Characteristics of newly stored carbon under bioenergy crops (continued)

- *Soil carbon inputs beneath hybrid poplar are strongly episodic and amounts of labile soil carbon equal or exceed stable soil carbon in years following re-establishment of the plantation*
- *Soil carbon inputs beneath switchgrass are more continuous and the majority of mineral soil carbon is stable (58 to 68%)*



Poplar Soil C Inputs (kg C m^{-2} yr^{-1})



Switchgrass Soil C Inputs (kg C m^{-2} yr^{-1})

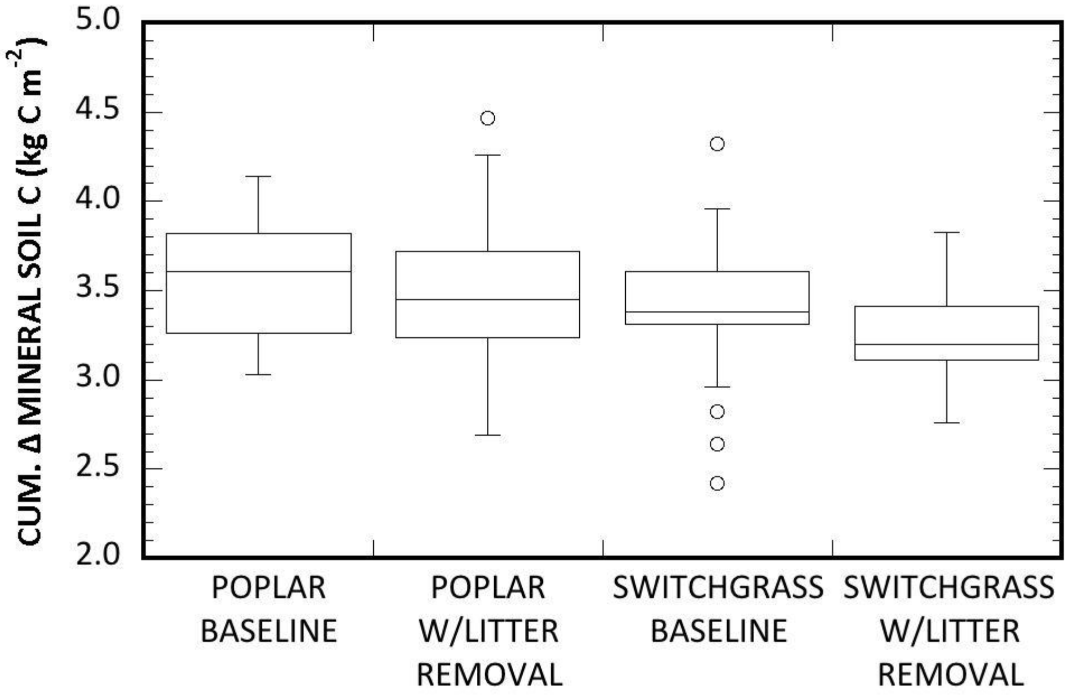
Comparison of predicted measures of soil carbon sequestration

Measure of Soil C Sequestration	Poplar	Switchgrass
Cumulative harvested biomass (kg m^{-2} over 30 years)	28 ±0.17	58 ±0.43
Cumulative N inputs (g N m^{-2} over 30 years)*	578 ±3.0	594 ±4.3
Normalized production (g biomass per g N input)	49 ±0.4	98 ±0.6
Cumulative Δ mineral soil C (kg C m^{-2} over 30 years)	3.5 ±0.1	3.2 ±0.1
Normalized cum. Δ soil C (g C increase per g N input)	4.2 ±0.2	5.4 ±0.1
Normalized annual Δ soil C (g C storage per g N input)	3.1 ±0.1	4.1 ±0.1
*N inputs = fertilization + atmospheric deposition + net soil N mineralization		

- *Switchgrass sequesters more carbon per unit of N input*
- *Rates of soil C sequestration are comparable to field rates, but are not fully realized until a decade after stand establishment*

