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Satellite Remote Sensing Applications for Cover Crops

W. Dean Hively, U.S. Geological Survey

in collaboration with United States Department of Agriculture - Agricultural Research Service, the Maryland Department of Agriculture, Soil Conservation Districts, Stroud Water Research Center, Penn State, USDA Conservation Effects Assessment Project, NASA, farmers, and others

•U.S. Department of the Interior
•U.S. Geological Survey

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Chesapeake Bay Program Agricultural Working Group
9/18/2025

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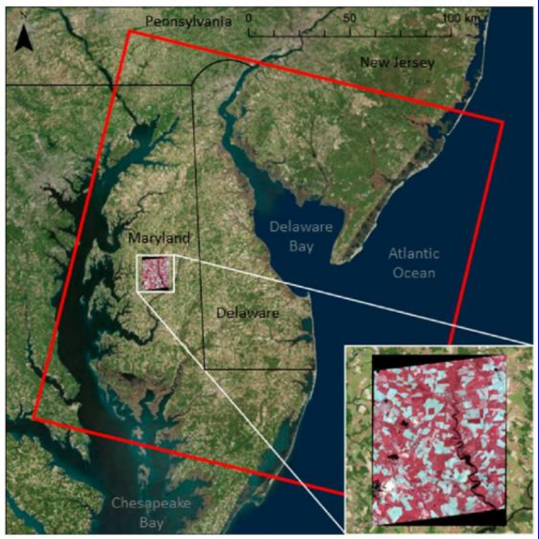
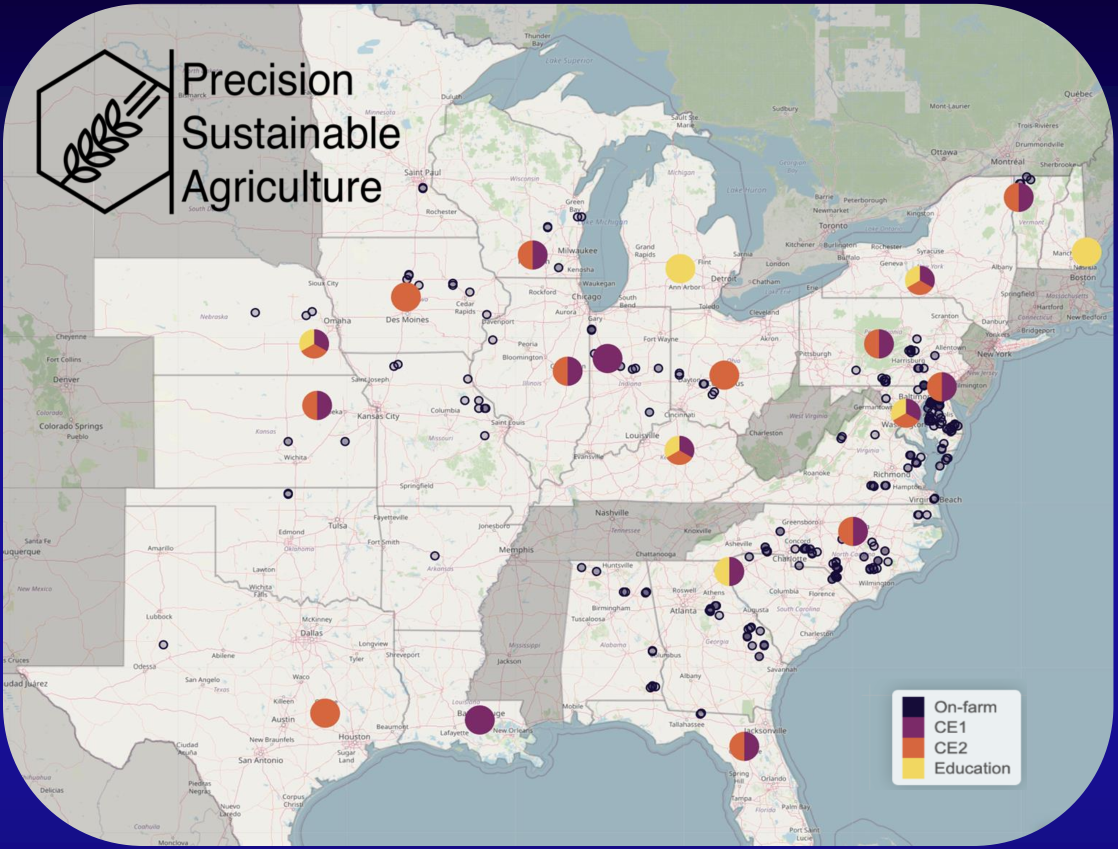
Delmarva Peninsula



Precision Sustainable Agriculture network



Current projects in MD, PA, MO, Spain

Past projects in DE, NY, IA, MS

USDA-ARS Beltsville Agricultural Research Center (BARC)

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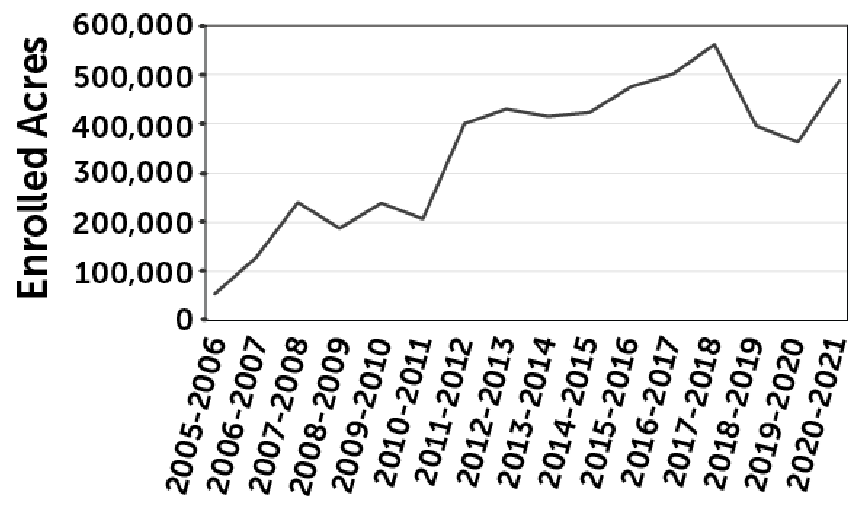
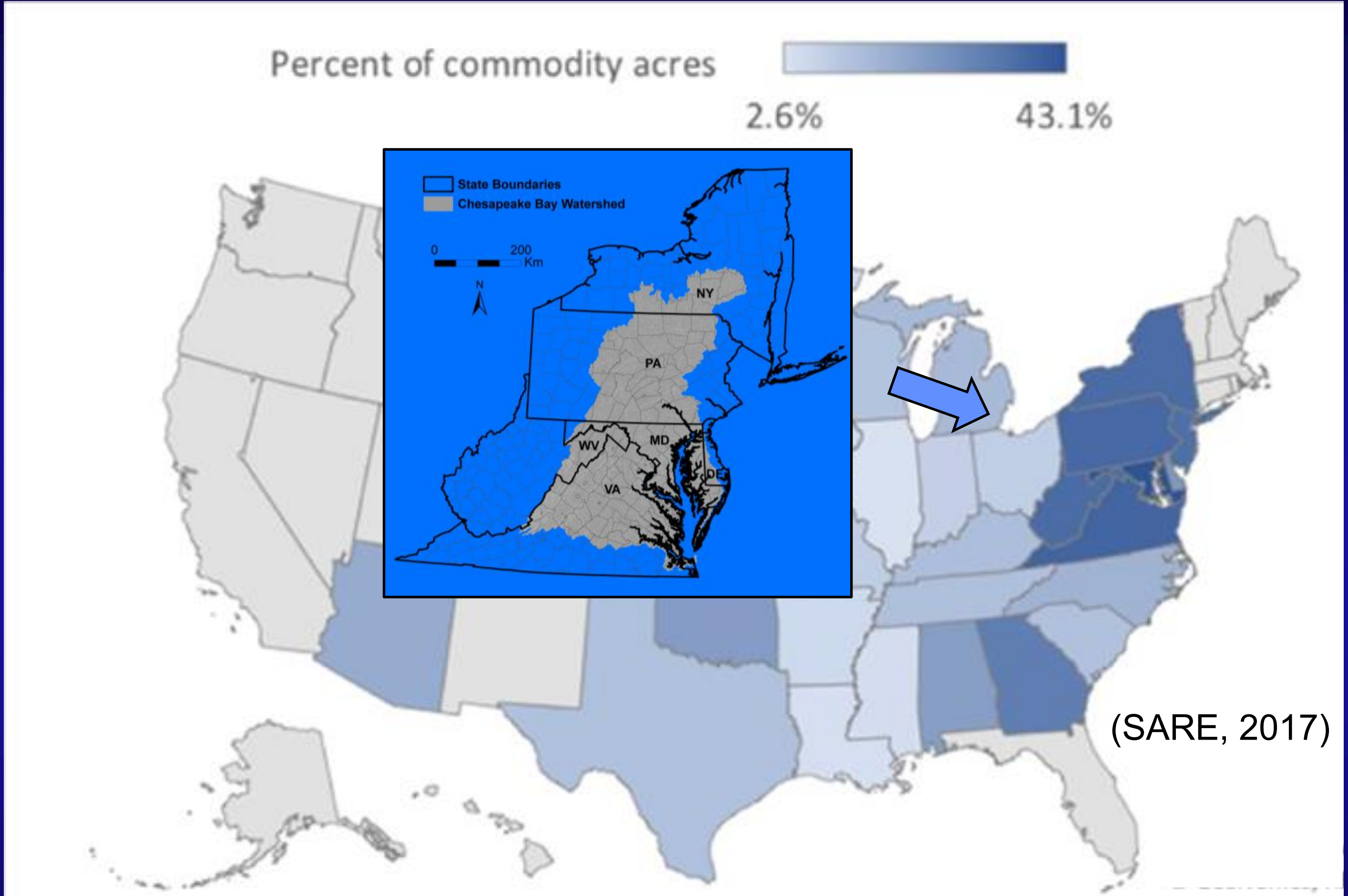
Mid-Atlantic cover crop use is highest in the nation

	% cropland in cover crops
DE	24
MD	43
NY	37
PA	37
VA	39
WV	37

*2017 Census of Agriculture



MD cover crops



(SARE, 2017)

Cover crop enrollment doubled from 2009 to 2013

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On-farm conservation performance is variable

Green vegetation
crop residue
and bare soil
reflect light differently

This can be seen from space

Mapping cover crop performance

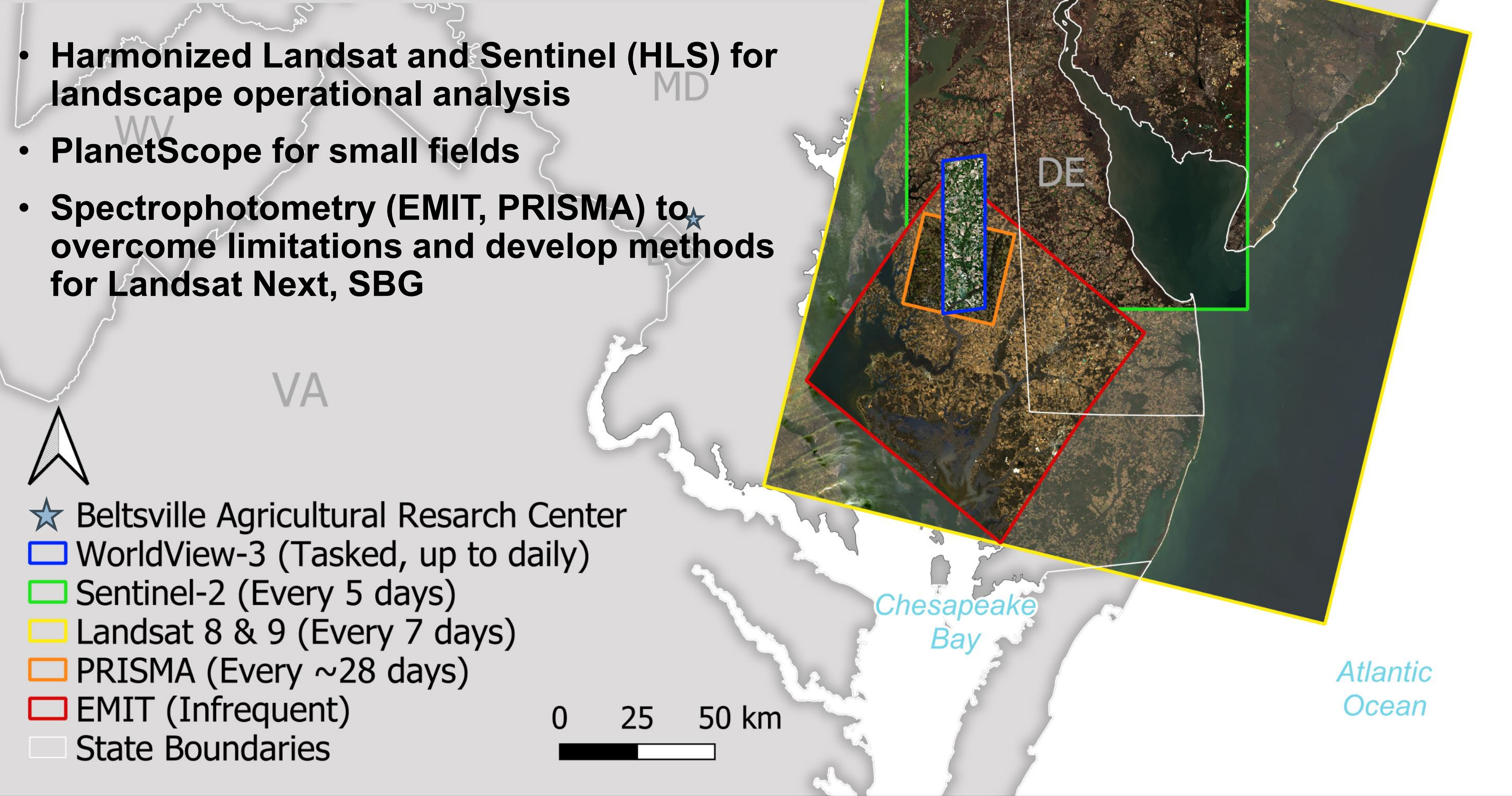
- We use satellite imagery to measure cover crop performance throughout the growing season

Well established with multispectral imagery:
- Aboveground biomass
- Fractional green cover
- Nitrogen content
- Green-up date
- Termination date

In development with hyperspectral imagery:
- Forage quality
- Species identification
- Weed identification

Multispectral and hyperspectral satellite imagery

- **Harmonized Landsat and Sentinel (HLS) for landscape operational analysis**
- **PlanetScope for small fields**
- **Spectrophotometry (EMIT, PRISMA) to overcome limitations and develop methods for Landsat Next, SBG**



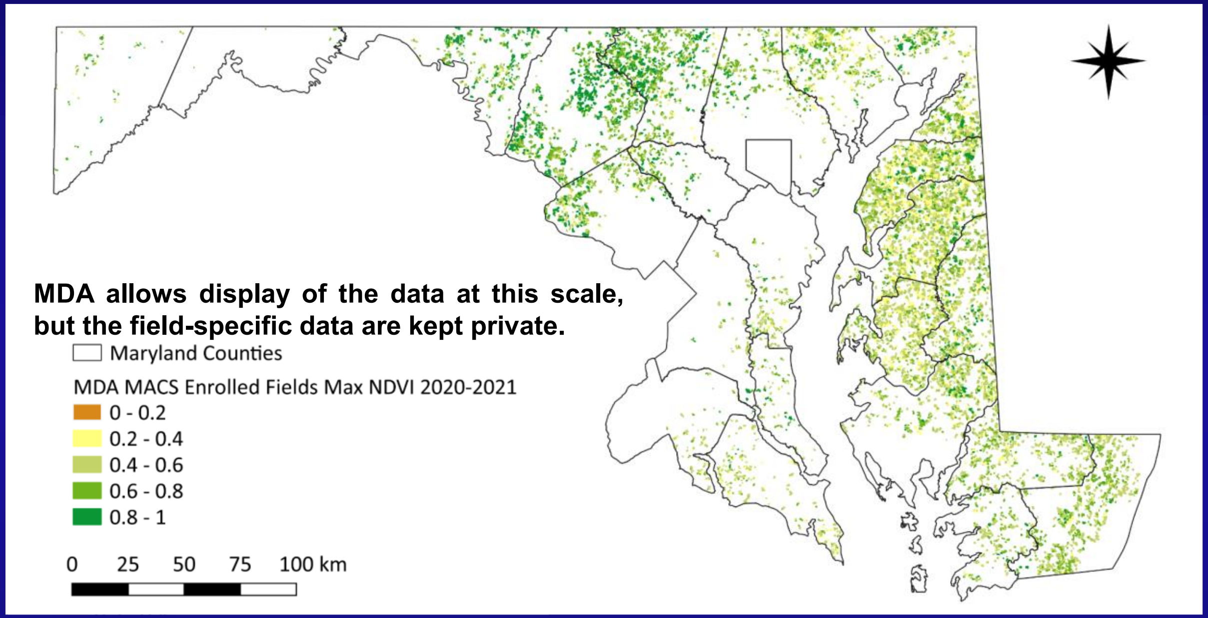
Satellite imagery sources

- **Harmonized Landsat and Sentinel (HLS)**
  - ~6 day revisit, 30m pixel, free: our main tool for landscape scale analysis
- **PlanetScope**
  - daily revisit, 4m pixel, costly: the best solution for small strip-cropped fields
- **EMIT**
  - hyperspectral imagery, 60m pixel, free but infrequent: best for cutting edge research, can identify species, forage quality, N concentration, crop residue cover, soil minerology; more challenging to acquire and process
- **Landsat Next, SBG**
  - If/when they are launched, these future NASA missions will provide high spectral resolution equivalent to EMIT with wall-to-wall coverage, 20m pixel, 6-day revisit – scheduled for 2032, will be a game changer

