Pennsylvania Department of Environmental Protection Remote Sensing Pilot Project

~~Draft~~ Methodology Guidance for Remote Sensing Verification of Conservation Tillage BMPs

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Introduction

Conservation tillage best management practices (BMPs), also known as reduced tillage BMPs, are crucial to the Chesapeake Bay Program's goals to reduce agricultural sediment and nutrient loads.[1] As single-year BMPs, conservation tillage BMPs must be reported annually for a state to be credited for associated Total Maximum Daily Load (TMDL) reductions in nitrogen, phosphorus, and sediment. Currently, the Chesapeake Bay Program has approved only two methods for reporting and verifying conservation tillage BMPs—driving transect surveys with in-field classification of conservation tillage regime[2] and remote surveys using photo-based classification of conservation tillage regime.[3] This document introduces guidance for a new methodology for reporting and verifying tillage BMPs using satellite remote sensing techniques.

Background

As shown in Figure 1~~Figure 1Figure 1~~, the Chesapeake Bay Program (CBP) identifies four types of tillage regimes based on the magnitude of crop residue coverage on fields immediately following crop planting.[4] The ~~Chesapeake Bay Program~~CBP's definitions for these tillage regimes are as follows:

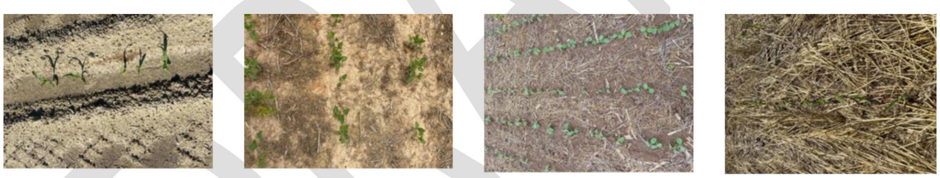
- **Conventional Tillage**: Any tillage routine that does not achieve 15% crop residue coverage immediately after planting is considered conventional tillage and does not qualify as a BMP.
- **Low Residue Tillage**: A conservation tillage routine that involves the planting, growing, and harvesting of crops with minimal disturbance to the soil in an effort to maintain 15% to 29% crop residue coverage immediately after planting each crop.
- **Conservation Tillage**: A conservation tillage routine that involves the planting, growing and harvesting of crops with minimal disturbance to the soil in an effort to maintain 30% to 59% crop residue coverage immediately after planting each crop.
- **High Residue, Minimum Soil Disturbance Tillage**: A conservation tillage routine that involves the planting, growing and harvesting of crops with minimal disturbance to the soil in an effort to maintain at least 60% crop residue coverage immediately after planting each crop.

Although the CBP defines conservation tillage specifically as a routine associated with 30% to 59% crop residue coverage remaining on the field immediately after planting, the term conservation tillage is more colloquially used to describe any non-conventional tillage regime

[1] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/PA-DEP-Remote-Sensing-Pilot-Project-Phase-1-MDP.pdf
[2] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/Transect_Survey_Recommendations_Report_3-16-17.pdf
[3] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/VA_DCR_2022_Tillage_Survey_AgWG_7-20-2023.pdf
[4] https://www.chesapeakebay.net/what/publications/quick-reference-guide-for-best-management-practices-bmps

that minimizes soil disturbance during crop planting and cultivation. Accordingly, in this report, low residue tillage, conservation tillage, and high residue minimum soil disturbance tillage are collectively referred to as reduced tillage or conservation tillage practices/BMPs.

To receive TMDL credit for the nutrient and sediment reductions afforded by conservation tillage BMPs, CBP reporting agencies (e.g., Pennsylvania Department of Environmental Protection) must regularly survey and quantify conservation tillage BMP implementation in accordance with the procedures set forth in the ~~Chesapeake Bay Program's~~CBP's BMP verification guidance documents. The existing methodologies for conservation tillage BMP verification in the Chesapeake Bay Watershed are documented in "Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Roadside Transect Surveys to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program Partnership's Watershed Model"[5] and "Virginia Tillage/Residue Survey - Using an Alternative Approach for Verification."[6] While effective, these methods ~~are~~ can be expensive and time consuming, requiring surveyors to drive thousands of miles throughout each jurisdiction of the Chesapeake Bay Watershed to manually classify the tillage regimes implemented in a sub-sample of agricultural fields.



Conventional Tillage | **Low Residue Tillage** | **Conservation Tillage** | **High Residue, Minimum Soil Disturbance Tillage**

Figure 1. Examples of tillage practices in agricultural fields. Only fields with over 15% crop residue coverage immediately after crop planting are considered BMPs in the CBP. Specific land use types that are eligible for conservation tillage BMPs in the CBP include full season soybeans, grain with manure, grain without manure, silage with manure, silage without manure, small grains and grains, double cropped land, and specialty crops. Images from "Virginia Tillage/Residue Survey – Using an Alternative Approach for Verification."[7]

Remote sensing-based BMP verification of conservation tillage practices is a promising potential verification approach that may reduce the labor, time, and costs currently invested in traditional transect surveys while simultaneously extending spatial and temporal survey coverage. Remote sensing describes the process of monitoring a distant target's characteristics by measuring the interaction of the target with electromagnetic radiation (i.e., light). In the case of conservation

[5] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/Transect_Survey_Recommendations_Report_3-16-17.pdf
[6] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/VA_DCR_2022_Tillage_Survey_AgWG_7-20-2023.pdf
[7] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/VA_DCR_2022_Tillage_Survey_AgWG_7-20-2023.pdf
https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/VA_DCR_2022_Tillage_Survey_AgWG_7-20-2023.pdf

tillage, different combinations of crop, soil, and residue coverage predictably impact wavelength-specific values known as surface reflectance values (see Figure 2~~Figure 2Figure 2~~~~Error! Reference source not found.~~). Remote sensing platforms, such as drones and satellites, are equipped with various sensors that can measure surface reflectance values with varying spatial, temporal, spectral, and radiometric resolution (see Table 1~~Table 1Table 1~~). Thus, using in-situ crop residue coverage data and coincident satellite measurements, models relating surface reflectance and crop residue coverage may be developed to track conservation tillage BMPs.