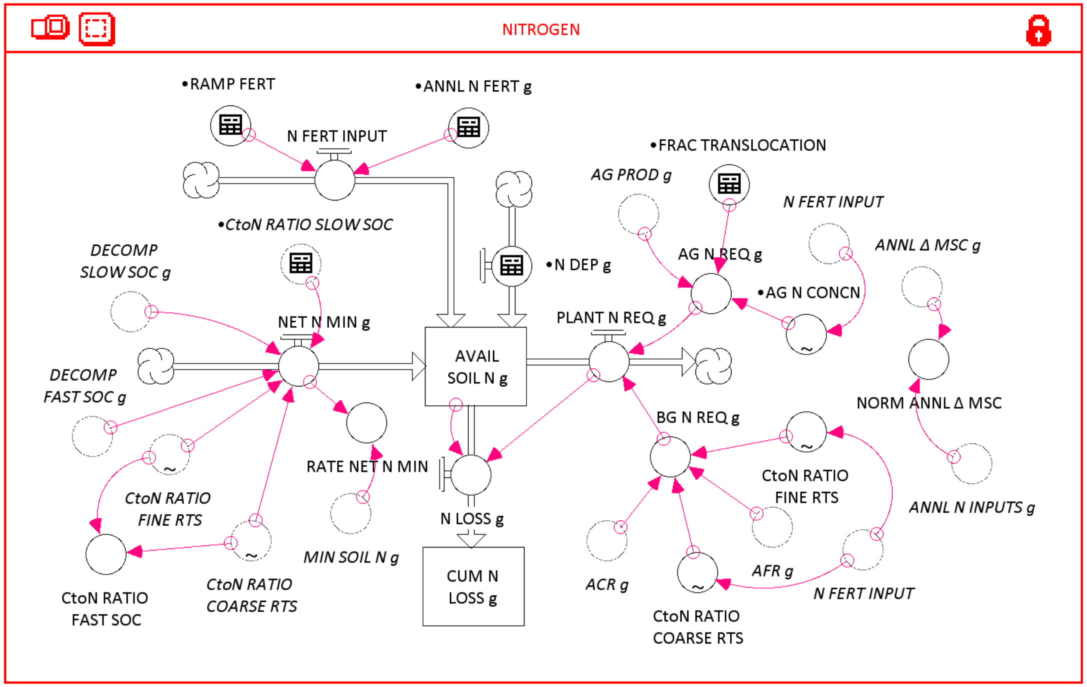
Impact of surface litter collection (residue removal) impact soil carbon and nitrogen

- *Surface litter removal does not significantly impact the cumulative change in mineral soil carbon or nitrogen stocks after 30 years*
- *Belowground inputs are more important to soil C sequestration*



Consistent with other studies, carbon cycling in surface litter is uncoupled from the mineral soil; except at sites with earthworms

Effect of nitrogen fertilization on soil nitrogen cycling



Several important processes related to N cycling:

1. Fertilizer N

2. N mineralization

= f(C/N ratios & decomposition)

