SOCCJ Soil & Water Research Summary

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1 Introduction & Data

The survey is taken once a year from 2020 to 2025. And there are 1858 observations, individuals, and each observation contains 1402 variables. The individuals are consistent across all years, while certain individuals are not observed in some years. And we focus on the variable recording whether using a method of production, Cover crops, for each individual in each year, leveled from 1 to 4, with 1 as not used last year and will not plan to use it, 2 as not used last year and not planning to use it within 3 years but open to use in future, 3 as not used last year but intend to use within 3 years, and 4 as already used last year. The data is blocked into 3 groups (time period), (2020, 2021), (2022, 2023), (2024, 2025). And we may assume data from different year blocks share some of the variables, that is part of the variables from year 2020, 2022, and 2024 are shared, but some are different. This is similar for year 2021, 2023, and 2025. The "cover crops", individual choices of method of production, is recorded in year 2021, 2023, 2025. And there is a group of other substitution methods of production also recorded as same 4 level variables in year 2021, 2023, 2025 together with "cover crops".

1.1 Scientific Questions

For this project, we focus on answering following questions:

(1) Which factors contributed to the individuals' choice of using "cover crops" from year (2020, 2021) to (2022, 2023);

(2) Which factors contributed to the individuals' choice of using "cover crops" from year (2022, 2023) to (2024, 2025);

After the investigation of the scientific questions (1) and (2) and based on the result we have from question (1) from year 2021 to 2023, we have an expectation, prediction, of the expected proportion of usage of "cover crops" in year 2025 given information in year block (2022, 2023), but the actual proportion of usage of "cover crops" in year 2025 is different from our expectation, prediction. Thus, the second part of scientific questions is

(3) what factors contribute to the differences between our expected, predicted, proportion of usage of "cover crops" in year 2025 and the actual proportion of usage of "cover crops" in year 2025.

2 Notation & Data Processing

- Individuals (i=1,. . . ,N) (about 1000).
- Years $(t \in 2020, \ldots, 2025)$.
- Blocks:
  - Block 1: (2020, 2021)
  - Block 2: (2022, 2023)

- Block 2: (2024, 2025)

- Ordered adoption state of cover crops (4 levels) in year ($t \in 2021, 2023, 2025$):

$$Y_{it} \in 1, 2, 3, 4$$

(1 = no use & no plan, ..., 4 = already used last year).

- Let

$$S_i^{(1)} = Y_{i,2021}, \quad Y_i^{(1)} = Y_{i,2023}, \quad S_i^{(2)} = Y_{i,2023}, \quad Y_i^{(2)} = Y_{i,2025}$$

be the "start" and "end" states for blocks 1→2 and 2→3.

- Covariates:
  - (X_{it}^{even}) for even years (2020, 2022, 2024) – "production / structural" covariates.
  - (X_{it}^{odd}) for odd years (2021, 2023, 2025) – attitudes, plans, etc.

  Some of these are shared across blocks (same conceptual variable re-asked).

- Other methods of production (substitutes) are also 4-level variables $(Z_{it}^{(k)})$.

- Panel attrition & refreshment → nonresponse indicators (R_{it}) and design weights (d_{it}). Ultimately we'll work with analysis weights (w_{it}) that combine design + nonresponse adjustments (IPCW + imputation based on PMM).

- PCA was applied to a selected subset of survey variables to reduce dimensionality and summarize their joint variation into a smaller number of orthogonal components. The number of components retained was determined using parallel analysis based on imputed data, ensuring that only components explaining more variance than expected under random noise were kept. Then, we use summation scales of variables, in original non-imputed data, grouped based on loadings as low-dimensional representations of the original variables for further analysis.

3 Analytical Framework

3.1 Construct transition datasets for the two periods

- Dataset A (2021 → 2023) Covariates:

$$\mathcal{X}_i^{(1)} = \big(X_{i,2020}, X_{i,2021}, X_{i,2022}, X_{i,2023}, Z_{\cdot,2021}, Z_{\cdot,2023}\big),$$

possibly with engineered lags/changes (e.g., $(X_{2023} - X_{2021})$).

- Dataset B (2023 → 2025) Covariates:

$$\mathcal{X}_i^{(2)} = \big(X_{i,2022}, X_{i,2023}, X_{i,2024}, X_{i,2025}, Z_{\cdot,2023}, Z_{\cdot,2025}\big),$$

remembering that some 2025 questions refer to 2024.

Keep weights $(w_i^{(1)})$ and $(w_i^{(2)})$ to account for design + attrition.

3.2 Q(1) & (2): model "transition behavior" and drivers

Objective: for each block (b=1,2), estimate

- Transition kernel

$$p_{k\to m}^{(b)}(x) = \Pr\big(Y^{(b)} = m, \big| , S^{(b)} = k,\ \mathcal{X}^{(b)} = x\big),$$

- upward-movement risk

$$u_k^{(b)}(x) = \Pr\big(Y^{(b)} > S^{(b)}, \big| , S^{(b)} = k,\ \mathcal{X}^{(b)} = x\big).$$

From these we can:

- describe transitions (Sankey-style) conditional on covariates;
- identify factors associated with more upward movement (from SHAP, partial dependence, or regression coefficients);
- optionally embed this in a causal estimator later (DML/TMLE) for selected modifiable factors.

3.3 Q(3): expected vs realized 2025 adoption

The analytical framework of this section is currently under development and has not yet been decided.

We want to compare:

- Expected 2025 adoption using only information up to block 2, what we would have predicted for 2025 if the world in 2024–2025 behaved like 2020–2023.
- Actual 2025 adoption with all later changes, including new covariate values in 2024–2025.

Possible set up:

- Fit a model for transition structure using block 1→2 (dataset A):

$$g^{(1)}(s, x_{\text{pre}}) \approx \mathbb{E}\big[Y^{(2)} \mid S^{(2)} = s,\ \mathcal{X}_{\le 2023} = x_{\text{pre}}\big]$$

  trained only on variables available by 2023.

- Apply $(g^{(1)})$ to the 2023 population (with 2022 and 2023 covariates) to obtain a predicted distribution $(\hat{Y}_{2025}^{\text{pred}})$ and its proportion $(\hat{\pi}_{2025}^{\text{pred}})$.
- Compare with realized 2025 adoption proportion $(\hat{\pi}_{2025}^{\text{obs}})$ (using directly 2025 data).

Define the gap

$$\Delta = \hat{\pi}_{2025}^{\text{obs}} - \hat{\pi}_{2025}^{\text{pred}}.$$

Fit a full model $(g^{(2)})$ on block 2→3 with more covariates $(\mathcal{X}^{(2)})$ (including 2024/25 covariates), then investigate

$$d_i = g^{(2)}(S_i^{(2)}, \mathcal{X}_i^{(2)}) - g^{(1)}(S_i^{(2)}, \mathcal{X}_i^{\text{pre}})$$

explained by new covariates.

4 Theoretical Models & Estimands

4.1 Transition Boosting for Q(1) & Q(2)

4.1.1 Multiclass transition model (focusing on transition kernel)

For each block $b \in \{1, 2\}$ and individual $i \in \{1, \ldots, N\}$, we observe an origin state $S_i^{(b)} \in \{1, 2, 3, 4\}$ and a destination state $Y_i^{(b)} \in \{1, 2, 3, 4\}$, together with a covariate vector $\mathcal{X}_i^{(b)}$. We model the transition probabilities $p_{k\to m}^{(b)}(x) = \Pr(Y^{(b)} = m \mid S^{(b)} = k, \mathcal{X}^{(b)} = x)$ using a multiclass gradient-boosted tree model.

We form a feature vector

$$x_i^{(b)} \equiv \big(S_i^{(b)},\ \mathcal{X}_i^{(b)}\big), \tag{1}$$

where $S_i^{(b)}$ is included as a categorical predictor (implemented via one-hot indicators in the model matrix; e.g., `Y_from1`, ..., `Y_from4`).

The model produces one real-valued *class margin* (score) for each destination level m:

$$f_m^{(b)}\big(x_i^{(b)}\big) \in \mathbb{R}, \qquad m = 1, 2, 3, 4. \tag{2}$$

The predicted transition probabilities are obtained through the softmax link:

$$\hat{p}_{im}^{(b)} = \Pr\Big(Y_i^{(b)} = m \,\Big|\, x_i^{(b)}\Big) = \frac{\exp\big(f_m^{(b)}(x_i^{(b)})\big)}{\sum_{r=1}^{4} \exp\big(f_r^{(b)}(x_i^{(b)})\big)}, \qquad m = 1, 2, 3, 4. \tag{3}$$

4.1.2 From leveled responses to multiclass training targets

For training, the original state and observed destination state $Y_i^{(b)} \in \{1, 2, 3, 4\}$ is represented by indicator variables $y_{im}^{(b)}$:

$$y_{im}^{(b)} = \mathbf{1}\{Y_i^{(b)} = m\}, \qquad m = 1, 2, 3, 4. \tag{4}$$

Given the softmax probabilities $\hat{p}_{im}^{(b)}$, the likelihood contribution of observation i can be written as

$$\Pr\Big(Y_i^{(b)} \,\Big|\, x_i^{(b)}\Big) = \prod_{m=1}^{4} \Big(\hat{p}_{im}^{(b)}\Big)^{y_{im}^{(b)}}. \tag{5}$$

We use analysis weights $w_i^{(b)}$ (design weights with attrition/nonresponse adjustments) in model training and in all summary estimands.

4.1.3 Loss function for training (weighted multiclass cross-entropy)

Let $\hat{p}_{im}^{(b)}$ be the softmax probabilities implied by margins $f_m^{(b)}(x_i^{(b)})$. The weighted multiclass negative log-likelihood (cross-entropy) optimized by XGBoost is:

$$\mathcal{L}^{(b)} = -\sum_{i=1}^{n_b} w_i^{(b)} \sum_{m=1}^{4} y_{im}^{(b)} \log \hat{p}_{im}^{(b)}, \tag{6}$$

equivalently

$$\mathcal{L}^{(b)} = -\sum_{i=1}^{n_b} w_i^{(b)} \log \hat{p}_{i,Y_i^{(b)}}^{(b)}. \tag{7}$$

4.1.4 Transition matrix estimation from fitted probabilities

After fitting the Transition Boosting model for block b, we compute fitted probabilities $\hat{p}_{im}^{(b)}$ for each observation. The weighted (model-based) transition matrix estimator is obtained by averaging predicted probabilities within each origin level k:

$$\widehat{T}_{k\to m}^{(b)} = \frac{\sum_{i:\, S_i^{(b)}=k} w_i^{(b)}\, \hat{p}_{im}^{(b)}}{\sum_{i:\, S_i^{(b)}=k} w_i^{(b)}}, \qquad k, m \in \{1,2,3,4\}. \tag{8}$$

This provides an estimate of the transition distribution in the weighted target population, as presented in Table 3 and Table 4.

4.1.5 Covariate ranking by gain (loss reduction attributed to splits)

We rank covariates using the *gain* importance from XGBoost. Conceptually, gain measures how much a covariate contributes to reducing the training objective through splits in the fitted tree ensemble.

For block b, the model is trained by minimizing the weighted multiclass cross-entropy loss

$$\mathcal{L}^{(b)} = -\sum_{i=1}^{n_b} w_i^{(b)} \log \hat{p}_{i,Y_i^{(b)}}^{(b)}, \tag{9}$$

where $\hat{p}_{i,Y_i^{(b)}}^{(b)}$ is the fitted probability assigned to the observed destination level $Y_i^{(b)}$ under the softmax model.

During training, XGBoost grows trees by selecting splits that decrease the loss. For a candidate split s, define its (training) loss reduction as

$$\Delta\mathcal{L}^{(b)}(s) \equiv \mathcal{L}^{(b)}_{\text{before split } s} - \mathcal{L}^{(b)}_{\text{after split } s}. \tag{10}$$

A split is beneficial when $\Delta\mathcal{L}^{(b)}(s) > 0$.

Let j denote a feature (a column) in the model matrix. The gain importance for feature j is defined as the sum of loss reductions over all splits in the fitted ensemble that use j:

$$\text{Gain}^{(b)}(j) = \sum_{s:\, \text{split } s \text{ uses feature } j} \Delta\mathcal{L}^{(b)}(s). \tag{11}$$

Because categorical covariates and year-suffixed covariates can expand into multiple model-matrix columns, we aggregate gain to a base covariate (denoted B). Let $j \in B$ indicate that column j belongs to base covariate B. The aggregated gain is

$$\text{Gain}^{(b)}(B) = \sum_{j\in B} \text{Gain}^{(b)}(j). \tag{12}$$

We rank covariates by $\text{Gain}^{(b)}(B)$ to identify which base covariates most strongly improve prediction of transition outcomes in the fitted Transition Boosting model, as presented in Table 5 and Table 6.

4.1.6 SHAP decomposition of margins and weighted signed summaries (shap_dir)

For a fixed block b (time block) and a fixed destination class m, TreeSHAP provides an additive decomposition of the fitted margin:

$$f_m^{(b)}(x_i^{(b)}) = \phi_{0m}^{(b)} + \sum_{j=1}^{p_b} \phi_{ijm}^{(b)}, \tag{13}$$

where $\phi_{0m}^{(b)}$ is a baseline margin and $\phi_{ijm}^{(b)}$ is the SHAP contribution of feature j for observation i and class m.