Numerous studies have demonstrated the viability of using remote sensing to characterize the degree of conservation tillage implemented in agricultural fields. Within the Chesapeake Bay Watershed for example, Hively et al. (2018) produced high accuracy models for predicting residue coverage using ~~from~~ the WorldView-3 (WV3) and Landsat 8 satellites.[8] In Hively et al.'s work, WV3 band indices, including the Shortwave Infrared Normalized Difference Residue Index (SINDRI) and the Lignin Cellulose Absorption Index (LCA), were used to produce models for predicting crop residue coverage with root mean squared errors (RMSE) of 7.15% and 8.40% and coefficients of determination of 0.94 and 0.92, respectively. In this same study, the Normalized Difference Tillage Index (NDTI) calculated using Landsat 8 imagery was used to produce a crop residue coverage model with an RMSE of 12.00% and a coefficient of determination value of 0.84. Other studies have similarly shown that satellite remote sensing can provide reliable estimates of conservation tillage implementation on broad spatial scales (e.g., Azzari et al., 2019;[9] Beeson et al., 2020;[10] Gowda et al., 2008).[11]

Although these models provide promising results, their applicability for larger-scale model training and implementation faces several limitations. For instance, the WV3 satellite generally requires expensive tasking (approximately $30 per square kilometer) to collect new imagery, and it has a relatively small historical imagery archive available for retrospective analyses.[12] Additionally, while Landsat 8 data is freely available and benefits from a large historical archive, its 30-meter spatial resolution and 16-day revisit frequency (effectively 8-day since the 2021 launch of Landsat 9) presents challenges in training and deploying models using this data source alone. Specifically, Landsat 8/9's coarse spatial resolution makes it difficult to properly resolve texture information associated with different practices, and its infrequent overpass timing makes it difficult to obtain consistent cloud-free satellite data.

Recent studies have shown that newer satellite data available at high spatial and temporal resolutions may enhance classification performance for identifying conservation tillage BMPs when compared to sensors with lower spatial and temporal resolution. For example, Liu et al.

[8] https://www.mdpi.com/2072-4292/10/10/1657
[9] https://www.sciencedirect.com/science/article/pii/S0034425718305157?via%3Dihub
[10] https://www.mdpi.com/2072-4292/12/16/2665
[11] https://www.tandfonline.com/doi/full/10.1080/01431160701581810?casa_token=d3PM0ShLpNUAAAAA%3ATcRLlpAmyeeQdT3BOiXwLGUq94h0KdbHtef7P7Av7LsdXKlWpLS2UgGxOpJwLJ9KiJ7pkMdWQc9_hA
[12] https://apollomapping.com/worldview-3-satellite-imagery

(2022) showed that, machine learning models using 3-meter PlanetScope imagery had the highest classification accuracy (86.5%) for identifying conservation tillage practices in smallholder systems in India when compared to 10-meter Sentinel-1 and Sentinel-2 data.[13] Likewise, Luo et al. (2023) observed that the accuracy of convolutional neural networks (CNNs) trained to use PlanetScope imagery to identify conservation tillage practices "continuously increased with increases in both temporal and spatial resolutions."[14] This finding echoes the findings of Watts et al. (2011)[15] and Zheng et al. (2012)[16] in which~~who~~ each study observed that the use of multi-temporal imagery improved classification of conservation tillage practices.

With the development of improved methods for data processing, as well as the planned launches of new sensors optimized for measuring crop residue (e.g., Landsat Next),[17] there is increasing recognition of the potential for remote sensing to enhance conservation tillage BMP verification. Beyond cost and time savings, a remote sensing-based BMP verification method offers the additional benefit of removing surveyor subjectivity during classification. Moreover, a remote sensing-based verification methodology enables spatially and temporally continuous classification of conservation tillage practices, which can support more effective and targeted outreach and policy decisions.

The CBP's 2016 report "Conservation Tillage Practices for Use in Phase 6.0 of the Chesapeake Bay Program Watershed Model" states that "remotely sensed (aerial/satellite) estimates are also likely feasible [for use in BMP verification] given proper calibration."[18] The same document notes that the expert panel convened to develop the report "envisions that potential opportunities may exist in the future for utilizing alternative forms of BMP verification, such as remote sensing from satellite, aerial, and drone imagery." In line with these insights, Table B-6 of the Agriculture BMP Verification Guidance document indicates that remote sensing methods are "potentially eligible" for use in verification of single year visual assessment BMPs, including conservation tillage practices. Clearly, as the CBP continues to promote conservation agriculture to reduce nutrient and sediment loading to the Chesapeake Bay, enhanced monitoring of tillage practices via remote sensing ~~is critical for~~has potential to play a crucial role in improving targeted outreach and reporting efforts.