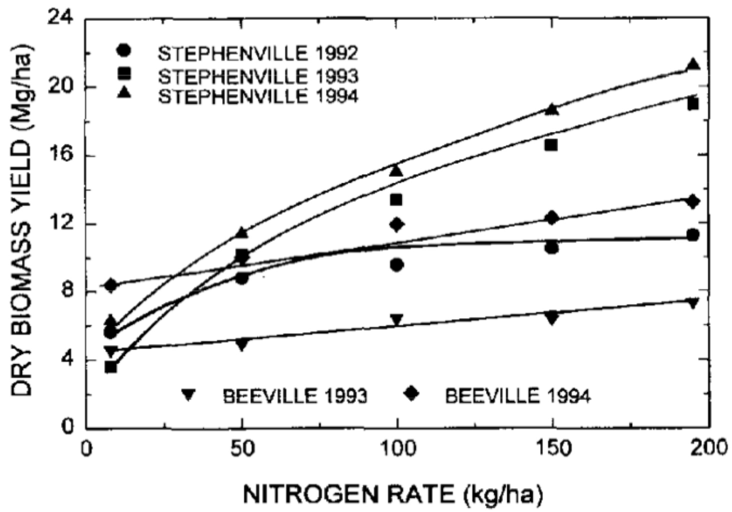
3. Plant N demand

4. N loss

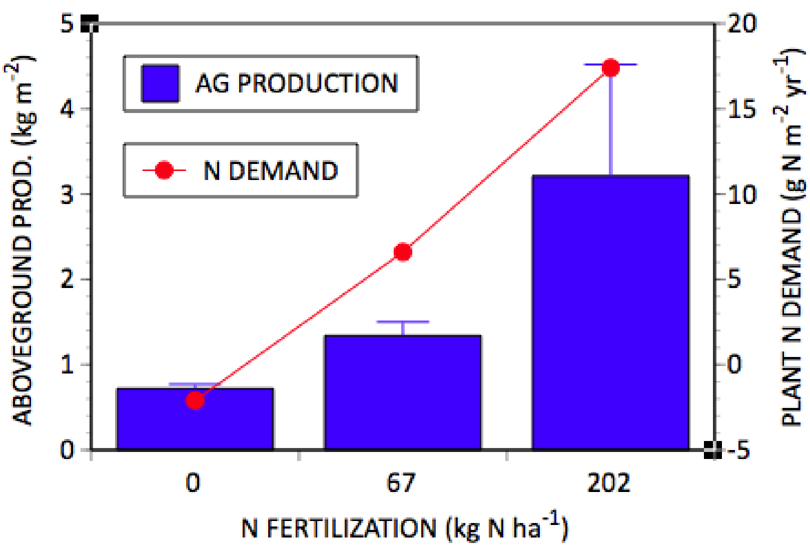
Processes contributing to available soil N in a "typical" year (g N m^{-2} yr^{-1})

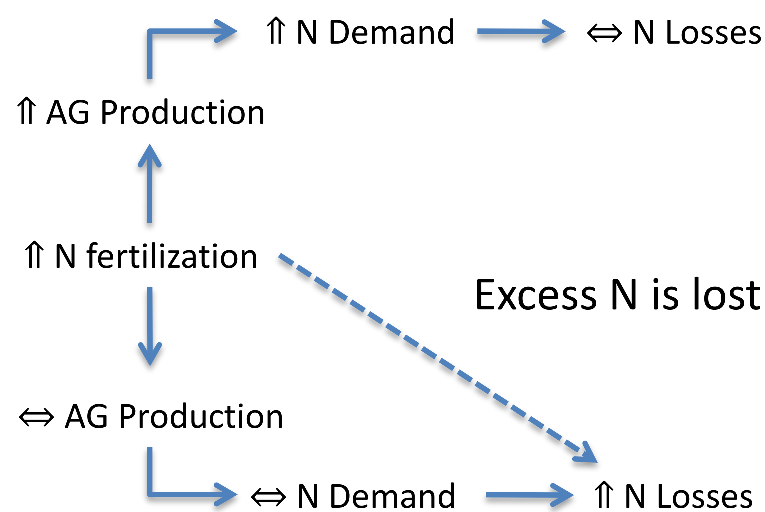
Crop	Fertilizer	Mineralization	Deposition	Requirement	N Loss
Switchgrass	6.7	17.2 ±0.7	0.51 ±0.02	13.2 ±0.6	11 ±1.1
Poplar	10.0	19.4 ±0.7	0.53 ±0.02	9.8 ±0.5	22 ±0.6