To summarize SHAP at the base-covariate level, we aggregate SHAP values across model-matrix columns belonging to the same base covariate c:

$$\Phi_{icm}^{(b)} = \sum_{j\in c} \phi_{ijm}^{(b)}. \tag{14}$$

To align interpretation with transition rows, we compute origin-stratified, weighted signed averages of SHAP contributions (denoted `shap_dir` in outputs):

$$\text{shap\_dir}^{(b)}_{k,m}(c) = \frac{\sum_{i:\, S_i^{(b)}=k} w_i^{(b)}\, \Phi^{(b)}_{icm}}{\sum_{i:\, S_i^{(b)}=k} w_i^{(b)}}, \qquad k, m \in \{1,2,3,4\}. \tag{15}$$

The SHAP direction (signed SHAP) summaries are presented from Table 7 to Table 14.

4.1.7 Permutation impact tables on the probability scale

To present probability-scale directional effects aligned with the transition matrix, we compute permutation impact for each base covariate $c \in \mathcal{C}_b$. For a fixed origin level s, we permute the covariate block c within the stratum $\{i : S_i^{(b)} = s\}$ to break the association between c and the remaining covariates. Let π denote a random permutation over indices in this stratum, and define the permuted feature vector

$$x_i^{(-c)} \;=\; \big(x^{(b)}_{i,-c},\; x^{(b)}_{\pi(i),c}\big), \tag{16}$$

where $x^{(b)}_{i,-c}$ denotes all features except group c, and $x^{(b)}_{\pi(i),c}$ denotes the permuted value of group c.

For destination level m, define the (weighted) probability-impact estimand

$$\Delta^{\text{PI},(b)}_{s\to m}(c) \;=\; \mathbb{E}_w\Big[\hat{p}^{(b)}_{im}(x_i^{(b)}) - \hat{p}^{(b)}_{im}(x_i^{(-c)}) \;\Big|\; S_i^{(b)} = s\Big]. \tag{17}$$

Its empirical weighted estimator is

$$\widehat{\Delta}^{\text{PI},(b)}_{s\to m}(c) \;=\; \frac{\sum_{i:\, S_i^{(b)}=s} w_i^{(b)} \Big(\hat{p}^{(b)}_{im}(x_i^{(b)}) - \hat{p}^{(b)}_{im}(x_i^{(-c)})\Big)}{\sum_{i:\, S_i^{(b)}=s} w_i^{(b)}}. \tag{18}$$

Because permutation is random, we average over R independent permutations to obtain a stable estimate:

$$\overline{\Delta}^{\text{PI},(b)}_{s\to m}(c) \;=\; \frac{1}{R}\sum_{r=1}^{R} \widehat{\Delta}^{\text{PI},(b,r)}_{s\to m}(c). \tag{19}$$

The permutation impact tables are presented from Table 15 to Table 22.

4.2 Markov Transition Model for Q(1) & Q(2)

4.2.1 Multiclass Markov transition model (transition kernel)

For each block $b \in \{1,2\}$ and individual $i \in \{1,\dots,N\}$, we observe an origin state $S_i^{(b)} \in \{1,2,3,4\}$ and a destination state $Y_i^{(b)} \in \{1,2,3,4\}$, together with a covariate vector $\mathcal{X}_i^{(b)}$ and an analysis weight $w_i^{(b)} > 0$. We define the (covariate-dependent) transition kernel

$$p^{(b)}_{k\to m}(x) = \Pr\big(Y^{(b)} = m \,\big|\, S^{(b)} = k,\; \mathcal{X}^{(b)} = x\big), \qquad k, m \in \{1,2,3,4\}. \tag{20}$$

The goal of the Markov Transition Model (MTM) is to estimate $p^{(b)}_{k\to m}(x)$ and to identify covariates in $\mathcal{X}^{(b)}$ that are most predictive of transition behavior.

We fit a single pooled multinomial logistic regression for each block b by modeling the conditional distribution of $Y_i^{(b)}$ given $(S_i^{(b)}, \mathcal{X}_i^{(b)})$, using destination level 1 as the reference category. Define the feature vector

$$x_i^{(b)} \equiv \big(S_i^{(b)},\; \mathcal{X}_i^{(b)}\big). \tag{21}$$

For each destination level $m \in \{2,3,4\}$, the baseline-category logit model specifies

$$\log\left(\frac{\Pr(Y_i^{(b)}=m \mid x_i^{(b)})}{\Pr(Y_i^{(b)}=1 \mid x_i^{(b)})}\right) = \eta_{im}^{(b)} = \alpha_m^{(b)} + \gamma_m^{(b)}\big(S_i^{(b)}\big) + \big(\mathcal{X}_i^{(b)}\big)^\top \beta_m^{(b)}. \tag{22}$$

Here:

- $\alpha_m^{(b)}$ is the intercept (baseline log-odds for destination m vs 1);
- $\gamma_m^{(b)}(S)$ is the initial-state effect (origin effect) for destination m vs 1;
- $\beta_m^{(b)}$ is the coefficient vector for covariates in $\mathcal{X}^{(b)}$ for destination m vs 1.

We treat S as a categorical predictor with reference level $S=1$, so that

$$\gamma_m^{(b)}(1) \equiv 0, \qquad \gamma_m^{(b)}(k) \text{ is estimated for } k \in \{2,3,4\}. \tag{23}$$

Given the linear predictors $\eta_{im}^{(b)}$, the MTM implied transition probabilities are

$$\hat{p}_{im}^{(b)} = \Pr\big(Y_i^{(b)}=m \mid x_i^{(b)}\big) = \frac{\exp(\eta_{im}^{(b)})}{1+\sum_{r=2}^{4}\exp(\eta_{ir}^{(b)})}, \qquad m=2,3,4, \tag{24}$$

and for the reference destination

$$\hat{p}_{i1}^{(b)} = \Pr\big(Y_i^{(b)}=1 \mid x_i^{(b)}\big) = \frac{1}{1+\sum_{r=2}^{4}\exp(\eta_{ir}^{(b)})}. \tag{25}$$

Odds ratios. For a numerical covariate x_j (a component of $\mathcal{X}$), holding all other predictors fixed, a one-unit increase in x_j changes the log-odds of $Y=m$ vs $Y=1$ by $\beta_{m,j}^{(b)}$, and the corresponding odds ratio is $\exp\big(\beta_{m,j}^{(b)}\big)$. For categorical covariates expanded into dummy variables, each dummy coefficient is interpreted as the log-odds difference relative to the baseline category (see below).

4.2.2 From leveled responses to multinomial likelihood targets

For training, define indicator variables for the destination class:

$$y_{im}^{(b)} = \mathbf{1}\{Y_i^{(b)}=m\}, \qquad m=1,2,3,4. \tag{26}$$

Given the MTM probabilities $\hat{p}_{im}^{(b)}$, the likelihood contribution of observation i can be written as

$$\Pr\big(Y_i^{(b)} \,\big|\, x_i^{(b)}\big) = \prod_{m=1}^{4}\big(\hat{p}_{im}^{(b)}\big)^{y_{im}^{(b)}}. \tag{27}$$

We incorporate analysis weights $w_i^{(b)}$ in estimation to account for design and attrition/nonresponse adjustments.

4.2.3 Loss function for training (weighted multinomial log-loss)

Let $\theta^{(b)}$ denote the collection of MTM parameters $\{\alpha_m^{(b)}, \gamma_m^{(b)}(\cdot), \beta_m^{(b)}\}_{m=2}^4$. The weighted multinomial negative log-likelihood (weighted log-loss / cross-entropy) is

$$\mathcal{L}^{(b)}(\theta^{(b)}) = -\sum_{i=1}^{n_b} w_i^{(b)} \sum_{m=1}^{4} y_{im}^{(b)} \log \hat{p}_{im}^{(b)}(\theta^{(b)}), \tag{28}$$

equivalently

$$\mathcal{L}^{(b)}(\theta^{(b)}) = -\sum_{i=1}^{n_b} w_i^{(b)} \log \hat{p}_{i,Y_i^{(b)}}^{(b)}(\theta^{(b)}). \tag{29}$$

Thus, weights enter multiplicatively in the objective: observations with larger $w_i^{(b)}$ exert greater influence on the fitted transition model.

4.2.4 Ridge-regularized MTM estimation

In practice, the multinomial MTM can become numerically unstable when the covariate dimension is large, when many categorical variables are expanded into sparse dummy indicators, or when strong multicollinearity is present. To stabilize estimation, we apply Ridge regularization to the MTM.

The (unpenalized) weighted multinomial log-loss is

$$\mathcal{L}^{(b)}(\theta^{(b)}) = -\sum_{i=1}^{n_b} w_i^{(b)} \log \hat{p}^{(b)}_{i,Y_i^{(b)}}(\theta^{(b)}). \tag{30}$$

Ridge regularization augments this objective by adding an ℓ_2 penalty on the (non-intercept) coefficients, minimizing

$$\widehat{\theta}^{(b)}(\lambda) = \arg\min_{\theta^{(b)}} \left\{ \mathcal{L}^{(b)}(\theta^{(b)}) + \lambda \left\| \theta^{(b)} \right\|_2^2 \right\}, \tag{31}$$

where $\lambda \geq 0$ controls the amount of shrinkage. Larger λ shrinks coefficients toward 0, reducing variance and mitigating instability due to multicollinearity and sparse dummy variables.

We select λ by cross-validation on the weighted multinomial log-loss, and we use the $\lambda_{1\text{se}}$ rule to choose a parsimonious model whose cross-validated loss is within one standard error of the minimum.

4.2.5 LASSO-regularized MTM estimation

Under LASSO, we estimate $\theta^{(b)}$ by minimizing the penalized objective

$$\widehat{\theta}^{(b)}(\lambda) = \arg\min_{\theta^{(b)}} \left\{ \mathcal{L}^{(b)}(\theta^{(b)}) + \lambda \sum_m \left\| \theta_m^{(b)} \right\|_1 \right\}, \tag{32}$$

where $\lambda \geq 0$ controls the amount of regularization. The ℓ_1 penalty encourages sparsity, where many coefficients (including dummy-variable coefficients) are shrunk exactly to 0, which yields an automatic variable-selection effect and improves numerical stability.

We select λ by cross-validation on the weighted multinomial log-loss, and we use the $\lambda_{1\text{se}}$ rule to choose a parsimonious model whose cross-validated loss is within one standard error of the minimum.

4.2.6 Transition matrix estimation from fitted MTM probabilities

After fitting the MTM for block b, we compute fitted probabilities $\hat{p}_{im}^{(b)}$ for each observation. The weighted (model-based) transition matrix estimator is obtained by averaging predicted probabilities within each origin level k:

$$\widehat{T}_{k\to m}^{(b)} = \frac{\sum_{i:\, S_i^{(b)}=k} w_i^{(b)}\, \hat{p}_{im}^{(b)}}{\sum_{i:\, S_i^{(b)}=k} w_i^{(b)}}, \qquad k, m \in \{1,2,3,4\}. \tag{33}$$

Each row sums to 1 by construction, and $\widehat{T}_{k\to m}^{(b)}$ is interpreted as the estimated (weighted) probability of transitioning from origin level k to destination level m in block b. The results of estimations of transition probabilities are presented in Table 23 and Table 24 for Ridge regularized estimation and Table 29 and Table 30 for LASSO regularized estimation.

4.2.7 Covariate ranking by permutation importance on weighted log-loss (single fitted model)

To rank covariates by predictive contribution while keeping a single fitted MTM, we compute permutation importance using the weighted log-loss. Let $\hat{p}^{(b)}_{i,Y_i^{(b)}}$ denote the fitted probability assigned to the observed destination $Y_i^{(b)}$ under the original (unpermuted) predictors. Define the baseline weighted log-loss

$$\widehat{\mathcal{L}}^{(b)}_{\text{base}} = -\sum_{i=1}^{n_b} w_i^{(b)} \log \hat{p}^{(b)}_{i,Y_i^{(b)}}. \tag{34}$$

For a covariate unit c (defined below), we permute the values of c across individuals to break its association with $(S, \mathcal{X}_{-c})$ while keeping the fitted MTM parameters fixed. Let π be a random permutation of indices $\{1, \ldots, n_b\}$ and write the permuted predictor vector as

$$x_i^{(-c)} \equiv \left(x_{i,-c}^{(b)},\ x_{\pi(i),c}^{(b)}\right). \tag{35}$$

We then recompute the predicted probabilities under the same fitted MTM, obtaining $\hat{p}_{i,Y_i^{(b)}}^{(b),\pi(c)}$, and compute the permuted weighted log-loss

$$\widehat{\mathcal{L}}_{\pi(c)}^{(b)} = -\sum_{i=1}^{n_b} w_i^{(b)} \log \hat{p}_{i,Y_i^{(b)}}^{(b),\pi(c)}. \tag{36}$$

The permutation importance score is defined as the increase in weighted log-loss:

$$\mathrm{Imp}^{(b)}(c) = \widehat{\mathcal{L}}_{\pi(c)}^{(b)} - \widehat{\mathcal{L}}_{\text{base}}^{(b)}. \tag{37}$$

In practice we average over $R = 5$ independent permutations:

$$\overline{\mathrm{Imp}}^{(b)}(c) = \frac{1}{R}\sum_{r=1}^{R} \mathrm{Imp}^{(b,r)}(c). \tag{38}$$

Larger $\overline{\mathrm{Imp}}^{(b)}(c)$ indicates that permuting c degrades predictive performance more, so c is ranked as more important.

Numerical vs categorical (dummy) variables. For a numerical covariate x_j, the permutation unit c is the single column x_j, and permutation means replacing x_{ij} by $x_{\pi(i)j}$. For a categorical covariate C expanded into dummy variables $\{D_\ell\}$ (baseline level c_0), there are two valid choices:

- **Dummy-level permutation (per-dummy ranking).** Treat each dummy column D_ℓ as its own unit c and permute that 0/1 column across individuals; this produces importance scores for each dummy level separately.
- **Block permutation (category-level ranking).** Treat the entire set of dummy columns belonging to C as a group and permute them jointly (equivalently, permute the original factor C); this preserves valid one-hot structure and yields an importance score for the base categorical variable.