[13] https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0277425
[14] https://www.sciencedirect.com/science/article/pii/S266601722300010X#bib74
[15] https://www.sciencedirect.com/science/article/pii/S0034425710002452?via%3Dihub
[16] https://www.sciencedirect.com/science/article/pii/S0034425711003439
[17] https://www.usgs.gov/landsat-missions/landsat-next
[18] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/CT_6.0_Conservation_Tillage_EP_Revised_Full_Report_12-14-16.2_FINAL_NEW_TEMPLATE.pdf

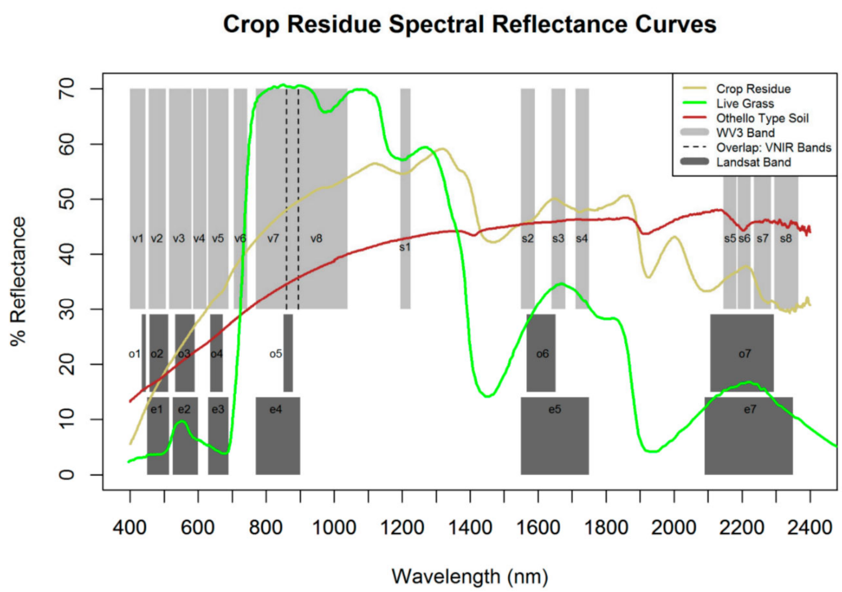


Figure 2. Reflectance curves for maize residue (tan line), live grass (green line), and an Othello silt-loam soil (red-line). The grey bars represent the spectral band widths of WorldView-3, Landsat 8 Operational Land Imager (OLI), and Landsat 7 ETM. Figure reproduced from Hively et al. (2018).[19]

Table 1. Spatial, temporal, spectral, and radiometric resolution of selected satellite platforms.

Satellite	Sensor	Spatial Resolution	Effective Temporal Resolution	Number of Spectral Bands	Radiometric Resolution	Data Availability
Landsat 8/9	Operational Land Imager (OLI)	30-meter (15-meter panchromatic band)	8 days	8	12-bit/14-bit	Publicly available
Sentinel-2	Multi-Spectral Instrument (MSI)	10-meter (20-meter or 60-meter depending on band)	5 days	13	12-bit	Publicly available
Planet SuperDove (PlanetScope)	PSB.SD	3-meter	1 day	8	12-bit	Commercially available

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[19] https://www.mdpi.com/2072-4292/10/10/1657

Satellite	Sensor	Spatial Resolution	Effective Temporal Resolution	Number of Spectral Bands	Radiometric Resolution	Data Availability
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Purpose

The primary intent of this document is to furnish stakeholders with recommendations and guidelines for designing, implementing, and analyzing remote sensing surveys aimed at estimating the implementation of conservation tillage BMPs in the Chesapeake Bay Watershed. The methodology broadly covers four sections:

(1) Model selection
(2) Survey design
(3) Survey implementation
(4) Analysis and reporting

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Intentionally, the proposed methodology provides a model-agnostic framework for implementing remote sensing surveys, which allows flexibility to accommodate future models such as those developed using data from forthcoming remote sensing platforms, improved data processing techniques, and/or regionally tuned field measurements. ~~The proposed methodology aims to enhance the accuracy, efficiency, and scalability of BMP verification efforts across the region, while adhering to the best practices outlined by the CBP in prior reports including "Conservation Tillage Practices for Use in Phase 6.0 of the Chesapeake Bay Program Watershed Model," "Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Remote Sensing to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program Partnership's Watershed Model,"[20] and "Strengthening Verification of Best Management Practices Implemented in the Chesapeake Bay Watershed."[21]~~ States within the Chesapeake Bay Watershed have collected—and continue to collect—field-measured conservation tillage data that can be used to fine tune and improve remote sensing derived conservation tillage estimates. By allowing flexibility in model selection (i.e., by allowing for model agnosticism), the proposed methodology enables states to develop and select the best-available technology for conservation tillage BMP identification within their jurisdiction so long as the model meets the criteria described in the methodology document. Overall, t~~T~~he proposed methodology aims to enhance the accuracy, efficiency, and scalability of BMP verification efforts across the region, while adhering to the best practices outlined by the CBP in prior reports including "Conservation Tillage Practices for Use in Phase 6.0 of the Chesapeake Bay Program Watershed Model," "Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Remote Sensing to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program Partnership's Watershed Model,"[22] and

~~[20] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/recommendation_report_draft_final.pdf~~

~~[21] https://d38c6ppuviqmfp.cloudfront.net/documents/Complete%20CBP%20BMP%20Verification%20Framwork%20with%20appendices.pdf~~

[22] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/recommendation_report_draft_final.pdf

"Strengthening Verification of Best Management Practices Implemented in the Chesapeake Bay Watershed."[23]

Methodology for Conservation Tillage BMP Verification via Remote Sensing

As noted in "Conservation Tillage Practices for Use in Phase 6.0 of the Chesapeake Bay Program Watershed Model," to receive credit for reduced tillage practices, states must report the following information to the National Environmental Information Exchange Network (NEIEN):

- BMP name (reduced tillage, conservation tillage or high residue tillage management)
- Measurement name (acres)
- Land use (CROP or an approved NEIEN agricultural land use class)
- Geographic location (county, county area within the Chesapeake Bay Watershed, hydrologic unit code, or state area within the Chesapeake Bay Watershed)
- Date of implementation (year residue cover was observed)

The following sections propose a methodology for reporting the above information using remotely sensed estimates of conservation tillage.