Importance of fertilizer response curves



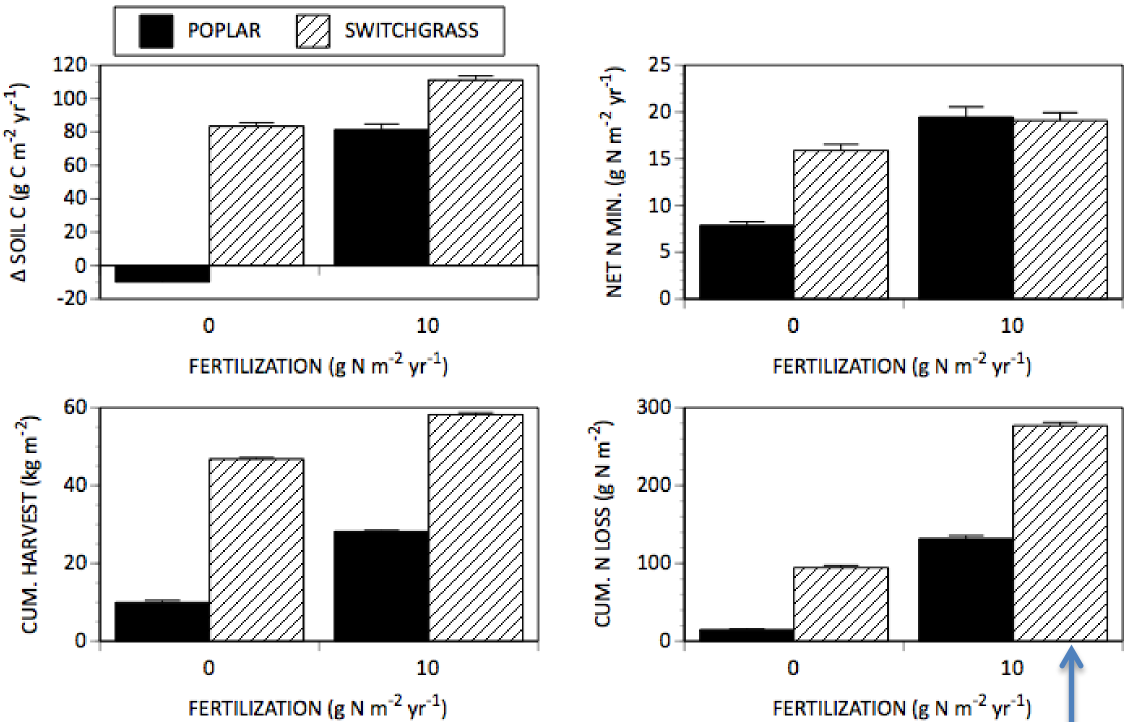
- *Sanderson et al. (1996, Bioresource Technology) have shown site to site variability in Alamo switchgrass response curves to N fertilizer*
- *End-of-growing season data from the fertilizer trial at Milan indicate increased N uptake and increased aboveground production with increasing N fertilization*





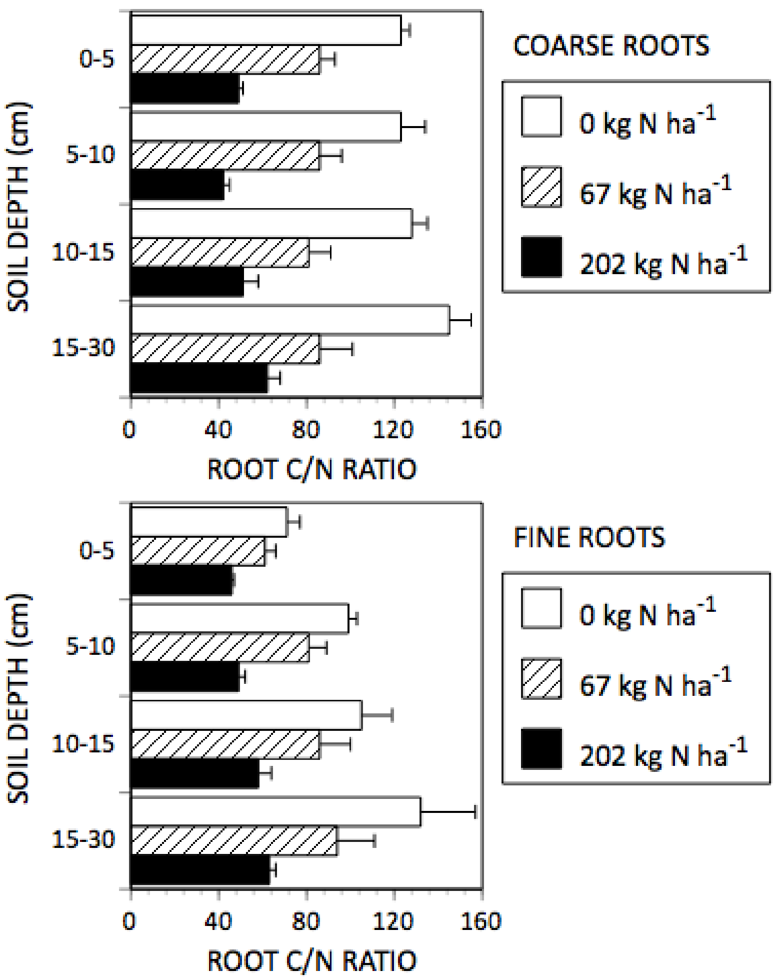
Comparative predicted response of poplar and switchgrass to nitrogen fertilization