In either case, the weighted log-loss is computed identically; only the definition of the permuted unit c differs.
The results of covariate ranking by permutation importance are presented in Table 25 and Table 26 for Ridge regularized estimation and Table 31 and Table 32 for LASSO regularized estimation.

4.2.8 Direction on log-odds tables (reference destination $Y = 1$)

To summarize the direction of association between covariates and transition outcomes on the log-odds scale, we construct "Direction on log-odds" tables from the fitted MTM coefficients with $Y = 1$ as the reference destination. For each destination $m \in \{2, 3, 4\}$, the MTM log-odds are

$$\log\left(\frac{\Pr(Y^{(b)} = m \mid S^{(b)}, \mathcal{X}^{(b)})}{\Pr(Y^{(b)} = 1 \mid S^{(b)}, \mathcal{X}^{(b)})}\right) = \alpha_m^{(b)} + \gamma_m^{(b)}\left(S^{(b)}\right) + \left(\mathcal{X}^{(b)}\right)^\top \beta_m^{(b)}. \tag{39}$$

Intercept row. The intercept entry in destination column m is $\alpha_m^{(b)}$, interpreted as the log-odds of $Y = m$ vs $Y = 1$ for individuals at the reference origin state $S = 1$ and with covariates at their reference/zero-coded values (baseline factor levels and 0 for numeric covariates as coded).

Initial-state effect rows. Because $S = 1$ is the reference origin level, we set $\gamma_m^{(b)}(1) = 0$ and report $\gamma_m^{(b)}(2), \gamma_m^{(b)}(3), \gamma_m^{(b)}(4)$ as log-odds shifts relative to $S = 1$:

$$\gamma_m^{(b)}(k) = \log\left(\frac{\text{odds}(Y = m \text{ vs } 1 \mid S = k, \mathcal{X})}{\text{odds}(Y = m \text{ vs } 1 \mid S = 1, \mathcal{X})}\right), \qquad k = 2, 3, 4. \tag{40}$$

Covariate rows: numerical variables. For a numerical covariate x_j, the table entry in destination column m is $\beta_{m,j}^{(b)}$. A one-unit increase in x_j changes the log-odds of $Y = m$ vs $Y = 1$ by $\beta_{m,j}^{(b)}$, and the corresponding odds ratio is $\exp\big(\beta_{m,j}^{(b)}\big)$.

Covariate rows: categorical variables (dummy variables kept separate). For a categorical covariate C with baseline level c_0 and dummy indicators $D_\ell = \mathbf{1}\{C = c_\ell\}$, $\ell = 1, \ldots, L$, we keep each dummy as its own row in the table (e.g., `C_level` in outputs). The table entry in destination column m is $\beta_{m,D_\ell}^{(b)}$, interpreted as the log-odds difference between level c_ℓ and baseline c_0 for $Y = m$ vs $Y = 1$, holding other predictors fixed.

Connection to transition probabilities. The direction tables summarize effects on the log-odds scale, while the transition matrix summarizes effects on the probability scale. Because probabilities are obtained through a softmax transformation, a positive coefficient $\beta_{m,j}^{(b)} > 0$ increases the log-odds of destination m relative to 1, but the resulting change in $\Pr(Y = m)$ depends on the full set of class scores $\{\eta_{ir}^{(b)}\}_{r=2}^{4}$.

The summary of directions of associations between covariates and transition outcomes on the log-odds scale are presented in Table 27 and Table 28 for Ridge regularized estimation and Table 33 and Table 34 for LASSO regularized estimation.

5 Results

5.1 Synthesis of covariate drivers for Q(1) & Q(2) across Transition Boosting and Ridge/LASSO Markov Transition Models

To answer Scientific Questions (1) and (2), we synthesize (i) Transition Boosting (TB) for nonlinear screening and probability-scale attribution, (ii) MTM (Ridge) for stable inference-ready covariate ranking and direction on the log-odds scale, and (iii) MTM (LASSO) as a sparse sensitivity screen under collinearity. We use MTM (Ridge) as the primary narration model, and TB as robustness to detect origin-specific heterogeneity and probability-scale impacts on $\widehat{T}_{s\to k}$.

Baseline transition regimes. Across both blocks, MTM (Ridge) indicates persistence-dominant transition structure, whereas TB allocates relatively more mass to cross-level movement. For 2021→2023, TB shown in Table 3 yields moderate persistence (e.g., $\widehat{T}_{1\to 1} = 0.47$, $\widehat{T}_{4\to 4} = 0.51$) while MTM (Ridge) in Table 23 shows stronger self-transition (e.g., $\widehat{T}_{1\to 1} = 0.68$, $\widehat{T}_{4\to 4} = 0.66$). For 2023→2025, TB shown in Table 4 suggests weaker persistence (e.g., $\widehat{T}_{4\to 4} = 0.28$, $\widehat{T}_{3\to 3} = 0.10$) while MTM (Ridge) in Table 24 remains persistence-dominant (e.g., $\widehat{T}_{4\to 4} = 0.65$, $\widehat{T}_{2\to 2} = 0.44$). Because the estimated transition matrices from MTM (Ridge) are more consistant with the actual proportions of transitional states presented in Table 1 and Table 2, we therefore interpret covariate effects primarily through MTM (Ridge) (ranking + direction), with TB used to validate and refine transition-mechanism interpretation on the probability scale.

Q(1): 2021→2023 drivers. TB gain ranking presented in Table 5 and MTM (Ridge) presented in Table 25 permutation importance agree on a core driver set dominated by the `Y23_20_`$\star$ management/practice variables and perceived barriers. The overlapping leading predictors include `Y23_20_N_mgmt_prac`, `Y23_17`, `Y23_20v`, `Y23_20u`, `Y23_20s`, `Y23_20t`, and `Y21_24_CC_barriers`. MTM (Ridge) log-odds direction tables 27 (reference destination $Y = 1$) indicate that `Y23_20_N_mgmt_prac`, `Y23_20v`, `Y23_20u`, `Y23_20s`, and `Y23_20t` are directionally associated with higher destinations ($Y \in \{2, 3, 4\}$ versus $Y = 1$), whereas `Y21_24_CC_barriers` is directionally consistent with reduced movement toward $Y = 4$. TB probability-scale permutation impacts corroborate these directions and highlight origin-specific contributions (e.g., for destination $Y = 4$, `Y23_20v` is positive across origins while `Y23_20s` is negative as presented in Table 18). MTM (LASSO) in Table 31 retains the same dominant subset (`Y23_20_N_mgmt_prac`, `Y23_17`, `Y23_20v`, `Y23_20u`, `Y21_24_CC_barriers`) and is treated as a sparse screen rather than a definitive selector under correlation.

Q(2): 2023→2025 drivers. In 2023→2025, cross-method overlap presented in Table 6 and Table 26 highlights `Y25_27q`, `Y25_27h`, `Y25_27r`, `Y25_25b`, `Y25_25c`, and `Y25_27o`, with MTM (Ridge) additionally elevating `Y25_27p`, `Y25_26_Compaction_mgmt_prac`, and `Y24_7_Stress`. MTM (Ridge) direction tables 28 indicate that `Y25_26_Compaction_mgmt_prac` and several `Y25_27`$\star$ variables shift log-odds toward $Y \in \{2, 3, 4\}$ (vs $Y = 1$), while `Y24_7_Stress` shifts log-odds toward $Y = 1$. TB probability-scale permutation impacts reveal strong origin heterogeneity (e.g., for destination $Y = 4$, `Y25_25b` is positive for $S = 1$ but negative for $S = 4$ as presented in Table 22), refining interpretation of $\widehat{T}_{s\to k}$ by baseline state. MTM (LASSO) again in Table 34 supports a compact subset (`Y25_27q`, `Y25_26_Compaction_mgmt_prac`, `Y25_25b`, `Y25_27p`, `Y25_27o`, `Y25_27h`, `Y25_27j`, `Y25_27r`) while being interpreted cautiously under collinearity.

Overall conclusion from cooperating methods. Combining MTM (Ridge) (stable ranking + log-odds direction), TB (nonlinear screening + probability-scale impacts on $\widehat{T}_{s\to k}$), and MTM (LASSO) (sparse sensitivity), the results support (i) a 2021→2023 driver regime dominated by `Y23_20_N_mgmt_prac` and related `Y23_20_`$\star$ covariates with counter-direction from `Y21_24_CC_barriers`, and (ii) a 2023→2025 regime dominated by `Y25_27q`, `Y25_27p`, `Y25_26_Compaction_mgmt_prac`, and `Y24_7_Stress`, with TB indicating that several key effects vary across origins S.

5.2 Original Proportion of Transitional States

Table 1: The transition proportions from year 2021 to year 2023.

from\to	1	2	3	4
1	0.66	0.19	0.06	0.09
2	0.35	0.41	0.13	0.11
3	0.19	0.32	0.30	0.19
4	0.16	0.08	0.12	0.65

Rows correspond to the initial (origin) cover-crop level $S = s$ and columns correspond to the destination level $Y = k$; the entry $T_{s\to k}$ is the proportion of observations transitioning from level s to level k, with each row summing to 1.

Table 2: The transition propotions from year 2023 to year 2025.

from\to	1	2	3	4
1	0.56	0.24	0.09	0.12
2	0.35	0.38	0.15	0.12
3	0.26	0.26	0.25	0.23
4	0.27	0.16	0.08	0.50

5.3 Transition Boosting

Table 3: The estimated transition distribution from year 2021 to year 2023.

from\to	1	2	3	4
1	0.47	0.26	0.11	0.16
2	0.34	0.33	0.13	0.20
3	0.27	0.30	0.22	0.21
4	0.25	0.11	0.13	0.51

Rows correspond to the initial (origin) cover-crop level $S = s$ and columns correspond to the destination level $Y = k$; the entry $\widehat{T}_{s\to k}$ is the estimated (weighted) probability of transitioning from level s to level k, with each row summing to 1.

Table 4: The estimated transition distribution from year 2023 to year 2025.

from\to	1	2	3	4
1	0.42	0.26	0.10	0.21
2	0.41	0.30	0.13	0.15
3	0.46	0.28	0.10	0.16
4	0.37	0.26	0.09	0.28

Table 5: Rank of covariates using the gain importance from XGBoost from year block (2020, 2021) to year block (2022, 2023).

	Covariates	Gain
1	Y23_20_N_mgmt_prac	0.09
2	Y23_17	0.07
3	Y23_20s	0.07
4	Y23_20t	0.05
5	Y23_20v	0.05
6	Y_from4	0.05
7	Y22_3_Productivist	0.03
8	Y23_18	0.03
9	Y21_24_CC_barriers	0.02
10	Y23_19	0.02
11	Y22_2_Opinion_leader	0.02
12	Y22_3_Steward	0.02
13	Y20_13_Stewardship_motive	0.02
14	Y22_17a_Trauma	0.02
15	Y23_33	0.02
16	Y23_20_EoF_prac	0.02
17	Y23_20u	0.02
18	Y21_11_4R_Info_ag	0.02
19	Y21_8_Soil_health	0.02
20	Y20_13_Social_motive	0.01
21	Y23_20_Other_prac	0.01
22	Y20_19	0.01
23	Y22_16_Public_entities	0.01
24	Y21_13v	0.01
25	Y22_16_Trusted_entities	0.01
26	Y20_4acde_scale	0.01
27	Y21_24_CC_support	0.01
28	Y20_14	0.01
29	Y21_24_CC_incentives	0.01
30	Y20_23abdl_scale	0.01
31	Y20_CC_Beliefs	0.01
32	Y22_16_Private_entities	0.01
33	Y21_13q	0.01
34	Y20_5abcdefghi_sum	0.01
35	Y20_3abcd_scale	0.01
36	Y21_24i	0.01
37	Y20_13_Regulatory_motive	0.01
38	Y20_11acdgi_scale	0.01
39	Y21_29	0.01
40	Y_from3	0.01
⋮		

Each row corresponds to a (year-suffixed) base covariate; the reported gain is the total loss reduction attributed to splits using that covariate (aggregated across expanded model-matrix columns), with larger gain indicating greater predictive contribution to the transition outcome.

Table 6: Rank of covariates using the gain importance from XGBoost from year block (2022, 2023) to year block (2024, 2025).

	Covariates	Gain
1	Y25_25b	0.19
2	Y25_27h	0.06
3	Y25_27r	0.05
4	Y25_25c	0.05
5	Y25_27q	0.05
6	Y23_21_Econ_capacity	0.03
7	Y25_27o	0.03
8	Y24_4	0.03
9	Y23_21_Agron_efficacy	0.02
10	Y25_27k	0.02
11	Y25_26_Compaction_mgmt_tech	0.02
12	Y25_26_Compaction_mgmt_prac	0.02
13	Y24_22_Conservation_advisor	0.02
14	Y25_26_Compaction_concern	0.02
15	Y23_20_N_mgmt_prac	0.02
16	Y25_27d	0.02
17	Y24_21_NRS_support	0.02
18	Y25_27j	0.02
19	Y23_20_EoF_prac	0.02
20	Y24_3_Satisfaction	0.02
21	Y25_25d	0.02
22	Y24_7_Stress	0.02
23	Y24_6	0.02
24	Y22_17a_Trauma	0.01
25	Y25_27c	0.01
26	Y22_3_Steward	0.01
27	Y22_2_Opinion_leader	0.01
28	Y23_20_Other_prac	0.01
29	Y25_27a	0.01
30	Y22_16_Public_entities	0.01
31	Y24_21_NRS_barriers	0.01
32	Y22_3_Productivist	0.01
33	Y22_16_Private_entities	0.01
34	Y23_19	0.01
35	Y23_33	0.01
36	Y25_27i	0.01
37	Y25_27p	0.01
38	Y25_25e	0.01
39	Y25_27f	0.01
40	Y25_27l	0.01
⋮		

Table 7: SHAP direction (signed SHAP) summary for destination level 1, stratified by origin state, from year block (2020, 2021) to year block (2022, 2023).