Model Selection

For the purposes of this report, the terms model and model workflow will be used to describe a set of steps used to transform input data, including remote sensing measurements, to a georeferenced mapping of conservation tillage implementation. The purpose of model selection in this methodology is to outline the key characteristics that remote sensing models should possess to effectively estimate the implementation of conservation tillage BMPs in the Chesapeake Bay Watershed. As the landscape of remote sensing technology and data processing continues to evolve, the proposed approach provides a flexible framework that allows for the integration of emerging tools, algorithms, and data sources. This ensures that future advancements can be incorporated into BMP verification efforts without requiring fundamental changes to the methodology.

Although this methodology does not mandate the use of any specific model or algorithm, it identifies critical requirements that a model must meet to be considered suitable for the task of

[23] https://d38c6ppuviqmfp.cloudfront.net/documents/Complete%20CBP%20BMP%20Verification%20Framwork%20with%20appendices.pdf

remotely sensing conservation tillage BMPs. The following criteria outline the essential components of a suitable model workflow:

1. **Comprehensive classification of tillage regimes:** A model workflow must be capable of distinguishing between the three types of reduced tillage BMPs defined by the CBP. Additionally, the model workflow should be able to accurately identify which croplands are eligible or ineligible for conservation tillage BMPs, either natively or using established land use categories. Model workflows that do not report data that can be separated into the 15-29%, 30-59%, and ≥60% crop residue cover categories defined by the CBP should be considered ineligible for BMP reporting and verification. For example, because the Conservation Technology Information Center's OpTIS 4.0 model reports conservation tillage implementation using different crop residue cover levels (namely, 0-15%, 16-3~~5~~0%, and 31-50%, and 51-100% crop residue cover), the OpTIS 4.0 model would be ineligible for use in BMP reporting and verification.[24] Some models report continuous estimates of percent residue cover (i.e., model outputs range from 0% to 100% crop residue cover). To use these models for conservation tillage BMP reporting and verification, the continuous outputs should be discretized using the CBP's definitions of tillage regimes.
2. **Adequate spatial resolution:** Remote sensing platforms record measurements at various spatial scales with pixels resolutions ranging from centimeter to kilometer levels. Models for use in conservation tillage BMP verification should generate outputs with a minimum pixel resolution of 60 meters. In other words, the tillage regime classification produced by a model workflow should report results using pixels of width 60 meters or less. This level of resolution ensures that the model can capture sufficient detail for accurate assessment of tillage practices across agricultural landscape and is based on recommendations from remote sensing experts convened as part of a technical advisory committee in the development of this report. Model workflows may incorporate data with spatial resolutions greater than 60 meters; however, workflows that do so should also include remote sensing measurements with sub-60-meter spatial resolution and should report and verify results at a sub-60-meter spatial scale.
3. **Transparent model documentation:** The methods and data used to develop and calibrate a model should be well-documented and transparent to enable scientific review and validation. In accordance with the 2013 Recommendations of the Citizens Advisory Committee workgroup, transparent model documentation would include clear information on "how the data were obtained, what measures are employed to ensure the data is accurate, who is responsible for data generation and collection as well as who is responsible for ensuring data accuracy, and the methods of analysis utilized."[25]

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[24] https://www.ctic.org/OpTIS_Tillage

[25] https://d38c6ppuviqmfp.cloudfront.net/documents/Complete%20CBP%20BMP%20Verification%20Framwork%20with%20appendices.pdf

4. **Performance evaluation:** The suitability of a model should not be determined by its theoretical design alone. After the model is implemented, its performance must be evaluated using established metrics (see Analysis and Reporting) to ensure that the model provides reliable estimates of conservation tillage BMP implementation. Model suitability should be determined on an annual basis. Accordingly, models that do not meet or exceed the established performance criteria in a given year are not used that year for BMP reporting, even if the same models historically met performance standards. The three conservation tillage BMPs (15-29% Low Residue Tillage, 30-59% Conservation Tillage, and over 60% High Residue Tillage) are evaluated independently with separate sampling data for validation and overall accuracy assessments.
5. **Separation of training and evaluation data:** To ensure unbiased estimates of model performance, it is critical that data collected to evaluate a model's performance in a given year (e.g., field measurements of percent residue cover) are in no way used to train or calibrate the remote sensing model. A model may be developed/calibrated using both historical data and data collected from the reporting year so long as these "training" datasets do not overlap with the dataset used to officially evaluate the model workflow performance (as described in Analysis and Reporting).

Commented [AH1]: Add clarifying sentence to address three separate BMPs re: Tetra Tech's comment.

Survey Design

To estimate conservation tillage BMP implementation across a jurisdiction using remote sensing, two main approaches can be employed: a statistical subsampling approach or a total area classification (TAC) approach. In subsampling approaches, a sufficient number of independent locations are randomly selected throughout a jurisdiction to estimate conservation tillage BMP implementation levels with defined confidence intervals and error tolerances. In TAC approaches, all areas suitable for conservation tillage BMPs are mapped and classified by their tillage regime to directly estimate BMP implementation.

Both of the existing, transect-based methodologies for conservation tillage BMP verification use a subsampling approach; however, due to agricultural field access limitations, the geographic scope of these surveys is generally limited to roadside fields. With remote sensing, larger areas can be "virtually" sampled with increased frequency and lower cost than with traditional methods. By replacing in-field observations of tillage regime with remotely sensed observations of tillage regime, remote sensing offers the ability to replicate traditional transect surveys (i.e., implement a virtual transect survey or VTS), sample from non-roadside fields missed in traditional transect surveys (i.e., implement a virtual field survey or VFS), or fully map conservation tillage implementation in a region via TAC.

