DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

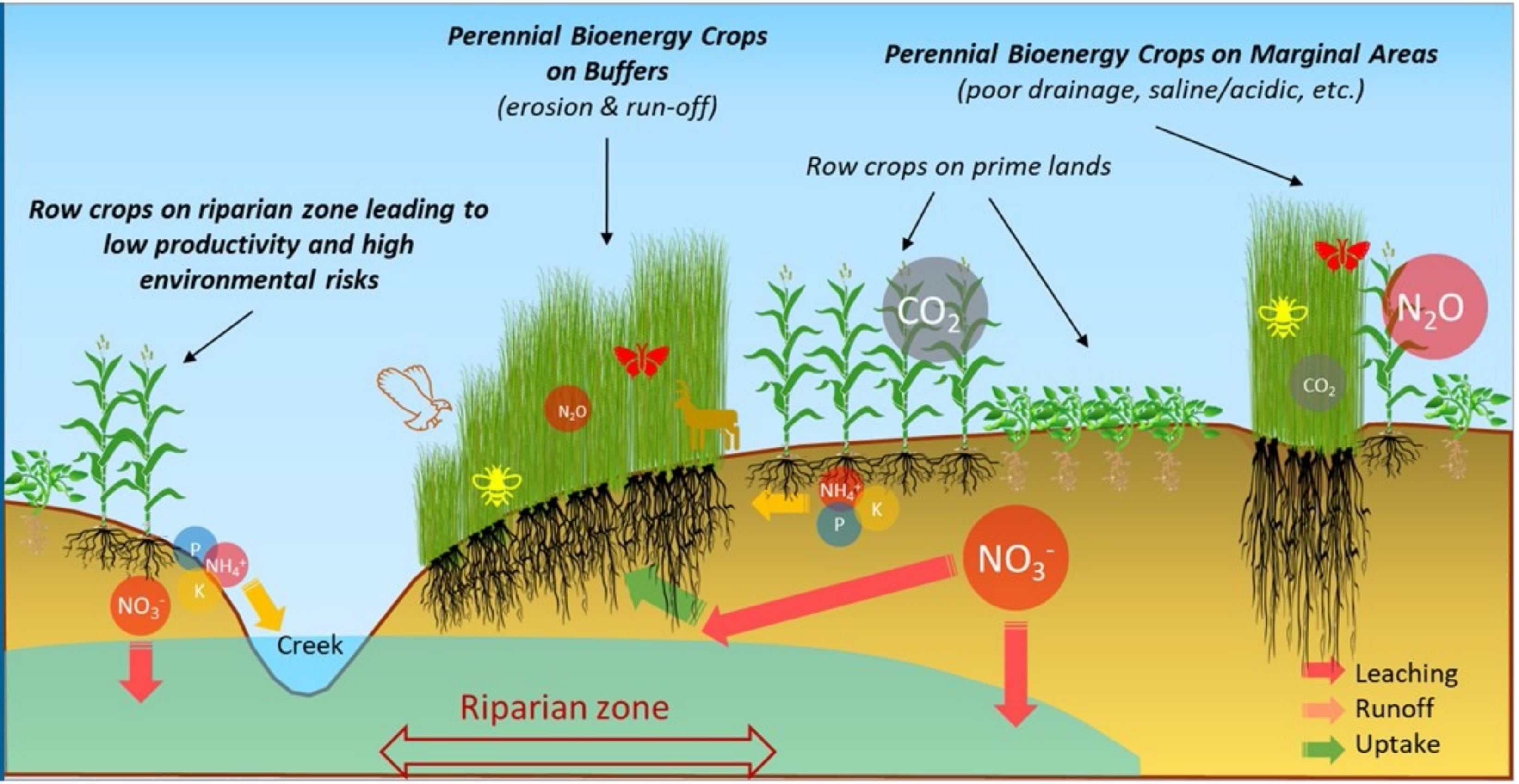
ISEE INSTITUTE FOR SUSTAINABILITY, ENERGY, AND ENVIRONMENT

Next-Generation Feedstocks for the Emerging Bioeconomy

20% of Completion (2019-2024)

Date: Mar 9, 2021
Feedstock Technology Program

D.K. Lee
University of Illinois at Urbana-Champaign

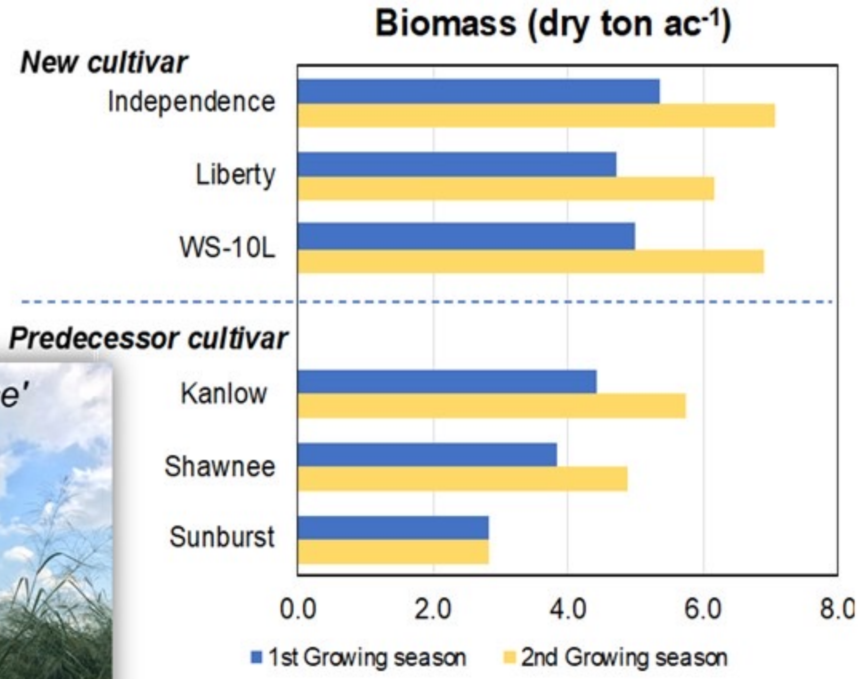


U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
BIOENERGY TECHNOLOGIES OFFICE

Project Overview

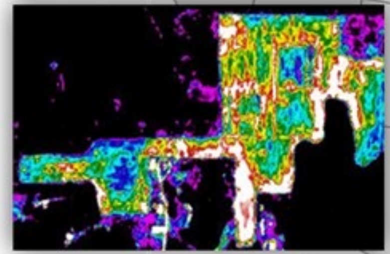
High-level Project Goal:
Develop productive, cost-effective, and sustainable warm-season perennial bioenergy feedstock production systems on marginal croplands across geographic locations in the Midwest

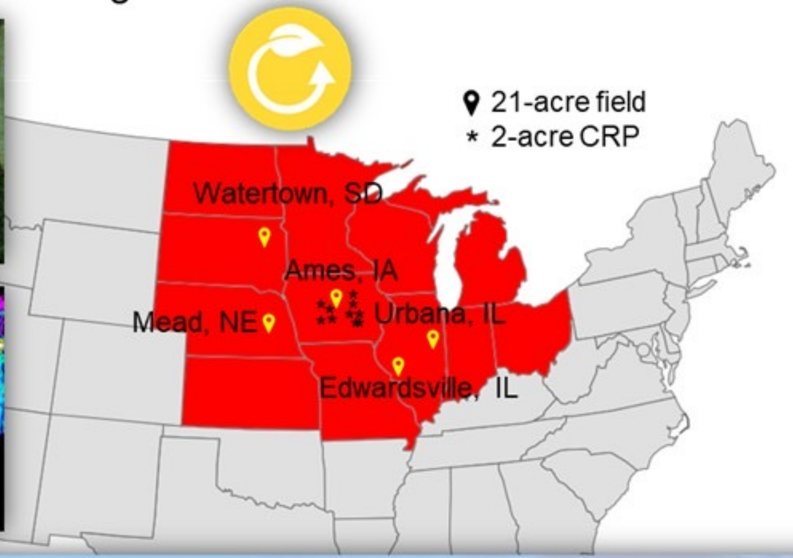
High-yielding bioenergy switchgrass



On-farm field scale production on marginal Land

Sustainable feedstock Production across geographic regions in Midwest





Context and project history:

- Lack of field-scale research with high-yielding switchgrass cultivars
- Demonstration of ecosystem service benefits of perennial energy crops

Project Frame

Feedstock

Objective 1&2

- Potentials of high-yielding switchgrass at field scale
- Best Management Practices
- Harvest logistics
- Feedstock quality

Sustainability

Objective 4

Ecosystem services (ES)

- CO_2, N_2O, CH_4 emissions
- Nutrient leaching (N&P)
- Water quantity (ET)
- Biodiversity
- Soil quality (SOC, WAS, etc.)

Bioeconomy

Objective 5

- Develop a regional feedstock cost-rate model for delivering switchgrass to bio-refinery locations

Plot-scale to field-scale → **Harvest logistics**

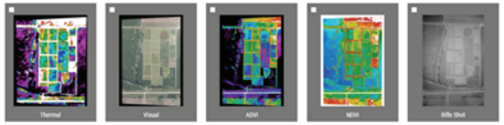
Objective 3

Machine learning (ML)

Input

- Soil data
- Weather data
- Field management
- Growth and development
- Phenotypical data
- ES measurements
- GPS coordinates

\+



Prediction
Yield&ES

Technoeconomic analysis

1 – Management (Team members)

Organization	Main Responsibility	Lead individual/POC
Prime: UIUC/ISEE (IL)	• Standardize the protocols and the templates for data collections • Coordinate with all PIs and compile the data and technical and financial report	D.K. Lee (PI) Anya Knecht (P.M.)
SDSU (SD)	• Field management and data collections	Arvid Boe (Co-PI)
ISU (IA)	• Field management and data collections	Emily Heaton (Co-PI)
USDA-ARS (NE)	• Field management and data collections • Feedstock chemical composition analysis	Rob Mitchell (Co-PI)
INL	• Feedstock chemical composition analysis	Amber Hoover (Co-PI)
ANL	• Develop machine learning model • Ecosystem services measurements for SD, NE, and IA	Cristina Negri (Co-PI)
Antares Group	• Feedstock harvest and logistics	Kevin Comer (Co-PI)
USDA-ARS	• Techno-economic analysis	David Archer (Co-PI)

Industry Partners/Collaborators

- **Dave Bushong**, POET-DSM Advanced Biofuels LLC
- **Frank Dohleman**, External Stakeholder Lead, Science, The Climate Corp.
- **Matt Lechtenberg**, Water Quality Coordinator, Iowa Department of Agriculture and Land Stewardship
- **Kevin Mason**, FDC Enterprises

1 – Management (Strategic plan)

Critical success factors:

- Development of BMP for sustainable biomass production of high-yielding energy crops
- On-farm field scale research - communication with farmers
- Demonstration of ecosystem services with cost-effectiveness data collection
- Identify value to farmers, biorefineries and to ecosystem services payers
- Development of a regional feedstock cost-rate model

Progress measurement:

- Milestone tracking
- Quality and extensiveness of field data collection, QA/QC
- Go/No-go decision points to redirect and assess project direction
- Quarterly team meetings and data sharing and validation via Slack and a Cloud system (Box)
- Quarterly and annual reporting

Interfaces:

- Collaboration with other DOE funded project team for data collection and analysis
  - DOE Bioenergy Center, GLBRC and CABBI: Switchgrass performance and ecosystem services
  - DOE ARPA-E: Field data collection, soil quality/SOC and greenhouse gas measurement
- Promotion of bioenergy crops via seed industries and ag industries
  - Ernst Seeds: Marketing of “Liberty” and “Independence” switchgrass
- Collaboration with commercial biorefineries for feedstock quality testing
  - POET-DSM Advanced Biofuels

CABBI CENTER FOR ADVANCED BIOENERGY AND BIOPRODUCTS INNOVATION

U.S. DEPARTMENT OF ENERGY

arpa·e CHANGING WHAT'S POSSIBLE

POET DSM Advanced Biofuels

ERNST SEEDS

GREAT LAKES BIOENERGY RESEARCH CENTER

2 – Approach (Technical)

Proof of concept (FY19)
Identify marginal lands

Field study (FY19-23)
Field-scale validation
Harvest logistics
BMPs
Ecosystem services

ML modeling (FY20-24)
Ground-truth data
Aerial imagery
Precision data science

- Compile field-based data (agronomic, logistical, environmental, etc.) to be used as input criteria for the techno-economic analysis
- Generate geospatially resolved techno-economic analysis to quantify opportunities to meet BETO's cost goal of less than $3/gge with > 6 ton dry matter per acre yield and feedstock delivery cost of less than $84/dry ton (final goal)

Develop a regional feedstock cost-rate model for delivering switchgrass to biorefinery locations (FY23-24)