Destination level: 1

	Covariates	1	2	3	4
1	(phi0_baseline)	0.803	0.803	0.803	0.803
2	Y23_20_N_mgmt_prac	0.010	-0.044	-0.100	-0.073
3	Y23_17	-0.002	-0.001	-0.006	-0.008
4	Y23_20s	0.051	-0.080	-0.086	-0.064
5	Y23_20t	0.035	-0.046	-0.110	-0.132
6	Y23_20v	-0.009	-0.016	-0.049	-0.075
7	Y22_3_Productivist	-0.006	-0.017	-0.009	-0.021
8	Y23_18	-0.001	-0.000	-0.001	-0.002
9	Y21_24_CC_barriers	0.001	0.001	-0.011	-0.022
10	Y23_19	-0.001	-0.000	-0.001	-0.001
11	Y22_2_Opinion_leader	-0.000	-0.007	-0.008	-0.008
12	Y22_3_Steward	0.001	0.000	0.001	-0.001
13	Y20_13_Stewardship_motive	-0.001	0.000	-0.004	-0.002
14	Y22_17a_Trauma	-0.006	-0.010	0.001	-0.005
15	Y23_33	-0.002	-0.004	-0.003	-0.001
16	Y23_20_EoF_prac	0.012	0.001	-0.010	-0.009
17	Y23_20u	-0.031	-0.026	-0.015	-0.011
18	Y21_11_4R_Info_ag	-0.001	-0.006	-0.005	-0.002
19	Y21_8_Soil_health	0.007	0.006	-0.013	-0.016
20	Y20_13_Social_motive	-0.000	0.000	-0.001	-0.001
21	Y23_20_Other_prac	-0.014	-0.014	-0.021	-0.029
22	Y20_19	-0.003	-0.003	-0.005	-0.003
23	Y22_16_Public_entities	-0.003	-0.003	-0.002	-0.002
24	Y21_13v	0.021	-0.016	-0.027	-0.020
25	Y22_16_Trusted_entities	-0.000	-0.002	0.000	-0.001
26	Y20_4acde_scale	-0.005	-0.004	-0.001	-0.001
27	Y21_24_CC_support	0.021	-0.007	-0.017	-0.010
28	Y20_14	0.003	-0.001	-0.002	-0.005
29	Y21_24_CC_incentives	0.010	-0.000	-0.009	-0.008
30	Y20_23abdl_scale	0.001	0.001	-0.001	-0.001
31	Y20_CC_Beliefs	0.001	0.001	-0.001	-0.002
32	Y22_16_Private_entities	0.001	-0.002	-0.002	-0.004
33	Y21_13q	0.000	-0.002	0.002	-0.000
34	Y20_5abcdefghi_sum	-0.003	0.000	-0.005	-0.004
35	Y20_3abcd_scale	-0.002	-0.001	-0.003	-0.006
36	Y21_24i	0.005	0.004	0.001	-0.012
37	Y20_13_Regulatory_motive	-0.003	-0.002	-0.001	0.001
38	Y20_11acdgi_scale	-0.002	-0.001	-0.004	0.001
39	Y21_29	0.001	0.000	-0.000	0.000
40	Y21_28	0.001	0.002	0.000	0.004
⋮					

Columns 1–4 correspond to the initial (origin) cover-crop level $S = s$; each cell reports the weighted mean signed SHAP contribution of that covariate to the destination-1 margin $f_1(x)$ among individuals with $S = s$. The first row ϕ_0 is the SHAP baseline margin for class 1 (the intercept/reference score); each subsequent row is a covariate (year-suffixed base variable), with positive values indicating the covariate tends to increase the class-1 margin (and thus, all else equal, increase $\Pr(Y = 1)$) within that origin stratum, and negative values indicating it tends to decrease the class-1 margin. For example, for `Y23_20s`, a positive value in column $s = 1$ means this covariate pushes predictions toward destination level 1 for those starting at level 1, whereas negative values in columns $s = 2, 3, 4$ mean it pushes predictions away from destination level 1 for those starting at levels 2–4 relative to the baseline ϕ_0. And similar interpretations apply to the rest SHAP direction summaries.

Table 8: SHAP direction (signed SHAP) summary for destination level 2, stratified by origin state, from year block (2020, 2021) to year block (2022, 2023).

Destination level: 2

	base	1	2	3	4
1	(phi0_baseline)	0.438	0.438	0.438	0.438
2	Y23_20_N_mgmt_prac	-0.086	-0.010	0.018	-0.036
3	Y23_17	0.002	0.002	0.002	0.001
4	Y23_20s	-0.086	-0.005	-0.010	-0.025
5	Y23_20t	-0.017	-0.000	0.007	-0.005
6	Y23_20v	-0.017	-0.009	-0.036	-0.047
7	Y22_3_Productivist	-0.001	0.001	-0.000	-0.002
8	Y23_18	0.000	-0.013	0.003	-0.024
9	Y21_24_CC_barriers	-0.008	-0.002	0.003	-0.003
10	Y23_19	-0.012	-0.004	-0.002	-0.021
11	Y22_2_Opinion_leader	-0.006	0.001	0.003	-0.001
12	Y22_3_Steward	-0.001	-0.001	-0.001	-0.003
13	Y20_13_Stewardship_motive	0.007	0.008	-0.002	-0.015
14	Y22_17a_Trauma	0.000	-0.002	-0.009	-0.005
15	Y23_33	-0.002	-0.001	-0.004	-0.004
16	Y23_20_EoF_prac	-0.005	0.001	0.005	-0.001
17	Y23_20u	-0.005	-0.004	-0.000	-0.009
18	Y21_11_4R_Info_ag	-0.005	-0.004	0.002	-0.003
19	Y21_8_Soil_health	0.018	0.009	-0.010	-0.020
20	Y20_13_Social_motive	0.000	0.001	-0.001	-0.001
21	Y23_20_Other_prac	-0.007	-0.004	0.001	-0.003
22	Y20_19	-0.002	-0.003	-0.012	-0.019
23	Y22_16_Public_entities	-0.002	0.000	0.000	-0.001
24	Y21_13v	-0.005	0.001	0.004	-0.000
25	Y22_16_Trusted_entities	-0.001	0.001	0.001	-0.003
26	Y20_4acde_scale	-0.001	-0.000	0.002	0.002
27	Y21_24_CC_support	-0.007	-0.001	-0.000	-0.003
28	Y20_14	0.002	-0.003	0.002	0.000
29	Y21_24_CC_incentives	-0.008	-0.003	0.002	0.001
30	Y20_23abdl_scale	-0.009	-0.000	-0.006	-0.002
31	Y20_CC_Beliefs	-0.000	-0.005	-0.001	-0.000
32	Y22_16_Private_entities	-0.003	-0.003	-0.002	-0.002
33	Y21_13q	0.020	-0.004	-0.036	-0.011
34	Y20_5abcdefghi_sum	-0.005	-0.004	-0.003	0.001
35	Y20_3abcd_scale	-0.000	-0.001	0.000	0.002
36	Y21_24i	0.006	0.006	0.002	-0.007
37	Y20_13_Regulatory_motive	0.001	0.002	-0.003	-0.003
38	Y20_11acdgi_scale	0.000	-0.000	-0.001	-0.000
39	Y21_29	-0.003	-0.001	0.003	0.002
40	Y21_28	-0.002	-0.000	0.001	0.000
⋮					

Table 9: SHAP direction (signed SHAP) summary for destination level 3, stratified by origin state, from year block (2020, 2021) to year block (2022, 2023).

Destination level: 3

	base	1	2	3	4
1	(phi0_baseline)	-0.047	-0.047	-0.047	-0.047
2	Y23_20_N_mgmt_prac	-0.059	-0.007	-0.018	-0.027
3	Y23_17	0.006	0.005	0.009	-0.002
4	Y23_20s	-0.004	-0.005	-0.000	-0.002
5	Y23_20t	-0.034	-0.021	0.004	-0.001
6	Y23_20v	-0.008	-0.010	0.008	0.013
7	Y22_3_Productivist	-0.008	-0.010	-0.011	-0.021
8	Y23_18	0.004	0.002	0.008	-0.018
9	Y21_24_CC_barriers	-0.002	-0.001	0.001	0.005
10	Y23_19	-0.000	-0.003	0.005	-0.002
11	Y22_2_Opinion_leader	0.002	-0.001	-0.001	-0.001
12	Y22_3_Steward	0.001	-0.001	-0.001	-0.003
13	Y20_13_Stewardship_motive	0.003	0.000	0.002	-0.009
14	Y22_17a_Trauma	-0.001	0.001	-0.003	0.002
15	Y23_33	-0.006	-0.015	-0.007	-0.004
16	Y23_20_EoF_prac	-0.032	-0.014	-0.009	-0.009
17	Y23_20u	-0.002	-0.004	-0.000	-0.003
18	Y21_11_4R_Info_ag	-0.002	-0.003	-0.003	-0.001
19	Y21_8_Soil_health	-0.018	-0.010	-0.001	0.004
20	Y20_13_Social_motive	-0.006	0.001	0.001	-0.003
21	Y23_20_Other_prac	-0.002	-0.001	0.000	0.002
22	Y20_19	-0.002	-0.003	-0.001	-0.000
23	Y22_16_Public_entities	-0.003	0.002	0.000	-0.002
24	Y21_13v	-0.002	-0.003	0.000	-0.000
25	Y22_16_Trusted_entities	0.002	0.000	-0.000	0.001
26	Y20_4acde_scale	-0.006	-0.007	-0.010	-0.011
27	Y21_24_CC_support	-0.002	0.000	-0.002	-0.001
28	Y20_14	0.000	-0.001	-0.002	-0.001
29	Y21_24_CC_incentives	0.004	-0.001	-0.002	-0.001
30	Y20_23abdl_scale	-0.009	-0.010	-0.001	0.003
31	Y20_CC_Beliefs	-0.004	-0.011	-0.006	0.008
32	Y22_16_Private_entities	-0.003	-0.001	-0.001	0.000
33	Y21_13q	-0.015	0.000	0.006	0.003
34	Y20_5abcdefghi_sum	0.000	-0.000	0.001	-0.002
35	Y20_3abcd_scale	0.000	-0.000	-0.002	-0.000
36	Y21_24i	0.000	0.000	-0.000	0.001
37	Y20_13_Regulatory_motive	-0.001	-0.001	-0.001	0.000
38	Y20_11acdgi_scale	-0.002	-0.002	-0.002	-0.001
39	Y21_29	-0.003	-0.001	-0.001	-0.001
40	Y21_28	-0.000	-0.000	0.000	-0.000
⋮					

Table 10: SHAP direction (signed SHAP) summary for destination level 4, stratified by origin state, from year block (2020, 2021) to year block (2022, 2023).

Destination level: 4

	base	1	2	3	4
1	(phi0_baseline)	0.619	0.619	0.619	0.619
2	Y23_20_N_mgmt_prac	-0.022	-0.020	-0.034	-0.012
3	Y23_17	-0.164	-0.173	-0.118	0.039
4	Y23_20s	-0.004	-0.002	-0.002	-0.003
5	Y23_20t	-0.002	-0.003	-0.002	-0.000
6	Y23_20v	-0.070	-0.052	-0.019	-0.007
7	Y22_3_Productivist	-0.008	0.000	-0.002	-0.002
8	Y23_18	-0.024	0.010	-0.013	0.071
9	Y21_24_CC_barriers	-0.047	-0.045	-0.013	0.058
10	Y23_19	-0.040	-0.037	-0.047	-0.015
11	Y22_2_Opinion_leader	-0.021	-0.004	-0.002	0.001
12	Y22_3_Steward	-0.030	-0.019	-0.019	0.011
13	Y20_13_Stewardship_motive	-0.004	-0.003	-0.003	-0.003
14	Y22_17a_Trauma	-0.003	-0.001	-0.000	-0.001
15	Y23_33	-0.006	-0.005	-0.009	-0.006
16	Y23_20_EoF_prac	-0.003	-0.001	-0.003	-0.002
17	Y23_20u	0.000	0.001	0.000	0.000
18	Y21_11_4R_Info_ag	0.001	-0.001	-0.000	-0.001
19	Y21_8_Soil_health	-0.020	-0.018	0.009	0.008
20	Y20_13_Social_motive	0.004	-0.016	-0.021	-0.005
21	Y23_20_Other_prac	-0.004	-0.004	-0.005	-0.002
22	Y20_19	-0.005	-0.005	-0.006	-0.008
23	Y22_16_Public_entities	-0.004	-0.005	-0.000	-0.007
24	Y21_13v	-0.030	-0.007	0.005	0.005
25	Y22_16_Trusted_entities	0.001	-0.001	-0.002	0.000
26	Y20_4acde_scale	-0.004	-0.003	-0.004	-0.004
27	Y21_24_CC_support	-0.001	-0.001	0.000	0.000
28	Y20_14	-0.008	-0.006	-0.005	-0.002
29	Y21_24_CC_incentives	-0.018	-0.007	-0.000	0.001
30	Y20_23abdl_scale	-0.001	-0.002	-0.002	-0.001
31	Y20_CC_Beliefs	-0.003	-0.004	-0.002	-0.002
32	Y22_16_Private_entities	-0.005	-0.003	0.001	-0.002
33	Y21_13q	-0.011	-0.004	0.005	-0.000
34	Y20_5abcdefghi_sum	0.001	-0.002	0.000	-0.001
35	Y20_3abcd_scale	-0.001	-0.001	-0.001	-0.002
36	Y21_24i	-0.022	-0.020	-0.015	0.009
37	Y20_13_Regulatory_motive	-0.000	0.000	-0.000	-0.001
38	Y20_11acdgi_scale	0.000	0.001	0.001	0.001
39	Y21_29	0.001	-0.003	-0.006	-0.006
40	Y21_28	0.000	0.000	0.000	0.000
⋮					

Table 11: SHAP direction (signed SHAP) summary for destination level 1, stratified by origin state, from year block (2022, 2023) to year block (2024, 2025).