The below steps describe a method for designing a remote sensing survey for conservation tillage BMP verification, building on the guidelines described in "Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Remote Sensing to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program

Partnership's Watershed Model"[26] and Appendix B of the BMP Verification Guidance document.[27] The methodology proposed is intended to support VTS, VFS, and TAC approaches. As described below, the methodology includes guidance for how a jurisdiction can decide where to apply a model workflow, the extent over which the model should be applied, and the data that should be collected to support verification.

To conduct a remote sensing survey:

1. **Estimate a minimum sample size using a multinomial distribution.**
   As described in "Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Remote Sensing to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program Partnership's Watershed Model,"[28] multinomial distributions can be used to determine the random sample size (n_0) needed to estimate conservation tillage implementation in an area with a given confidence level and allowable error. The equation to calculate the minimum random sample size needed to estimate the relative proportion of each class within a multinomial population is:

$$n_0 = \frac{q(1-q) * \chi^2_{\left(1,1-\frac{\alpha}{k}\right)}}{d^2}$$

   Where:

   n_0 = the minimum size of the random sample

   q = the *a priori* estimate of the proportion for each category (e.g., 0.5 to represent a non-informative prior)

   $\chi^2_{\left(1,1-\frac{\alpha}{k}\right)}$= the Chi-square value for one degree of freedom and the given number of classes and confidence level

   k = the number of classes in the population

   $\alpha = 1 - p$

   p = the selected confidence level (e.g., 0.90 to represent a 90% confidence interval)

   d = the allowable error (e.g., 0.10 to represent an allowable error of $\pm 10\%$)

   As applied to conservation tillage BMP verification via remote sensing, it is recommended n_0 be calculated with k = 5, $p \geq 0.90$, $d \geq 0.10$, and q = 0.5.

   - The value for the number of classes in the population (k) should be set to five so that a remote sensing survey can properly estimate the relative proportions of areas

[26] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/recommendation_report_draft_final.pdf
[27] https://d38c6ppuviqmfp.cloudfront.net/documents/Appendix+B+-Ag+BMP+Verification+Guidance+Final.pdf
[28] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/recommendation_report_draft_final.pdf

implementing the four tillage regimes (conventional tillage, reduced tillage, conservation tillage, and high residue tillage management) as well as areas not eligible for conservation tillage management (e.g., pastures).

- In the initial design of a remote sensing survey, it is recommended that the confidence level (p) and allowable error (d) be selected such that $p \geq 0.90$ and $d \geq 0.10$. When a confidence level of 0.90 and an error margin of 0.10 are used, the random sample will produce estimates of the true population parameters (i.e., the actual levels of conservation tillage BMP implementation within a jurisdiction) that have a 90% probability of falling within $\pm$10% of the true values. However, as noted in Appendix B of the BMP Verification Guidance document,[29] "States will need to apply their judgment in making decisions on the values for d and α. Improved precision (smaller d) or greater confidence (smaller α) will require increased sampling, while reduced sampling levels will result in lower confidence levels or increased allowable errors."
- Although prior information from historical transect surveys may be used to select *a priori* estimates of conservation tillage implementation levels, a non-informative prior of q = 0.5 is recommended for the initial design of a remote sensing survey of conservation tillage BMPs. Selecting a non-informative prior ensures the sample size is sufficient to estimate the proportion of implementation for all five classes in the populations.

With k = 5, p = 0.90, d = 0.05~~10,~~ and q = 0.5, the minimum sample size needed to estimate the relative proportions of conservation tillage BMP implementation in an area is n_0 = 541. As noted in "Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Remote Sensing to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program Partnership's Watershed Model,"[30] over-sampling by at least 2.5% to 5% is recommended in initial conservation tillage surveys to minimize impacts from reductions in the surveyable area throughout time. Accordingly, the total number of sample points to include in a remote sensing survey (n) by multiplying the calculated value for n_0 by a safety factor (SF):

$$n = SF * n_0$$

Where:

n = the size of the sample to be used in the remote sensing survey

SF = the selected safety factor (e.g., 1.05 to oversample by 5%)

n_0 = the minimum size of the multinomial random sample calculated above

[29] https://d38c6ppuviqmfp.cloudfront.net/documents/Appendix+B+-Ag+BMP+Verification+Guidance+Final.pdf
[30] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/recommendation_report_draft_final.pdf

2. Select survey areas.

Once a sample size (n) is calculated using the steps above, the exact sampling locations of the n samples need to be identified. In the Chesapeake Bay region, random sampling locations have traditionally been defined along pre-established transect routes. To maintain continuity and long-term comparability, it is recommended to retain some or all of these historical sample locations within the geographic area being surveyed. Additional survey points can then be distributed across non-roadside fields that are missed in traditional surveys. If n_h of the remote sensing sampling locations are fixed to the historical transect sampling locations, a total of n_a new sampling locations should be distributed across non-roadside fields such that $n = n_h + n_a$.

As described in Appendix B of the BMP Verification Guidance document,[31] random or stratified random sampling can be used to select locations for the n_a sampling locations to be distributed across non-roadside fields. It is recommended that the CBP's Land Use/Land Cover layer[32] be used to restrict the sampling of the n_a non-roadside fields to agricultural areas only. Around each of the n sample locations, a square buffer should be constructed such that a remote sensing survey area at least 1-acre in size is constructed. If the total area in acres (A_n) of the union of the n buffer boxes is less than n_0 acres, n should be increased until $A_n \geq n_0$ acres (or until all agricultural areas in the region are totally covered by the buffer boxes).

3. Identify verification data to collect with a secondary methodology.

Ground truthing is the process of collecting in-field data to verify the remote sensing results and ensure the ~~accuracy~~ accurate estimation of ~~the estimated~~ conservation tillage BMP implementation. Once locations for the remote sensing survey have been selected, overlapping ground truth locations should be identified to support accuracy assessment and BMP verification.