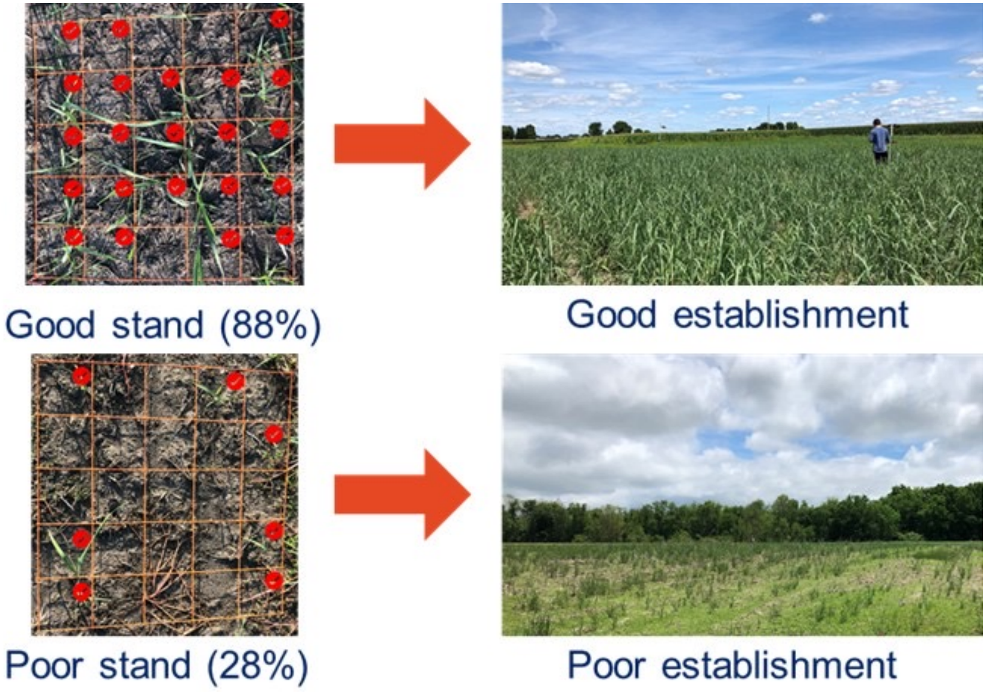
Metrics:

✓ **6 ton/ac biomass yield**
✓ **Significantly better ecosystem services than row crops**

Go/No-go Decision Points:

✓ FY19 – Switchgrass establishment was evaluated based on stands with seedling density using a grid measurement (see picture)
✓ FY20 – Low yield will be defined as < 3.0 ton/ac
✓ FY21 – Low yield will be defined as < 4.5 ton/ac.

Frequency Grid (40% Threshold)



2 – Approach (Technical metrics)

Establishment
- Seed bed preparation/Planting
- Weed control

Maintenance
- Fertilization/Weed control
- Sustainable biomass harvest

Ecosystem service
- Water quality/quantity
- Soil health/C sequestration/GHG
- Biodiversity

Field preparation (Apr – May) | Fertilization (Jun) | Harvest (Nov – Dec)

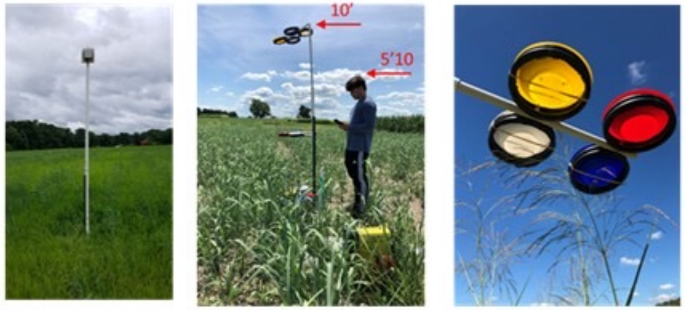
Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sept | Oct | Nov | Dec

Ecosystem service measurements (Apr – Nov)

Soil sampling & processing

- GHGs (CO_2/N_2O/CH_4) measurement (Left)
- Water quality/nutrient leaching (Right)

Soil sensors with 3 depths for evapotranspiration (ET)



Biodiversity measurements
- Avian acoustic monitoring (Left)
- Insects & pollinators (Middle, Right)

2 – Approach (potential challenges)

Challenge 1:

- Establishment challenges on marginal lands (spring flooding) during the first year and spring work delay, weed control and fertilization.

Challenge 2:

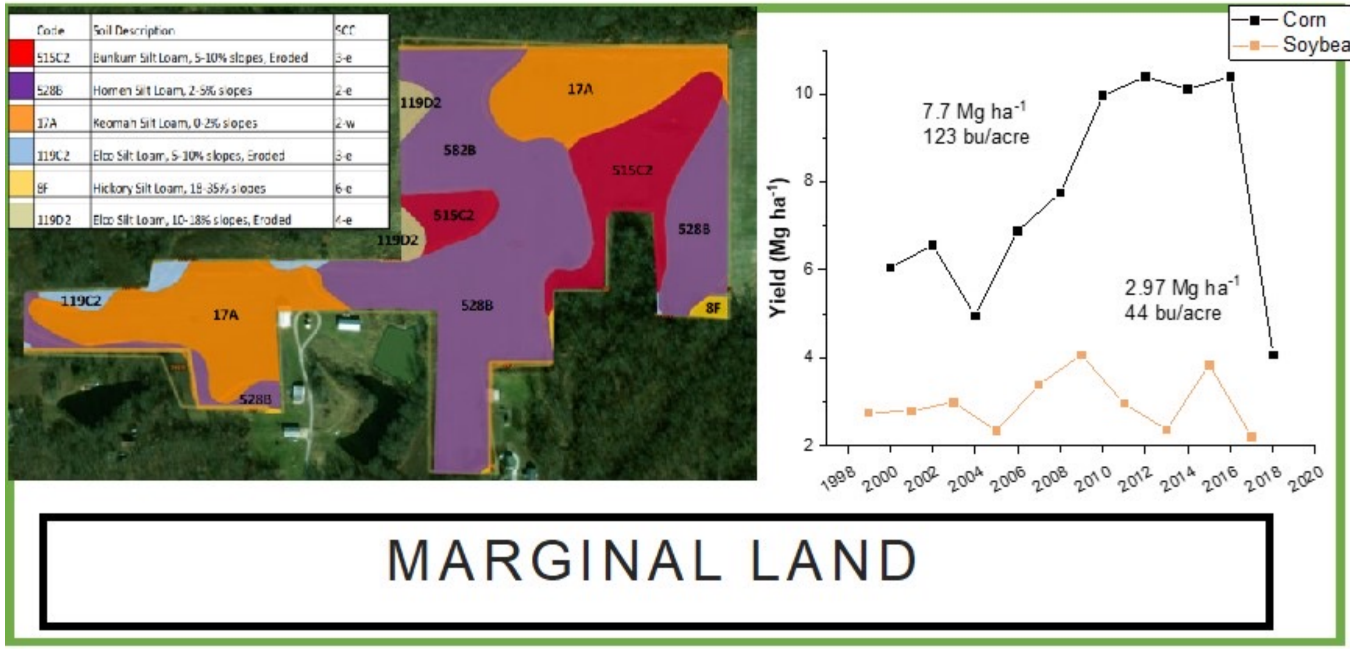
- During the Covid-19 pandemic, travelling long distances becomes even more challenging, which likely compromises the sampling frequency for the ES measurements. Since the ES attributes are very dynamic, limited data points possibly lead to the misjudgment in the cropping system impact on the environment.

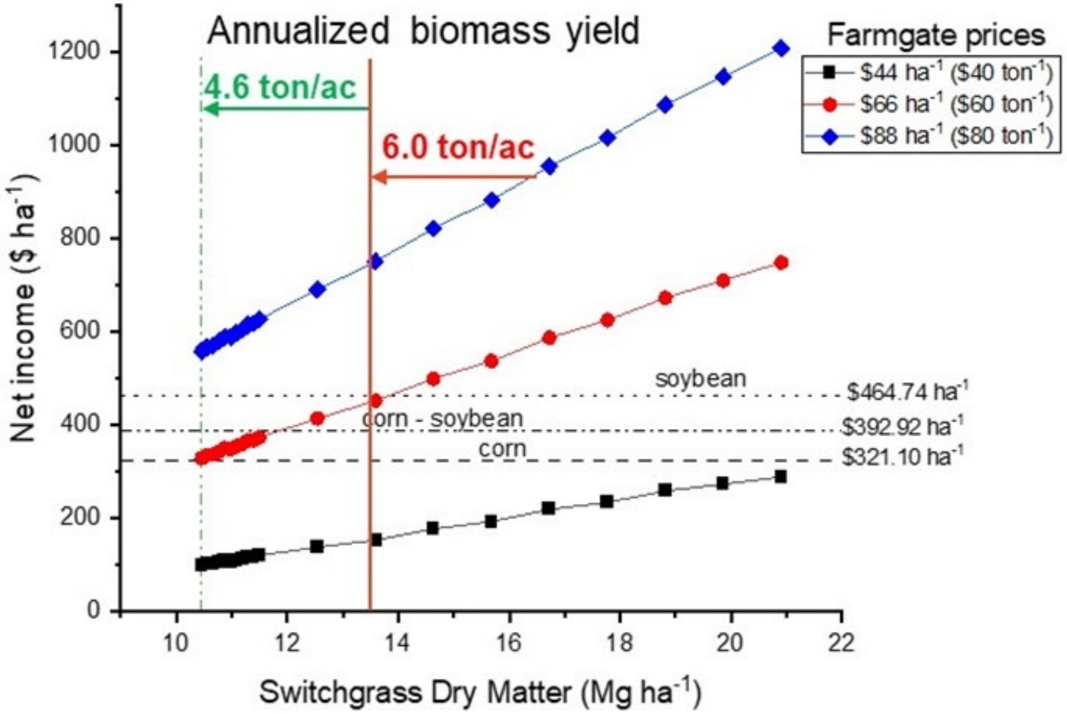
Spring flooding

Inconsistent establishment

Restrictions due to Covid-19

3 – Impact (Significance of outcomes)



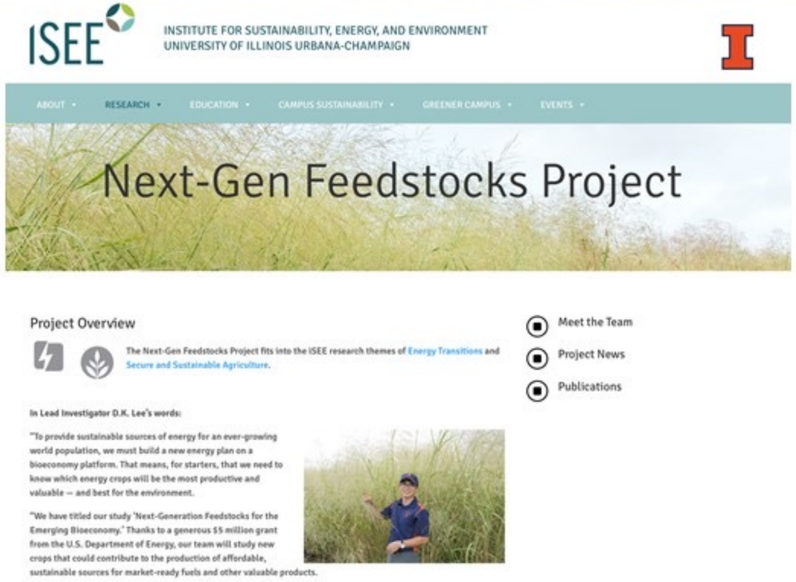


This project will

- Contribute to BETO’s goal of producing >4 dry tons/acre annually at a cost of ≤$84/dry ton with high-yielding bioenergy switchgrass on marginal lands
- Encourage producers to integrate switchgrass on their farms by 1) demonstrating the economic benefits of feedstock production and the potentially monetizable ecosystem service benefits of switchgrass; 2) providing new decision-making tools to expand sustainable production systems using high-performance computing, data science, and precision farming technology.
- Collaborate with biorefineries to provide critical access to conversion technology insights with feedstock produced by farm practices

3 – Impact (Significance of outcomes)

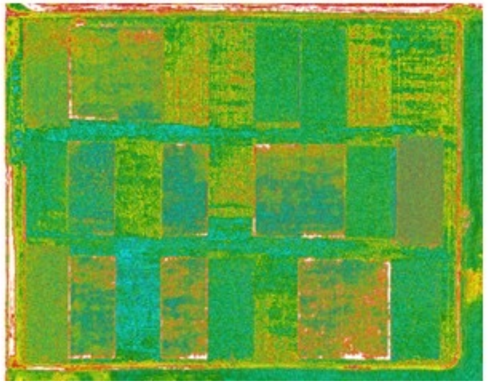
- Annual on-site field day with local stakeholders to showcase production systems and local specific best management guides for switchgrass
- Peer-reviewed publications and presentations at various national and international conferences
- Two public data repositories
  - The Bioenergy Knowledge Discovery Framework (KDF) for biomass yield and composition
  - The Bioenergy Feedstock Library for biomass samples and data
  - GitHub for the ML-model source code
- Project webpage (UIUC, iSEE) to disseminate our findings
- Promote bioenergy switchgrass cultivars, ‘Liberty’ and ‘Independence’ through our commercial partners (seed producers and seed companies)