Collaboration with conservation stakeholders to inform adaptive management

Agronomy data from cost-share program enrollment records:

- Cover crop species
- Planting date, method, rate
- Previous crop
- Termination date and method
- Field boundaries
- > 25,000 fields/year in Maryland



Maryland cover crop enrollment		
Year	# Fields	Acres
2019-20	26,393	156,900
2020-21	21,538	129,300

12-years of MD enrollment data

Research collaboration with Maryland Dept. of Agriculture allows access to site-specific cover crop management data for MD farms

Thank you Dawn Bradley and Jason Keppler for your collaboration

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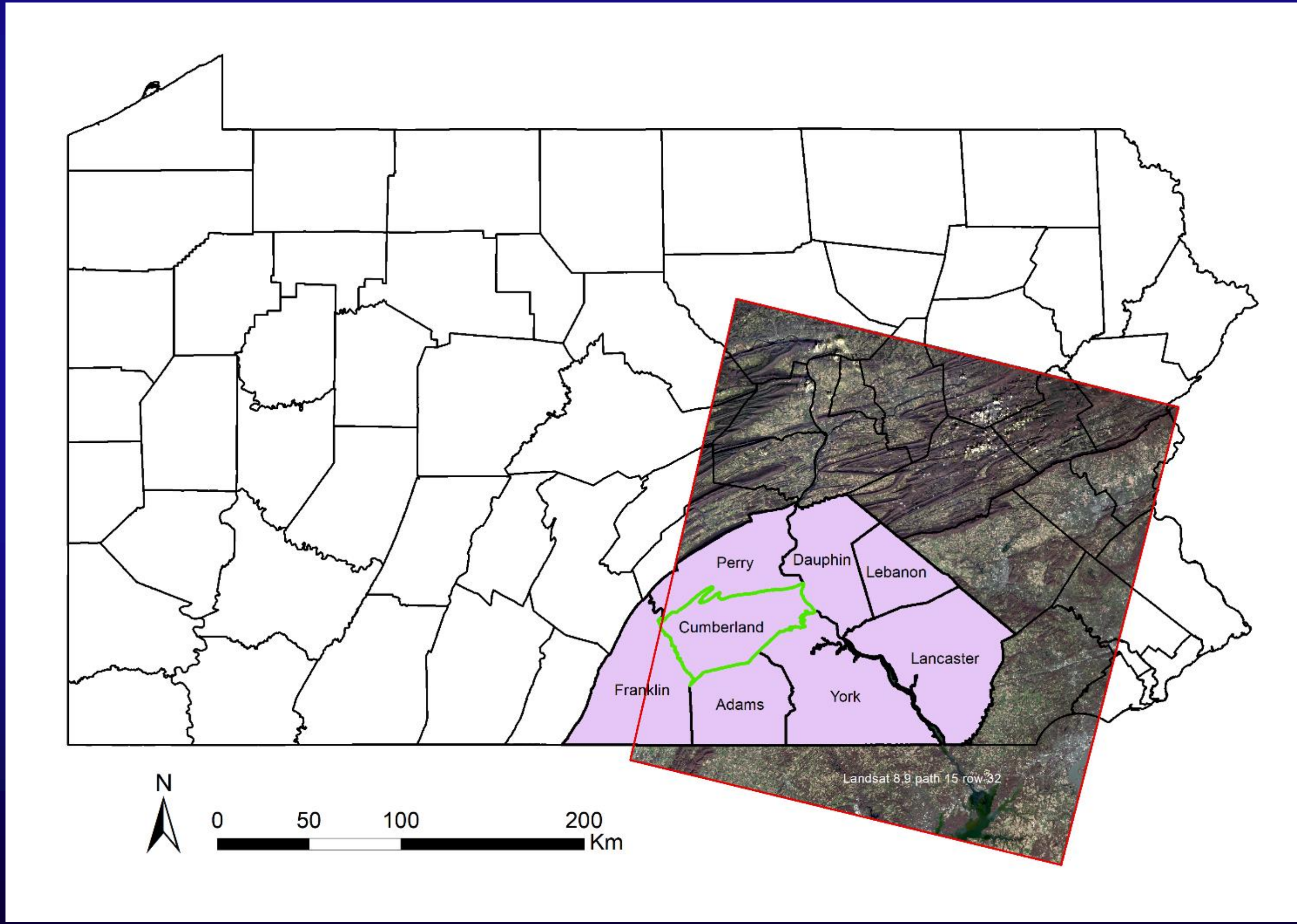
Pennsylvania cover crop remote sensing, 2024-2027

- Adapting tools developed in Maryland to the Pennsylvania landscape
- 2024 in Cumberland county, 2025 in Cumberland and Perry, 8 counties by 2027 (?)
- Objectives:
  - Produce daily growth curves for fields identified as cover crop
  - Collect field data to calibrate performance analysis on enrolled fields
  - Develop methods to support verification (25% groundcover in late March)
  - Species identification, mapping



Thank you Cumberland and Perry county staff for your involvement!

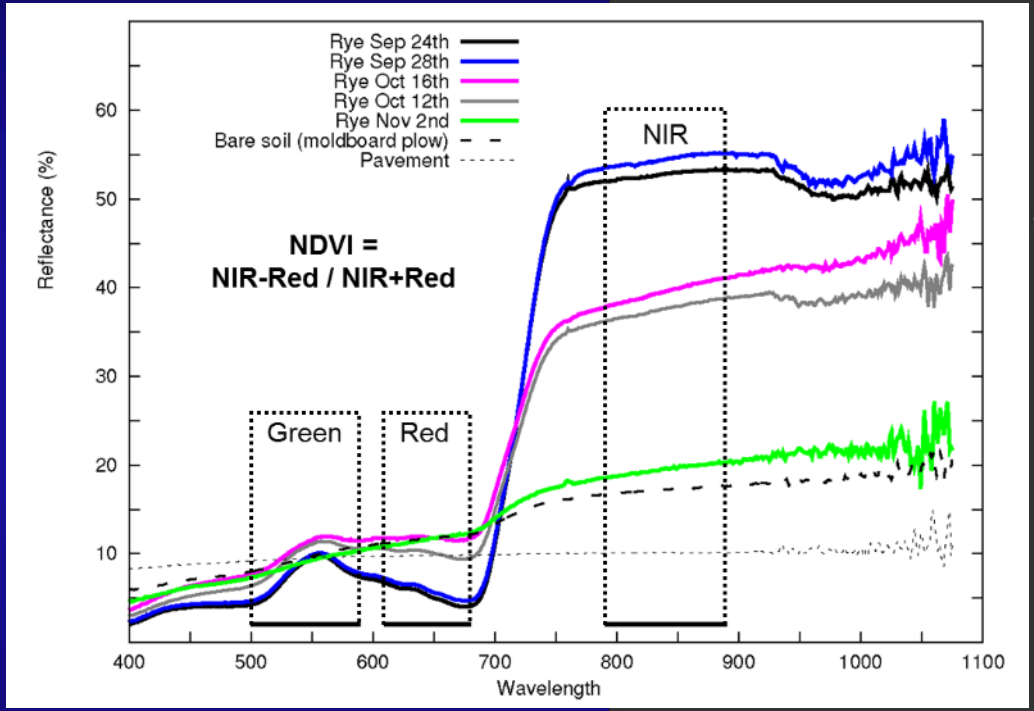
USGS *Funded by CSS, NFWF*

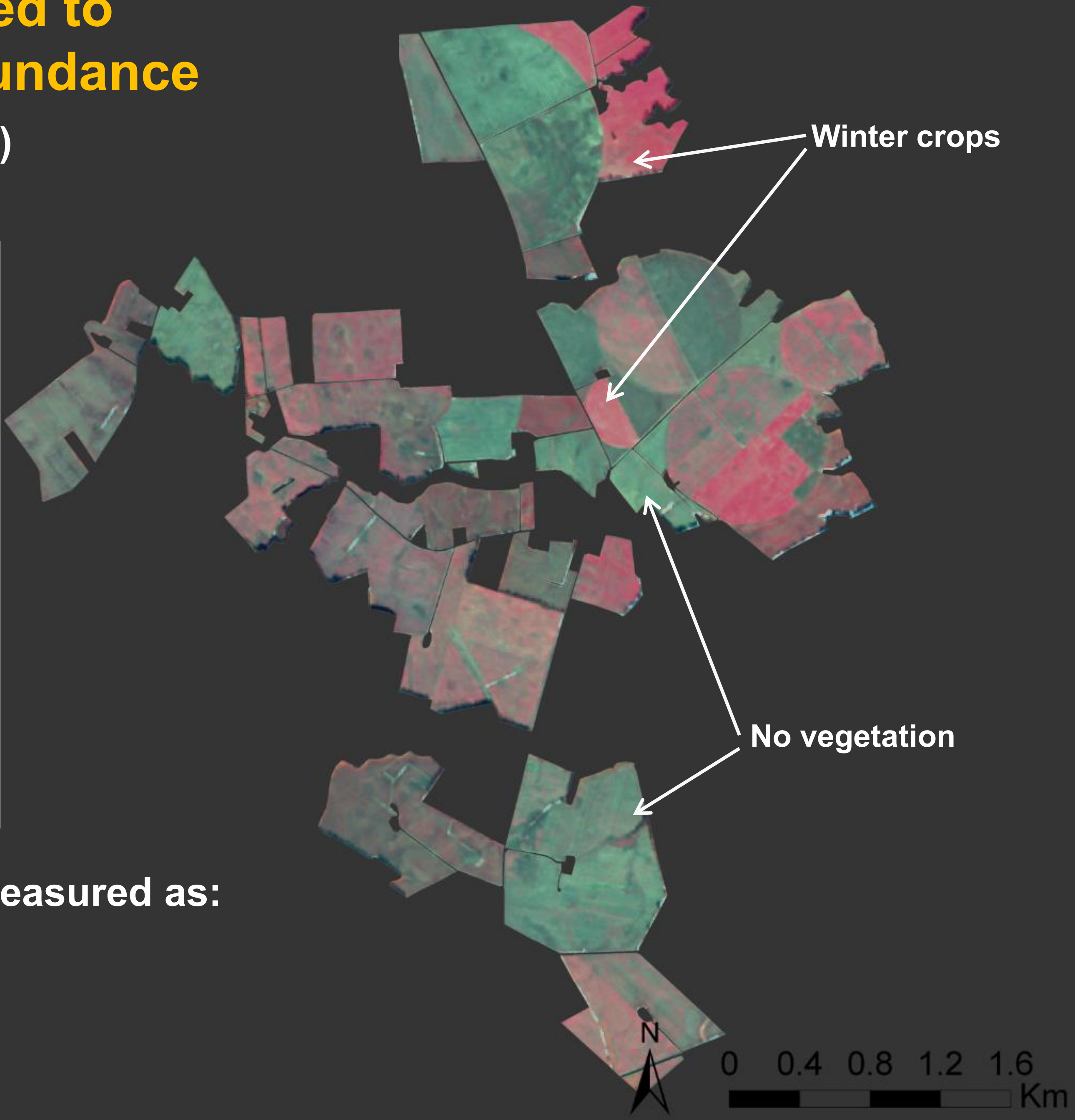
STROUD WATER RESEARCH CENTER

Satellite NDVI is used to measure vegetation abundance

Normalized difference vegetation index (NDVI)

measures biomass from 0-2000 kg/ha





Cover crop performance is measured as:

- Aboveground biomass
- Fractional green cover
- Nitrogen content

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MDA enrollment data – agronomic management

Cover crop species

Planting date

Planting method

Planting rate

Previous crop

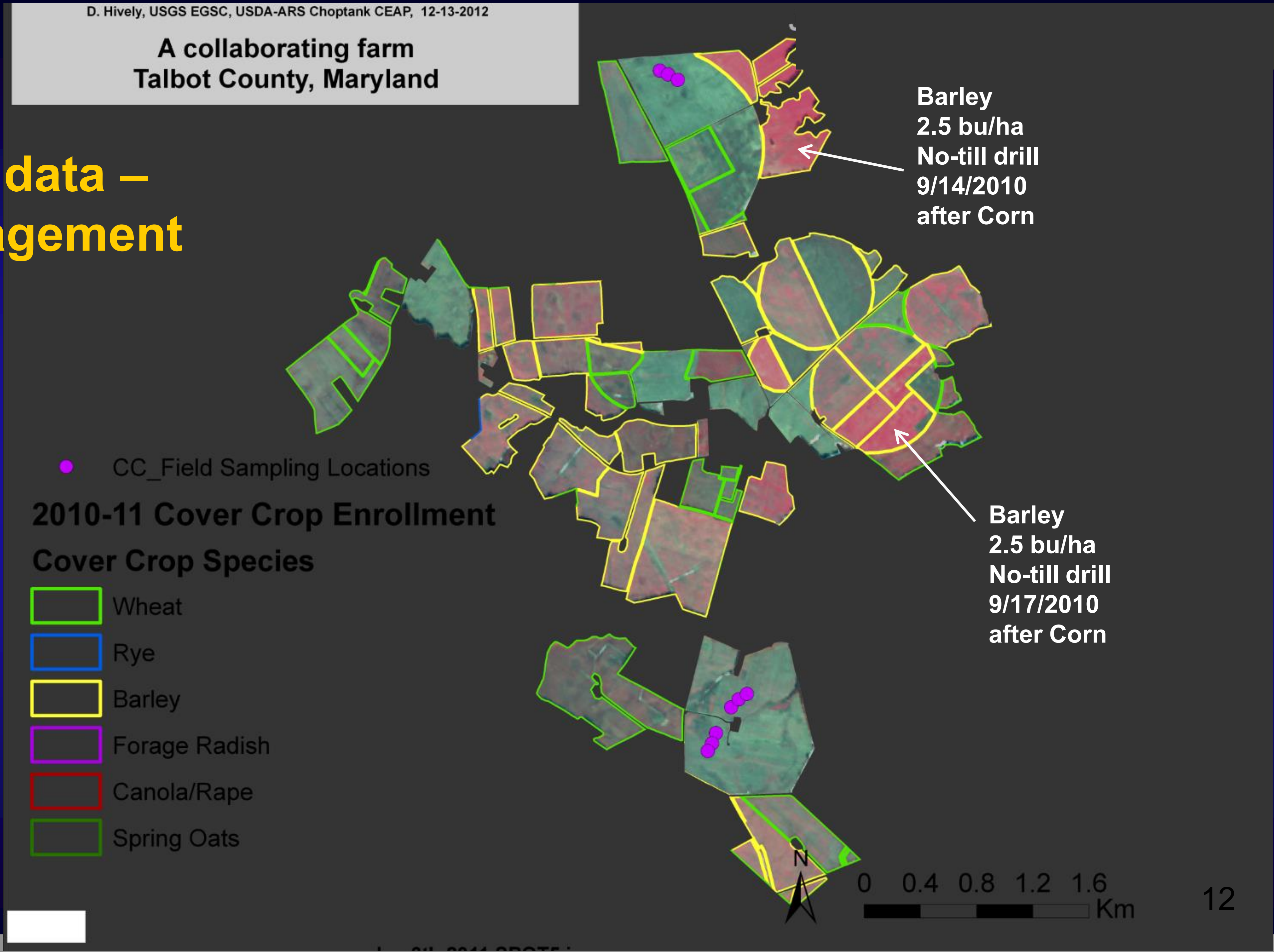
Termination date

Termination method

Watershed HUC 12 ID

County

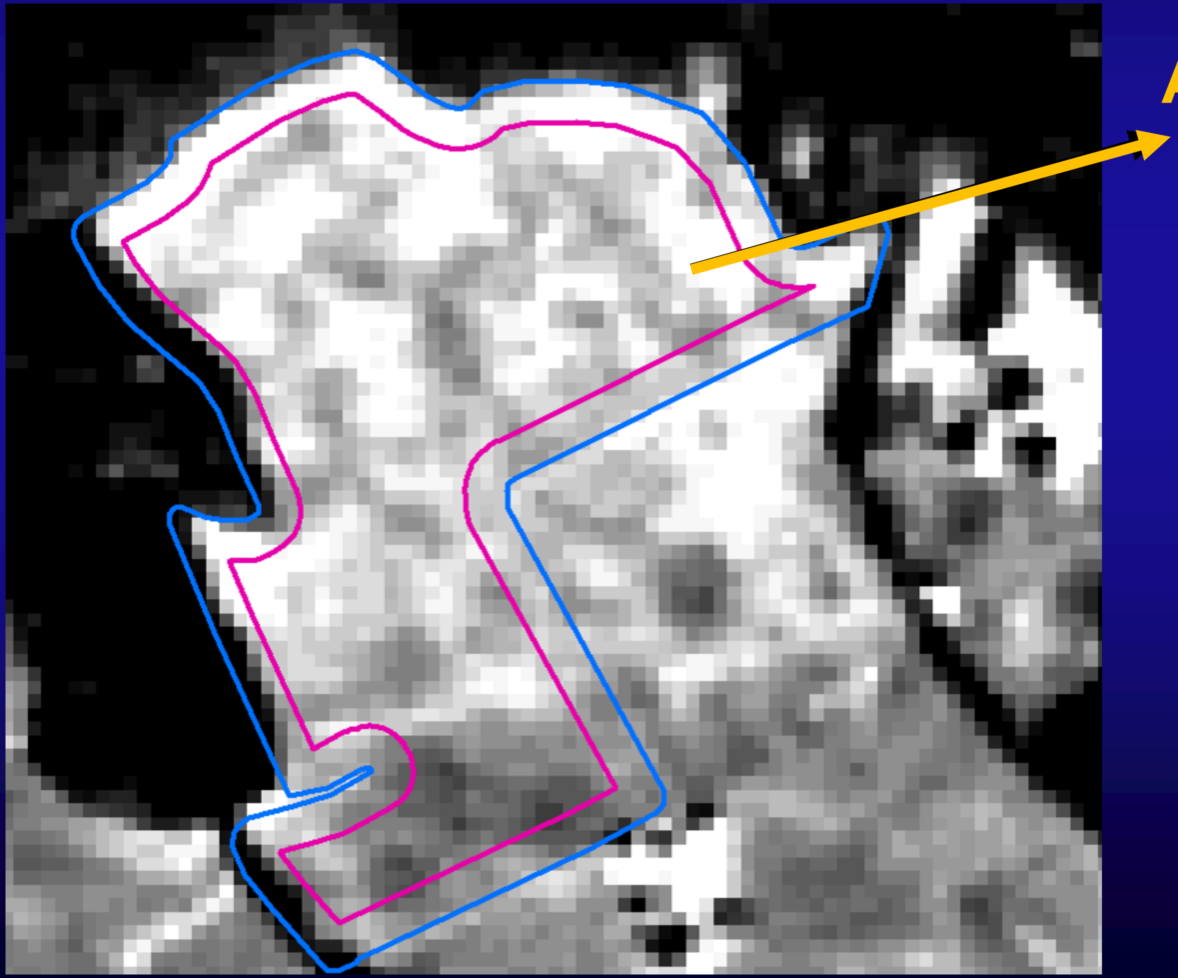
Field boundary



Calculate satellite vegetation index time series for each field

- Harmonized Landsat and Sentinel (HLS) satellite imagery
- Up to 5-day repeat frequency depending on clouds