- *Change in soil C over 30-years is somewhat similar with fertilization, but there is a loss of soil C under poplar without N fertilization.*
- *Annual rates of net soil N mineralization are less under poplar in the absence of fertilization.*
- *Fertilization improves cumulative biomass yield in poplar more than in switchgrass.*
- *Fertilization potentially increases N losses via leaching because there is more excess N.*



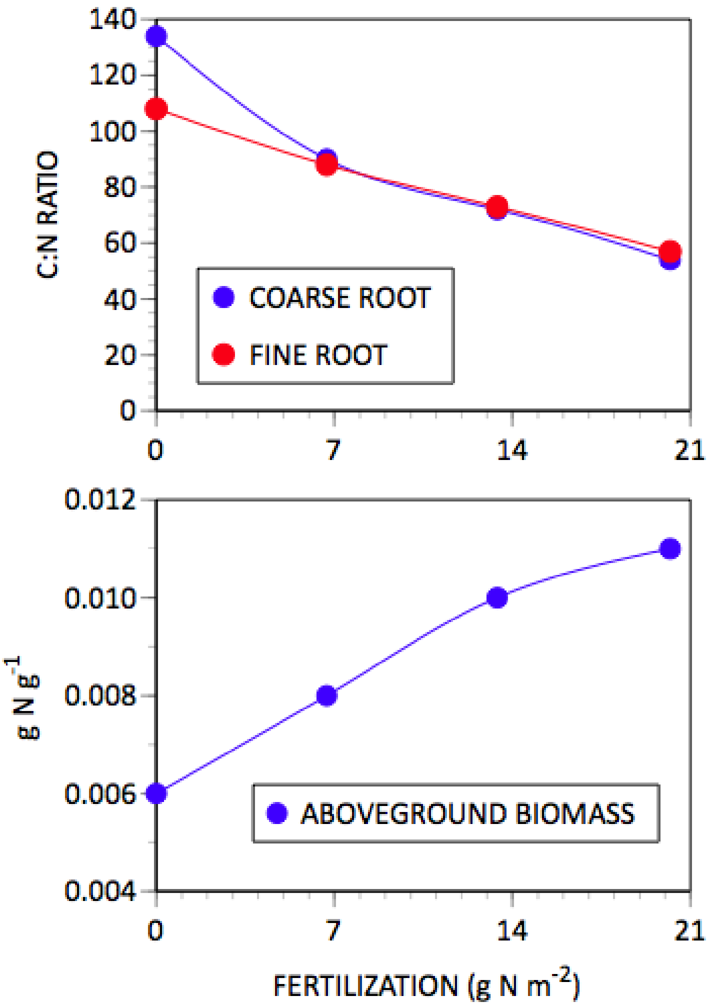
Note: Ramping fertilizer N inputs down to zero over the first decade of stand development reduces N losses by approx. 50% and reduces cumulative harvest over 30-years by only 15%.

Nitrogen fertilization is also changing plant tissue chemistry



- *At Milan, fertilization increased root N concentrations and decreased root C/N ratios – the fertilizer response of coarse and fine root C/N ratios has been incorporated into SWGM.*
- *Fertilization also increased N concentrations and decreased C/N ratios in aboveground biomass and surface litter – the fertilizer response of aboveground tissue N concentrations has been incorporated into SWGM.*
- *The response of poplar root and leaf tissue chemistry to fertilization is unknown.*

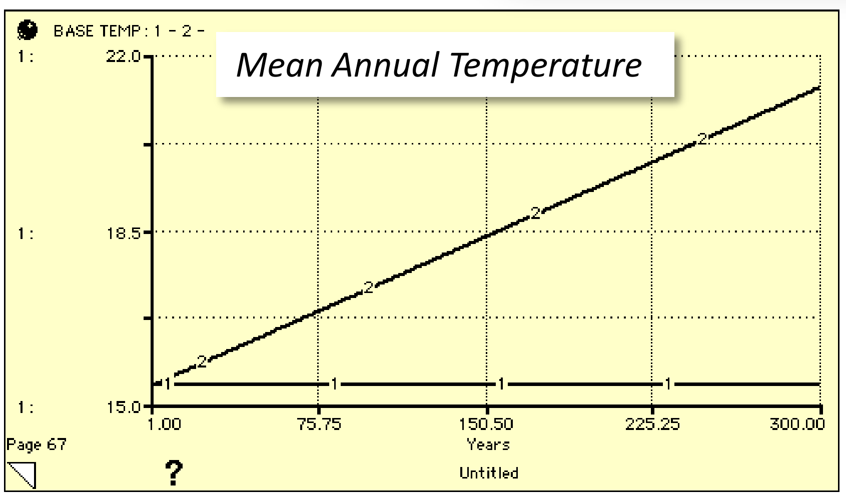
Effects of changing switchgrass tissue chemistry are secondary to temperature