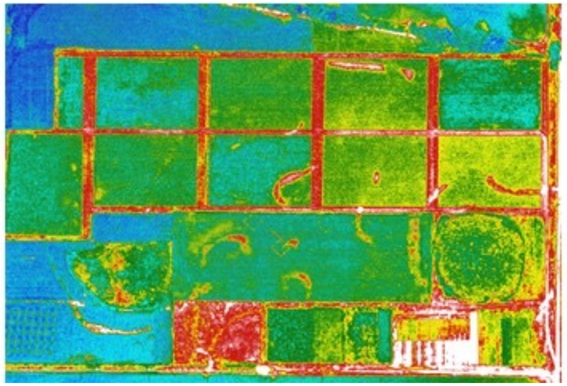


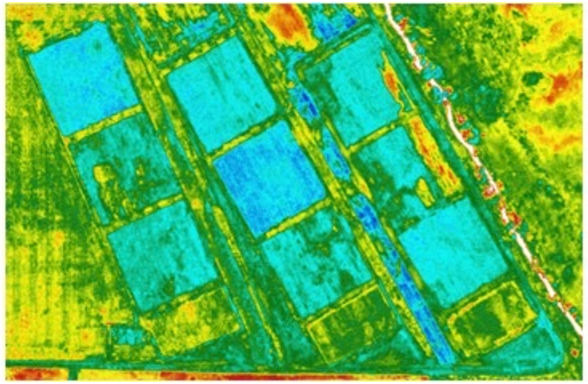
4 – Progress and Outcomes (Field-scale, FY 19-20)

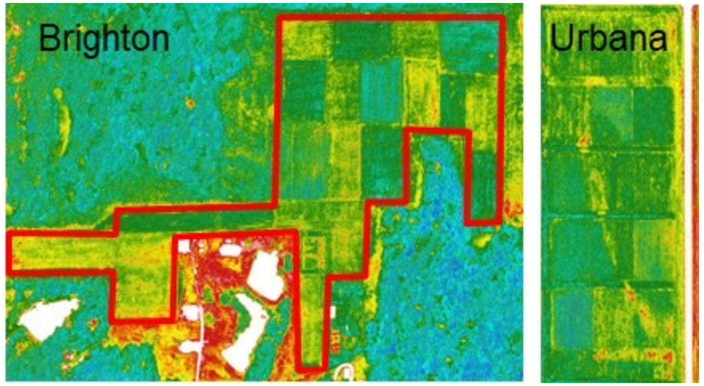
Task 1: Establishment of field-scale switchgrass production systems on all marginal croplands (SD, NE, IA, IL)

Bi-weekly normalized difference vegetation index (NDVI) aerial images









SD site:
- Land degradation with high soil erosion
- High soil variation + poor drainage

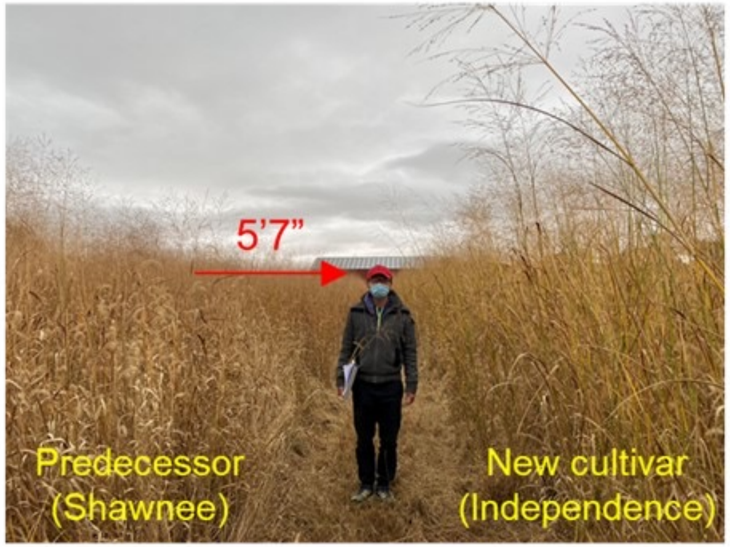
NE site:
- Marginal crop production due to combination of poorly drained soils and erosion

IA site:
- Marginal crop production due to combination of poorly drained soils and erosion

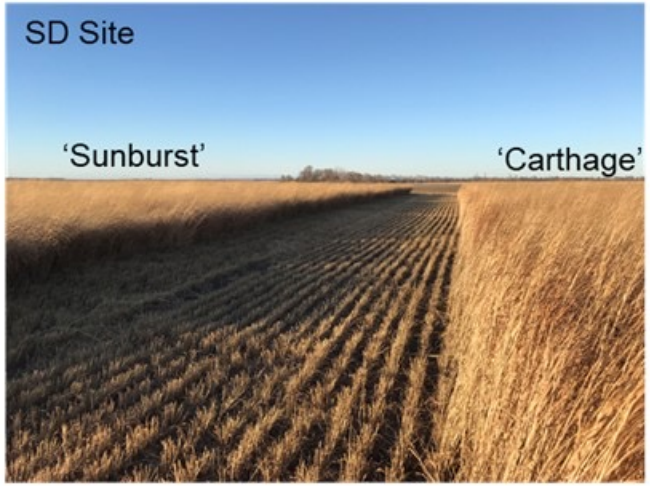
IL site:
- Marginal crop production due to combination of nutrient leaching and soil erosion

Field-Scale Plot Establishment – Frequency Measurement (40% threshold)
- SD (> 90%): Four SW cultivars of ‘Sunburst’, ‘Carthage’, ‘Liberty’, and ‘Independence’
- NE (> 75%): Two SW cultivars of ‘Liberty’, and ‘Independence’, one low diversity grass mixtures (BB, IN, SO), and big bluestem
- IA (> 50%): Three SW cultivars of ‘Shawnee’, ‘Liberty’, and ‘Independence (Replanted in 2019 Spring)
- IL (> 55%): Three SW cultivars of ‘Shawnee’, ‘Liberty’, and ‘Independence’

4 – Progress and Outcomes (Field-scale)

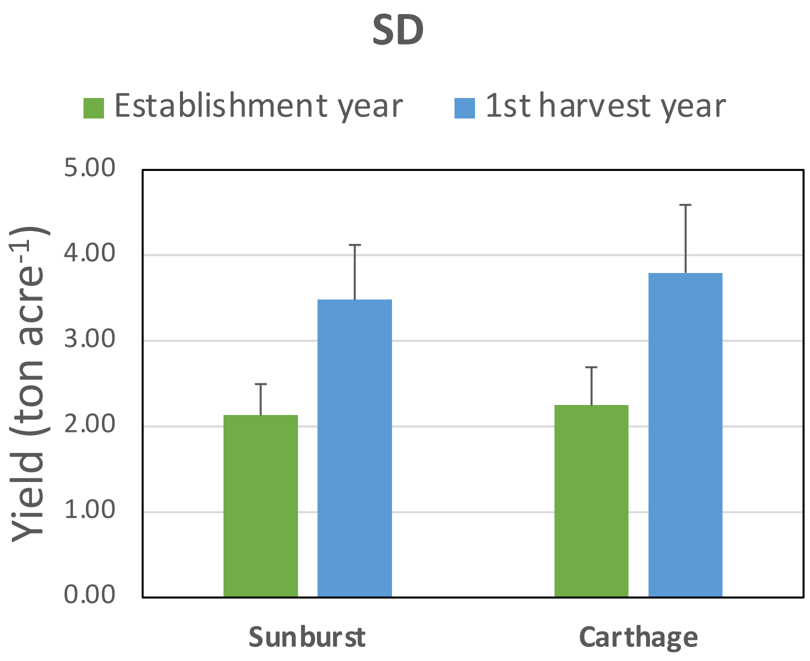


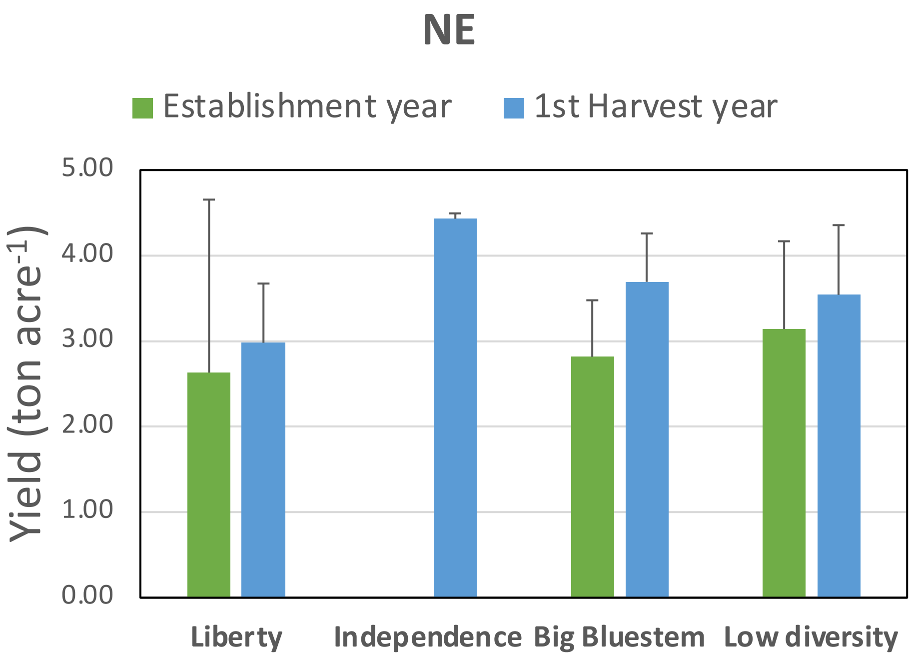
Well established field-scale plots
Harvesting activity in fall 2020

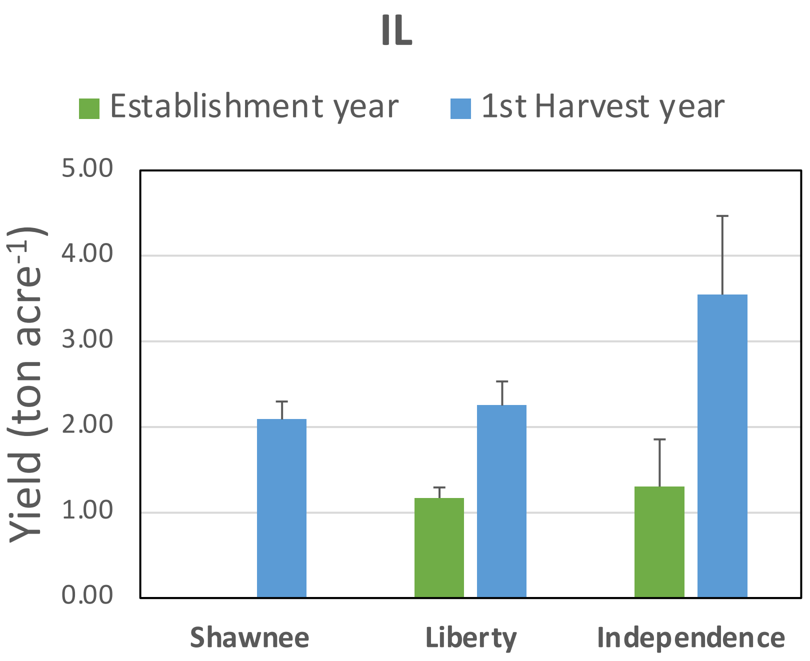


4 – Progress and Outcomes (Field-scale, FY 19-20)

Biomass yields during establishment year and 1st growing season







Takeaway

- Go/No-Go decision: >2 ton/ac for SD and >3 ton/ac for NE and IL for 1st harvest year
- New SW cultivars (‘Carthage’, ‘Liberty’, and ‘Independence’) showed higher yield potentials than the predecessor variety (‘Sunburst’ and ‘Shawnee’)

4 – Progress and Outcomes (Small-scale. FY 19-20)