Normalized difference vegetation index (NDVI)



Average NDVI per field, per image date

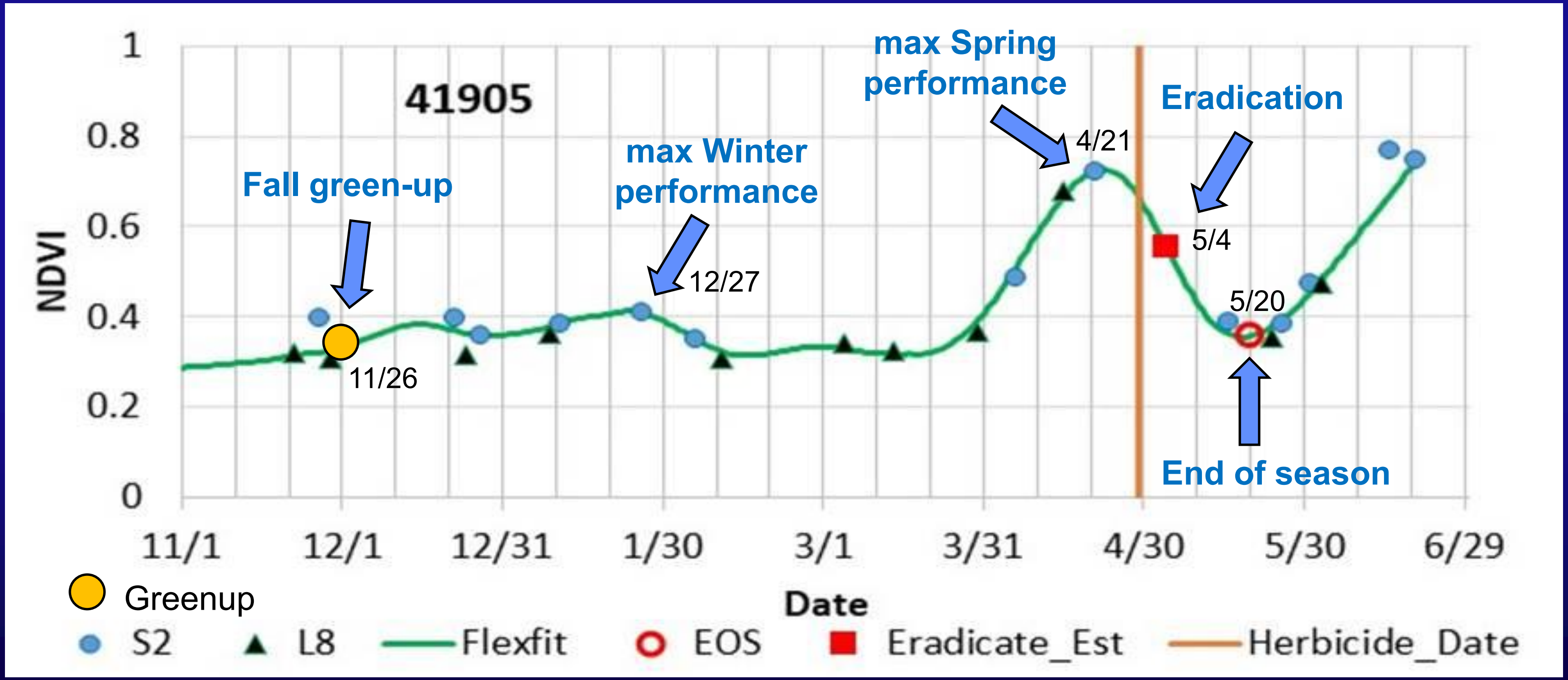
Normalized difference vegetation index

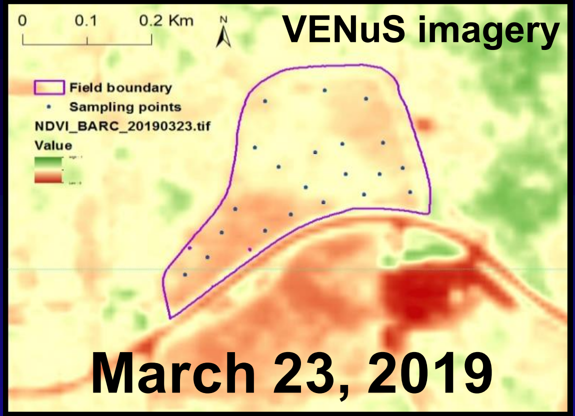
Curve fitting approach to phenology identifies:

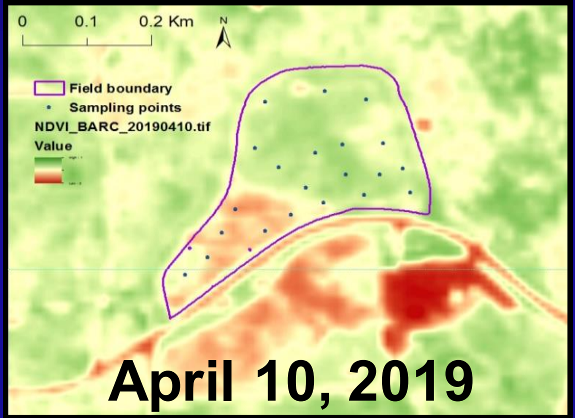
- Green-up date
- Green-up momentum
- Maximum wintertime and springtime NDVI and associated performance
- Termination date

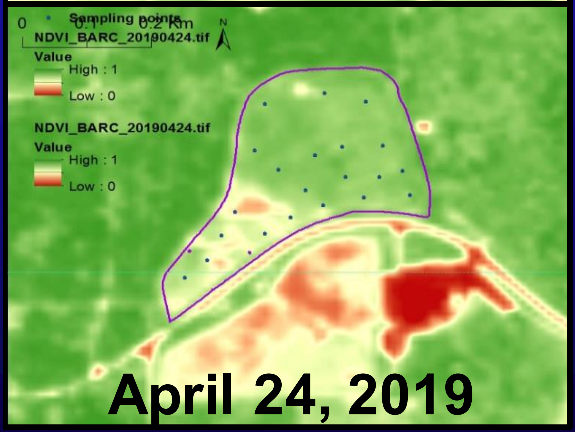
Field-specific growth curves

- Greenup and termination dates are identified from vegetation index inflection points using Harmonized Landsat Sentinel data
- Winter and spring maximum NDVI values are used to quantify environmental performance (biomass, fractional ground cover)









USGS USDA ARS

These data are preliminary and are subject to revision.

On-farm data collection provides cal/val

Physical sampling of plants and residue

- Biomass (weight per 0.5 m^2 quadrat)
- Ground cover (by photo analysis)
- Plant nitrogen content, C:N ratio
- Plant growth stage, height, tillering, etc…

- 3 quadrats per field, > 10 photos
- 60 m apart to fall in different pixels
- Avoiding edges and irregular areas
- > 2000 on-farm samples over 10 yr

Thank you conservation district staff and farmers for supporting field access!

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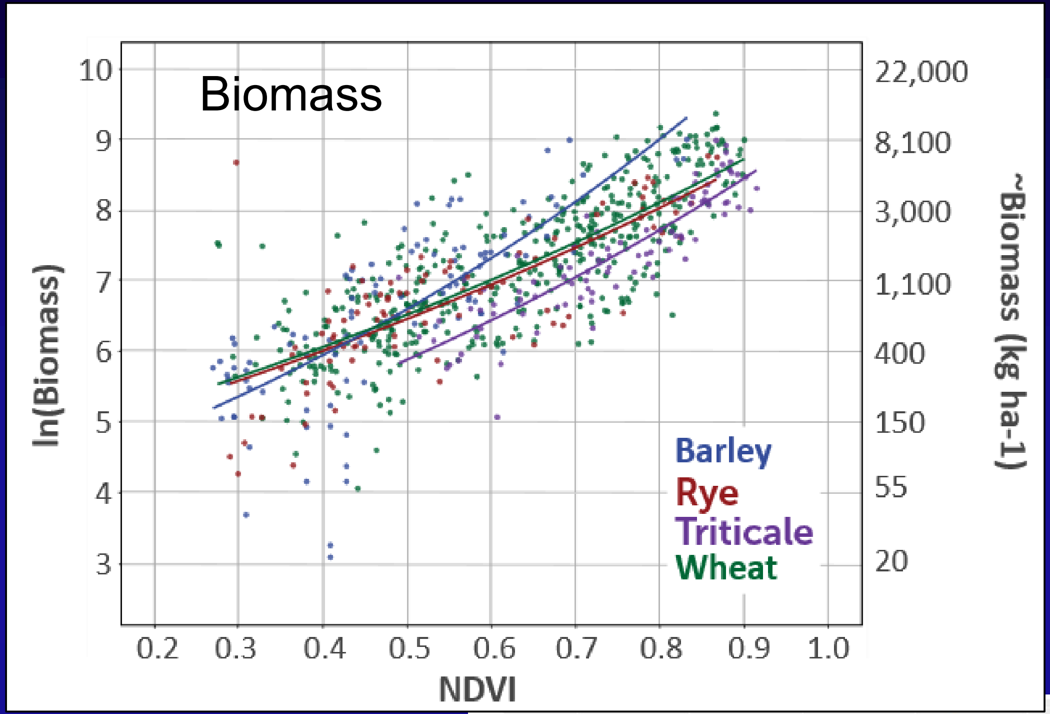
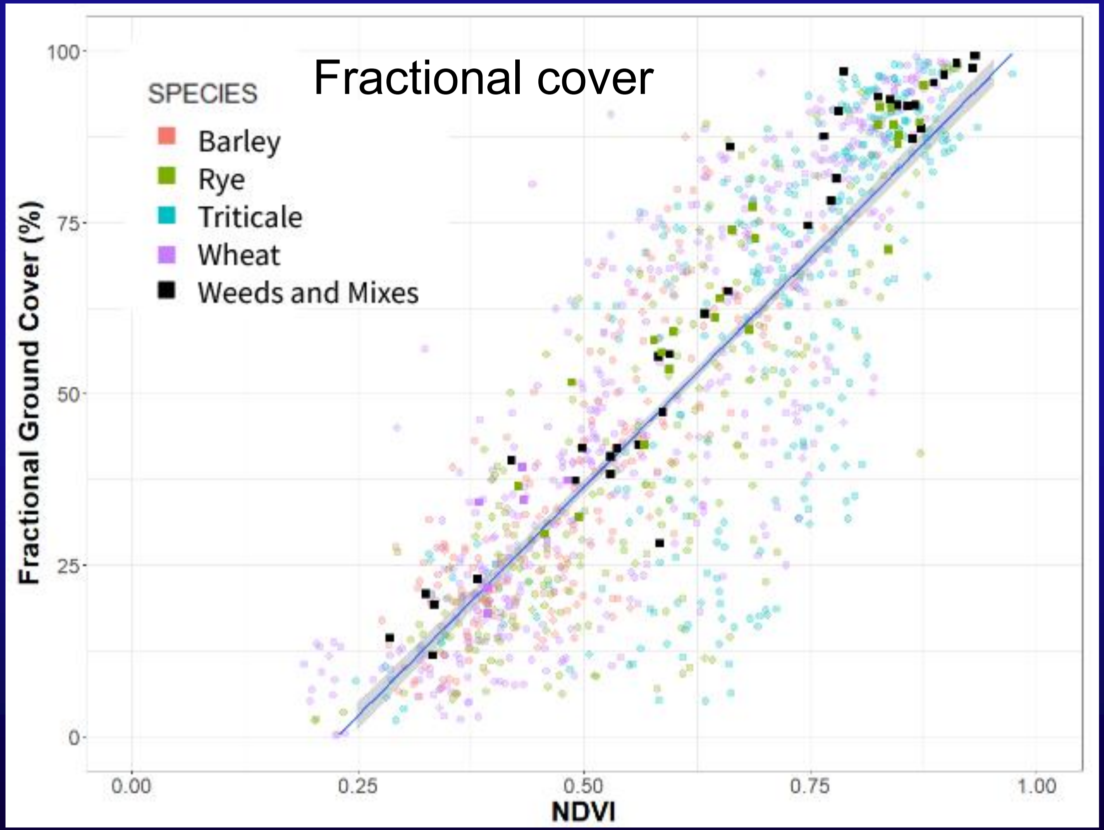
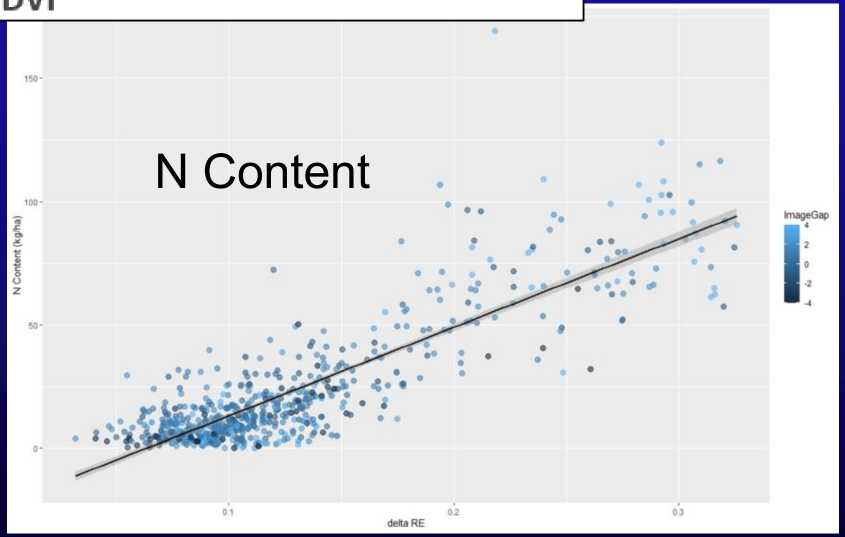
On-farm data collection provides cal/val

- Aboveground biomass
- Nitrogen and carbon content
- Fractional vegetative cover







These data are preliminary and are subject to revision.

Caveats of HLS satellite imagery analysis for cover crops

Requires cloud-free, snow-free conditions (difficult in NY winter)

Small fields and strip cropping require small pixels

Saturates above 1500 kg/ha

Cannot distinguish mixes

Interference from weeds

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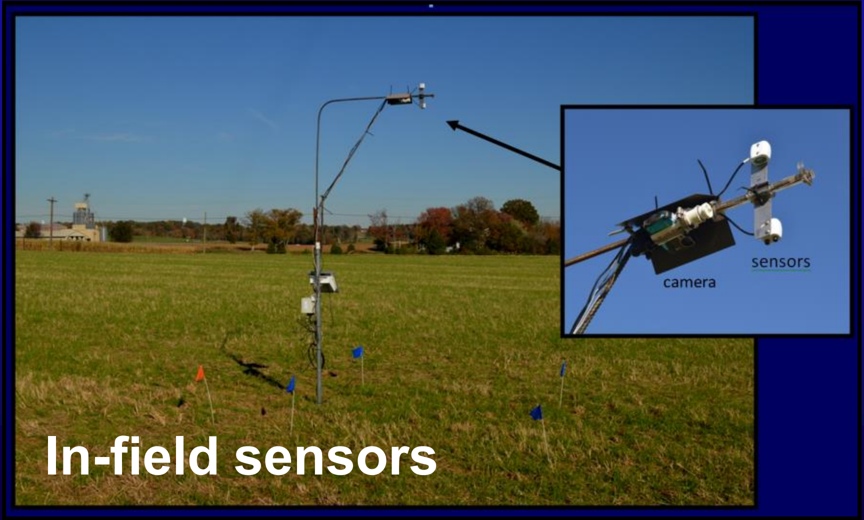
Proximal technology to expand understanding



Spaceborne Hyperspectral Approaches for Monitoring the Performance of Agricultural Conservation Practices

Cover crop species

Important for nutrient provisioning and decomposition dynamics




Cover crop carbon traits

Influences agroecological services: soil health, nutrients, GHG, etc.



Crop residue cover & quality

Important for soil health and carbon sequestration



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Adjustment for surface moisture conditions

What factors affect cover crop success?