Destination level: 1

	base	1	2	3	4
1	(phi0_baseline)	1.092	1.092	1.092	1.092
2	Y25_25b	-0.048	-0.000	-0.016	-0.065
3	Y25_27h	-0.022	-0.049	0.010	-0.077
4	Y25_27r	-0.061	-0.037	-0.016	0.001
5	Y25_25c	-0.030	0.002	-0.027	-0.077
6	Y25_27q	-0.011	-0.053	-0.002	-0.044
7	Y23_21_Econ_capacity	-0.013	-0.008	0.004	-0.013
8	Y25_27o	0.010	0.003	-0.012	-0.006
9	Y24_4	-0.000	0.005	-0.021	-0.016
10	Y23_21_Agron_efficacy	-0.012	-0.004	-0.001	-0.002
11	Y25_27k	-0.009	-0.018	-0.023	-0.015
12	Y25_26_Compaction_mgmt_tech	0.000	-0.014	0.000	-0.007
13	Y25_26_Compaction_mgmt_prac	-0.013	-0.011	0.002	0.000
14	Y24_22_Conservation_advisor	0.000	-0.004	0.001	0.000
15	Y25_26_Compaction_concern	-0.003	-0.007	0.001	-0.007
16	Y23_20_N_mgmt_prac	-0.014	-0.002	0.003	0.005
17	Y25_27d	-0.009	-0.005	-0.014	-0.016
18	Y24_21_NRS_support	-0.008	-0.010	0.010	-0.004
19	Y25_27j	-0.000	0.012	0.028	0.013
20	Y23_20_EoF_prac	0.000	-0.002	-0.003	-0.001
21	Y24_3_Satisfaction	-0.006	-0.007	-0.014	-0.007
22	Y25_25d	-0.021	-0.006	-0.015	-0.050
23	Y24_7_Stress	-0.011	-0.019	-0.008	-0.008
24	Y24_6	-0.006	-0.008	0.006	-0.006
25	Y22_17a_Trauma	-0.003	-0.002	-0.001	-0.000
26	Y25_27c	-0.002	-0.003	-0.006	0.001
27	Y22_3_Steward	-0.008	-0.006	-0.001	-0.006
28	Y22_2_Opinion_leader	-0.001	-0.002	0.001	-0.001
29	Y23_20_Other_prac	0.003	-0.006	0.003	-0.011
30	Y25_27a	-0.003	-0.004	-0.010	-0.006
31	Y22_16_Public_entities	-0.008	-0.003	-0.001	-0.011
32	Y24_21_NRS_barriers	-0.002	-0.000	-0.004	-0.001
33	Y22_3_Productivist	-0.000	-0.001	0.002	-0.003
34	Y22_16_Private_entities	-0.007	-0.003	-0.006	-0.014
35	Y23_19	0.002	0.002	-0.007	-0.005
36	Y23_33	-0.001	0.000	0.001	-0.002
37	Y25_27i	-0.004	-0.004	-0.002	-0.002
38	Y25_27p	0.002	0.004	-0.002	0.005
39	Y25_25e	0.000	0.000	-0.000	-0.000
40	Y25_27f	-0.000	-0.001	-0.000	-0.000
⋮					

Table 12: SHAP direction (signed SHAP) summary for destination level 2, stratified by origin state, from year block (2022, 2023) to year block (2024, 2025).

Destination level: 2

	base	1	2	3	4
1	(phi0_baseline)	0.629	0.629	0.629	0.629
2	Y25_25b	-0.112	0.022	-0.033	-0.166
3	Y25_27h	-0.002	0.001	-0.009	-0.000
4	Y25_27r	0.005	-0.000	0.005	-0.006
5	Y25_25c	-0.035	-0.001	-0.027	-0.074
6	Y25_27q	-0.048	-0.024	-0.069	-0.015
7	Y23_21_Econ_capacity	-0.006	-0.009	-0.024	-0.009
8	Y25_27o	-0.018	-0.004	-0.009	-0.007
9	Y24_4	-0.017	-0.023	0.006	0.007
10	Y23_21_Agron_efficacy	-0.001	-0.006	-0.011	-0.004
11	Y25_27k	-0.028	-0.015	0.002	-0.013
12	Y25_26_Compaction_mgmt_tech	0.001	-0.001	0.000	-0.004
13	Y25_26_Compaction_mgmt_prac	0.003	0.007	-0.006	-0.018
14	Y24_22_Conservation_advisor	-0.003	-0.008	-0.012	-0.007
15	Y25_26_Compaction_concern	-0.011	-0.003	-0.012	-0.010
16	Y23_20_N_mgmt_prac	-0.001	-0.007	-0.011	-0.010
17	Y25_27d	-0.033	-0.025	-0.006	-0.005
18	Y24_21_NRS_support	-0.002	0.002	-0.003	0.001
19	Y25_27j	0.001	0.001	-0.002	-0.000
20	Y23_20_EoF_prac	-0.007	-0.011	-0.006	-0.006
21	Y24_3_Satisfaction	-0.006	-0.009	-0.003	-0.005
22	Y25_25d	-0.003	-0.001	-0.002	-0.004
23	Y24_7_Stress	-0.003	0.002	-0.005	0.002
24	Y24_6	0.000	-0.001	-0.006	-0.000
25	Y22_17a_Trauma	-0.002	-0.002	-0.002	-0.002
26	Y25_27c	-0.001	-0.006	-0.006	-0.004
27	Y22_3_Steward	0.001	-0.006	-0.009	-0.000
28	Y22_2_Opinion_leader	0.005	-0.004	-0.005	0.004
29	Y23_20_Other_prac	-0.005	-0.002	-0.001	0.004
30	Y25_27a	-0.013	-0.008	0.002	-0.001
31	Y22_16_Public_entities	0.001	-0.001	-0.002	-0.001
32	Y24_21_NRS_barriers	-0.000	-0.002	0.002	0.000
33	Y22_3_Productivist	-0.005	-0.003	-0.004	-0.005
34	Y22_16_Private_entities	-0.001	-0.000	0.001	-0.002
35	Y23_19	-0.003	-0.008	0.001	-0.000
36	Y23_33	0.001	-0.003	-0.003	-0.001
37	Y25_27i	-0.005	-0.003	-0.001	-0.003
38	Y25_27p	0.001	0.001	0.002	0.003
39	Y25_25e	0.001	-0.000	0.001	0.001
40	Y25_27f	-0.004	-0.003	0.003	-0.005

Table 13: SHAP direction (signed SHAP) summary for destination level 3, stratified by origin state, from year block (2022, 2023) to year block (2024, 2025).

Destination level: 3

	base	1	2	3	4
1	(phi0_baseline)	-0.251	-0.251	-0.251	-0.251
2	Y25_25b	-0.015	0.007	0.001	-0.035
3	Y25_27h	-0.045	-0.066	-0.001	-0.040
4	Y25_27r	-0.010	-0.002	-0.012	-0.029
5	Y25_25c	-0.003	0.001	0.003	0.005
6	Y25_27q	-0.008	-0.001	-0.000	-0.005
7	Y23_21_Econ_capacity	-0.014	0.000	0.001	-0.007
8	Y25_27o	-0.006	-0.009	-0.004	-0.006
9	Y24_4	-0.000	-0.001	-0.001	0.001
10	Y23_21_Agron_efficacy	-0.009	-0.014	-0.017	-0.015
11	Y25_27k	-0.004	-0.003	-0.002	-0.003
12	Y25_26_Compaction_mgmt_tech	-0.006	-0.006	-0.011	-0.010
13	Y25_26_Compaction_mgmt_prac	-0.006	-0.003	-0.005	-0.002
14	Y24_22_Conservation_advisor	-0.013	-0.005	-0.002	-0.009
15	Y25_26_Compaction_concern	-0.004	-0.000	-0.007	-0.000
16	Y23_20_N_mgmt_prac	-0.004	-0.003	-0.004	-0.003
17	Y25_27d	-0.005	-0.003	-0.003	-0.005
18	Y24_21_NRS_support	-0.005	-0.000	-0.014	-0.005
19	Y25_27j	-0.005	-0.008	-0.032	-0.015
20	Y23_20_EoF_prac	-0.005	-0.001	-0.005	-0.007
21	Y24_3_Satisfaction	-0.002	-0.005	-0.003	-0.002
22	Y25_25d	0.003	0.003	0.003	0.007
23	Y24_7_Stress	-0.002	-0.001	-0.003	-0.002
24	Y24_6	-0.011	-0.013	-0.018	-0.015
25	Y22_17a_Trauma	-0.020	-0.010	-0.012	-0.019
26	Y25_27c	-0.000	-0.000	-0.001	0.000
27	Y22_3_Steward	-0.004	0.004	0.001	-0.006
28	Y22_2_Opinion_leader	-0.004	-0.000	-0.002	-0.002
29	Y23_20_Other_prac	-0.009	-0.012	-0.012	0.004
30	Y25_27a	0.001	0.001	0.000	0.001
31	Y22_16_Public_entities	-0.016	-0.006	-0.008	-0.017
32	Y24_21_NRS_barriers	-0.000	-0.001	-0.003	-0.003
33	Y22_3_Productivist	-0.001	-0.003	0.001	-0.001
34	Y22_16_Private_entities	0.005	0.002	0.000	0.002
35	Y23_19	-0.010	-0.004	-0.001	0.008
36	Y23_33	-0.002	-0.002	0.002	0.001
37	Y25_27i	-0.006	-0.006	-0.004	-0.006
38	Y25_27p	-0.007	-0.021	-0.011	-0.012
39	Y25_25e	-0.003	0.018	0.002	-0.008
40	Y25_27f	-0.002	0.001	-0.005	-0.005
⋮					

Table 14: SHAP direction (signed SHAP) summary for destination level 4, stratified by origin state, from year block (2022, 2023) to year block (2024, 2025).

Destination level: 4

	base	1	2	3	4
1	(phi0_baseline)	0.234	0.234	0.234	0.234
2	Y25_25b	-0.188	-0.449	-0.391	-0.095
3	Y25_27h	-0.010	-0.010	-0.005	0.000
4	Y25_27r	-0.004	-0.001	-0.001	-0.003
5	Y25_25c	-0.009	-0.044	-0.026	0.046
6	Y25_27q	-0.001	-0.001	0.000	0.000
7	Y23_21_Econ_capacity	-0.001	-0.006	-0.010	-0.004
8	Y25_27o	-0.009	-0.004	0.003	-0.004
9	Y24_4	-0.008	-0.002	-0.019	-0.015
10	Y23_21_Agron_efficacy	-0.002	-0.004	-0.002	-0.000
11	Y25_27k	-0.003	-0.001	-0.000	-0.005
12	Y25_26_Compaction_mgmt_tech	-0.008	-0.004	-0.019	-0.002
13	Y25_26_Compaction_mgmt_prac	-0.012	-0.011	-0.028	-0.008
14	Y24_22_Conservation_advisor	-0.035	-0.010	-0.041	-0.017
15	Y25_26_Compaction_concern	-0.003	-0.005	-0.001	-0.003
16	Y23_20_N_mgmt_prac	-0.023	0.004	0.008	0.011
17	Y25_27d	0.001	0.000	-0.001	0.001
18	Y24_21_NRS_support	-0.002	0.003	0.000	0.006
19	Y25_27j	-0.007	-0.012	-0.008	-0.007
20	Y23_20_EoF_prac	-0.000	-0.000	0.001	0.001
21	Y24_3_Satisfaction	-0.003	-0.000	-0.001	-0.002
22	Y25_25d	-0.005	-0.006	-0.004	-0.004
23	Y24_7_Stress	-0.003	-0.002	-0.001	-0.003
24	Y24_6	-0.002	0.001	0.002	0.000
25	Y22_17a_Trauma	-0.003	0.000	0.002	-0.003
26	Y25_27c	-0.002	-0.003	-0.002	-0.004
27	Y22_3_Steward	0.000	0.000	-0.000	-0.000
28	Y22_2_Opinion_leader	-0.003	-0.001	-0.006	-0.001
29	Y23_20_Other_prac	0.000	-0.000	-0.005	-0.008
30	Y25_27a	-0.000	-0.002	-0.004	-0.003
31	Y22_16_Public_entities	0.002	-0.000	-0.001	-0.000
32	Y24_21_NRS_barriers	-0.002	-0.002	-0.008	-0.000
33	Y22_3_Productivist	-0.004	-0.002	-0.001	-0.003
34	Y22_16_Private_entities	0.002	0.001	0.001	0.002
35	Y23_19	0.002	0.001	-0.002	-0.007
36	Y23_33	-0.000	-0.004	-0.006	0.002
37	Y25_27i	-0.000	-0.000	-0.001	-0.001
38	Y25_27p	-0.001	-0.002	-0.001	-0.001
39	Y25_25e	-0.030	-0.038	-0.027	-0.021
40	Y25_27f	-0.006	-0.001	-0.009	-0.005
⋮					

Table 15: Permutation impact (probability-scale) summary for destination level 1, stratified by origin state, from year block (2020, 2021) to year block (2022, 2023).