Task 3: Small-scale plot evaluation on marginal croplands

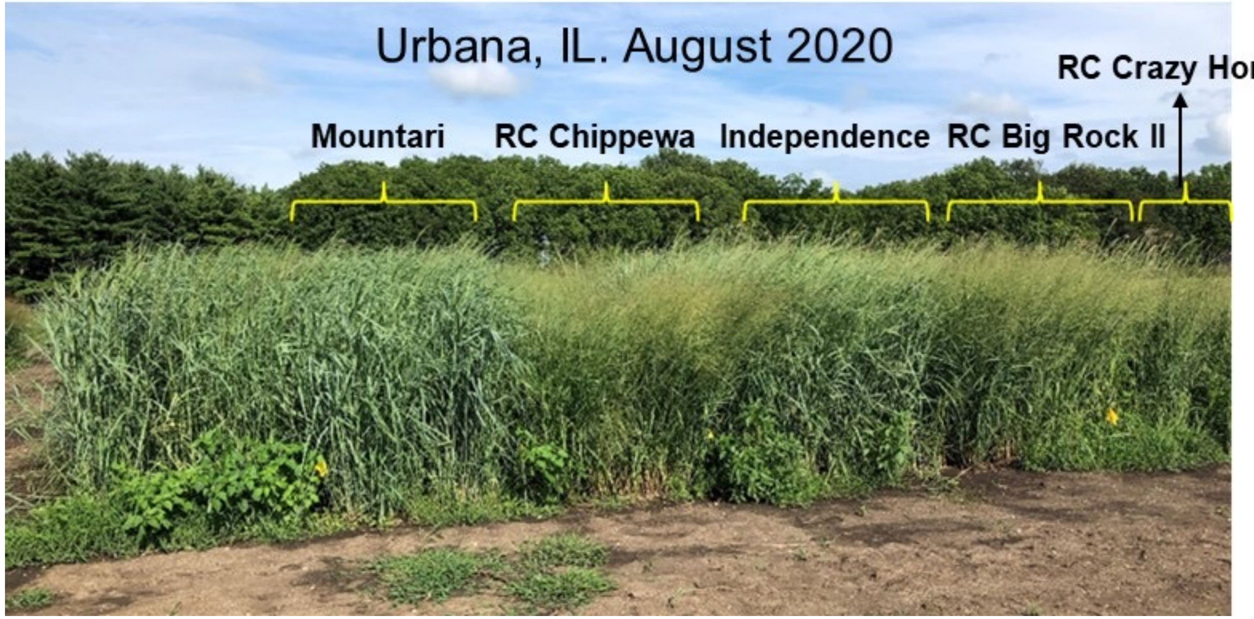
Species	Cultivars
Switchgrass (SW)	11~15
Big bluestem (BB)	5~7
Prairie cordgrass (PCG)	1

Takeaway
Small-scale plot evaluation revealed many potential cultivars with high biomass yield comparable to 'Liberty' and 'Independence' for future application

Small-Scale Plot Establishment – Frequency Measurement (40% threshold)

No. of Cultivars

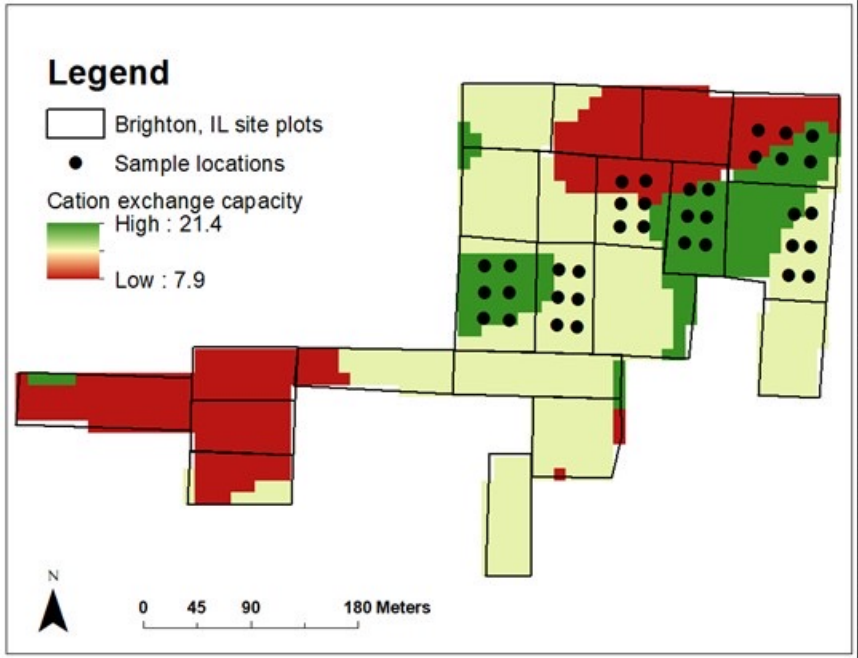
Location	SW		BB		PCG	
	Total	> 40%	Total	> 40%	Total	> 40%
SD	12	7	4	3	1	0
NE	12	11	5	5	1	0
IA	11	10	5	3	1	1
IL	15	14	7	5	1	0



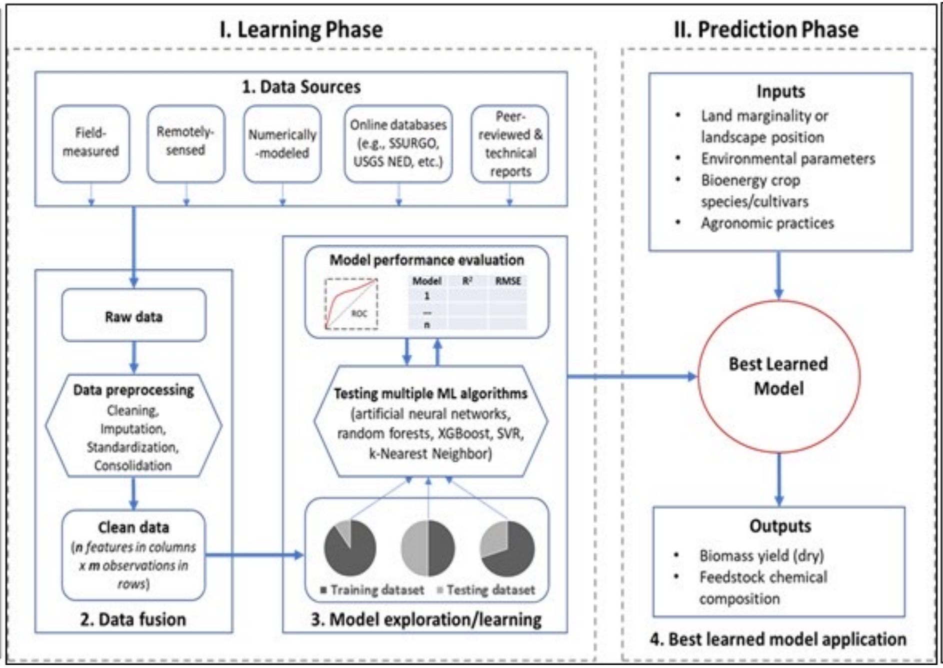
4 – Progress and Outcomes (Machine learning works, FY 19-20)

Task 3: Machine learning and model development

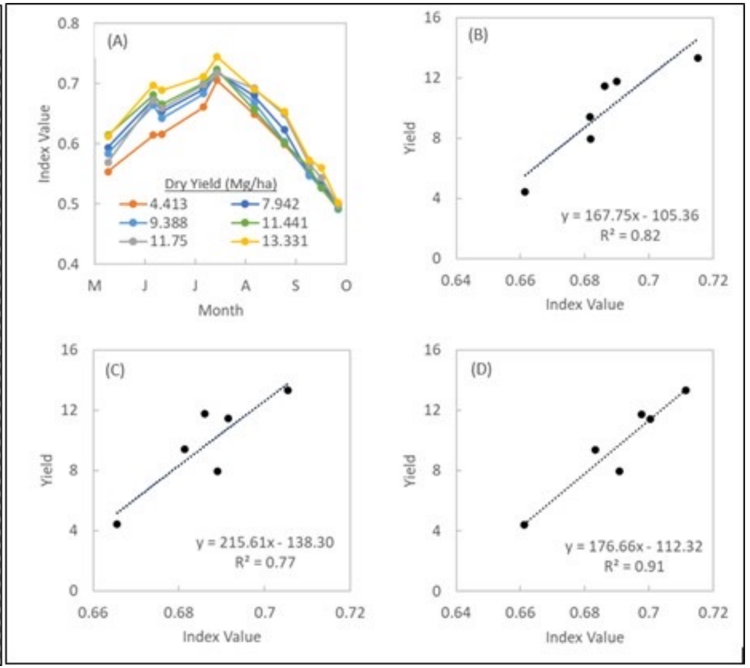
Generated gridded (10 m) dataset of relevant soil parameters for ML model development



Developed a machine learning conceptual model/workflow



Tested a remote sensing model to estimate biomass yield at harvest time



4 – Progress and Outcomes (ML model development)

1-m² quadrat samples for the ML task completed for all sites

Quadrat sample harvest: IL on Dec 01; SD on Nov 11; NE on Nov 02; IA on Nov 04

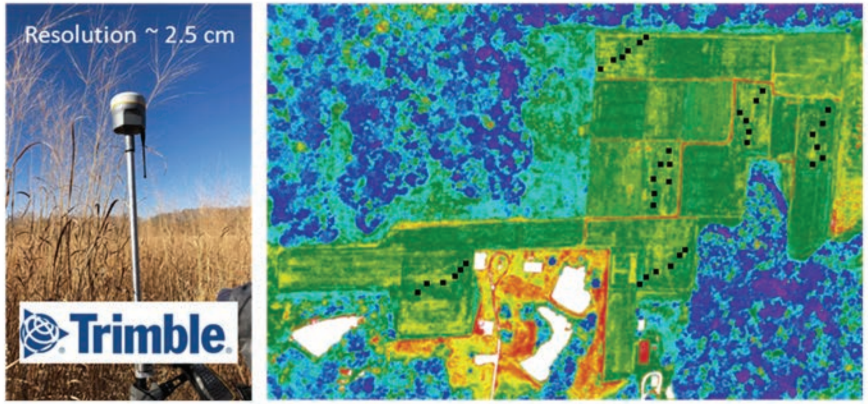
1. Collect biomass

2. Stand count

3. Dry samples if needed

4. Weigh bundles

5. Record coordinates

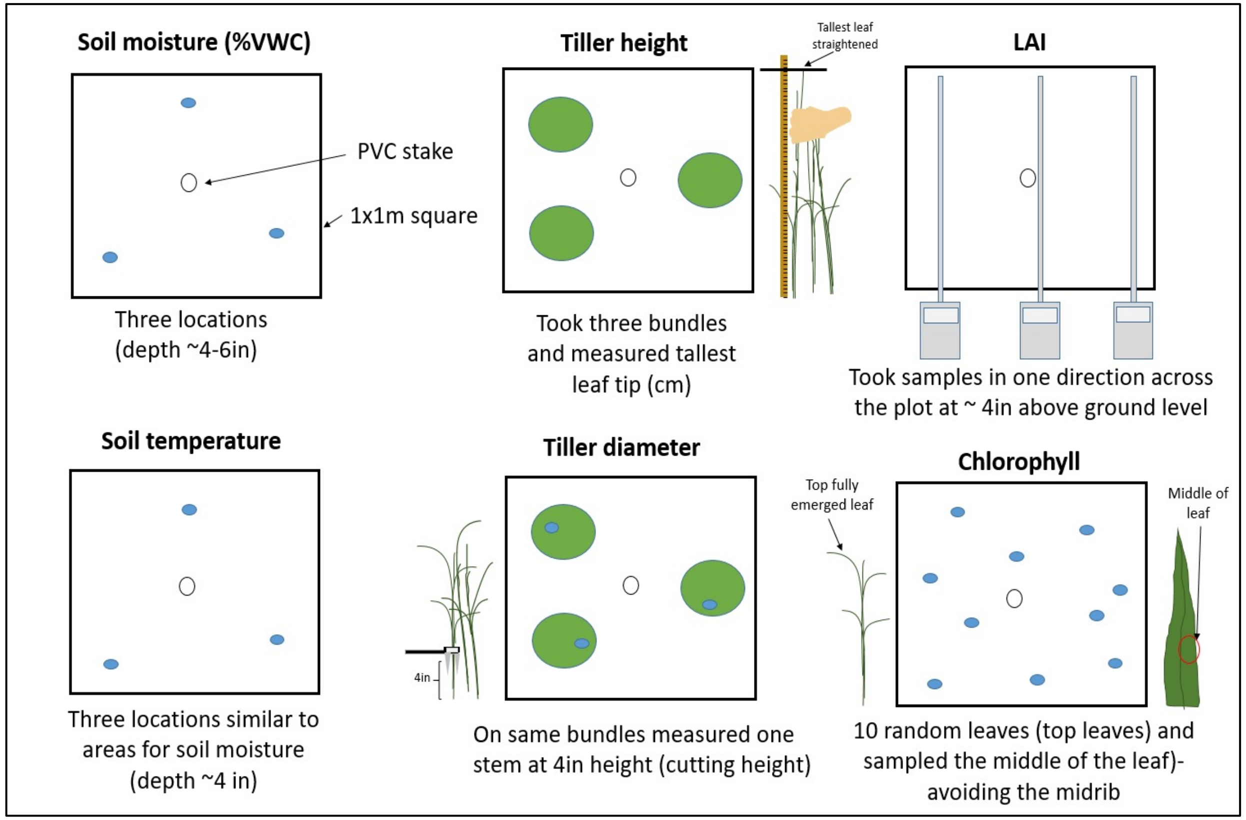


4 – Progress and Outcomes (ML, FY 19-20)

- Ground-based biomass measurements are required for the development of machine learning model with predictive capabilities of biomass attributes.