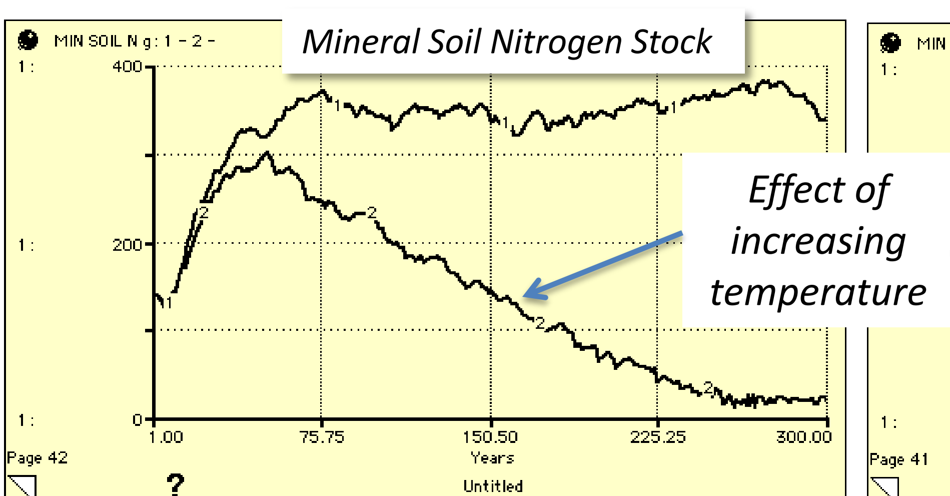
Cumulative Change in Mineral Soil Carbon (After 28 Years)		
FERTILIZATION ($g\ N\ m^{-2}$)	MAT = 7.7 °C	MAT = 15.4 °C
0	4.9 ±0.08	3.2 ±0.10
6.7	4.8 ±0.11	3.1 ±0.07
13.4	4.6 ±0.06	3.3 ±0.08

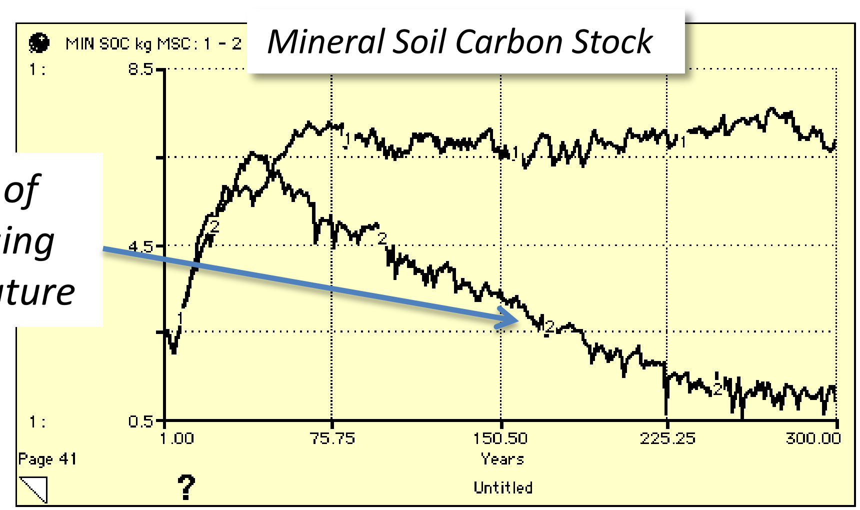
- *Changes in mean annual temperature appear to be a more important control on predicted soil carbon sequestration than changes in fertilizer nitrogen or changes in switchgrass tissue chemistry*

Is soil quality under switchgrass sustainable under climate change?