Destination level: 1

	base	1	2	3	4
1	(baseline_transition_prob)	0.467	0.338	0.270	0.251
2	Y23_20_N_mgmt_prac	0.000	0.009	0.012	0.024
3	Y23_17	-0.000	-0.003	-0.002	0.012
4	Y23_20s	0.021	0.013	0.033	0.023
5	Y23_20t	0.007	0.023	0.018	0.013
6	Y23_20v	-0.013	-0.007	0.003	0.008
7	Y22_3_Productivist	0.002	-0.005	-0.003	-0.004
8	Y23_18	0.002	0.001	0.002	0.005
9	Y21_24_CC_barriers	0.001	0.003	-0.003	-0.000
10	Y23_19	-0.004	-0.004	-0.005	0.000
11	Y22_2_Opinion_leader	0.001	-0.001	-0.001	-0.000
12	Y22_3_Steward	0.000	-0.000	-0.000	-0.002
13	Y20_13_Stewardship_motive	-0.000	0.001	-0.000	-0.002
14	Y22_17a_Trauma	0.002	-0.001	0.001	-0.000
15	Y23_33	-0.000	-0.001	-0.001	0.001
16	Y23_20_EoF_prac	-0.001	0.002	0.001	0.002
17	Y23_20u	0.003	0.004	0.001	0.005
18	Y21_11_4R_Info_ag	0.000	-0.000	-0.000	-0.000
19	Y21_8_Soil_health	-0.000	0.001	-0.000	-0.001
20	Y20_13_Social_motive	-0.001	0.001	0.001	-0.000
21	Y23_20_Other_prac	0.001	0.005	0.003	0.005
22	Y20_19	0.001	0.001	-0.001	0.000
23	Y22_16_Public_entities	0.001	-0.001	-0.001	-0.000
24	Y21_13v	0.001	0.002	0.003	0.002
25	Y22_16_Trusted_entities	-0.000	-0.001	0.000	-0.000
26	Y20_4acde_scale	-0.001	0.000	0.001	-0.001
27	Y21_24_CC_support	0.000	-0.000	-0.001	0.001
28	Y20_14	-0.000	0.000	-0.000	0.000
29	Y21_24_CC_incentives	0.002	0.001	0.000	0.001
30	Y20_23abdl_scale	0.001	-0.000	0.000	0.000
31	Y20_CC_Beliefs	0.001	0.001	0.000	-0.002
32	Y22_16_Private_entities	0.000	-0.000	0.000	-0.001
33	Y21_13q	-0.000	-0.001	0.001	0.001
34	Y20_5abcdefghi_sum	0.001	0.001	0.001	0.000
35	Y20_3abcd_scale	0.003	0.002	0.002	0.000
36	Y21_24i	0.000	0.000	0.001	-0.001
37	Y20_13_Regulatory_motive	0.000	0.000	0.000	0.000
38	Y20_11acdgi_scale	0.000	0.000	-0.000	-0.000
39	Y21_29	-0.000	-0.000	-0.001	-0.000
40	Y21_28	-0.000	0.000	-0.001	-0.000
⋮					

Columns 1–4 correspond to the initial (origin) cover-crop level $S = s$; the first row gives the baseline weighted transition probability $\widehat{T}_{s\to 1} = \mathbb{E}_w[\hat{p}_{i1} \mid S = s]$ from the fitted Transition Boosting model. Each subsequent row is a covariate (year-suffixed base variable), and each cell reports the estimated permutation impact $\Delta_{s,1}(b) = \mathbb{E}_w[\hat{p}_{i1} - \hat{p}_{i1}^{(-b)} \mid S = s]$, where $\hat{p}_{i1}^{(-b)}$ is computed after permuting covariate block b within the origin stratum. A positive value means the covariate helps predict destination level 1 in that origin group (permuting it reduces $\Pr(Y = 1)$), whereas a negative value means the covariate suppresses destination level 1 on average (permuting it increases $\Pr(Y = 1)$). For example, for `Y23_20s`, the negative entry in column $s = 1$ indicates that shuffling this covariate slightly increases the predicted probability of ending in level 1 among those starting in level 1, so its observed alignment acts (on average) against destination level 1 relative to the baseline transition probability. And similar interpretations apply to the rest permutation impact tables.

Table 16: Permutation impact (probability-scale) summary for destination level 2, stratified by origin state, from year block (2020, 2021) to year block (2022, 2023).

Destination level: 2

	base	1	2	3	4
1	(baseline_transition_prob)	0.257	0.333	0.299	0.113
2	Y23_20_N_mgmt_prac	-0.005	-0.009	-0.008	-0.011
3	Y23_17	-0.003	-0.007	-0.005	-0.002
4	Y23_20s	0.002	-0.003	-0.018	-0.010
5	Y23_20t	0.000	-0.008	-0.009	-0.005
6	Y23_20v	0.001	-0.008	-0.014	-0.006
7	Y22_3_Productivist	-0.001	0.003	0.002	0.000
8	Y23_18	-0.001	-0.002	0.003	0.001
9	Y21_24_CC_barriers	-0.000	0.001	0.002	-0.003
10	Y23_19	-0.005	-0.006	-0.003	0.000
11	Y22_2_Opinion_leader	-0.001	0.001	0.000	0.001
12	Y22_3_Steward	0.000	-0.002	-0.001	-0.001
13	Y20_13_Stewardship_motive	-0.000	-0.000	-0.000	0.006
14	Y22_17a_Trauma	-0.001	0.002	-0.001	0.000
15	Y23_33	-0.000	0.000	0.001	0.000
16	Y23_20_EoF_prac	0.000	-0.001	-0.001	-0.002
17	Y23_20u	0.000	-0.001	-0.001	-0.002
18	Y21_11_4R_Info_ag	0.001	0.000	0.001	0.000
19	Y21_8_Soil_health	0.001	0.000	-0.001	0.001
20	Y20_13_Social_motive	-0.001	0.001	0.001	0.000
21	Y23_20_Other_prac	-0.002	-0.003	-0.001	-0.002
22	Y20_19	-0.000	-0.000	0.001	0.000
23	Y22_16_Public_entities	0.000	-0.001	-0.001	-0.000
24	Y21_13v	-0.000	-0.001	-0.002	-0.002
25	Y22_16_Trusted_entities	0.001	0.001	-0.000	-0.001
26	Y20_4acde_scale	-0.001	-0.000	-0.001	-0.002
27	Y21_24_CC_support	0.001	0.000	0.000	-0.001
28	Y20_14	0.001	0.000	0.001	0.000
29	Y21_24_CC_incentives	0.000	0.000	-0.000	-0.001
30	Y20_23abdl_scale	0.000	0.002	-0.001	0.000
31	Y20_CC_Beliefs	-0.000	-0.000	-0.000	-0.001
32	Y22_16_Private_entities	0.001	0.000	-0.000	-0.000
33	Y21_13q	0.001	0.000	-0.001	-0.000
34	Y20_5abcdefghi_sum	-0.001	-0.001	-0.001	-0.000
35	Y20_3abcd_scale	-0.002	-0.001	-0.002	-0.000
36	Y21_24i	-0.000	-0.000	-0.000	0.001
37	Y20_13_Regulatory_motive	-0.000	0.001	-0.000	-0.000
38	Y20_11acdgi_scale	0.000	-0.000	0.000	-0.000
39	Y21_29	-0.001	-0.000	0.000	-0.000
40	Y21_28	0.000	0.001	0.001	0.001
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Table 17: Permutation impact (probability-scale) summary for destination level 3, stratified by origin state, from year block (2020, 2021) to year block (2022, 2023).

Destination level: 3

	base	1	2	3	4
1	(baseline_transition_prob)	0.111	0.128	0.223	0.126
2	Y23_20_N_mgmt_prac	-0.003	-0.004	-0.004	-0.010
3	Y23_17	-0.005	-0.011	-0.004	-0.001
4	Y23_20s	-0.012	-0.005	-0.008	-0.007
5	Y23_20t	-0.004	-0.010	-0.005	-0.007
6	Y23_20v	0.003	-0.004	-0.007	-0.006
7	Y22_3_Productivist	-0.001	0.001	-0.003	-0.001
8	Y23_18	0.000	-0.001	0.002	0.003
9	Y21_24_CC_barriers	0.000	-0.001	-0.002	-0.003
10	Y23_19	-0.004	-0.007	-0.006	-0.001
11	Y22_2_Opinion_leader	-0.001	-0.001	-0.002	-0.002
12	Y22_3_Steward	0.000	-0.000	0.000	0.000
13	Y20_13_Stewardship_motive	0.001	-0.000	0.000	-0.002
14	Y22_17a_Trauma	-0.001	-0.000	-0.001	-0.000
15	Y23_33	-0.001	-0.001	-0.000	-0.001
16	Y23_20_EoF_prac	-0.000	-0.001	0.000	-0.001
17	Y23_20u	-0.003	-0.002	0.001	-0.001
18	Y21_11_4R_Info_ag	-0.001	0.001	-0.001	-0.001
19	Y21_8_Soil_health	-0.001	-0.002	-0.002	-0.001
20	Y20_13_Social_motive	-0.002	-0.000	0.001	0.000
21	Y23_20_Other_prac	-0.001	-0.002	-0.001	-0.001
22	Y20_19	-0.001	-0.001	0.001	-0.000
23	Y22_16_Public_entities	-0.001	0.002	0.001	0.000
24	Y21_13v	-0.001	-0.001	-0.001	-0.003
25	Y22_16_Trusted_entities	-0.000	0.000	-0.000	0.000
26	Y20_4acde_scale	0.000	-0.000	-0.000	0.003
27	Y21_24_CC_support	-0.001	0.000	0.001	-0.001
28	Y20_14	-0.001	-0.001	-0.001	-0.001
29	Y21_24_CC_incentives	-0.001	-0.001	-0.001	-0.001
30	Y20_23abdl_scale	-0.001	-0.002	0.000	-0.001
31	Y20_CC_Beliefs	-0.001	-0.000	-0.000	0.004
32	Y22_16_Private_entities	-0.000	-0.000	-0.000	0.000
33	Y21_13q	-0.000	0.000	-0.001	-0.000
34	Y20_5abcdefghi_sum	0.000	-0.000	0.000	0.000
35	Y20_3abcd_scale	-0.001	-0.000	-0.000	0.000
36	Y21_24i	-0.001	-0.000	-0.001	-0.001
37	Y20_13_Regulatory_motive	-0.000	-0.001	0.000	0.000
38	Y20_11acdgi_scale	0.000	-0.000	-0.000	-0.000
39	Y21_29	-0.000	0.000	-0.000	-0.001
40	Y21_28	-0.000	-0.000	0.000	-0.001
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Table 18: Permutation impact (probability-scale) summary for destination level 4, stratified by origin state, from year block (2020, 2021) to year block (2022, 2023).

Destination level: 4

	base	1	2	3	4
1	(baseline_transition_prob)	0.165	0.201	0.207	0.511
2	Y23_20_N_mgmt_prac	0.008	0.004	0.000	-0.003
3	Y23_17	0.009	0.020	0.010	-0.009
4	Y23_20s	-0.011	-0.005	-0.007	-0.006
5	Y23_20t	-0.003	-0.005	-0.004	-0.002
6	Y23_20v	0.008	0.019	0.017	0.004
7	Y22_3_Productivist	-0.000	0.001	0.004	0.005
8	Y23_18	-0.001	0.001	-0.006	-0.009
9	Y21_24_CC_barriers	-0.001	-0.003	0.003	0.007
10	Y23_19	0.013	0.018	0.015	0.000
11	Y22_2_Opinion_leader	-0.000	0.002	0.003	0.001
12	Y22_3_Steward	-0.000	0.002	0.001	0.003
13	Y20_13_Stewardship_motive	-0.000	-0.001	0.000	-0.002
14	Y22_17a_Trauma	-0.001	-0.001	0.000	-0.000
15	Y23_33	0.001	0.001	0.000	-0.000
16	Y23_20_EoF_prac	0.001	-0.000	-0.000	0.002
17	Y23_20u	-0.000	-0.002	-0.002	-0.002
18	Y21_11_4R_Info_ag	-0.000	-0.001	-0.000	0.001
19	Y21_8_Soil_health	0.001	0.000	0.003	0.001
20	Y20_13_Social_motive	0.004	-0.001	-0.002	-0.000
21	Y23_20_Other_prac	0.002	-0.001	-0.001	-0.001
22	Y20_19	0.000	0.000	-0.000	0.000
23	Y22_16_Public_entities	-0.000	0.000	0.000	0.000
24	Y21_13v	-0.000	-0.000	0.000	0.002
25	Y22_16_Trusted_entities	-0.001	-0.000	0.000	0.001
26	Y20_4acde_scale	0.001	0.001	0.001	-0.000
27	Y21_24_CC_support	-0.000	-0.000	-0.000	0.001
28	Y20_14	-0.000	0.000	0.000	0.000
29	Y21_24_CC_incentives	-0.001	-0.000	0.001	0.001
30	Y20_23abdl_scale	0.000	-0.000	0.000	0.000
31	Y20_CC_Beliefs	0.000	0.000	0.000	-0.001
32	Y22_16_Private_entities	-0.000	0.000	0.001	0.001
33	Y21_13q	-0.000	0.000	0.001	0.000
34	Y20_5abcdefghi_sum	-0.000	-0.000	-0.000	-0.000
35	Y20_3abcd_scale	-0.000	-0.000	0.000	-0.000
36	Y21_24i	0.001	0.000	-0.000	0.001
37	Y20_13_Regulatory_motive	0.000	-0.001	0.000	-0.000
38	Y20_11acdgi_scale	-0.000	0.000	0.000	0.000
39	Y21_29	0.002	0.000	0.001	0.001
40	Y21_28	-0.000	-0.000	-0.000	0.001
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Table 19: Permutation impact (probability-scale) summary for destination level 1, stratified by origin state, from year block (2022, 2023) to year block (2024, 2025).