Species choice


Planting date

Planting method

Aerial Seeding

Broadcast +/- tillage
or stalk chop

No-till drill or
light tillage + drill

Termination date

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Termination method

Herbicide

Plow

Green chop

Roller-crimp

Harvest

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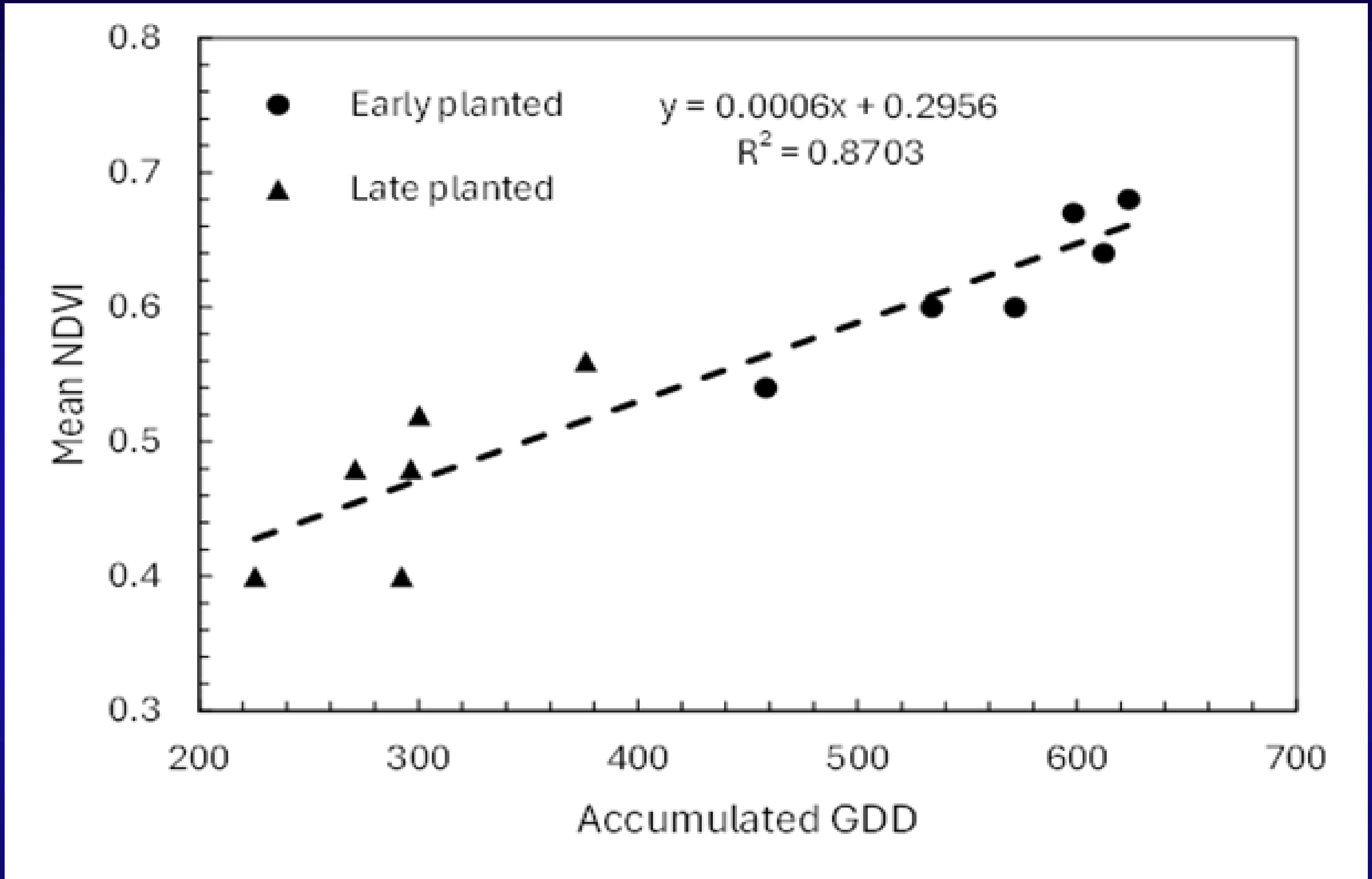
Weather, soils, nutrient availability

Warmer winters produce better cover crops across the farm landscape (also more weeds)



Annual average wintertime maximum NDVI for all drilled wheat cover crop fields enrolled in the MACS program, 2018-2023, with correlation to accumulated annual wintertime growing degrees (GDD)

USGS

Hively et al., 2025

Connecting measured performance to agronomy

Seasonal performance measures from satellite imagery:
(> 25,000 fields/year in MD)

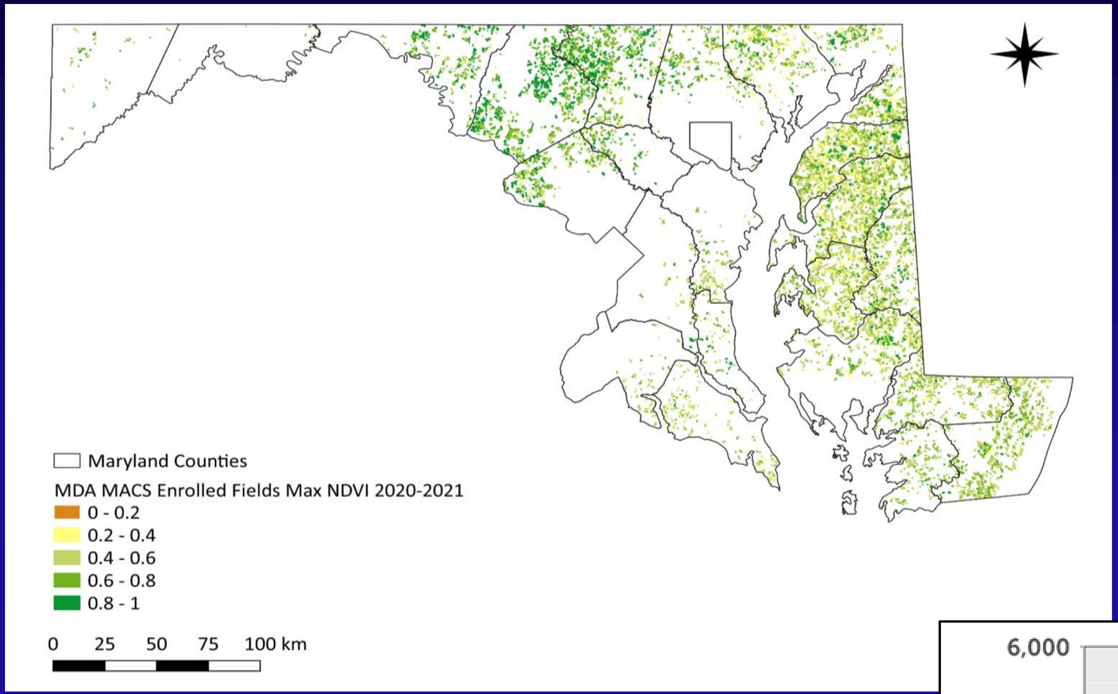
- Aboveground biomass
- Nitrogen content
- Fractional vegetative cover

  - Modelling of N leaching (SWAT)
  - Modelling of erosion (RUSLE2)
  - Modelling of C dynamics (SWAT-C)

Agronomy data from enrollment:

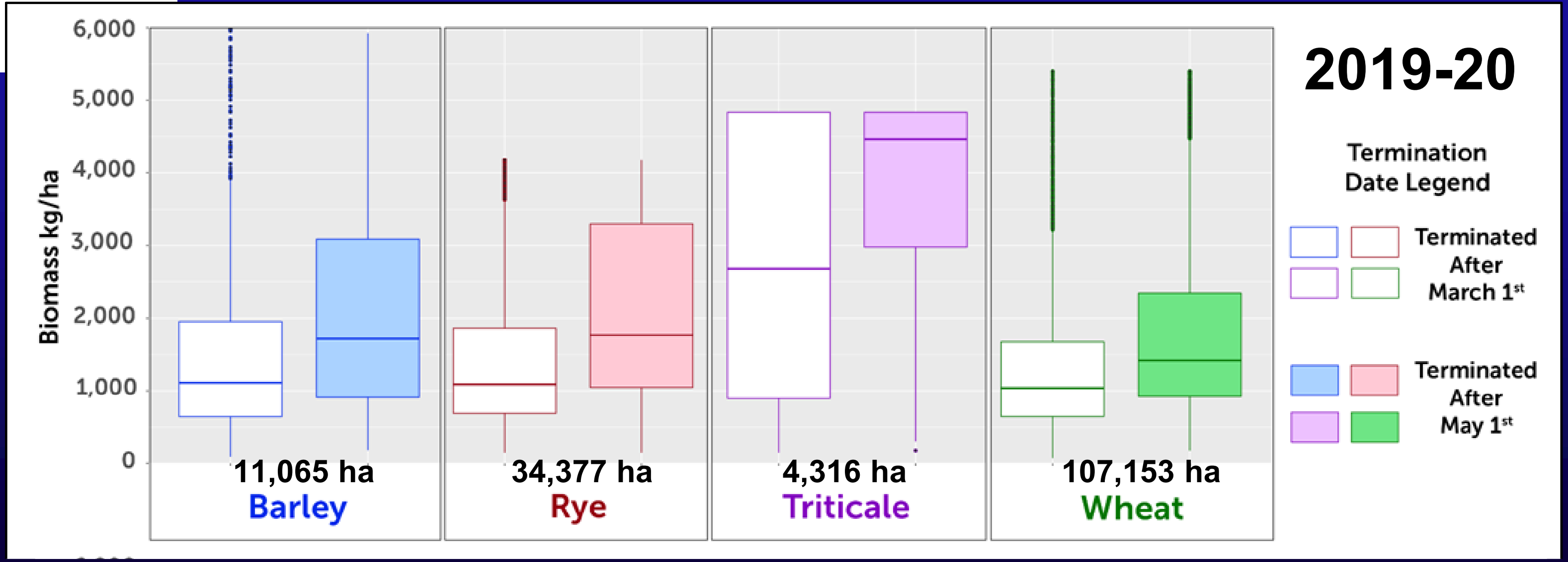
- Cover crop species
- Planting date, method, rate
- Previous crop
- Termination date and method
- Watershed HUC 12 ID
- County ID
- Field boundary

Some results from Maryland:



- Triticale was the top performer (often planted early after corn silage harvest)
- Late termination incentive (after May 1) increased biomass by 69% and N uptake by 48%
- SWAT modeling estimated a 29% reduction in N leaching in Tuckahoe due to winter cover crops

- Wheat underperformed but comprised 68% of acreage
- 32% of MDA cover crops were late-planted wheat, with minimal N uptake in Fall



Thieme et al., 2022, Agronomy Journal. https://doi.org/10.1002/agj2.21207

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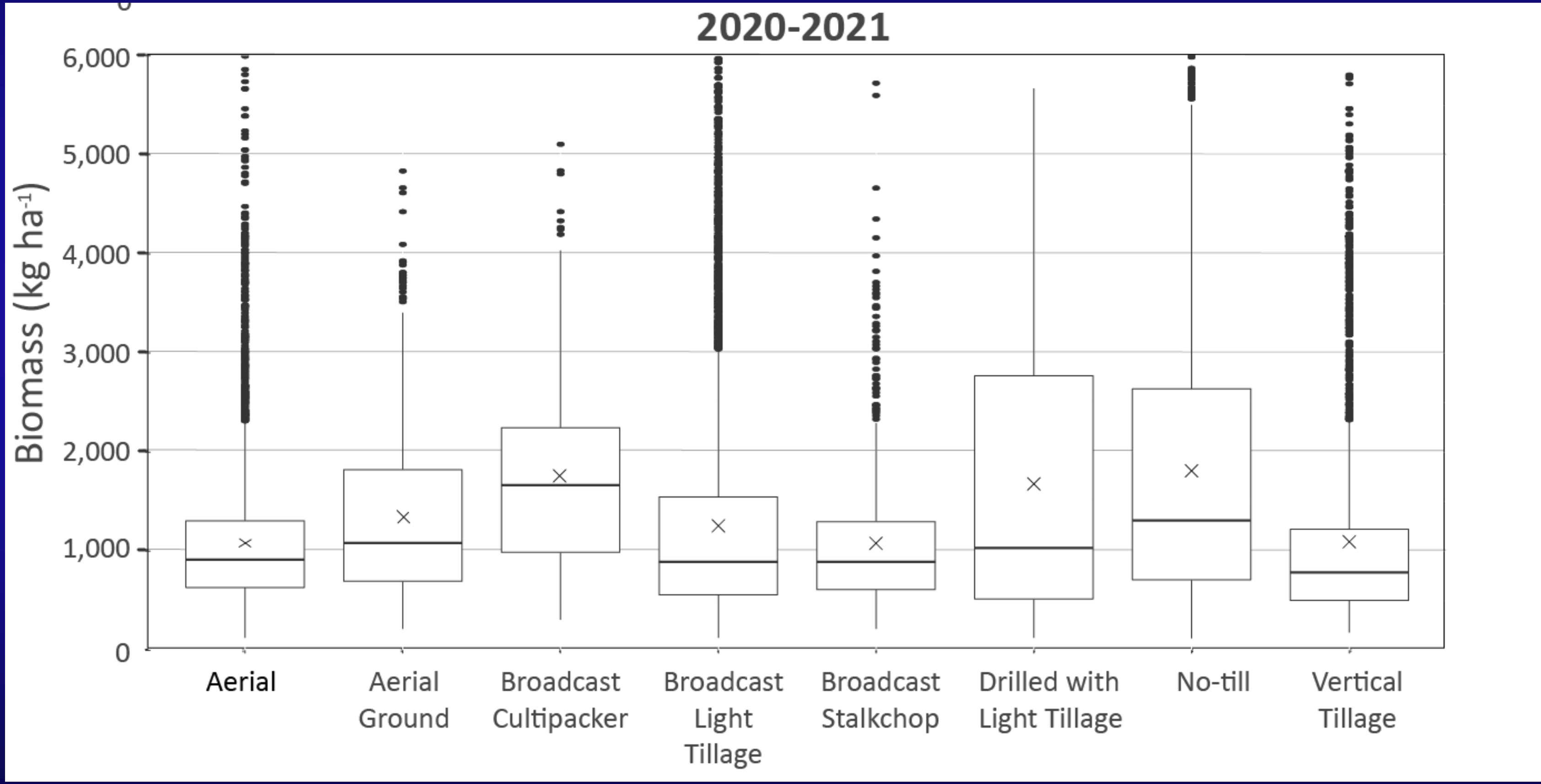
Some results from Maryland:

- **Planting methods promoting higher seed-soil contact (drilled) outperformed broadcast and aerial seeding**



Thieme et al., 2022, Agronomy Journal. https://doi.org/10.1002/agj2.21207

Monitoring, reporting, and verification

Disclaimers

- The USGS is not in any way responsible for verifying conservation practice implementation in the Chesapeake Bay watershed – that is the purview of the states. Our team does develop and provide remote sensing tools that can be used by state agencies to assist in conservation program management and practice verification, but the use and decision making is their responsibility, we simply provide the tools.

- The standard disclaimer for unpublished information: These data are preliminary and are subject to revision. They are being provided to meet the need for timely best science. The data have not received final approval by the U.S. Geological Survey (USGS) and is provided on the condition that neither the USGS nor the U.S. Government shall be held liable for any damages resulting from the authorized or unauthorized use of the information

Cover crop verification scenarios

1. Field locations and agronomy are known, field boundaries digitized

2. Field locations are unknown, remote sensing is used to identify them

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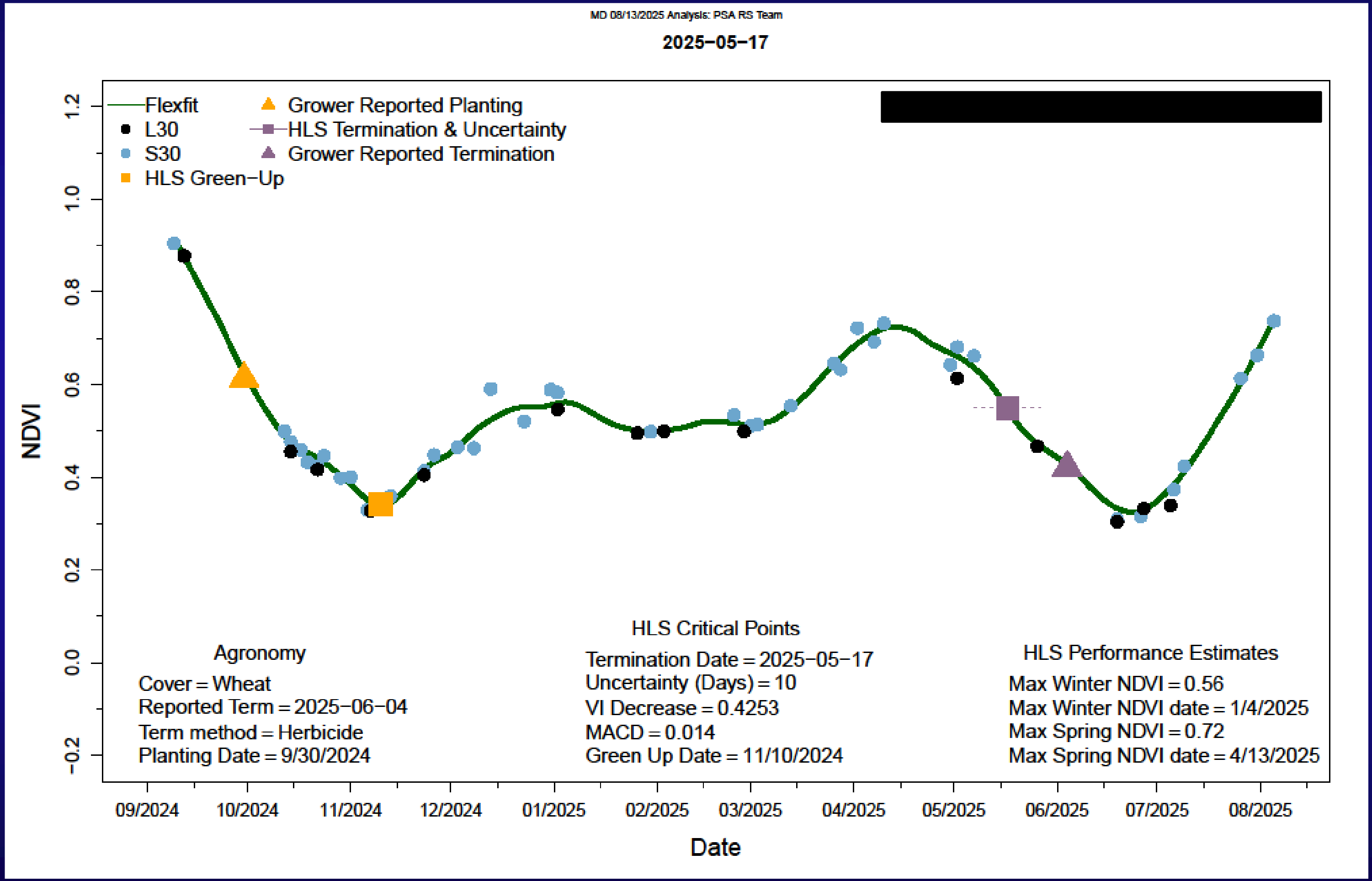
Verification scenarios for enrolled cover crop fields

Field locations and agronomy are known, field boundaries digitized

- **Fall greenup identified, significant biomass in December = established**
- **Termination identified between March 1 and June 15 = ok**



This cover crop had a significant effect on winter N leaching, and significant additional growth in the springtime

These data are preliminary and are subject to revision.