- *Rate of increase in mean annual temperature (15.4 °C) was 0.02 °C yr^{-1}*
- *Both mineral soil nitrogen and carbon decline over time*
- *Multiple aspects of sustainable production are potentially affected by downward trajectories of soil C and N*

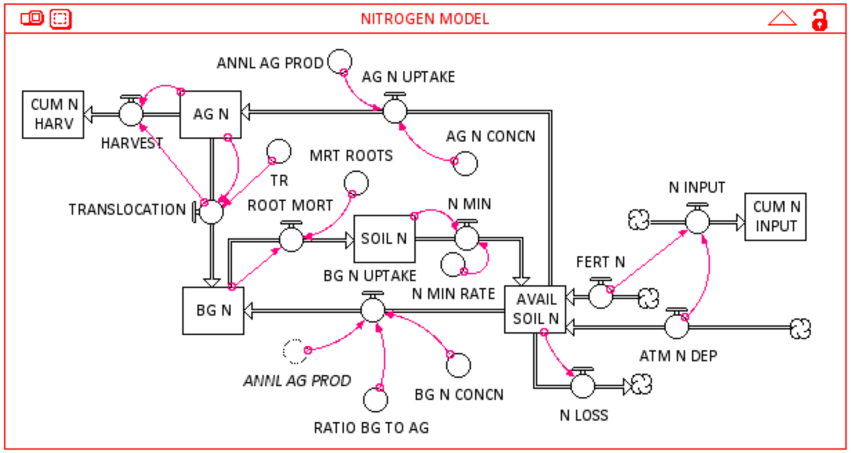


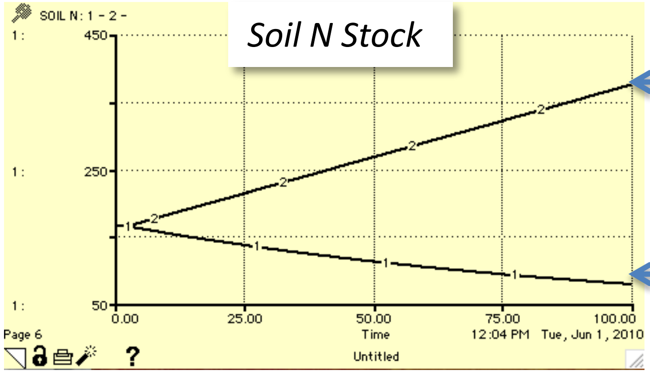


Last, is soil N the driver or the passenger?

MODEL-BASED EXPERIMENTS

- *In SWGM and RSPM, soil N is calculated from soil C – consistent with field studies indicating N availability is a function of accumulating soil OM*
- *There is an alternative, unresolved viewpoint, i.e. soil C accrual = f (N availability)*





GREAT PLAINS

Long-term Nitrogen Fertilization Benefits Soil Carbon Sequestration

By A.D. Halvorson and C.A. Reule

"Positive effects of nitrogen fertilization on soil organic carbon were clearly demonstrated in a long-term dryland annual cropping study under no-till conditions in Colorado."

TECHNICAL REPORTS: PLANT & ENVIRONMENT INTERACTIONS

The Myth of Nitrogen Fertilization for Soil Carbon Sequestration

S. A. Khan,* R. L. Mulvaney, T. R. Ellsworth, and C. W. Boast University of Illinois

"Current fertilizer N management practices … exacerbate soil C loss."

With fertilization, soil N increases (sustainable)

Without fertilization, soil N declines due to continuous N removal in plant harvest (unsustainable)

Summary

- *Site-specific, research models are useful in addressing science questions about inter-relationships among ecosystem processes that impact biofuel sustainability*
  1) *Maximization of production and soil quality*
  2) *Minimization of nutrient inputs and nutrient loss*
- *Field data from the Mitigation SFA studies have been used to parameterize a switchgrass model that indicates rates of soil C sequestration on the order of 100 g C m^{-2} yr^{-1} (after 10 years)*
- *Rates of aboveground production coupled with patterns of plant C allocation are key to maximizing soil C and N accrual and maintaining soil quality*
- *Predicted aboveground production (normalized for fertilizer N inputs) is twofold greater in switchgrass than in poplar while rates of soil C accrual are nearly 33% higher under switchgrass*
- *Response curves for aboveground production and root C/N ratios as a function of fertilization are important site-specific controls on soil C dynamics beneath and greatly influence model predictions*
- *Role of soil N as a control on soil C sequestration needs additional research – ongoing studies may help resolve this question at Milan*

Thanks