- 1m^2 subplots were identified at the beginning of the season for monitoring soil and biomass parameters under a single switchgrass cultivar at each field site with the highest fertilizer application rate of 50 lb N/acre.
  - Independence: IL and NE
  - Carthage: SD
  - Liberty: IA

- Subplots were monitored monthly (June-Oct) using non-destructive techniques and were harvested for biomass after a killing frost, shortly before the whole field was harvested (Nov-Dec).



Next-Generation Feedstocks for the Emerging Bioeconomy Support (FY20-FY22)

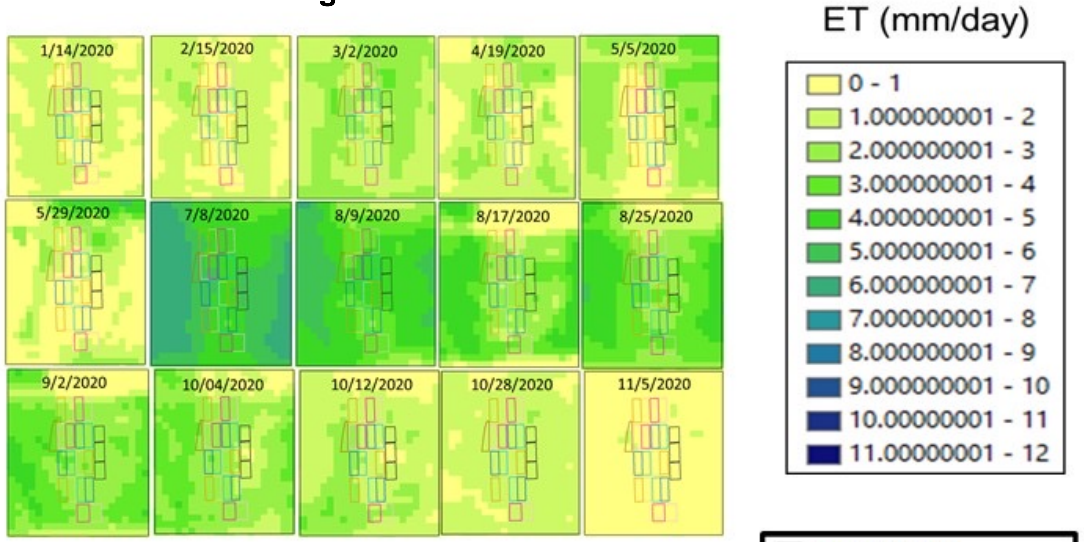
Project Overview

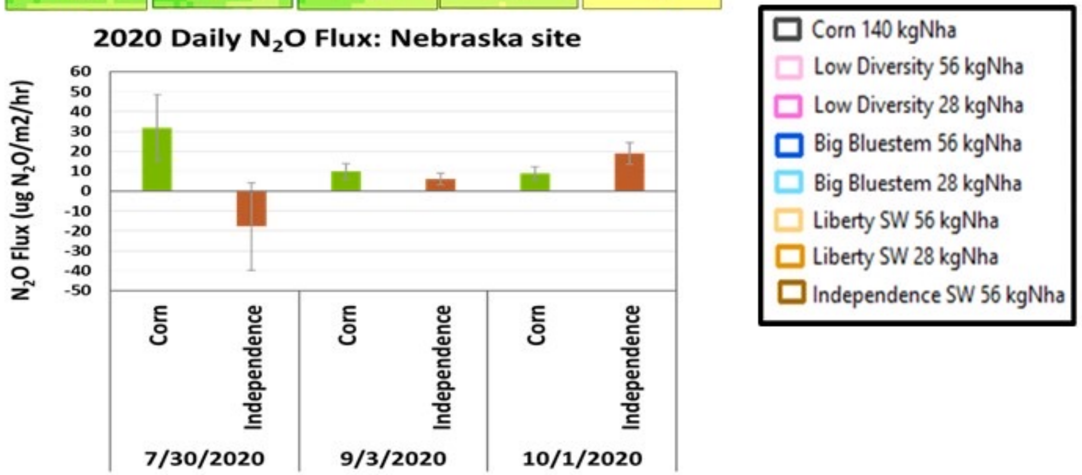
- Supplemental AOP (WBS 1.1.1.1051) aimed at complementing the “Next-Generation Feedstocks for the Emerging Bioeconomy” (WBS 1.1.1.105).
- Extend the ecosystem services (ES) impact assessment under WBS 1.1.1.105 to a wider geographical range (Nebraska, Iowa, and South Dakota sites).
- Support the generation of dataset needed for the machine learning (ML) model development.
- Expand the predictive capabilities of the proposed ML model under WBS 1.1.1.105 (focused on dry biomass yield and quality only) to ES impacts (focused on ET and GHG emissions).

Task 1 – ES Impact Assessment (IA, NE, SD sites) (Progress)

- Completed GHG emissions monitoring for the 2020 growing season
- Completed ET estimates for the 2019 and 2020 growing seasons for the NE site

2020 Remote Sensing -based ET Estimates at the NE Site

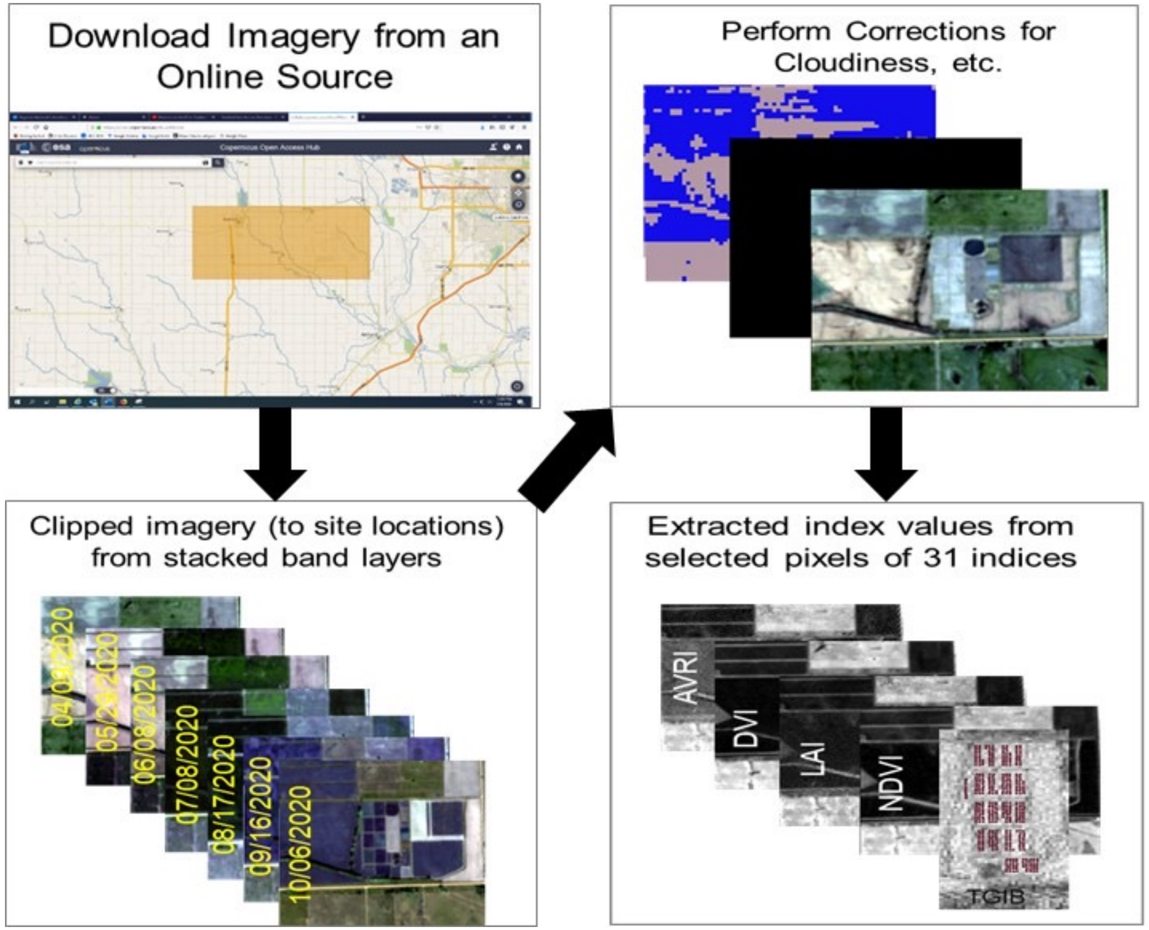




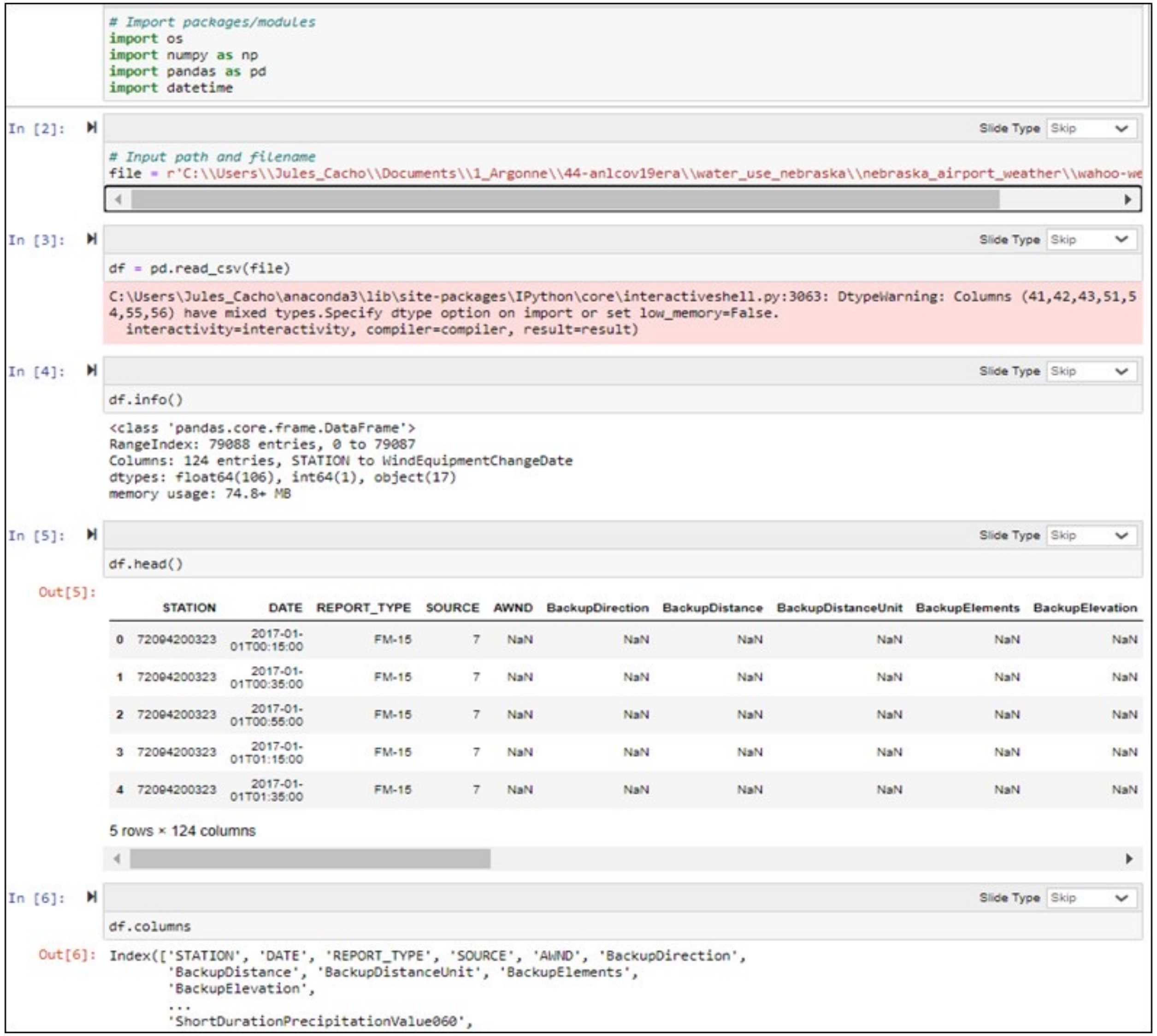
Next-Generation Feedstocks for the Emerging Bioeconomy Support (FY20-FY22)