In traditional driving transect surveys, 10% of conservation tillage BMP observations are verified through a secondary field visit. However, given the larger area observable via remote sensing, ground truthing 10% of observations is likely infeasible, especially for the VFS and TAC approaches. As an alternative to ground truthing 10% of remote sensing observations, the "Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Roadside Transect Surveys to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program Partnership's Watershed Model"[33] concluded that a minimum sample size of 20 ground truth observations could instead be used to verify the performance of a remote sensing method for detecting BMPs. Accordingly, three verification collection frameworks are noted below.

[31] https://d38c6ppuviqmfp.cloudfront.net/documents/Appendix+B+-Ag+BMP+Verification+Guidance+Final.pdf
[32] https://www.chesapeakeconservancy.org/conservation-innovation-center/high-resolution-data/lulc-data-project-2022/
[33] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/Transect_Survey_Recommendations_Report_3-16-17.pdf

1. When possible, it is recommended that 10% of the n_h historical sampling locations included in the remote sensing survey of a region be selected for verification via a ground-truth method. Ideally, the selection of these points would result in a verification sample area of at least $0.1 * n_0$ acres.
2. When the first ~~this~~ verification approach is infeasible due to cost or logistical constraints, jurisdictions may choose to adhere to the recommendation to use at least 20 ground truth observations of BMP implementation within the remote sensing survey area. These verification points ~~should~~would ideally be selected at historical sampling sites located throughout the remote sensing survey area.

~~1.~~ A third option for verification is to collect ground-truth data over a larger representative area, such as a Hydrologic Unit Code (HUC) area or hydrogeomorphic region. Ideally, ground-truth data collected across these larger regions would occur at $0.1 * n_0$ or more distinct locations and represent an area of at least $0.1 * n_0$ acres. This option may be preferred in regions that do not have historical transect surveys, such as those jurisdictions that were historically restricted from performing roadside transect surveys due to insufficient access to roadside fields. This option allows data from nearby representative regions (e.g., a hydrogeomorphic region) to be used in the performance assessment and verification of the remote sensing method for estimating conservation tillage BMP implementation within a particular jurisdiction.

3.

For each verification approach, practitioners should carefully design the field sampling strategy to capture a representative range of farming conditions and practices to minimize the risk of bias in verification. Accordingly, additional stratified random sampling should be considered if different geographies, crop types, and/or management conditions are not sufficiently represented in the initial sample design. If practical, collecting more verification data than what is called for in each of these approaches is highly recommended.

In all three verification approaches, it ~~is~~ will be critical to delineate the areal boundaries of the ground-truth sites prior to or during the verification process. This step is essential for accurate comparisons between the ground-truth data and the remote sensing estimates. By defining clear boundaries for each ground-truth site, it ensures that the data collected is appropriately aligned with the corresponding remote sensing pixels. As later described, the ground-truth data will then be compared to the remote sensing estimates of conservation tillage on a pixel-by-pixel basis to assess and correct the performance of the remote sensing method.

Survey Implementation

Once the remote sensing survey has been developed, data collection and model application can proceed. The following points outline key considerations for this phase of the methodology:

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1. **Data collection period**: As noted in the definitions of each tillage regime, conservation tillage classification is intended to reflect soil disturbance conditions immediately after planting each crop. Accordingly, in general, data collection should be restricted to the period from the start of March to the end of June.
2. **Use of ancillary data layers**: When utilizing ancillary data layers (e.g., soil types, weather conditions, or crop type information) to support model estimation of conservation tillage regimes, the model documentation should clearly identify and link (as appropriate) these ancillary layers. The sources, resolutions, and temporal relevance of these data should be clearly documented. Ancillary layers should be carefully selected based on relevance to the model and the specific conservation tillage practices being assessed.
3. **Adherence to CBP guidelines for ground-truth data collection**: Any field visits conducted for model verification or ground truthing should adhere to CBP guidelines. These guidelines ensure that field data collection is consistent with established best practices, which promotes the comparability and quality of the verification results across jurisdictions.
4. **Avoidance of double counting**: It is crucial to avoid double counting, which means ensuring that each pixel included in the remote sensing survey is assigned to only (at most) one tillage regime. Double counting can lead to inflated estimates of conservation tillage BMP implementation and undermine the accuracy of the model's results. When analyzing remote sensing data, any pixel that represents a mix of tillage practices should be appropriately categorized to reflect the predominant tillage regime within that area. This practice ensures that the analysis yields a clear and accurate representation of conservation tillage across the jurisdiction.
5. **Technical knowledge and training:** Individuals designing the remote sensing surveys and implementing data collection, model application, and verification processes should have sufficient technical knowledge of the remote sensing methodologies and procedures outlined in this report as well as the related guidance documents "Conservation Tillage Practices for Use in Phase 6.0 of the Chesapeake Bay Program Watershed Model," "Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Remote Sensing to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program Partnership's Watershed Model,"[34] and "Strengthening Verification of Best Management Practices Implemented in the Chesapeake Bay Watershed."[35] For those implementing the remote sensing model and performing results analysis, training on the remote sensing methodology and prior GIS experience is highly recommended to ensure that all personnel are adequately prepared to carry out the procedures with consistency and accuracy. Training should review the remote sensing methodology for conservation tillage

[34] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/recommendation_report_draft_final.pdf

[35] https://d38c6ppuviqmfp.cloudfront.net/documents/Complete%20CBP%20BMP%20Verification%20Framwork%20with%20appendices.pdf

BMP verification and walkthrough examples of generating field delineations for ground-truth verification and performing final accuracy analyses.

Analysis and Reporting

Following the remote sensing classification of tillage regime and the collection of ground-truth data, an overall estimate of conservation tillage BMP implementation can be developed. Assuming data is collected at n_{gt} ground-truth sites over a total area of A_{gt} acres, a confusion matrix can be generated on a pixel-by-pixel basis by comparing remote sensing measurements to ground-truth observations (as shown in Table 2~~Table Table 2Table 2~~).