76% of MDA fields were in the successful category in 2025

USGS

Conclusion: successful cover crop, recommend release payment

Verification scenarios for enrolled cover crop fields

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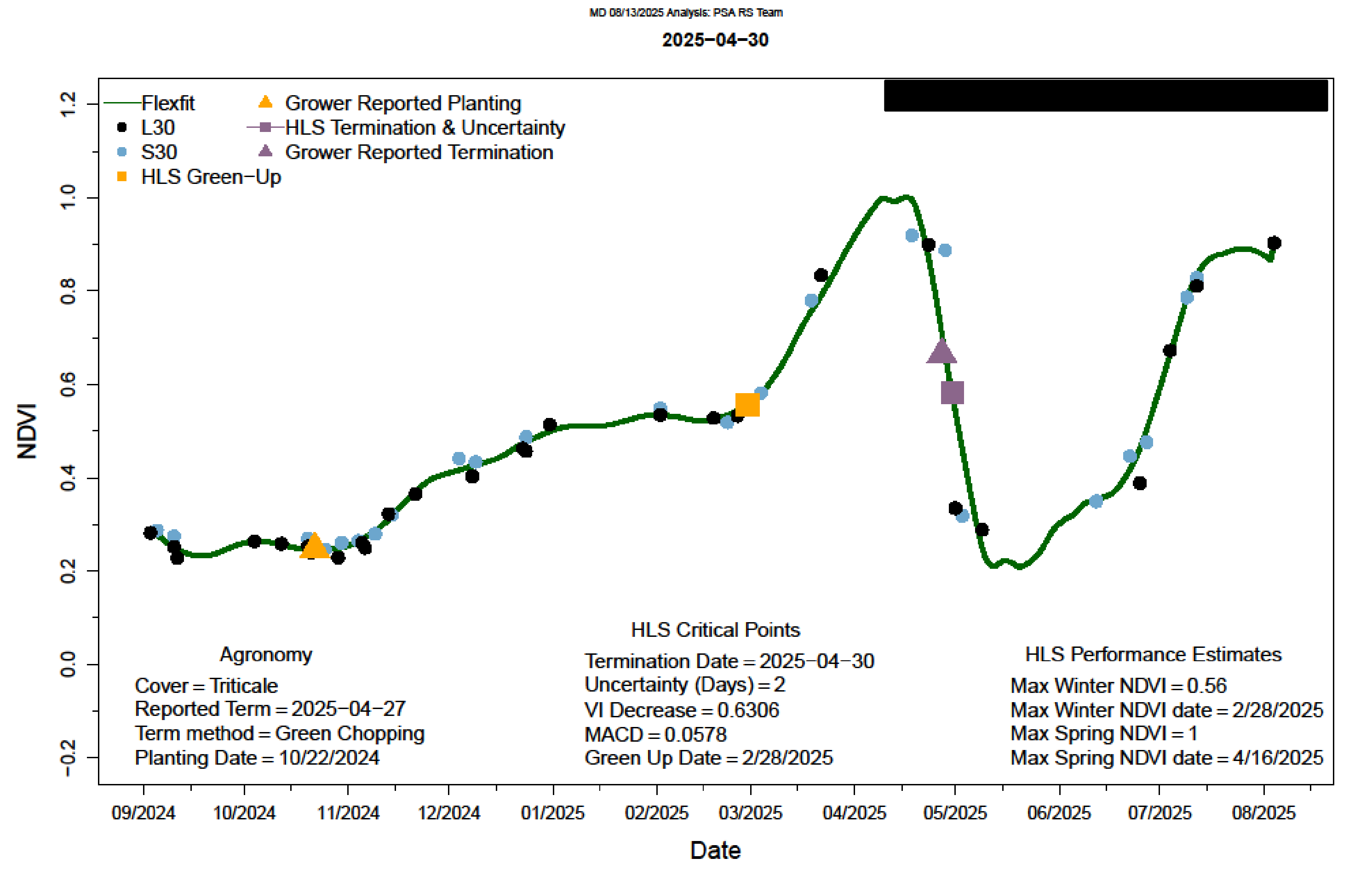


These data are preliminary and are subject to revision.

This cover crop had a significant effect on winter N leaching, and significant additional growth in the springtime, likely a highly manured soil on a dairy farm

USGS

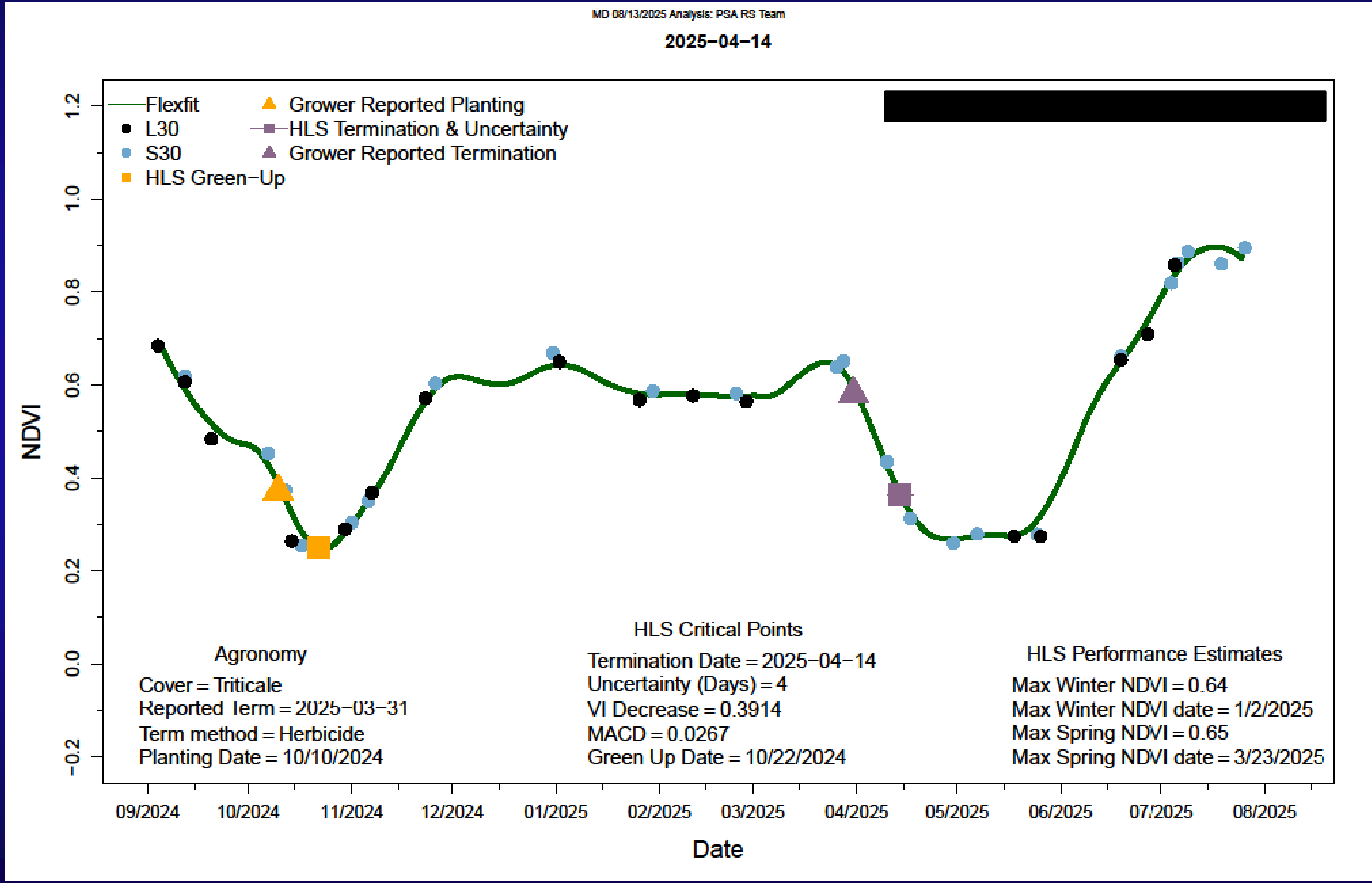
Conclusion: successful cover crop, recommend release payment

Verification scenarios for enrolled cover crop fields

Field locations and agronomy are known, field boundaries digitized

- **Fall greenup identified, significant biomass in December = established**
- **Termination identified between March 1 and June 15 = ok**

This cover crop had a significant effect on winter N leaching, was terminated prior to spring growth period



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USGS

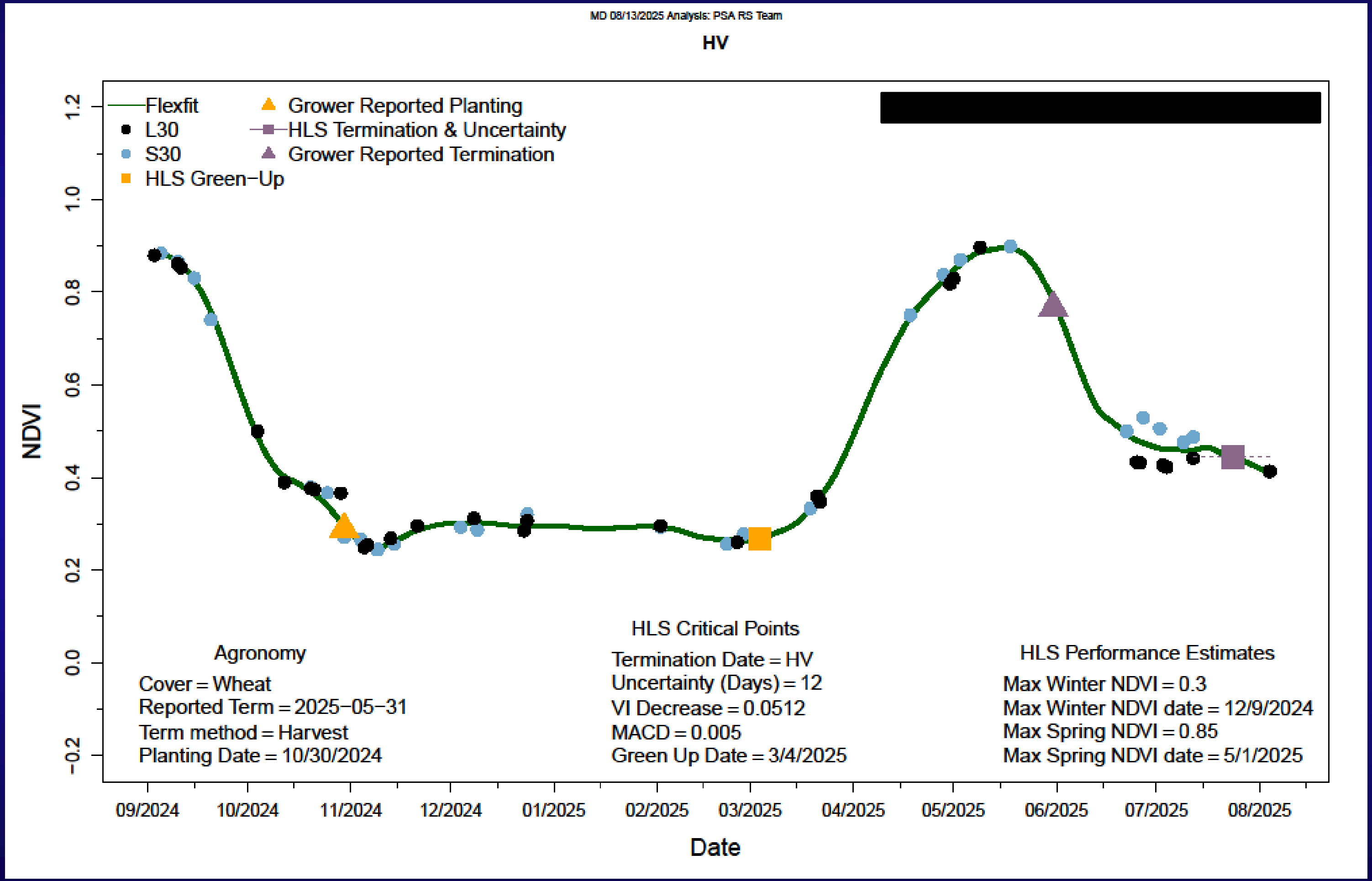
Conclusion: successful cover crop, recommend release payment

Verification scenarios for enrolled cover crop fields

Field locations and agronomy are known, field boundaries digitized

- **Fall green-up not identified, minimal biomass in December = questionable**
- **Significant biomass accumulation in April = established**
- **Termination identified between March 1 and June 15 = ok**

This cover crop had minimal effect on winter N leaching, but significant growth in the springtime



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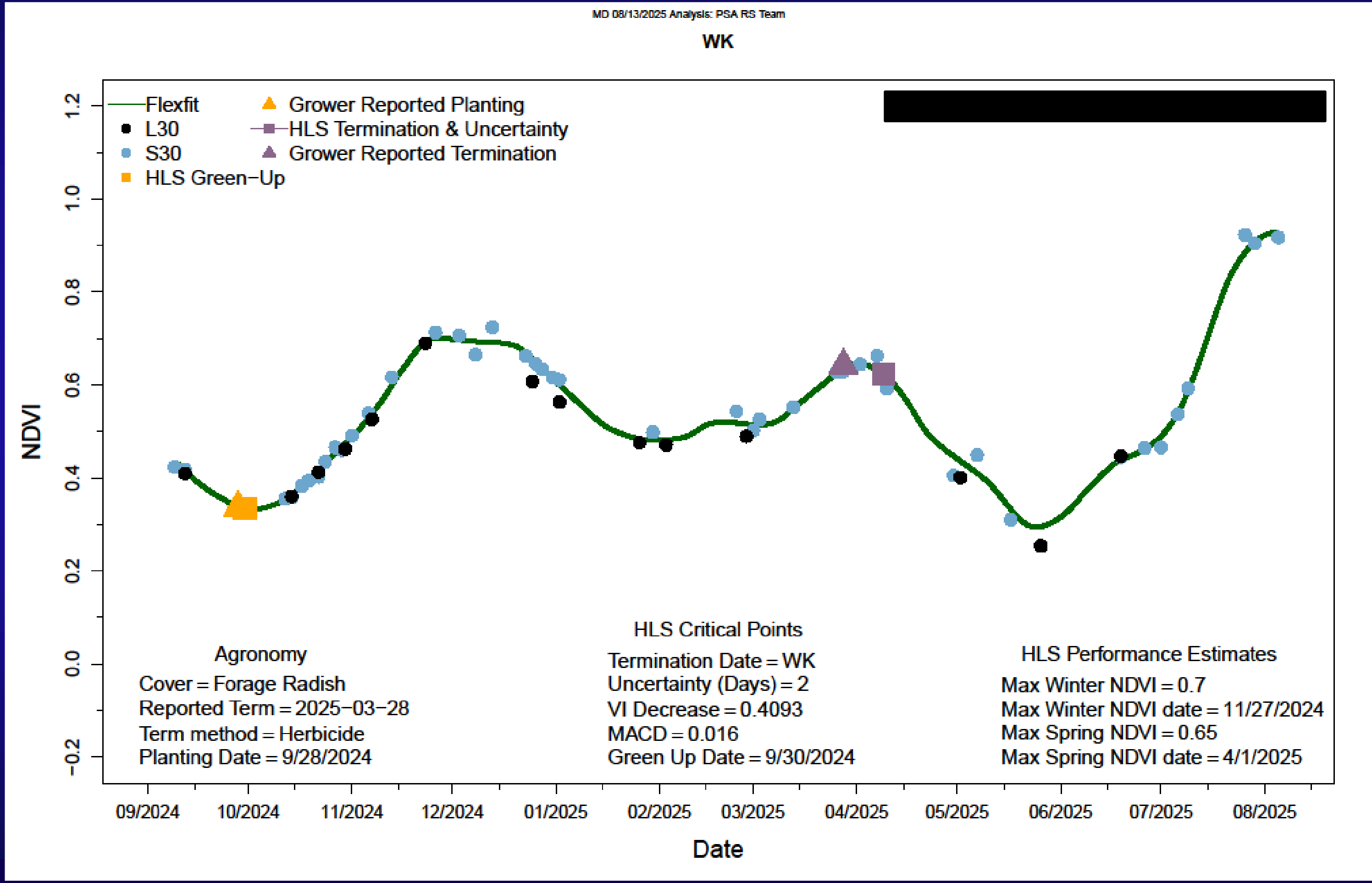
USGS

Conclusion: successful cover crop, recommend release payment

Verification scenarios for enrolled cover crop fields

Field locations and agronomy are known, field boundaries digitized

- **Fall greenup identified, significant biomass in December = established**
- **Winter kill species = ok**
    - **can look to identify termination after first hard frost**
    - **Sometimes winter kill species survive to spring growth after winter downturn**



This cover crop had a significant effect on winter N leaching, but early release of N, better to grow in a mix with a cereal

These data are preliminary and are subject to revision.