Destination level: 1

	base	1	2	3	4
1	(baseline_transition_prob)	0.423	0.411	0.456	0.372
2	Y25_25b	-0.001	0.009	0.030	0.086
3	Y25_27h	-0.010	-0.001	0.021	0.001
4	Y25_27r	-0.016	0.005	0.031	0.028
5	Y25_25c	0.007	0.008	0.020	0.062
6	Y25_27q	0.009	0.010	0.032	0.000
7	Y23_21_Econ_capacity	0.000	-0.002	0.012	-0.001
8	Y25_27o	-0.002	-0.001	-0.001	-0.002
9	Y24_4	0.004	-0.004	-0.011	-0.005
10	Y23_21_Agron_efficacy	-0.003	-0.003	-0.002	0.001
11	Y25_27k	-0.001	0.005	0.011	0.004
12	Y25_26_Compaction_mgmt_tech	0.002	-0.006	0.001	0.002
13	Y25_26_Compaction_mgmt_prac	-0.001	-0.003	0.007	0.009
14	Y24_22_Conservation_advisor	0.000	-0.003	0.004	-0.001
15	Y25_26_Compaction_concern	0.000	-0.002	0.002	0.001
16	Y23_20_N_mgmt_prac	-0.001	-0.004	0.001	0.000
17	Y25_27d	0.001	0.002	0.001	-0.001
18	Y24_21_NRS_support	-0.001	-0.003	0.007	0.002
19	Y25_27j	-0.006	-0.006	0.005	0.001
20	Y23_20_EoF_prac	-0.000	-0.002	-0.001	-0.000
21	Y24_3_Satisfaction	0.001	-0.000	0.000	0.001
22	Y25_25d	0.002	0.001	0.004	0.015
23	Y24_7_Stress	-0.002	-0.004	-0.000	0.001
24	Y24_6	-0.000	-0.003	0.004	0.000
25	Y22_17a_Trauma	0.002	0.002	0.004	0.003
26	Y25_27c	-0.001	-0.001	-0.001	0.000
27	Y22_3_Steward	-0.001	-0.002	0.003	0.001
28	Y22_2_Opinion_leader	-0.001	-0.002	0.003	0.001
29	Y23_20_Other_prac	-0.000	-0.002	0.001	-0.001
30	Y25_27a	-0.000	-0.000	-0.002	-0.000
31	Y22_16_Public_entities	0.000	-0.001	0.002	-0.000
32	Y24_21_NRS_barriers	-0.001	-0.001	-0.001	0.000
33	Y22_3_Productivist	0.002	0.002	0.005	0.002
34	Y22_16_Private_entities	0.001	0.002	0.002	-0.001
35	Y23_19	-0.000	-0.001	-0.003	-0.001
36	Y23_33	-0.001	-0.000	0.000	-0.000
37	Y25_27i	-0.002	-0.000	-0.000	-0.001
38	Y25_27p	-0.001	-0.000	-0.001	0.000
39	Y25_25e	-0.002	-0.001	-0.001	-0.003
40	Y25_27f	-0.001	-0.002	0.001	0.000
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Table 20: Permutation impact (probability-scale) summary for destination level 2, stratified by origin state, from year block (2022, 2023) to year block (2024, 2025).

Destination level: 2

	base	1	2	3	4
1	(baseline_transition_prob)	0.264	0.305	0.285	0.261
2	Y25_25b	-0.035	-0.005	0.009	0.062
3	Y25_27h	0.004	-0.002	-0.004	0.000
4	Y25_27r	0.008	-0.008	-0.014	-0.015
5	Y25_25c	0.000	0.000	0.007	0.024
6	Y25_27q	-0.000	-0.005	-0.021	0.005
7	Y23_21_Econ_capacity	-0.001	0.000	-0.002	0.000
8	Y25_27o	-0.000	-0.001	0.001	0.002
9	Y24_4	-0.004	0.000	0.017	0.006
10	Y23_21_Agron_efficacy	0.001	-0.000	0.003	0.001
11	Y25_27k	0.005	-0.004	-0.005	-0.002
12	Y25_26_Compaction_mgmt_tech	0.000	-0.001	0.004	-0.003
13	Y25_26_Compaction_mgmt_prac	-0.000	-0.002	-0.004	-0.006
14	Y24_22_Conservation_advisor	0.003	-0.004	0.001	0.001
15	Y25_26_Compaction_concern	0.002	-0.000	-0.001	-0.002
16	Y23_20_N_mgmt_prac	0.002	0.000	0.000	-0.000
17	Y25_27d	0.006	0.003	0.005	0.005
18	Y24_21_NRS_support	-0.000	0.000	-0.002	-0.002
19	Y25_27j	0.001	-0.004	-0.002	-0.003
20	Y23_20_EoF_prac	0.000	-0.001	0.001	0.001
21	Y24_3_Satisfaction	-0.000	-0.001	0.001	-0.001
22	Y25_25d	-0.002	-0.002	-0.002	-0.006
23	Y24_7_Stress	0.002	0.003	0.002	-0.000
24	Y24_6	0.000	0.001	-0.003	-0.000
25	Y22_17a_Trauma	-0.000	0.000	-0.001	0.000
26	Y25_27c	0.002	0.001	0.001	0.000
27	Y22_3_Steward	0.003	0.002	-0.001	0.002
28	Y22_2_Opinion_leader	0.003	0.000	0.000	0.002
29	Y23_20_Other_prac	-0.002	0.002	0.002	0.000
30	Y25_27a	0.000	0.000	0.004	0.001
31	Y22_16_Public_entities	0.002	0.002	0.001	0.002
32	Y24_21_NRS_barriers	-0.001	0.000	0.002	-0.002
33	Y22_3_Productivist	-0.001	-0.003	-0.003	-0.002
34	Y22_16_Private_entities	-0.002	-0.002	-0.001	-0.000
35	Y23_19	0.000	-0.002	0.004	0.001
36	Y23_33	0.002	0.000	0.001	0.001
37	Y25_27i	0.001	-0.001	0.002	0.001
38	Y25_27p	-0.001	-0.001	0.001	-0.000
39	Y25_25e	-0.002	-0.001	-0.001	-0.004
40	Y25_27f	-0.002	-0.003	-0.000	-0.001
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Table 21: Permutation impact (probability-scale) summary for destination level 3, stratified by origin state, from year block (2022, 2023) to year block (2024, 2025).

Destination level: 3

	base	1	2	3	4
1	(baseline_transition_prob)	0.102	0.131	0.101	0.091
2	Y25_25b	-0.021	-0.010	-0.012	-0.010
3	Y25_27h	0.009	0.006	-0.008	0.001
4	Y25_27r	0.008	0.005	-0.010	-0.009
5	Y25_25c	-0.003	0.002	-0.005	-0.018
6	Y25_27q	-0.004	-0.002	-0.006	-0.003
7	Y23_21_Econ_capacity	-0.000	0.002	-0.006	0.003
8	Y25_27o	0.002	-0.001	-0.001	-0.001
9	Y24_4	-0.001	-0.000	-0.002	-0.002
10	Y23_21_Agron_efficacy	0.002	0.003	-0.001	-0.002
11	Y25_27k	-0.002	-0.002	-0.003	-0.002
12	Y25_26_Compaction_mgmt_tech	-0.003	-0.001	-0.008	0.000
13	Y25_26_Compaction_mgmt_prac	-0.002	0.001	-0.002	-0.003
14	Y24_22_Conservation_advisor	-0.000	0.000	0.002	-0.002
15	Y25_26_Compaction_concern	-0.002	0.003	-0.002	0.003
16	Y23_20_N_mgmt_prac	0.000	0.000	-0.001	-0.001
17	Y25_27d	-0.004	-0.003	-0.002	-0.003
18	Y24_21_NRS_support	0.002	0.003	-0.002	0.001
19	Y25_27j	0.004	0.010	-0.002	0.002
20	Y23_20_EoF_prac	0.001	0.003	-0.000	-0.001
21	Y24_3_Satisfaction	0.000	0.000	-0.001	-0.000
22	Y25_25d	-0.000	0.002	-0.003	-0.008
23	Y24_7_Stress	0.000	0.001	-0.001	-0.001
24	Y24_6	0.001	0.001	-0.000	0.001
25	Y22_17a_Trauma	-0.002	-0.001	-0.003	-0.003
26	Y25_27c	-0.001	-0.000	-0.000	-0.001
27	Y22_3_Steward	-0.002	0.001	-0.001	-0.003
28	Y22_2_Opinion_leader	-0.002	-0.000	-0.003	-0.002
29	Y23_20_Other_prac	0.002	-0.001	-0.002	0.001
30	Y25_27a	0.000	-0.000	-0.001	-0.001
31	Y22_16_Public_entities	-0.003	-0.001	-0.002	-0.003
32	Y24_21_NRS_barriers	0.000	-0.000	-0.001	-0.000
33	Y22_3_Productivist	0.000	0.001	-0.001	-0.000
34	Y22_16_Private_entities	0.001	0.000	-0.001	0.001
35	Y23_19	-0.000	0.003	-0.001	0.000
36	Y23_33	-0.001	-0.000	-0.000	-0.001
37	Y25_27i	0.001	0.001	-0.000	-0.000
38	Y25_27p	0.002	0.001	0.001	-0.000
39	Y25_25e	-0.005	-0.001	-0.003	0.001
40	Y25_27f	0.001	0.001	0.001	0.000
⋮					

Table 22: Permutation impact (probability-scale) summary for destination level 4, stratified by origin state, from year block (2022, 2023) to year block (2024, 2025).

Destination level: 4

	base	1	2	3	4
1	(baseline_transition_prob)	0.211	0.154	0.158	0.276
2	Y25_25b	0.056	0.006	-0.026	-0.138
3	Y25_27h	-0.003	-0.003	-0.009	-0.002
4	Y25_27r	-0.000	-0.002	-0.007	-0.004
5	Y25_25c	-0.004	-0.011	-0.021	-0.068
6	Y25_27q	-0.004	-0.004	-0.004	-0.002
7	Y23_21_Econ_capacity	0.001	-0.001	-0.004	-0.002
8	Y25_27o	0.000	0.003	0.001	0.001
9	Y24_4	0.002	0.004	-0.003	0.001
10	Y23_21_Agron_efficacy	-0.000	-0.000	-0.000	-0.000
11	Y25_27k	-0.001	0.001	-0.003	-0.001
12	Y25_26_Compaction_mgmt_tech	0.001	0.009	0.003	0.001
13	Y25_26_Compaction_mgmt_prac	0.003	0.003	-0.001	-0.000
14	Y24_22_Conservation_advisor	-0.003	0.008	-0.008	0.002
15	Y25_26_Compaction_concern	-0.001	-0.001	0.001	-0.001
16	Y23_20_N_mgmt_prac	-0.001	0.003	0.001	0.001
17	Y25_27d	-0.004	-0.002	-0.003	-0.002
18	Y24_21_NRS_support	-0.001	-0.001	-0.003	-0.000
19	Y25_27j	0.000	-0.000	-0.001	-0.000
20	Y23_20_EoF_prac	-0.001	-0.001	-0.001	-0.000
21	Y24_3_Satisfaction	-0.001	0.001	-0.001	-0.000
22	Y25_25d	0.001	-0.002	0.001	-0.001
23	Y24_7_Stress	-0.000	0.000	-0.001	-0.000
24	Y24_6	-0.001	0.001	-0.000	-0.001
25	Y22_17a_Trauma	0.000	-0.001	0.000	-0.001
26	Y25_27c	-0.000	0.001	0.001	0.000
27	Y22_3_Steward	0.000	-0.001	-0.001	-0.000
28	Y22_2_Opinion_leader	-0.000	0.002	-0.000	-0.000
29	Y23_20_Other_prac	-0.001	0.002	-0.000	-0.000
30	Y25_27a	0.000	0.000	0.000	-0.000
31	Y22_16_Public_entities	0.001	-0.000	-0.001	0.001
32	Y24_21_NRS_barriers	0.001	0.001	-0.001	0.002
33	Y22_3_Productivist	-0.001	0.000	-0.001	0.000
34	Y22_16_Private_entities	0.000	-0.000	-0.000	0.001
35	Y23_19	0.000	-0.000	-0.000	-0.001
36	Y23_33	0.001	0.000	-0.001	-0.000
37	Y25_27i	-0.000	-0.001	-0.001	-0.001
38	Y25_27p	0.000	0.000	-0.000	0.000
39	Y25_25e	0.009	0.003	0.006	0.006
40	Y25_27f	0.001	0.003	-0.001	-0.000
⋮					

5.4 Markov Transition Model (Ridge)

Table 23: The estimated transition distribution from year 2021 to year 2023.

from\to	1	2	3	4
1	0.68	0.18	0.05	0.09
2	0.35	0.41	0.14	0.09
3	0.11	0.35	0.29	0.25
4	0.15	0.06	0.13	0.66

Rows correspond to the initial (origin) cover-crop level $S = s$ and columns correspond to the destination level $Y = k$; the entry $\widehat{T}_{s\to k}$ is the estimated (weighted) probability of transitioning from level s to level k, with each row summing to 1.