Task 2 – ML model development, ES Impacts focused (Progress)

- Processed 2020 satellite imagery for generating gridded biomass dataset outside of the IL study sites (e.g., IA, NE, and SD sites)
- Completed the conceptual ML model development framework/workflow
- Coded in Python the model's input module for automating input data preprocessing



Python script for weather data preprocessing



```
# Import packages/modules
import os
import numpy as np
import pandas as pd
import datetime

In [2]:
# Input path and filename
file = r'C:\\Users\\Jules_Cacho\\Documents\\1_Argonne\\44-anlcov19era\\water_use_nebraska\\nebraska_airport_weather\\wahoo-we

In [3]:
df = pd.read_csv(file)
C:\Users\Jules_Cacho\anaconda3\lib\site-packages\IPython\core\interactiveshell.py:3063: DtypeWarning: Columns (41,42,43,51,5
4,55,56) have mixed types.Specify dtype option on import or set low_memory=False.
  interactivity=interactivity, compiler=compiler, result=result)

In [4]:
df.info()
<class 'pandas.core.frame.DataFrame'>
RangeIndex: 79088 entries, 0 to 79087
Columns: 124 entries, STATION to WindEquipmentChangeDate
dtypes: float64(106), int64(1), object(17)
memory usage: 74.8+ MB

In [5]:
df.head()
Out[5]:
```

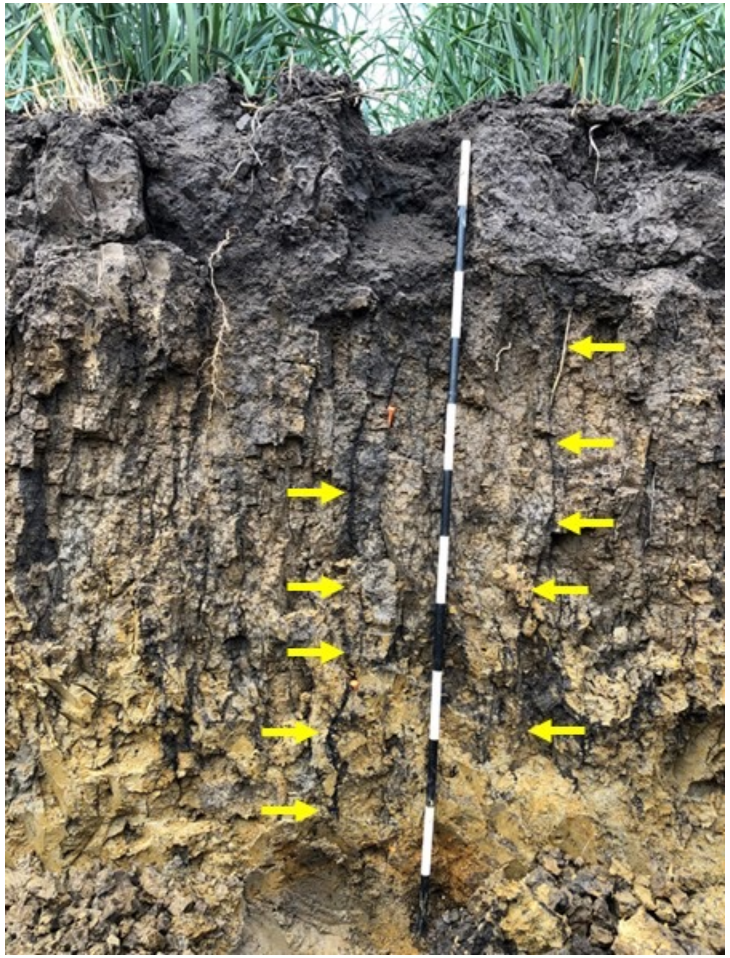
	STATION	DATE	REPORT_TYPE	SOURCE	AWND	BackupDirection	BackupDistance	BackupDistanceUnit	BackupElements	BackupElevation
0	72094200323	2017-01-01T00:15:00	FM-15	7	NaN	NaN	NaN	NaN	NaN	NaN
1	72094200323	2017-01-01T00:35:00	FM-15	7	NaN	NaN	NaN	NaN	NaN	NaN
2	72094200323	2017-01-01T00:55:00	FM-15	7	NaN	NaN	NaN	NaN	NaN	NaN
3	72094200323	2017-01-01T01:15:00	FM-15	7	NaN	NaN	NaN	NaN	NaN	NaN
4	72094200323	2017-01-01T01:35:00	FM-15	7	NaN	NaN	NaN	NaN	NaN	NaN

5 rows × 124 columns

```
In [6]:
df.columns
Out[6]: Index(['STATION', 'DATE', 'REPORT_TYPE', 'SOURCE', 'AWND', 'BackupDirection',
       'BackupDistance', 'BackupDistanceUnit', 'BackupElements',
       'BackupElevation',
       ...
       'ShortDurationPrecipitationValue060',
```

4 – Progress and Outcomes (Ecosystem Services (ES)- Soil health, FY 19-20)

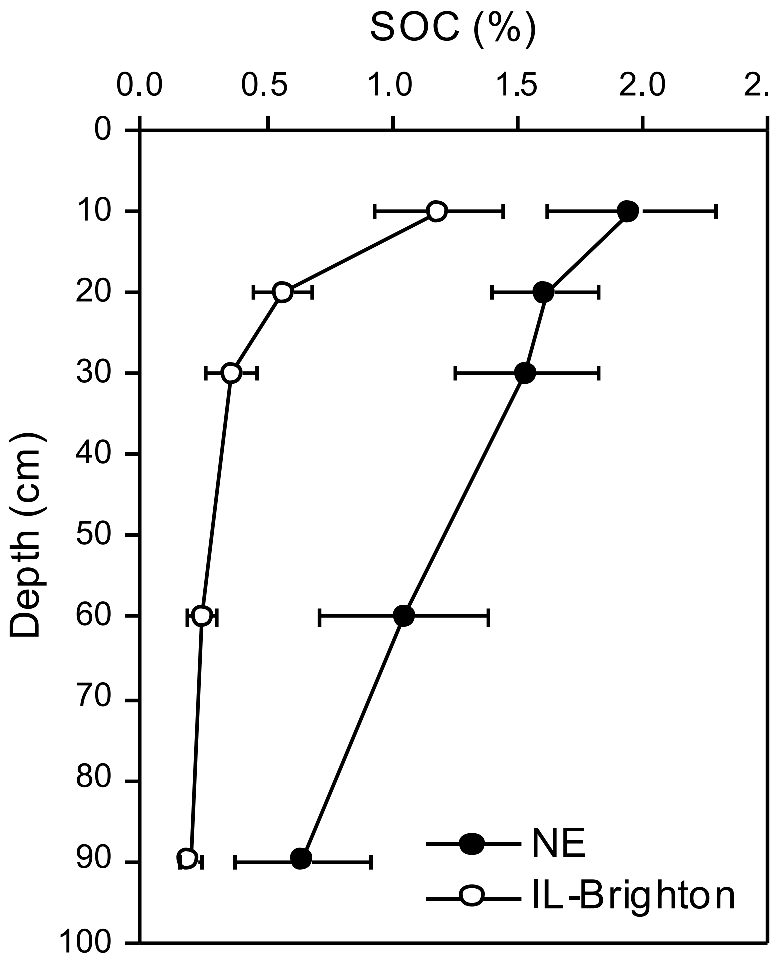
- Deep root penetration
- Carbon translocation (arrow)



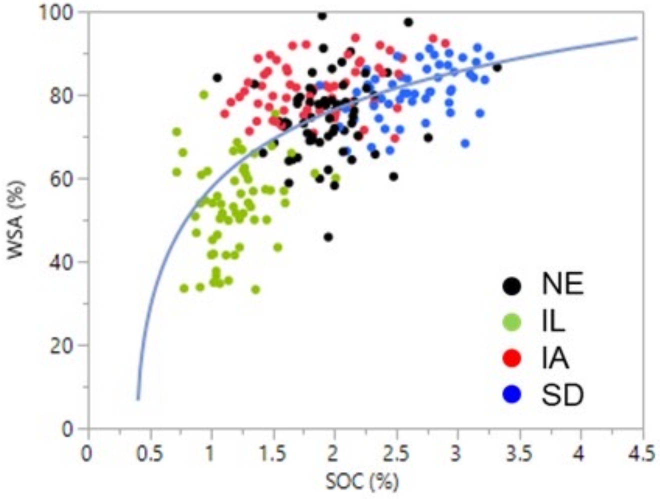
The soil profile of the 1-year-old perennial grass field

Task 4: Ecosystem service measurement

Baseline soil analysis completed: bulk density, pH, SOC, water aggregate stability (WAS), etc.

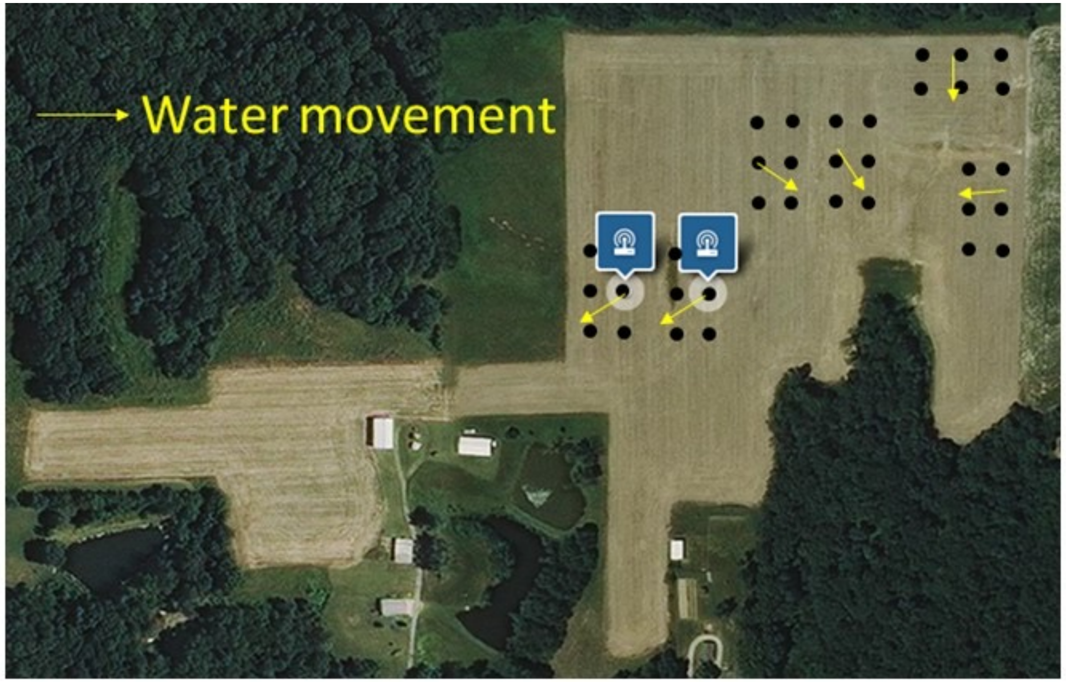


- Soil carbon improves soil health



$$Y = (3319.0 + 3638.5*Log(X))^{1/2}$$
$$R^2 = 0.4258$$

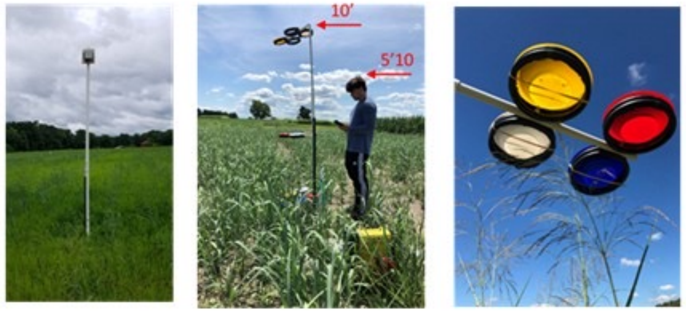
4 – Progress and Outcomes (ES – GHG emissions)



IL site field map (Top) and weather data (Bottom)

- GHGs (CO_2/N_2O/CH_4) measurement (Left)
- Water quality/nutrient leaching (Right)