4% of MDA fields were in the winter kill category in 2025

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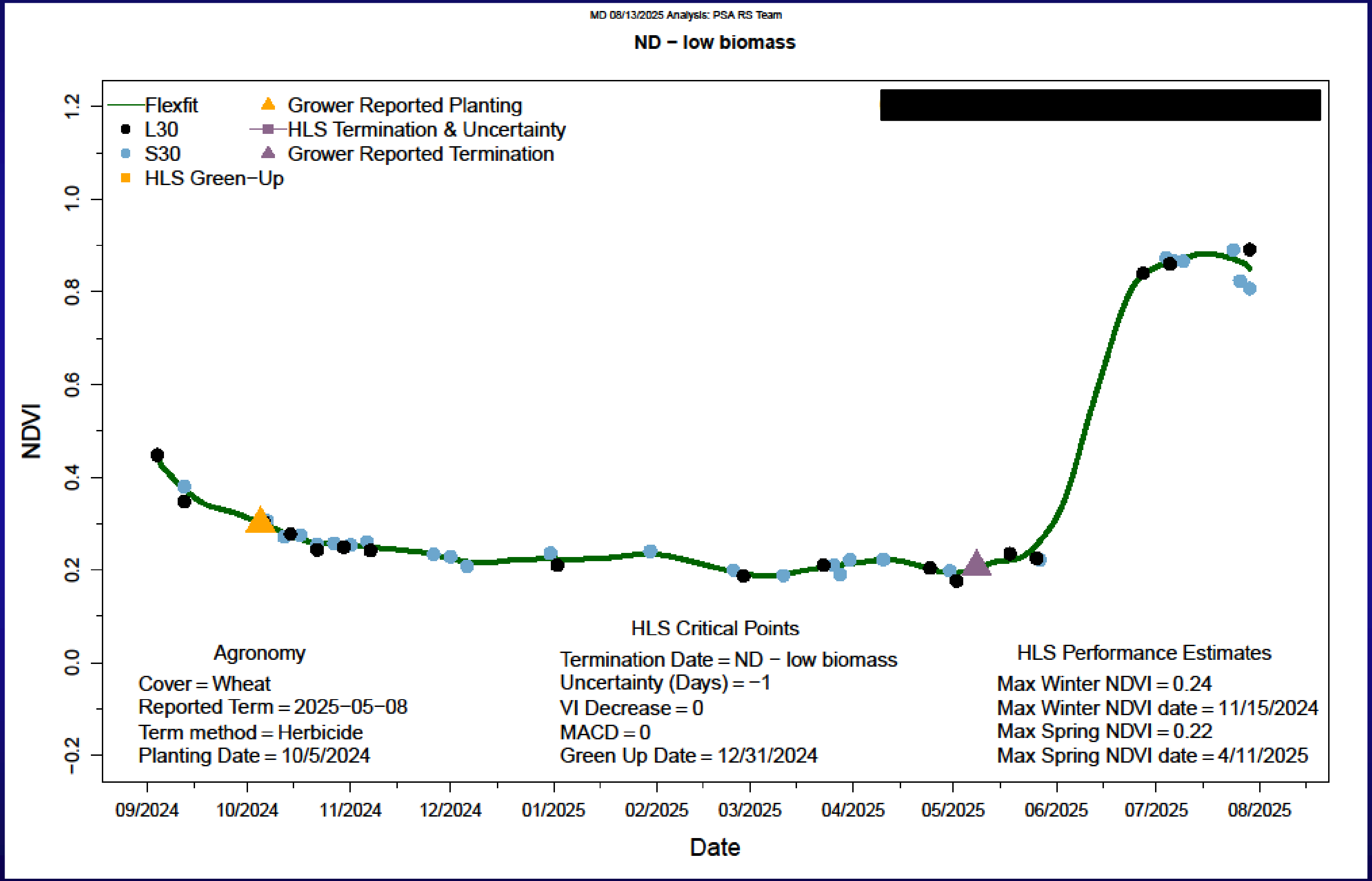
Conclusion: successful cover crop, recommend release payment

Verification scenarios for enrolled cover crop fields

Field locations and agronomy are known, field boundaries digitized

- **Fall green-up not identified, minimal biomass in December = questionable**
- **Continued minimal biomass in springtime = questionable**
  - **failed establishment**
  - **poor performance, geese impacts**
  - **or not planted**



This cover crop had minimal benefit, failed, or perhaps was not planted

4% of MDA fields were in the low performance category in 2025

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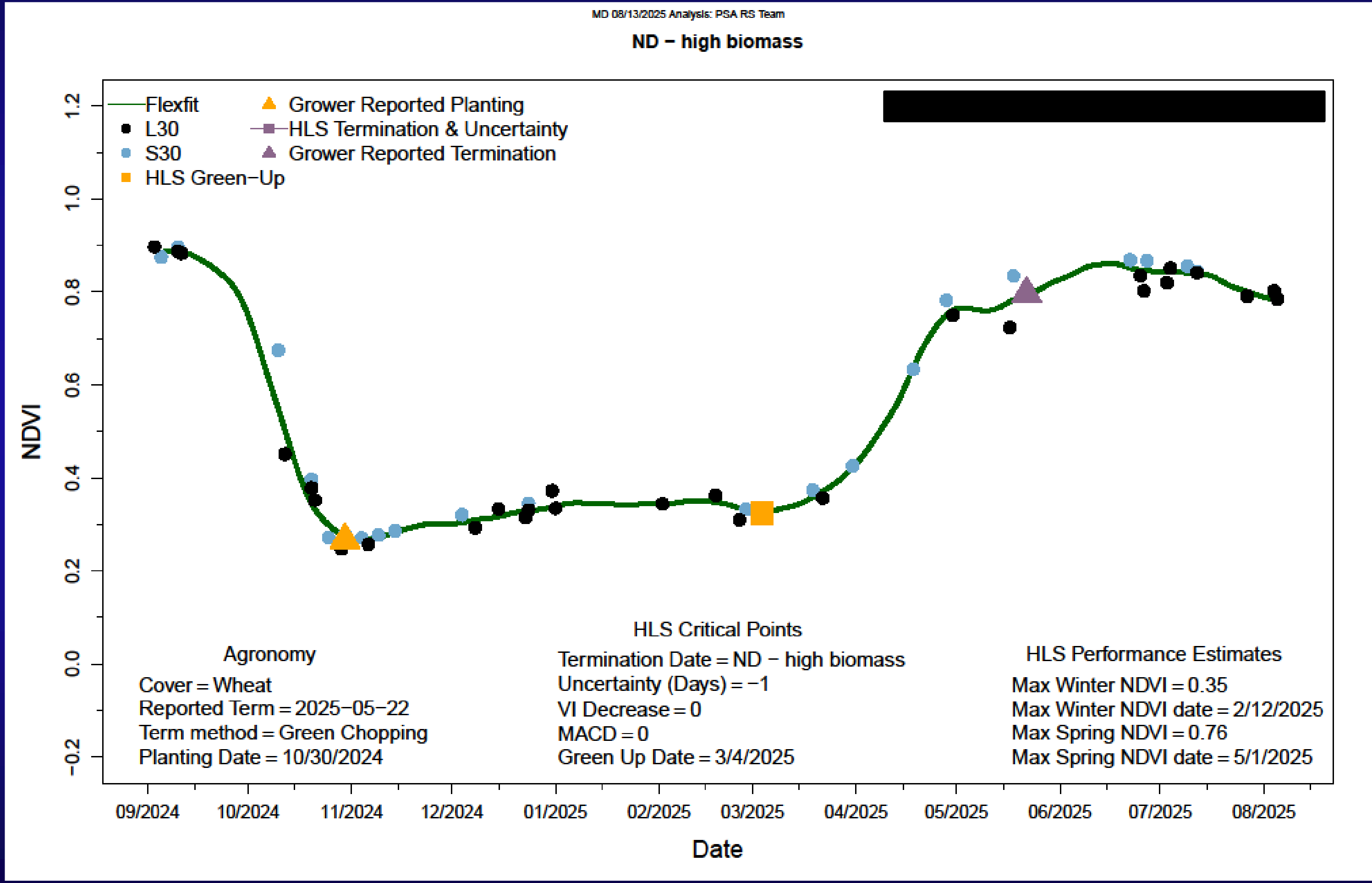
Conclusion: unsuccessful cover crop, recommend field visit

Verification scenarios for enrolled cover crop fields

Field locations and agronomy are known, field boundaries digitized

- **No termination detected, significant biomass increase through June = questionable**
  - **could be cereal grain for harvest or mis-enrollment**
  - **could also be planting green or satellite imagery gap**



This cover crop had minimal effect on winter N leaching, but significant growth in the springtime, however, it may be being taken to cereal grain harvest

4% of MDA fields were recommended for field check in 2025

These data are preliminary and are subject to revision.

USGS

Conclusion: may be cereal grain for harvest, recommend field visit

Validation of questionable high biomass fields

- **In May of 2024 MDA field staff visited 40 fields across Maryland for we recommended springtime field checks**
- **They found 3 scenarios:**

Cover crop still growing or going to grain harvest

Cover terminated, we later detected this with more imagery

Mis-identification of field during enrollment

Also, 12% of MDA fields were too small for HLS analysis in 2025

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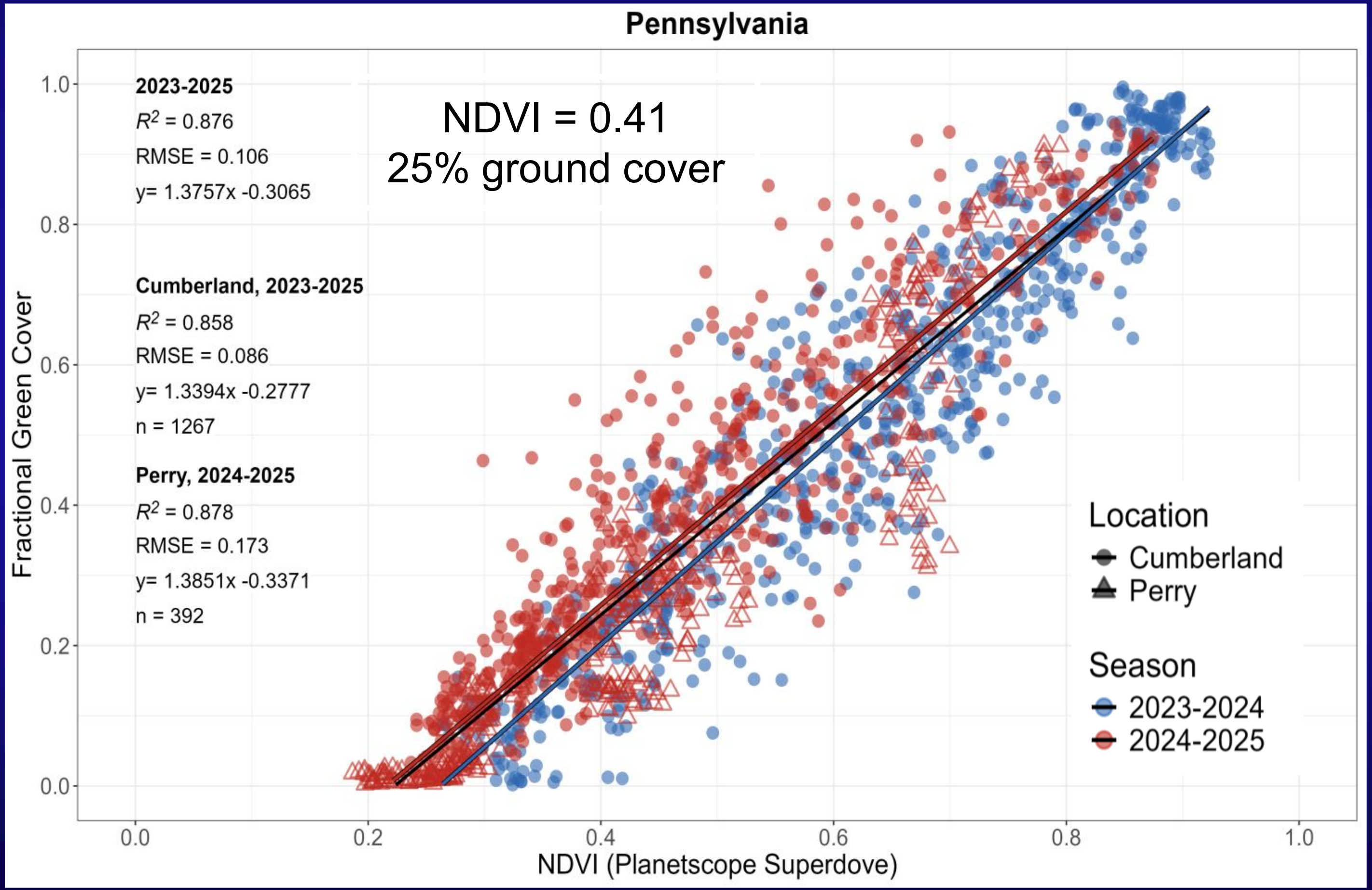
Verification scenarios for enrolled cover crop fields

Field locations and agronomy are known, field boundaries digitized

- **Springtime vegetation indices can be calibrated to measure fractional ground cover**
  - Identify fields meeting 25% green vegetation in last week of March **(e.g., Cumberland County, PA)**
  - Repeat analysis 2 weeks later to identify fields that have truly failed to perform

Mapping springtime fractional cover could potentially focus verification site visits on underperforming fields, reducing demands on county staff



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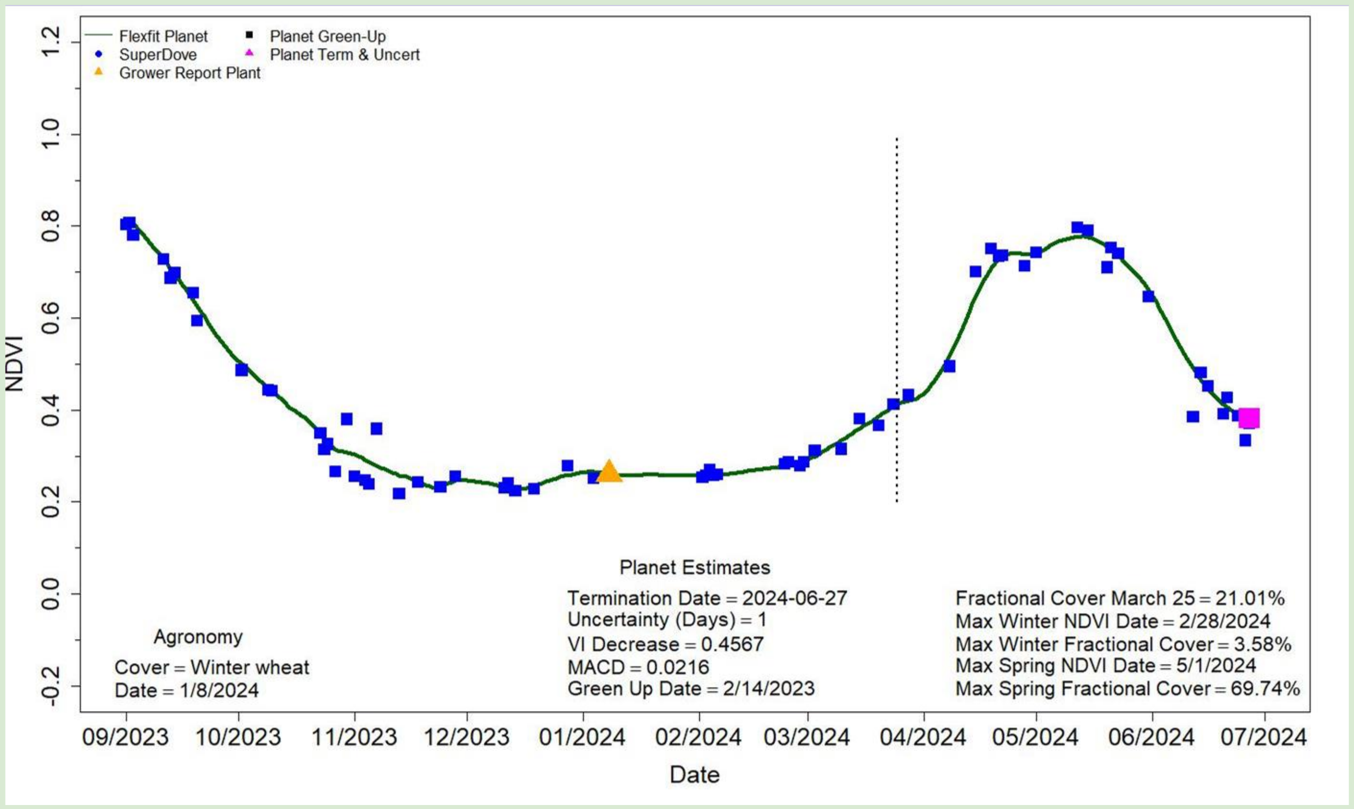