Table 2. Example confusion matrix for comparison of ground-truth observations and remote sensing classifications

		Ground Truth Observation					
	Class ID	**Not eligible for tillage**	**≤15% residue**	**15-29% residue**	**30-59% residue**	**≥60% residue**	**Row Total**
Remote Sensing Classification	**Not eligible for tillage**	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$	$a_{1,4}$	$a_{1,5}$	$\boldsymbol{a_{1+}}$
	≤15% residue	$a_{2,1}$	$a_{2,2}$	$a_{2,3}$	$a_{2,4}$	$a_{2,5}$	$\boldsymbol{a_{2+}}$
	15-29% residue	$a_{3,1}$	$a_{3,2}$	$a_{3,3}$	$a_{3,4}$	$a_{3,5}$	$\boldsymbol{a_{3+}}$
	30-59% residue	$a_{4,1}$	$a_{4,2}$	$a_{4,3}$	$a_{4,4}$	$a_{4,5}$	$\boldsymbol{a_{3+}}$
	≥60% residue	$a_{5,1}$	$a_{5,2}$	$a_{5,3}$	$a_{5,4}$	$a_{5,5}$	$\boldsymbol{a_{5+}}$
	Column Total	$\boldsymbol{a_{+1}}$	$\boldsymbol{a_{+2}}$	$\boldsymbol{a_{+3}}$	$\boldsymbol{a_{+4}}$	$\boldsymbol{a_{+5}}$	$\boldsymbol{A_{gt}}$

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In the confusion matrix, $a_{i,j}$ represents the total area over which remote sensing classification yielded the i^{th}class and ground-truthing yielded the j^{th} class. To calculate $a_{i,j}$, a GIS software should be used to compute the areal intersection of the ground-truth field delineations and the remote sensing classifications. Ideally, the intersection should be restricted such that only those pixels that fall entirely within the field delineation area are included in the confusion matrix calculations (see Figure 3~~Figure 3~~, for example). However, states may choose to implement other methods (e.g., selecting pixels with ≥50% spatial overlap with the field delineations) to compute the spatial intersections.

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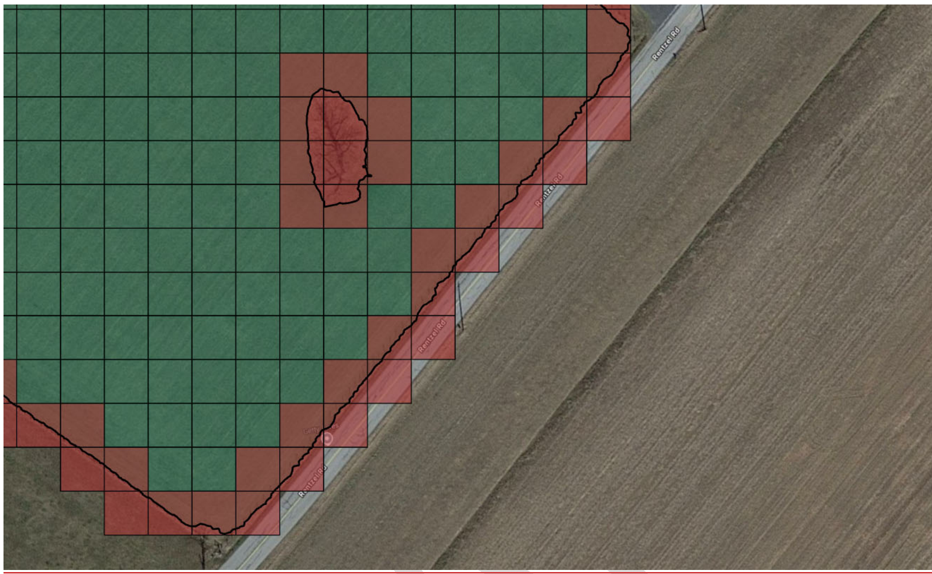

Figure 3. An example of identifying “mixed pixels” to exclude from remote sensing analyses. The thick black outline shows the original field delineation. This original delineation is crossed by several pixels (red) that have spectral responses that are combinations of the agricultural field's spectral signature and other objects’ spectral signatures (e.g., those of the road and tree). Unless steps are taken to perform spectral unmixing, these mixed pixels should not be used for classification of the tillage regime. One method for removing these mixed pixels would be to erode (i.e., apply a negative buffer to) the original field delineation such that mixed pixels do not exist within the eroded polygon.

Figure 4~~Figure 4Figure 3~~ shows an example of an intersection of a remote sensing classification output and a field delineation. In Figure 4~~Figure 4Figure 3~~, the total area of each cell would be tabulated in the confusion matrix and this process would be repeated for all n_{gt} ground-truth sites.

~~*Table 2. Example confusion matrix for comparison of ground-truth observations and remote sensing classifications*~~

		~~**Ground Truth Observation**~~					
	~~**Class ID**~~	~~**Not eligible for tillage**~~	~~**<15% residue**~~	~~**15-29% residue**~~	~~**30-59% residue**~~	~~**≥60% residue**~~	~~**Row Total**~~
~~**Remote Sensing Classification**~~	~~**Not eligible for tillage**~~	$a_{1,1}$	$a_{1,2}$	$a_{1,3}$	$a_{1,4}$	$a_{1,5}$	$\boldsymbol{a_{1+}}$
	~~**<15% residue**~~	$a_{2,1}$	$a_{2,2}$	$a_{2,3}$	$a_{2,4}$	$a_{2,5}$	$\boldsymbol{a_{2+}}$
	~~**15-29% residue**~~	$a_{3,1}$	$a_{3,2}$	$a_{3,3}$	$a_{3,4}$	$a_{3,5}$	$\boldsymbol{a_{3+}}$