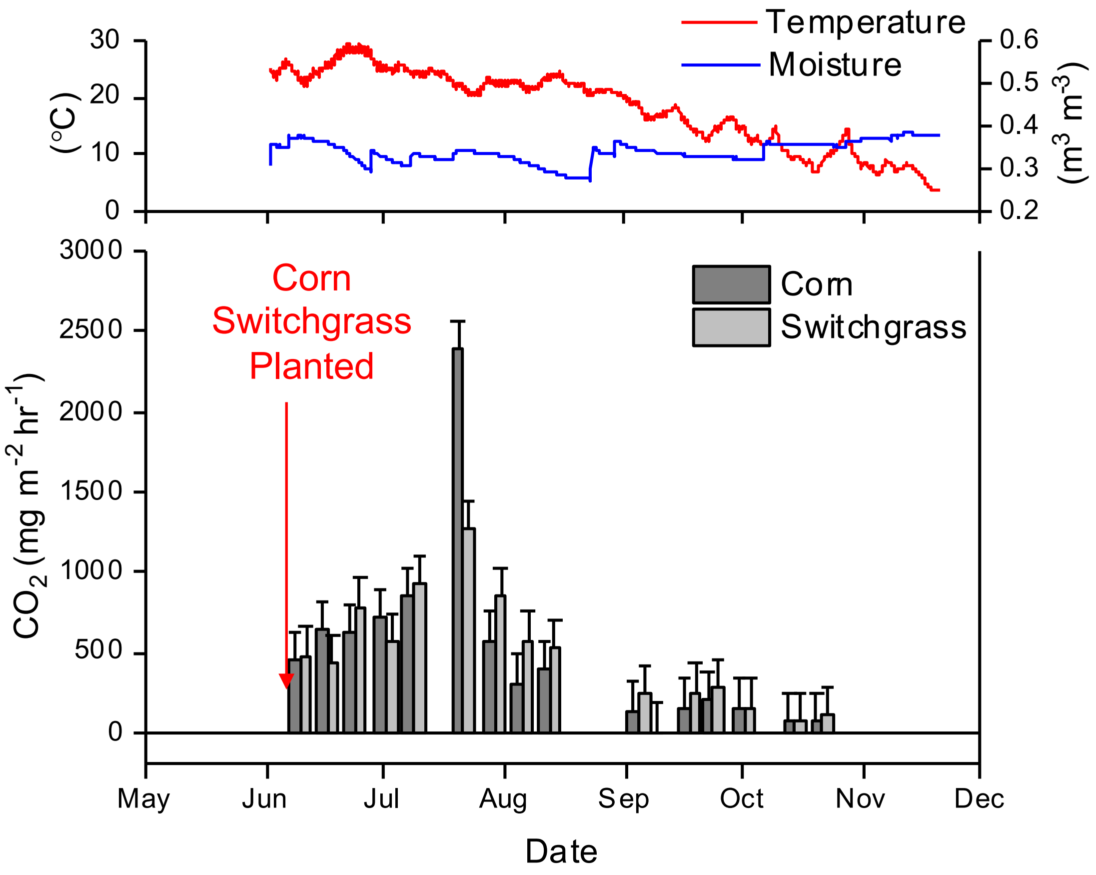
Soil sensors with 3 depths for evapotranspiration (ET)

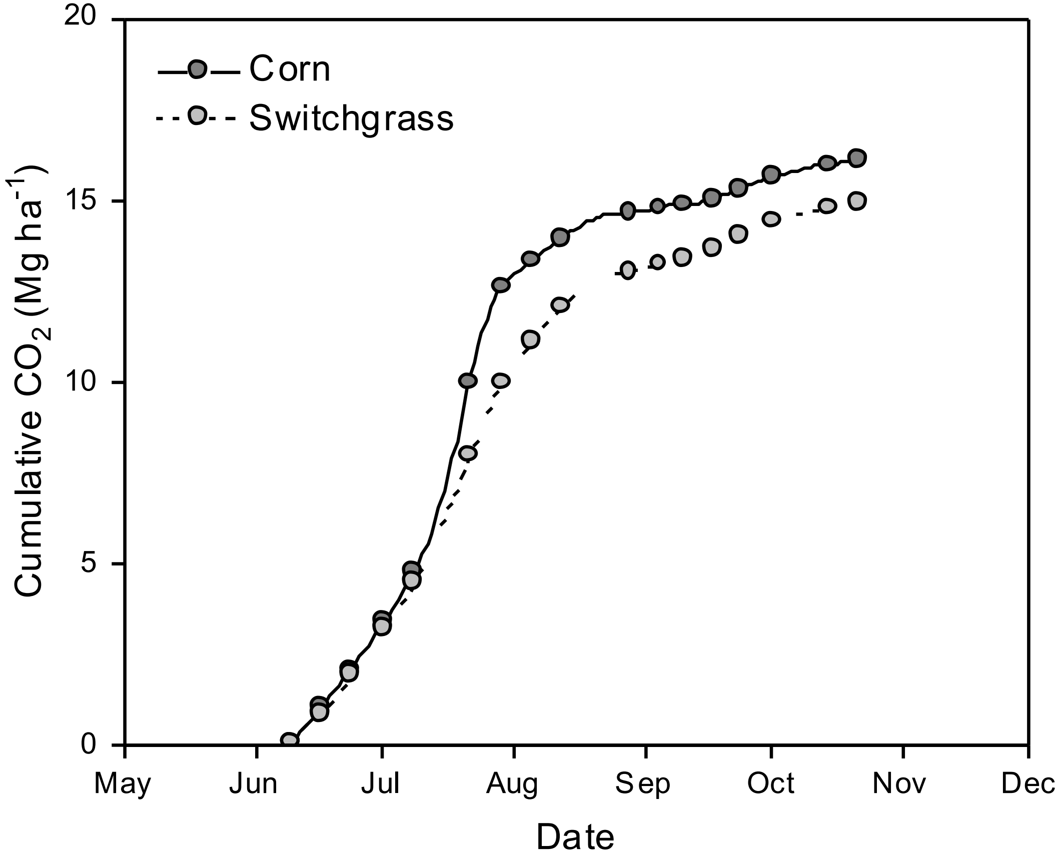


Biodiversity measurements
- Avian acoustic monitoring (Left)
- Insects & pollinators (Middle, Right)

4 – Progress and Outcomes (ES – Soil CO_2 emissions)

Establishment year, IL site



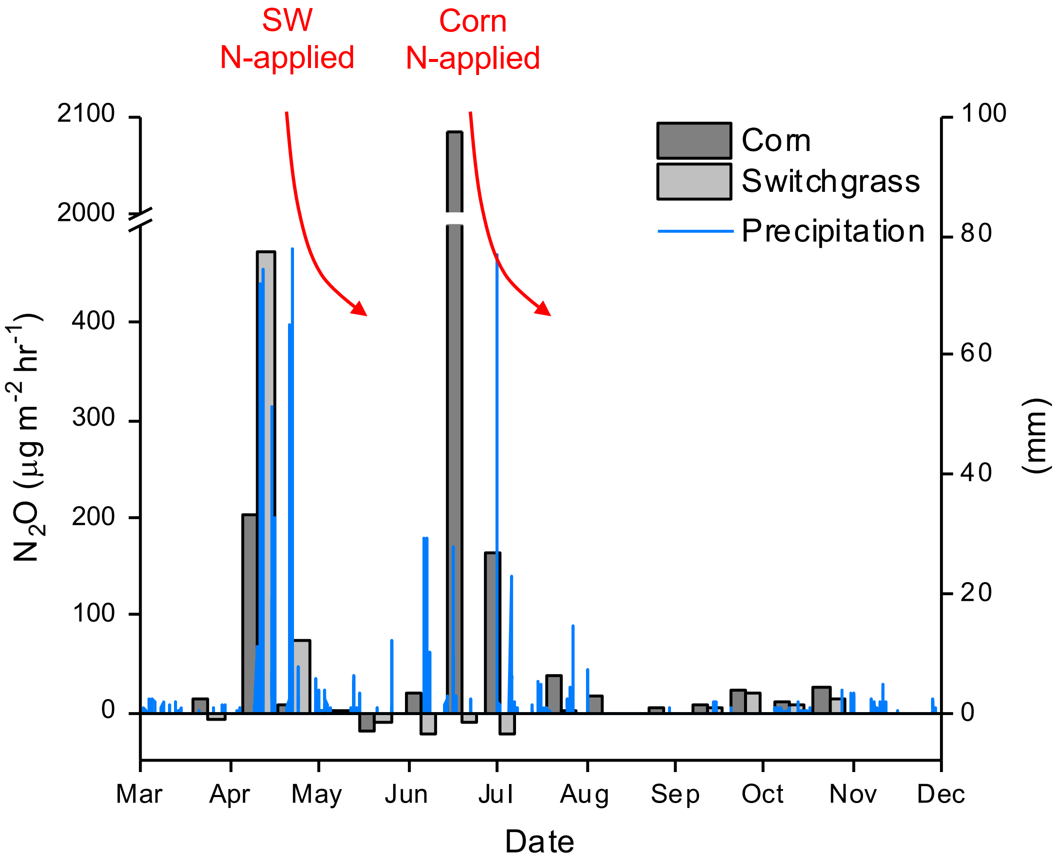


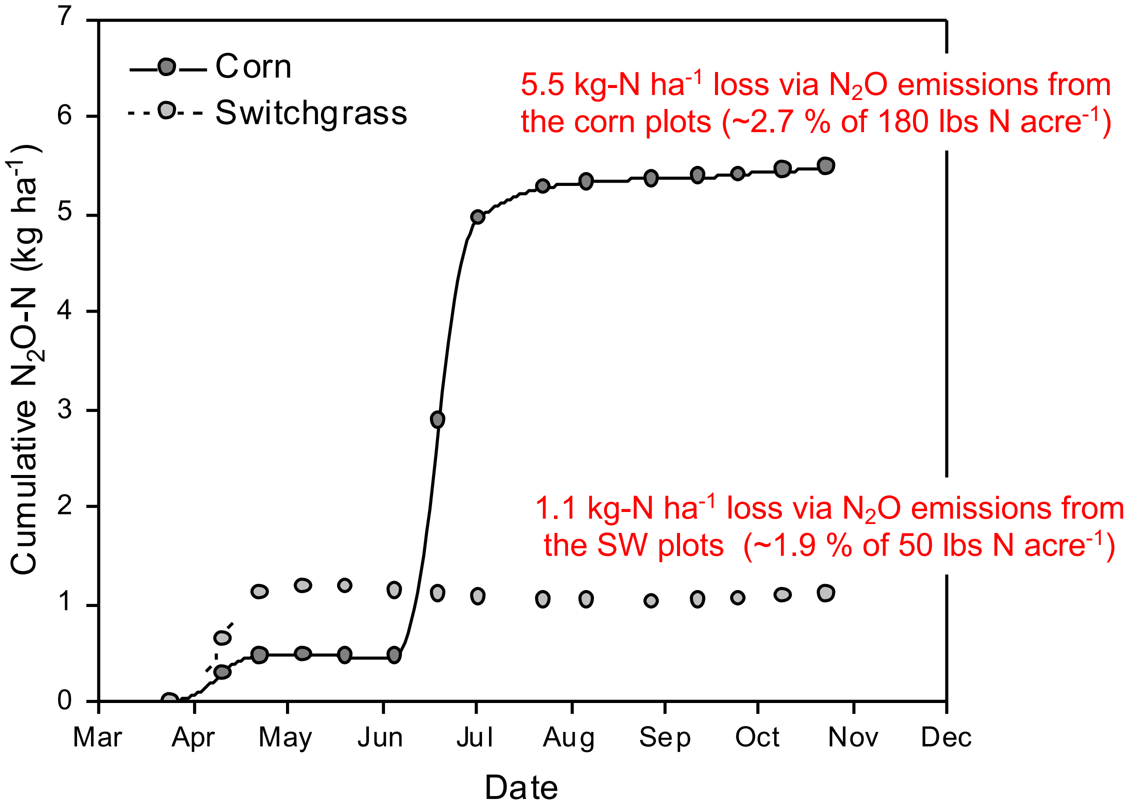
Takeaway

- Annual CO_2 emissions were higher in the corn plots than the switchgrass plots

4 – Progress and Outcomes (ES – Soil N_2O emissions)