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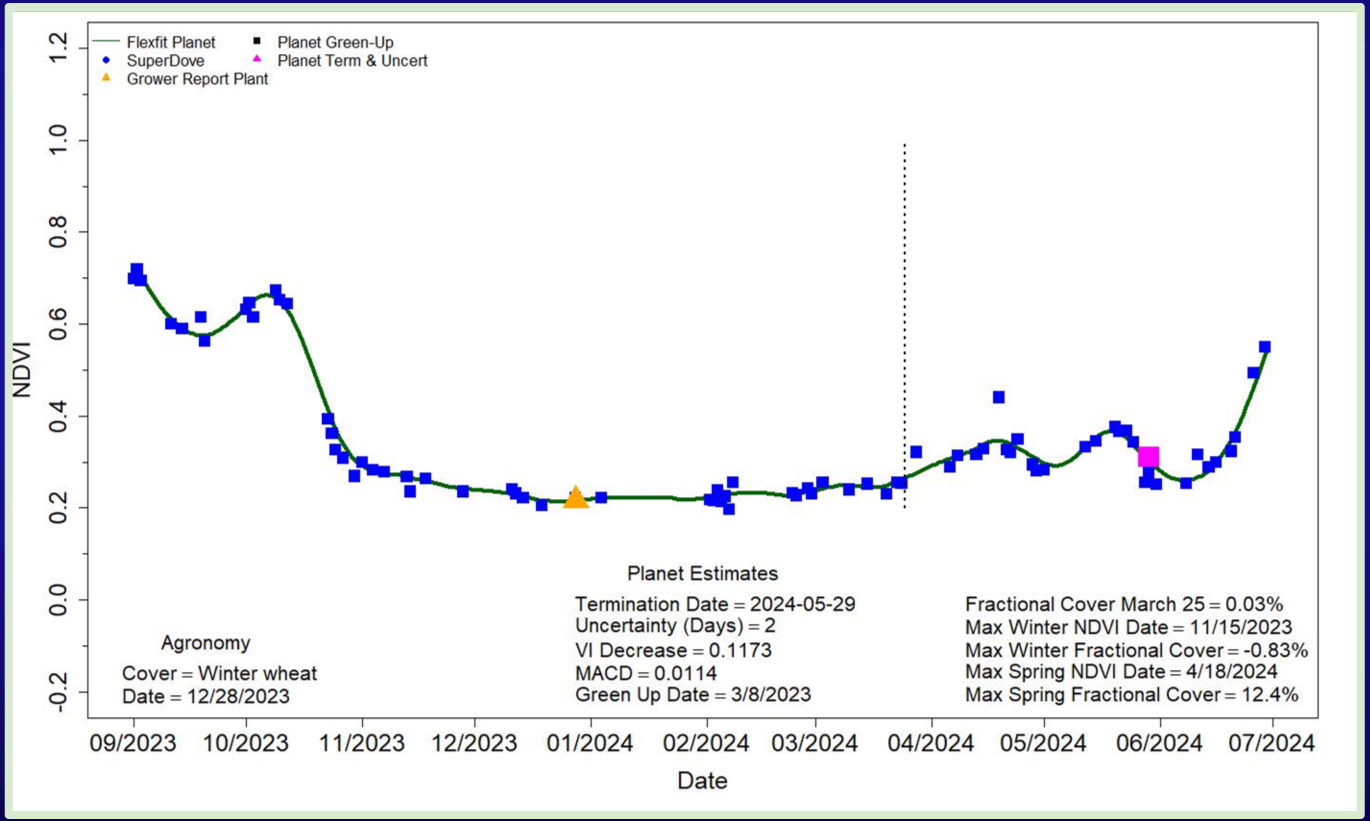

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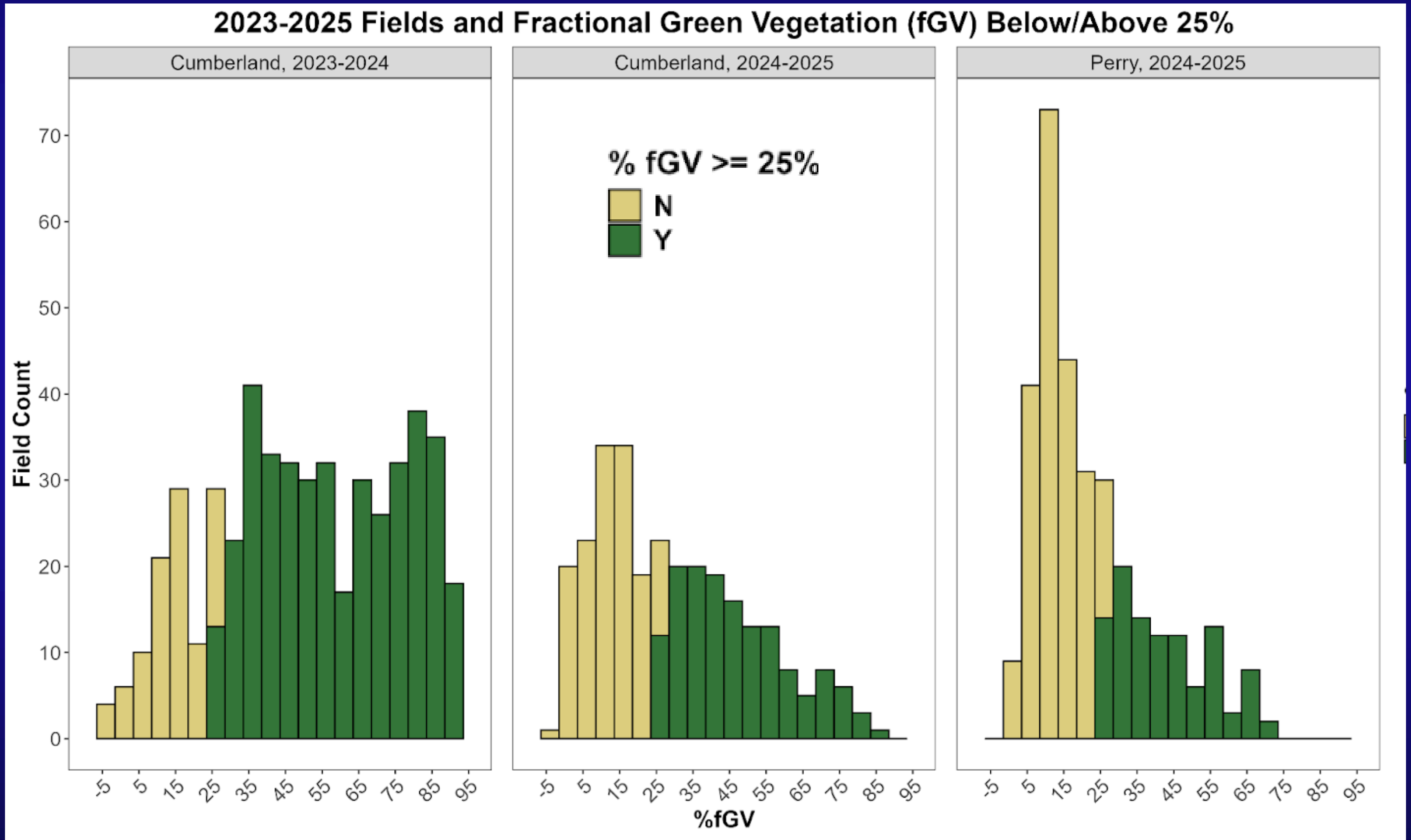

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Possible remote sensing applications
for known enrolled fields

- Satellite detection of wintertime biomass in December can identify clearly established cover crop fields, potentially reducing the need for site visits by conservation staff
  - However, satellite detection of fall emergence dates might not be adequate to verify planting date thresholds (e.g., before October 15 = early planting)
- Satellite detection of springtime termination dates can identify clearly terminated vs. questionable fields, potentially focusing site visits on the questionable fields, thereby reducing the need for site visits by conservation district staff
- Satellite analysis can measure cover crop performance (aboveground biomass, N content, fractional ground cover) and the performance data can inform adaptive management by farmers and conservation program managers
  - Measurement of springtime fractional ground cover can assess program compliance (25% cover in PA)
- If cover crops have poor performance, satellite detection of winter biomass is uncertain, and detection of springtime termination is not possible

Cover crop verification scenarios

1. Field locations and agronomy are known, field boundaries digitized

2. Field locations are unknown, remote sensing is used to identify them

Cover crop identification – where are the fields?

Actual cover crop locations are known by:

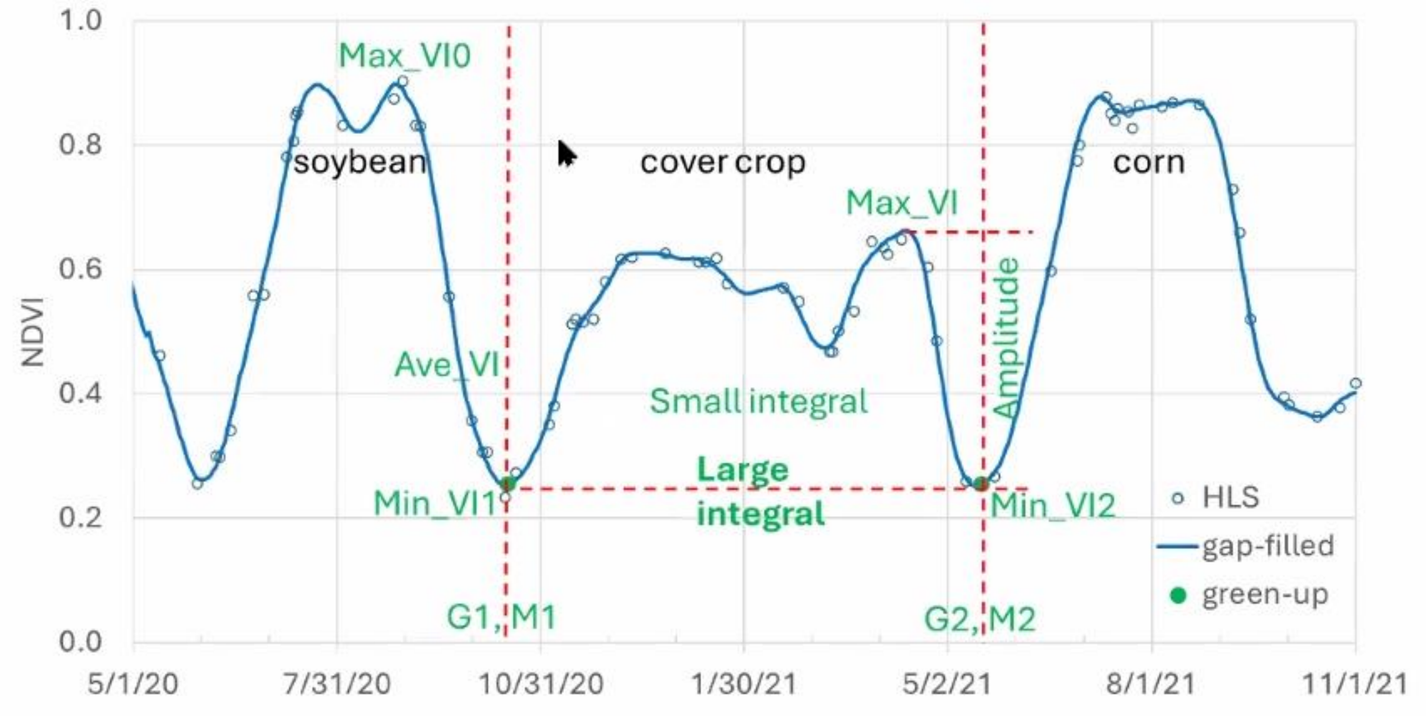
- Cost-share program managers
- Transect surveys
- Individual farmers
- CAST by county
- Census of agriculture by county

Wintertime green vegetation can be:

- Cover crop
- Weeds
- Small grain crop
- Pasture/hay
- Lawn
- Forest

Cover crop identification – USDA-ARS method

- USDA-ARS (Feng Gao) is developing a CONUS cover crop map which will be public, free, and transparent methodology
- Calibrated using data from Beltsville Agricultural Research Center, MD, and from Maryland cover crop enrollment data (I provide access as a coauthor, with permission from MDA)



WCC likelihood score
- Max VI
- Amplitude VI
- Small Integral of VI
- Large integral of VI

- Scores each pixel in an HLS time series for the likelihood of being a winter cover crop
- 1 = low, 10 = high
- Above 3 is fairly likely

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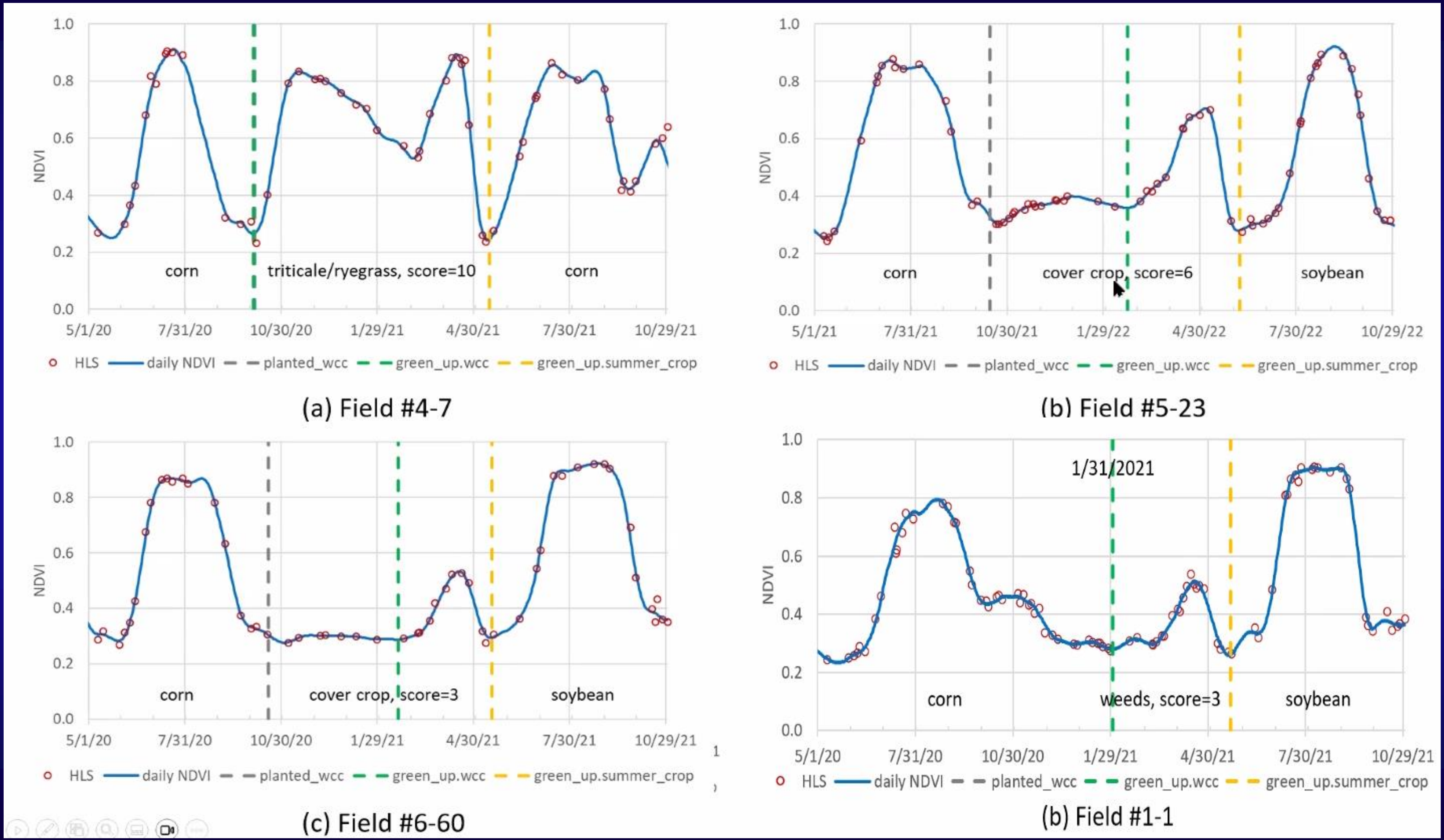
These data are preliminary and are subject to revision.