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~~30-59% residue~~	$a_{4,1}$	$a_{4,2}$	$a_{4,3}$	$a_{4,4}$	$a_{4,5}$	$\boldsymbol{a_{3+}}$
~~≥60% residue~~	$a_{5,1}$	$a_{5,2}$	$a_{5,3}$	$a_{5,4}$	$a_{5,5}$	$\boldsymbol{a_{5+}}$
~~Column Total~~	$\boldsymbol{a_{+1}}$	$\boldsymbol{a_{+2}}$	$\boldsymbol{a_{+3}}$	$\boldsymbol{a_{+4}}$	$\boldsymbol{a_{+5}}$	$\boldsymbol{A_{gt}}$

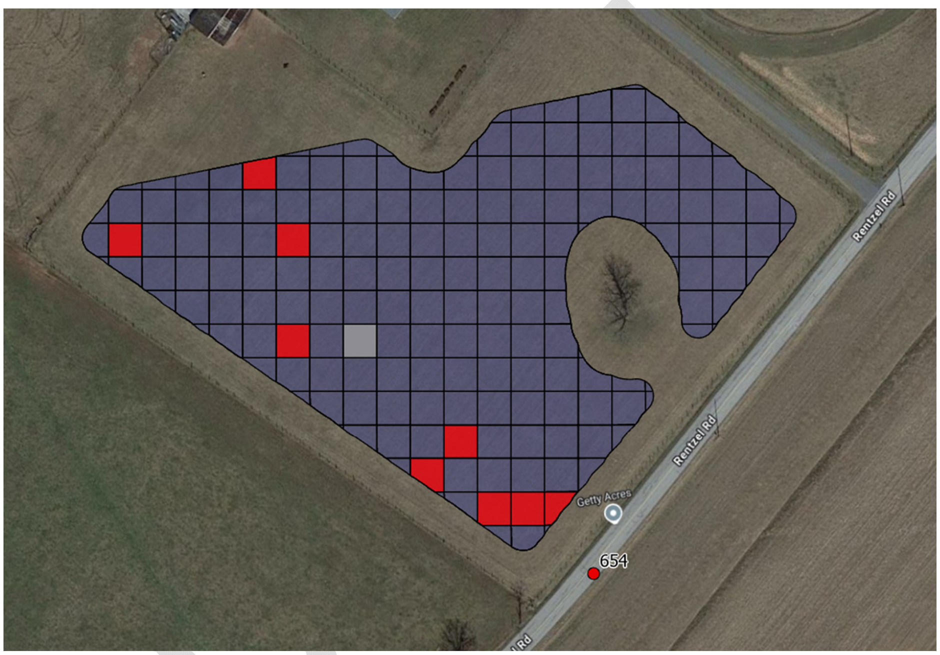

Figure 443. An example BMP verification analysis for a theoretical field. Blue cells identify locations where both ground-truth observation and remote sensing classification identified ≥60% crop residue cover. Red cells identify locations where ground-truth observations identified ≥60% crop residue cover but remote sensing classification identified 30-59% crop residue cover. The gray cell identifies a location where ground-truth observations identified ≥60% crop residue cover but remote sensing classification identified 15-29% crop residue cover.

Following construction of the confusion matrix, the procedure described in "Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Roadside Transect Surveys to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program Partnership's Watershed Model"[36] should be used to calculate:

[36] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/Transect_Survey_Recommendations_Report_3-16-17.pdf

(1) unbiased estimates of the true (adjusted) marginal proportions of each tillage regime with bounds from the selected confidence intervals
(2) producer’s accuracy (also referred to as the hit rate) and variance for each marginal proportion
(3) user’s accuracy (also referred to as the post agreement rate) and variance for each marginal proportion
(4) overall accuracy and variance

Once these values have been calculated, the estimated proportions for each tillage regime can be scaled by the estimated total acreage of croplands eligible for conservation tillage to determine the acreage of each type of conservation tillage BMP implemented in the region.

~~Alternatively~~When field verification reveals any systematic bias, the ratio of the user’s accuracy to the producer’s accuracy can be used to correct for bias in the estimated proportions prior to computing the total conservation tillage BMP implementation areas, as described in “Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Remote Sensing to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program Partnership’s Watershed Model.”[37] This correction method is recommended if:

(1) the overall accuracy is calculated to be at least 71%
(2) the lower confidence limit values of both the producer’s accuracy and the user’s accuracy are at least 70%

The January 2017 “Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Remote Sensing to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program Partnership’s Watershed Model”[38] notes that “Conclusions reached by Sullivan et al. (2008) indicate that a remote sensing method with an overall accuracy of 71% to 78% is acceptable.” Despite this statement, the recommendation report does not directly establish clear acceptance criteria for remote sensing BMP verification results. ~~Additionally,~~Conversely, the March 2017 “Recommendation Report for the Establishment of Uniform Evaluation Standards for Application of Roadside Transect Surveys to Identify and Inventory Agricultural Conservation Practices for the Chesapeake Bay Program Partnership’s Watershed Model”[39] concludes ~~concludes~~ that results from roadside transect surveys ~~may~~ are~~be~~ acceptable if the lower confidence limit on the overall accuracy exceeds 50%.

[37] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/recommendation_report_draft_final.pdf
[38] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/recommendation_report_draft_final.pdf
[39] https://d18lev1ok5leia.cloudfront.net/chesapeakebay/documents/Transect_Survey_Recommendations_Report_3-16-17.pdf

Accordingly, for this methodology, which applies exclusively to conservation tillage BMP remote sensing, it is recommended that to use the proportions resulting from the analysis, the lower confidence limit on the overall accuracy exceeds 50 ~~percent~~%. However, states are encouraged to strive for the highest level of accuracy attainable.