1st growing season, IL site



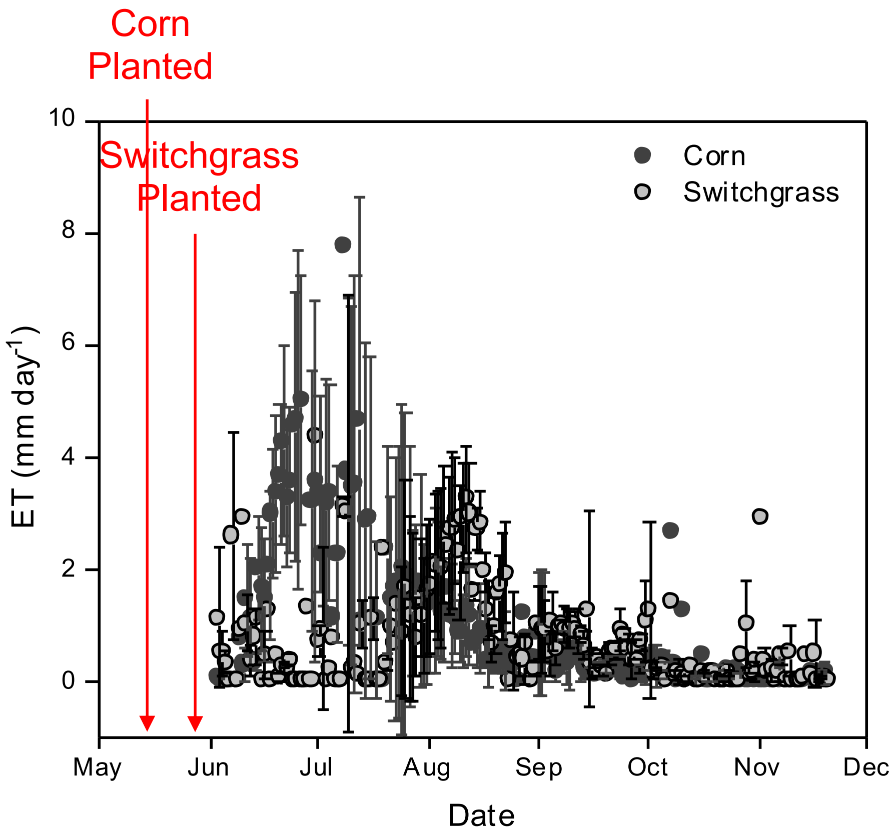


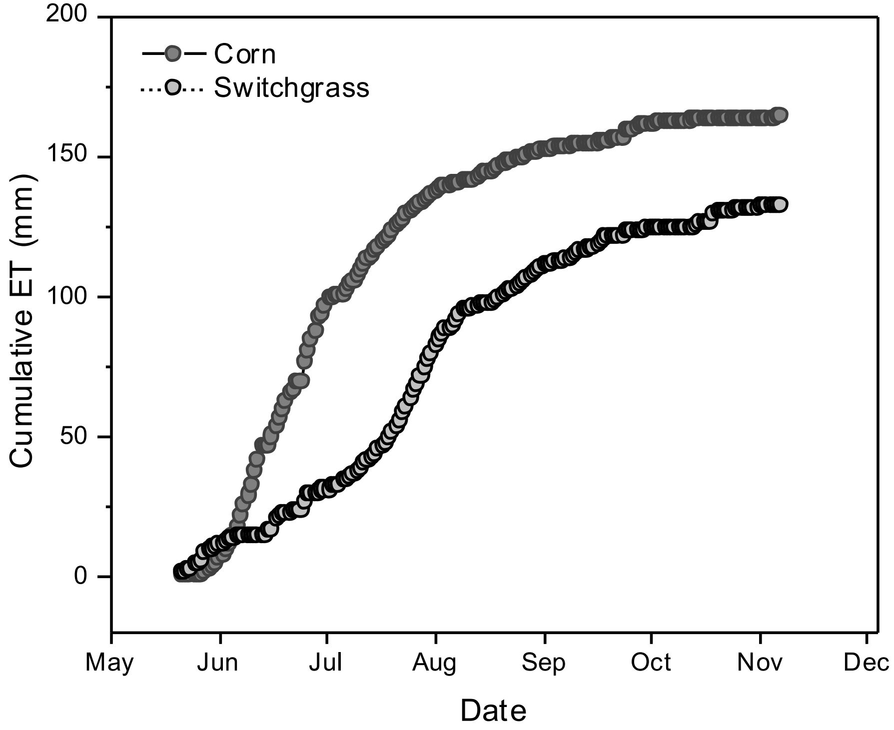
Takeaway

- Increased N_2O emissions followed the field activities (N application) and precipitation
- The switchgrass plots had lower N_2O emissions than the corn plots.

4 – Progress and Outcomes (ES – Evapotranspiration, ET)

Soil sensors with 3 depths





Takeaway

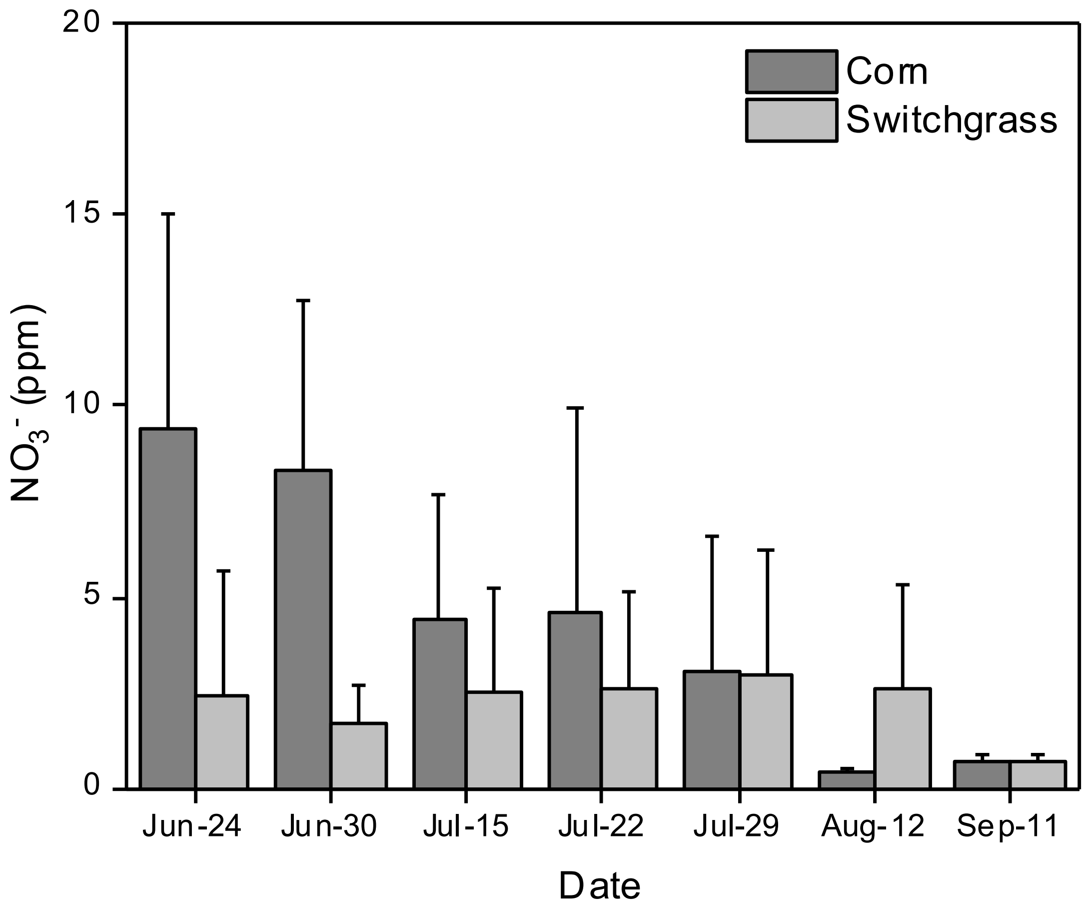
- The switchgrass field had lower ET than the corn field.

4 – Progress and Outcomes (ES – Water quality, NO_3-N leaching)

Takeaway

- The switchgrass field had lower NO_3^- leaching than the corn plots.
- The leached NH_4^+ and PO_4^{3-} were similar (negligible) between SW and corn plots (not shown).

90-cm soil leachate (N fertilizer applied on May-15)



4 – Progress and Outcomes (Feedstock harvest & logistics, FY 19-20)

Task 5: Feedstock harvest and logistics

Status: for mature switchgrass stands

- Harvest operations and data collection methods, and database have been established for measuring performance and cost parameters.
- Year 1 data collection completed, Year 2 underway. Video/photos of all operations.
- A harvest cost and performance model will be developed to use historical and on-going field- and farm-scale harvest performance and cost data to estimate field- and farm-scale results for higher-yielding ASEC switchgrass expectations based on plot-scale results. Efficiency changes for each field operation will be based on yield increases.

- **4 – Progress and Outcomes (Future works, FY 20-21)**

Task 1. Field scale plots

Y-1 biomass data analysis
Y-2 biomass harvest

Task 2. Small plots

Y-1 biomass data analysis
Y-2 biomass harvest

Task 3. ML model development

Continue populating the machine learning framework and model with yearly field data

Task 4. Ecosystem service measurement

Continuous measurement for the season 3

Task 5. Feedstock harvest and logistics

Deploy state-of-the-art perennial grass harvest and logistics equipment to harvest larger commercial-scale fields

Task 6. Feedstock chemical composition

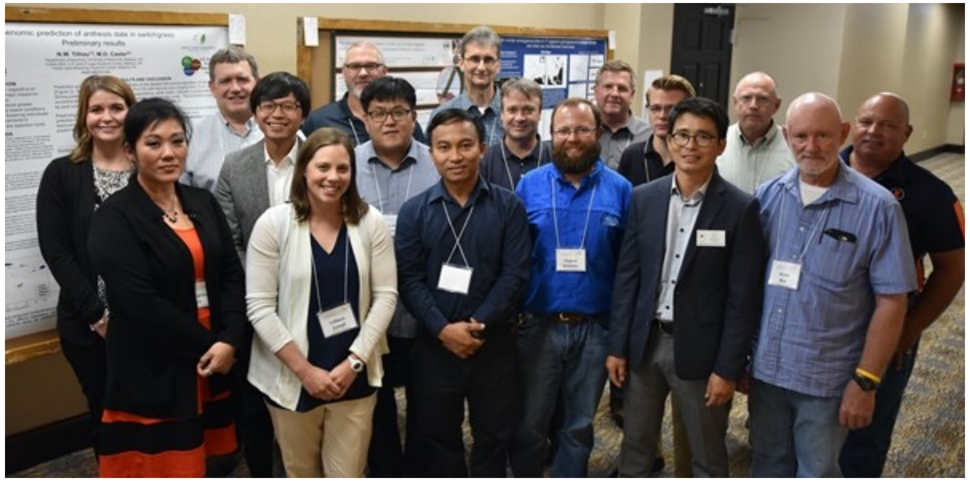
Initiation of feedstock chemical composition analysis with Y-1 feedstock and data deposit

Task 7. Techno-economic analysis

Modeling of farm productivity and feedstock introduction with Y-1 information

Summary (FY 19-20)

- **The newly introduced bioenergy type switchgrass was successfully established on marginally productive croplands in SD, NE, IA, and IL.**
  - Best management practices resulted in successful establishment
  - Year-1 biomass yields demonstrated promising biomass yield (>6 ton/ac)
  - Other promising species and cultivars for future applications were identified
- **Bioenergy switchgrass feedstock production systems demonstrated the potential benefits of ecosystem services on the marginal croplands compared to the row cropping system (i.e., corn),**
  - Increased C sequestration (SOC) likely improves soil health (water stable aggregate)
  - Reduced soil GHG emissions, especially N_2O emissions by approximately 5-fold.
  - Improved water quality
  - More efficient water use (low evapotranspiration)
- **An ML (data-driven) model can address modeling needs when process-based models are unable (theoretical/scale limitation) to support TEA, LCA, and meta-analyses**



DOE-ASEC Switchgrass Team

Quad Chart Overview (Competitive Project)

Timeline
- Start: 10/01/2018
- End: 09/30/2024

	FY20 Costed	Total Award
DOE Funding	(10/01/2018 – 9/30/2020) *$1,073,189*	*$5,000,000*
Project Cost Share	$269,061	$1,251,399

Project Partners*
- University of Illinois at Urbana-Champaign
- Iowa State University
- South Dakota State University
- Antares Group
- USDA-ARS, Lincoln, NE and Mandan, ND
- Argonne National Lab
- Idaho National Lab

Project Goal
The goal of the project is to research and develop productive, cost-effective, and sustainable warm-season perennial bioenergy feedstock production systems on marginally productive croplands across geographic locations in the Midwest.

End of Project Milestone
- Develop BMP for sustainable feedstock production of switchgrass on marginal lands in Midwestern regions to meet BETO's goal of >4 dry tons/ac at the cost of delivered feedstock to ≤$84/dry ton
- Demonstrate ecosystem service benefits of switchgrass feedstock production systems
- Develop a fully functional ML-based predictive model and a publicly available regional feedstock cost-rate model for delivering switchgrass to the biorefinery

Funding Mechanism
FOA: DE-FOA-0001917,
Affordable and Sustainable Energy Crops (ASEC), 2018

Additional Slides

Presentations

- Switchgrass V International Conference: Dedicated Energy Crops and Native Grasses for the Emerging Bioeconomy

- Zumpf, C., Cacho, J., Quinn, J., Negri, M.C., Lin, C., and Lee, D.K. (2020). Water Use Estimates of Bioenergy Switchgrass Cropping Systems in the U.S. Midwest. Poster presentation at the 2020 Annual ASA, CSSA, SSSA meeting on Nov. 9-13th (Virtual).

- Zumpf, C., Cacho, J., Quinn, J., Negri, M.C., Lin, C., and Lee, D.K. (*Submitted*). Water Use and Greenhouse Gas Emissions of Bioenergy Switchgrass Production Systems in the U.S. Midwest. International Association of Landscape Ecology, 2021 North America Annual Meeting (Virtual).