Cover crop identification – USDA-ARS method



(a) Field #4-7

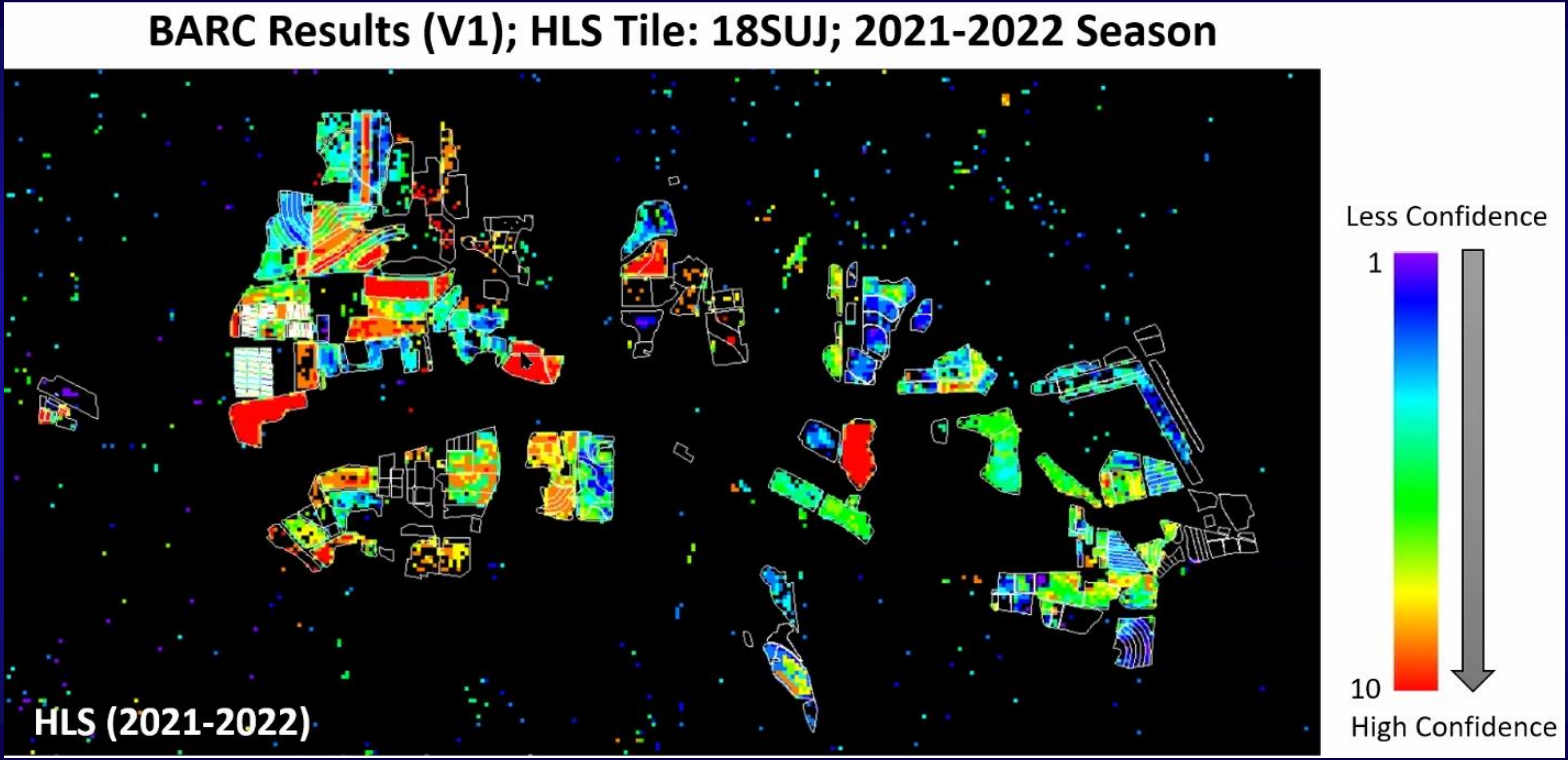
(b) Field #5-23

(c) Field #6-60

(b) Field #1-1

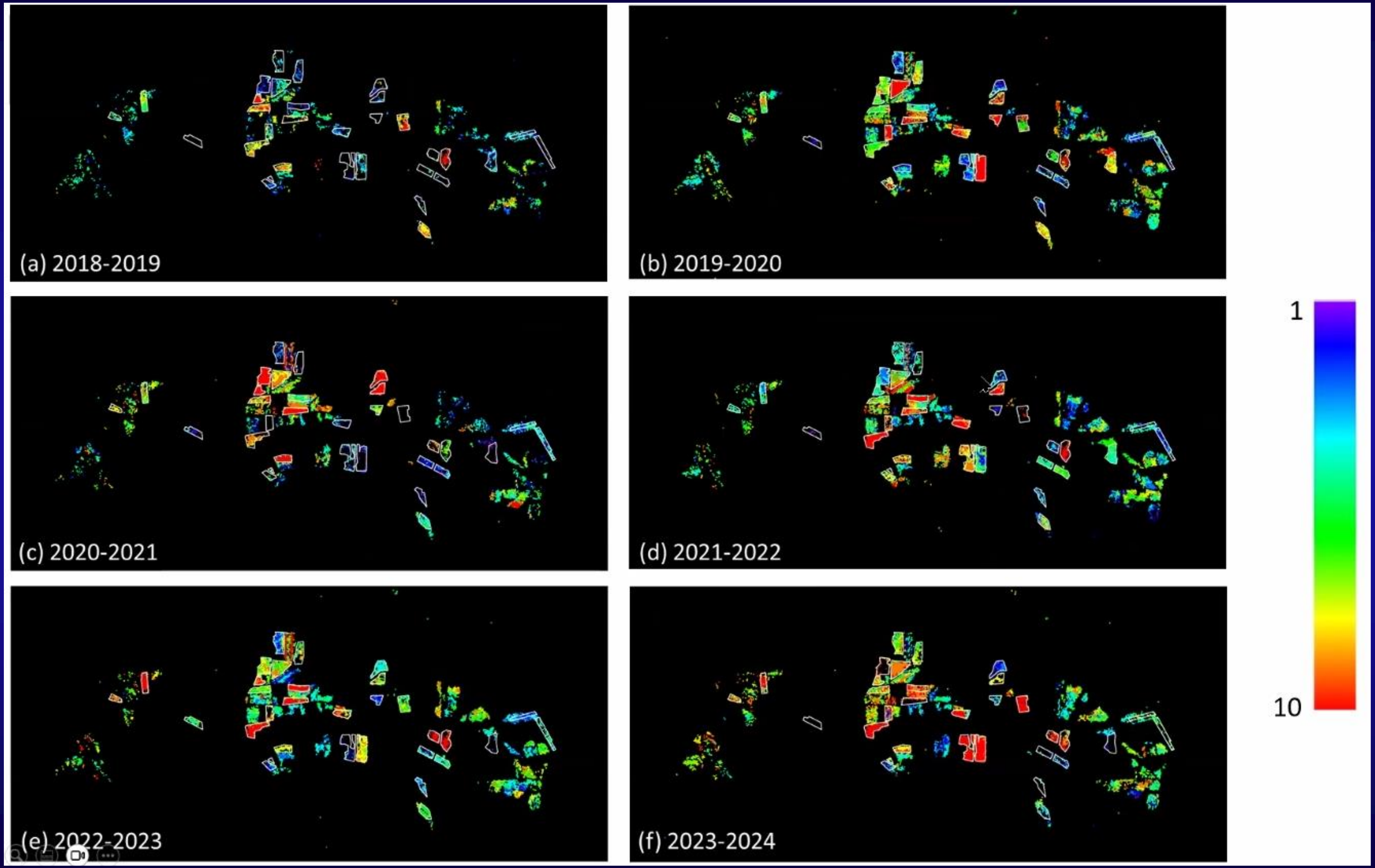
These data are preliminary and are subject to revision.

Cover crop identification – USDA-ARS method



These data are preliminary and are subject to revision.

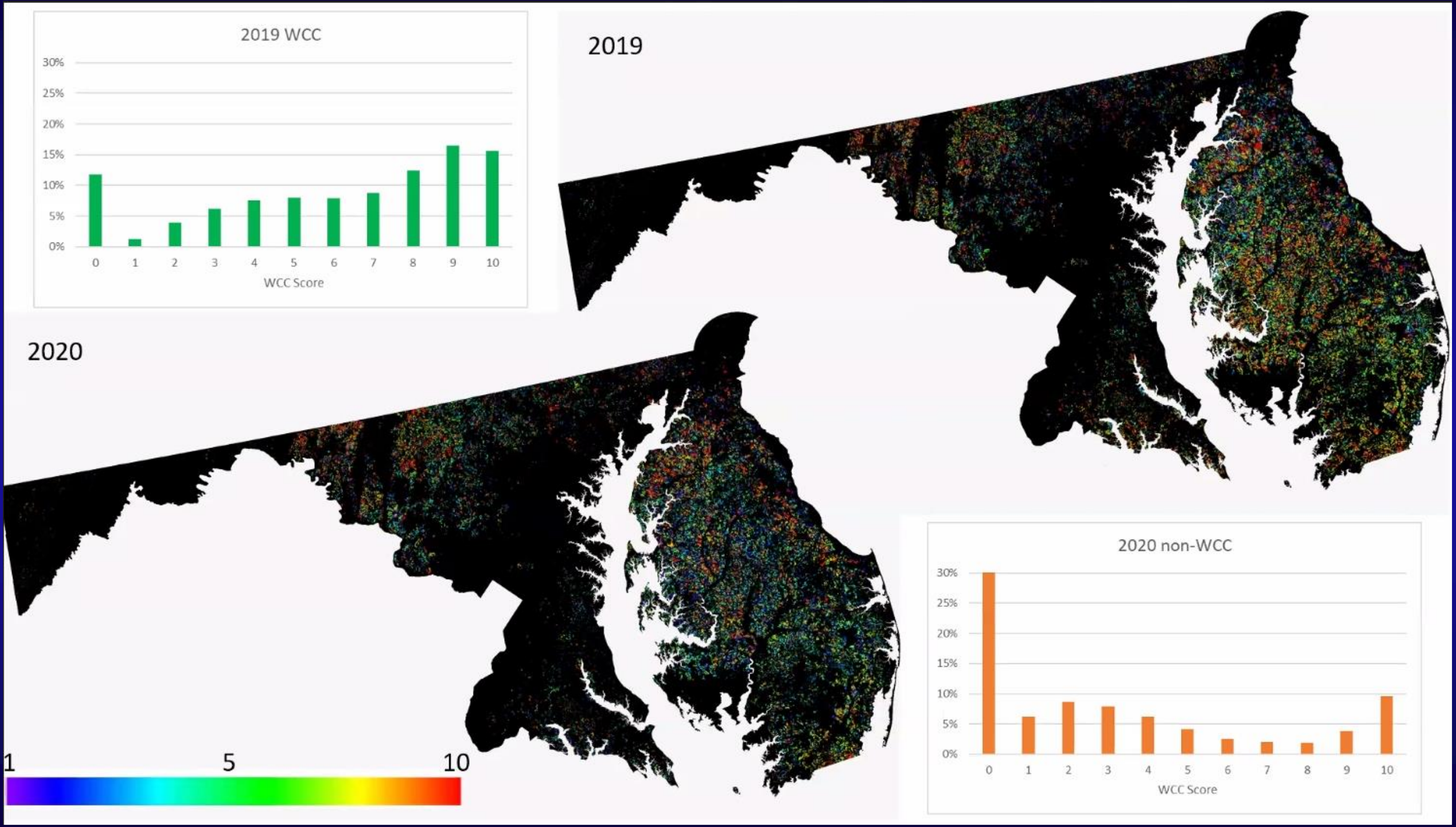
Cover crop identification – USDA-ARS method



- Calculated for each cover crop year
- Accuracy using BARC dataset is 88% using likelihood #3
- Accuracy using MD enrolled fields is 84% using likelihood #4

These data are preliminary and are subject to revision.

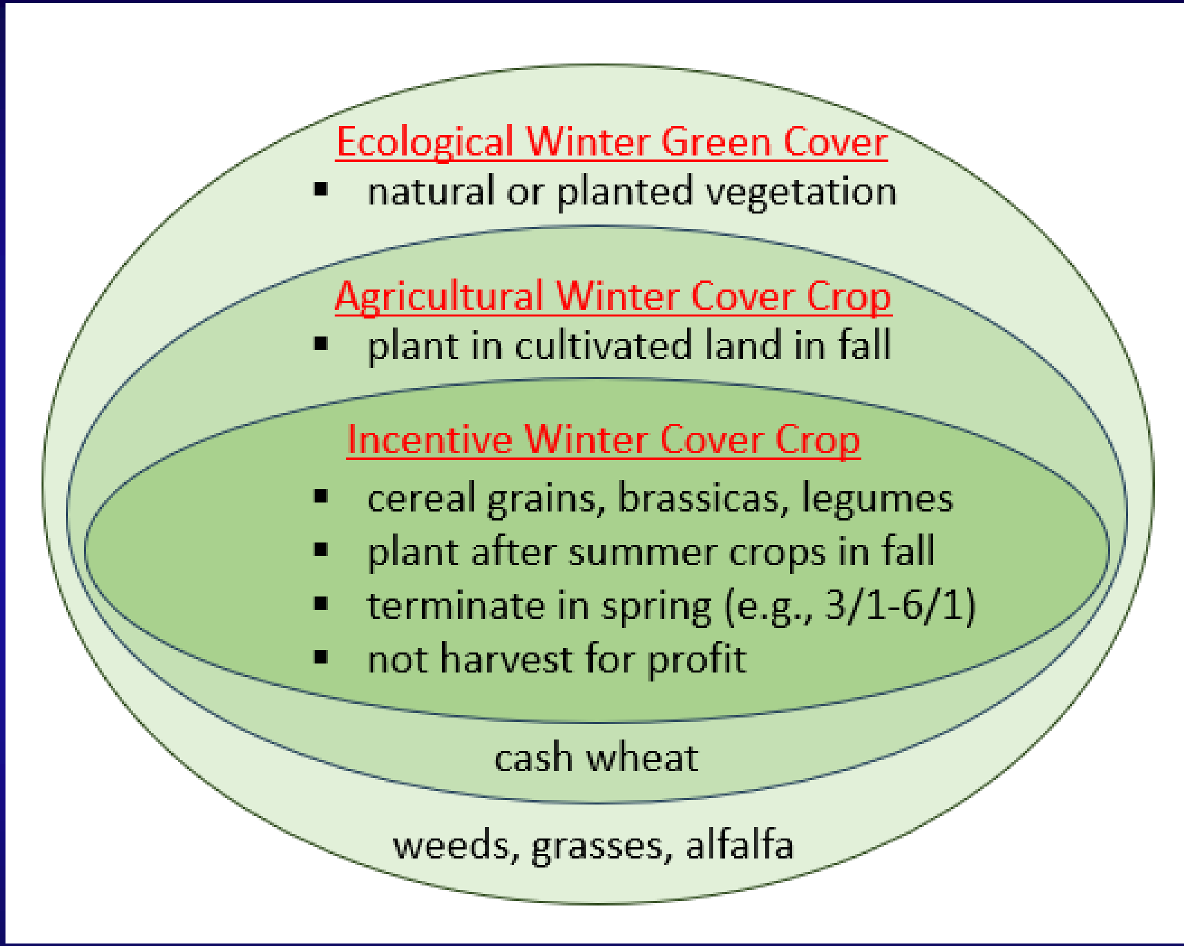
Cover crop identification – USDA-ARS method



- Manuscript in draft

These data are preliminary and are subject to revision.

Cover crop identification – USDA-ARS method



- Separates agricultural from incentive winter cover based on termination date (later for cereal grain crops)
- The pixel-based classification is not masked to cropland

Possible remote sensing applications
for cropland where enrollment is not known

- A landscape remote sensing analysis of cropland in December could identify all fields with significant amounts of green vegetation, which could include cover crops, weeds, and cereal grain crops
- USDA-ARS cover crop mapping analysis (Feng Gao) can identify pixels with likelihood of being an incentive cover crop
  - Currently shared for 2020-21 and 2021-22 for comparison to CAST cover crop data
  - This product requires a mask to limit to analysis to cropland. Perhaps the agricultural land classification from USGS/Chesapeake Consortium (Claggett) could be used to identify cropland + pasture/hay, and HLS satellite analysis and/or the Cropland Data Layer could be used to eliminate pasture/hay. The remaining polygons could then be used to mask the Feng Gao cover crop product to cropland.
- Care must be taken to separate cover crops from weeds and cereal grain crops
- Poor performing cover crops would not be detected
  - However, these fields have minimal environmental benefit and perhaps should not be counted toward bay restoration progress? (!! this is a concept for discussion, not a recommendation !!)

What is not currently possible

- Accurate classification of planting date relative to specific cutoff dates (Oct 15)
  - Emergence is detected about 2 weeks after planting, depending on planting method and weather conditions
- Identification of cover crop species and planting methods
- Identification of fertilizer applications
- Identification of poor performing cover crops with minimal establishment

- Therefore, remote sensing cannot identify and classify cover crops according to the variable efficiency tables developed by the CBP expert panels that are currently used to credit cover crop implementation

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A new framework?

- Identify cover crops using remote sensing, and quantify their performance
  - Biomass, N content, fractional ground cover
- For nitrogen modelling, credit cover crops based on aboveground N content
- For sediment and phosphorus modelling, credit cover crops based on fractional ground cover by estimating cover impacts on soil erosion
- As sensors improve, identify species and functional groups to improve N modeling
- Poor performing fields would receive little to no credit
- Years with bad weather would receive less credit than years with good growing conditions
- Some error would be inherent in the classification and measurement
- Small fields require smaller pixel imagery (PlanetScope)
- Calibration development across the watershed would be required

This scenario might actually provide a more accurate quantification of actual cover crop impacts on water quality outcomes

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A second scenario

- Keep to the current established guidelines for reporting planting and management of cover crops
- Improve geospatial recordkeeping by digitizing boundaries of enrolled fields and associated agronomic management in the fall, to support a wintertime remote sensing analysis of enrolled fields
- Use remote sensing to confirm the emergence, growth and termination of cover cropped fields
- Focus verification site visits on the subset of questionable fields, resulting in a substantial reduction in staff time dedicated to verification
- Use remote sensing performance analysis to support adaptive management and promote successful cover cropping strategies

This scenario would provide consistency with current guidelines, while substantially reducing staff time dedicated to field visits

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Thank you

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posted to USDA-ARS Sustainable Agricultural Systems Laboratory
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https://www.precisionsustainableag.org/remote-sensing-1
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https://www.usgs.gov/staff-profiles/wells-dean-hively

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