Table 24: The estimated transition distribution from year 2023 to year 2025.

from\to	1	2	3	4
1	0.64	0.22	0.06	0.07
2	0.33	0.44	0.15	0.08
3	0.28	0.21	0.20	0.30
4	0.18	0.08	0.09	0.65

Table 25: Permutation-importance ranking of covariates for the Markov Transition Model (MTM) from year block (2020, 2021) to year block (2022, 2023).

	var	Δ_logloss_mean	Δ_logloss_sd	nperm
1	Y23_20_N_mgmt_prac	0.0175	0.0038	5.0000
2	Y23_20v	0.0130	0.0017	5.0000
3	Y23_17	0.0118	0.0016	5.0000
4	Y23_20u	0.0107	0.0027	5.0000
5	Y23_14	0.0052	0.0013	5.0000
6	Y23_20s	0.0051	0.0022	5.0000
7	Y21_24_CC_barriers	0.0048	0.0012	5.0000
8	Y21_33	0.0048	0.0013	5.0000
9	Y23_20t	0.0048	0.0004	5.0000
10	Y21_13v	0.0048	0.0006	5.0000
11	Y21_13u	0.0046	0.0012	5.0000
12	Y20_18	0.0043	0.0009	5.0000
13	Y22_3_Steward	0.0037	0.0010	5.0000
14	Y20_4b	0.0035	0.0006	5.0000
15	Y21_24_CC_benefits	0.0032	0.0013	5.0000
16	Y20_13_Stewardship_motive	0.0031	0.0007	5.0000
17	Y21_11_4R_Info_ag	0.0030	0.0012	5.0000
18	Y23_20_Other_prac	0.0028	0.0006	5.0000
19	Y23_15	0.0028	0.0007	5.0000
20	Y23_20_EoF_prac	0.0026	0.0010	5.0000
21	Y20_23i	0.0026	0.0011	5.0000
22	Y20_11acdgi_scale	0.0024	0.0009	5.0000
23	Y20_9	0.0024	0.0008	5.0000
24	Y21_8_Soil_health	0.0024	0.0009	5.0000
25	Y23_18	0.0024	0.0013	5.0000
26	Y20_3e	0.0023	0.0008	5.0000
27	Y20_14	0.0022	0.0007	5.0000
28	Y21_24_CC_support	0.0022	0.0004	5.0000
29	Y20_3abcd_scale	0.0020	0.0007	5.0000
30	Y22_3_Productivist	0.0017	0.0006	5.0000
31	Y20_13_Regulatory_motive	0.0017	0.0010	5.0000
32	Y20_4acde_scale	0.0016	0.0014	5.0000
33	Y22_2_Opinion_leader	0.0015	0.0008	5.0000
34	Y20_13_Social_motive	0.0013	0.0007	5.0000
35	Y20_23abdl_scale	0.0012	0.0010	5.0000
36	Y23_35	0.0012	0.0007	5.0000
37	Y21_24i	0.0012	0.0013	5.0000
38	Y20_26b	0.0012	0.0009	5.0000
39	Y20_12_Agron_efficacy	0.0011	0.0004	5.0000
40	Y20_36	0.0011	0.0006	5.0000
⋮				

Each row corresponds to one covariate `var`, evaluated by permuting its values across individuals (holding the fitted MTM fixed) and recomputing the weighted multinomial log-loss. The column Δ`logloss_mean` reports the average increase in weighted log-loss relative to the unpermuted baseline, $\Delta\mathcal{L} = \mathcal{L}_{\pi(\texttt{var})} - \mathcal{L}_{\text{base}}$, where larger values indicate greater predictive contribution of that covariate to transition outcomes. The column Δ`logloss_sd` is the standard deviation of $\Delta\mathcal{L}$ across `nperm` random permutations. Covariates are sorted in descending order of Δ`logloss_mean`; variables near the top are most influential for predicting cover-crop transition probabilities under the MTM.

Table 26: Permutation-importance ranking of covariates for the Markov Transition Model (MTM) from year block (2022, 2023) to year block (2023, 2025).

	var	Δ_logloss_mean	Δ_logloss_sd	nperm
1	Y25_27q	0.0133	0.0019	5.0000
2	Y25_27p	0.0117	0.0029	5.0000
3	Y25_26_Compaction_mgmt_prac	0.0107	0.0028	5.0000
4	Y24_7_Stress	0.0077	0.0008	5.0000
5	Y25_27h	0.0074	0.0014	5.0000
6	Y25_27o	0.0073	0.0015	5.0000
7	Y25_25b	0.0063	0.0022	5.0000
8	Y25_27i	0.0055	0.0012	5.0000
9	Y25_27r	0.0053	0.0013	5.0000
10	Y25_27j	0.0052	0.0030	5.0000
11	Y25_27m	0.0045	0.0015	5.0000
12	Y25_25e	0.0044	0.0018	5.0000
13	Y25_26_Compaction_concern	0.0041	0.0007	5.0000
14	Y25_25c	0.0040	0.0002	5.0000
15	Y25_25d	0.0039	0.0017	5.0000
16	Y23_33	0.0038	0.0018	5.0000
17	Y25_27c	0.0038	0.0013	5.0000
18	Y24_21_NRS_support	0.0037	0.0018	5.0000
19	Y25_27a	0.0035	0.0008	5.0000
20	Y24_6	0.0034	0.0008	5.0000
21	Y25_27l	0.0031	0.0015	5.0000
22	Y25_27k	0.0030	0.0019	5.0000
23	Y23_20t	0.0028	0.0006	5.0000
24	Y25_27f	0.0028	0.0009	5.0000
25	Y23_20v	0.0022	0.0002	5.0000
26	Y25_26_Compaction_mgmt_tech	0.0022	0.0006	5.0000
27	Y22_16_Trusted_entities	0.0020	0.0013	5.0000
28	Y22_17a_Trauma	0.0019	0.0008	5.0000
29	Y23_15	0.0018	0.0013	5.0000
30	Y25_27d	0.0018	0.0009	5.0000
31	Y23_21_Agron_efficacy	0.0018	0.0010	5.0000
32	Y25_27g	0.0018	0.0006	5.0000
33	Y23_14	0.0017	0.0011	5.0000
34	Y23_20_EoF_prac	0.0015	0.0008	5.0000
35	Y25_27b	0.0015	0.0009	5.0000
36	Y23_20s	0.0015	0.0004	5.0000
37	Y22_3_Steward	0.0014	0.0005	5.0000
38	Y23_20u	0.0014	0.0008	5.0000
39	Y24_3_Satisfaction	0.0012	0.0005	5.0000
40	Y24_22_Conservation_advisor	0.0012	0.0004	5.0000
⋮				

Table 27: Summary of the directions of associations between covariates and transition outcomes on the log-odds scale from year block (2020, 2021) to year block (2022, 2023).

	term	2	3	4
1	(Intercept)	-0.938	-3.710	-3.048
2	S=2	1.309	1.434	0.430
3	S=3	2.185	3.147	2.301
4	S=4	0.170	2.047	2.861
5	Y23_20_N_mgmt_prac	0.080	0.084	0.094
6	Y23_20v	0.058	0.104	0.140
7	Y23_17_level1	0.052	0.051	0.306
8	Y23_20u	0.076	0.118	0.094
9	Y23_14_level1	0.049	0.039	0.228
10	Y23_20s	0.035	0.062	0.082
11	Y21_24_CC_barriers	-0.022	-0.003	-0.154
12	Y21_33_level2	-0.220	0.052	0.189
13	Y23_20t	0.021	0.071	0.050
14	Y21_13v	0.045	0.036	0.084
15	Y21_13u	0.027	0.059	-0.016
16	Y20_18_level1	0.041	0.046	0.159
17	Y22_3_Steward	0.016	-0.010	0.070
18	Y20_4b	-0.021	0.013	-0.065
19	Y21_24_CC_benefits	0.023	0.138	0.124
20	Y20_13_Stewardship_motive	-0.028	-0.010	0.018
21	Y21_11_4R_Info_ag	0.059	0.008	0.031
22	Y23_20_Other_prac	0.048	0.126	0.079
23	Y23_15_level1	0.145	0.057	-0.020
24	Y23_20_EoF_prac	0.074	0.077	0.030
25	Y20_23i	-0.037	-0.003	-0.059
26	Y20_11acdgi_scale	-0.078	-0.021	-0.091
27	Y20_9_level1	-0.048	0.045	0.112
28	Y21_8_Soil_health	-0.026	0.005	0.083
29	Y23_18	0.001	0.019	0.032
30	Y20_3e	-0.047	-0.055	-0.002
31	Y20_14	-0.005	0.001	0.018
32	Y21_24_CC_support	0.147	0.190	0.115
33	Y20_3abcd_scale	-0.032	-0.096	-0.039
34	Y22_3_Productivist	-0.050	-0.054	-0.075
35	Y20_13_Regulatory_motive	-0.038	-0.040	-0.048
36	Y20_4acde_scale	-0.053	-0.103	-0.082
37	Y22_2_Opinion_leader	-0.046	-0.040	0.012
38	Y20_13_Social_motive	-0.049	-0.052	-0.049
39	Y20_23abdl_scale	-0.022	0.055	0.057
40	Y23_35	-0.002	-0.000	-0.001
⋮				

Direction on log-odds for the Markov Transition Model (MTM) with destination level $Y = 1$ as the reference category. Each row corresponds to a model term (`term`), including the intercept, initial-state indicators ($S = 2, 3, 4$; with $S = 1$ as the reference so its effect is 0), and covariates (with categorical covariates represented by separate dummy variables such as `_level`ℓ, relative to their baseline level). Columns `2`, `3`, and `4` report the estimated coefficients $\hat{\eta}_m(\texttt{term})$ in the baseline-category multinomial logit: $\log\{\Pr(Y = m \mid S, X)/\Pr(Y = 1 \mid S, X)\}$ for $m \in \{2, 3, 4\}$. A positive value in column m indicates that increasing the term (or being in that category/level) increases the log-odds—and hence the odds—of transitioning to destination level m relative to destination level 1, holding other predictors fixed; a negative value indicates a decrease. The odds ratio for a one-unit change in a numeric covariate (or for a dummy level vs baseline) is $\exp(\hat{\eta}_m)$.

Table 28: Summary of the directions of associations between covariates and transition outcomes on the log-odds scale from year block (2022, 2023) to year block (2023, 2025).

	term	2	3	4
1	(Intercept)	-4.084	-5.397	-6.577
2	S=2	1.162	1.327	0.394
3	S=3	0.507	1.609	1.610
4	S=4	0.075	1.296	2.668
5	Y25_27q	0.090	0.089	0.115
6	Y25_27p	0.045	0.077	0.103
7	Y25_26_Compaction_mgmt_prac	0.237	0.222	0.333
8	Y24_7_Stress	-0.157	-0.079	-0.105
9	Y25_27h	0.051	0.073	0.100
10	Y25_27o	0.052	0.050	0.100
11	Y25_25b	-0.001	0.001	0.004
12	Y25_27i	0.060	0.029	0.072
13	Y25_27r	0.044	0.063	0.072
14	Y25_27j	0.081	0.063	0.082
15	Y25_27m	0.036	0.066	0.081
16	Y25_25e	-0.001	-0.000	0.002
17	Y25_26_Compaction_concern	0.098	0.078	0.039
18	Y25_25c	-0.000	0.000	0.003
19	Y25_25d	-0.001	-0.000	0.002
20	Y23_33	0.000	0.001	0.002
21	Y25_27c	0.045	0.027	0.067
22	Y24_21_NRS_support	0.073	0.036	0.095
23	Y25_27a	0.032	0.057	0.025
24	Y24_6	-0.057	-0.060	-0.045
25	Y25_27l	0.044	0.050	0.059
26	Y25_27k	0.019	0.041	0.052
27	Y23_20t	-0.016	-0.005	0.035
28	Y25_27f	0.003	0.038	0.047
29	Y23_20v	-0.027	0.002	0.008
30	Y25_26_Compaction_mgmt_tech	0.008	-0.099	-0.102
31	Y22_16_Trusted_entities	0.070	0.046	0.043
32	Y22_17a_Trauma	0.023	0.016	0.011
33	Y23_15_level1	0.112	0.012	0.113
34	Y25_27d	-0.001	0.021	0.036
35	Y23_21_Agron_efficacy	0.041	0.019	-0.040
36	Y25_27g	-0.020	0.019	0.021
37	Y23_14_level1	0.099	0.038	0.079
38	Y23_20_EoF_prac	0.002	-0.017	0.040
39	Y25_27b	0.002	-0.008	0.027
40	Y23_20s	0.025	0.002	0.033
⋮				

5.5 Markov Transition Model (LASSO)

Table 29: The estimated transition distribution from year 2021 to year 2023.

from\to	1	2	3	4
1	0.68	0.18	0.05	0.09
2	0.35	0.41	0.14	0.09
3	0.11	0.35	0.29	0.25
4	0.15	0.06	0.13	0.66

Rows correspond to the initial (origin) cover-crop level $S = s$ and columns correspond to the destination level $Y = k$; the entry $\widehat{T}_{s\to k}$ is the estimated (weighted) probability of transitioning from level s to level k, with each row summing to 1.

Table 30: The estimated transition distribution from year 2023 to year 2025.

from\to	1	2	3	4
1	0.64	0.22	0.06	0.07
2	0.33	0.44	0.15	0.08
3	0.28	0.21	0.20	0.30
4	0.18	0.08	0.09	0.65

Table 31: Permutation-importance ranking of covariates for the Markov Transition Model (MTM) from year block (2020, 2021) to year block (2022, 2023).

	var	Δ_logloss_mean	Δ_logloss_sd	nperm
1	Y23_20_N_mgmt_prac	0.0518	0.0109	5.0000
2	Y23_17	0.0388	0.0047	5.0000
3	Y23_20v	0.0282	0.0036	5.0000
4	Y23_20u	0.0113	0.0043	5.0000
5	Y21_24_CC_barriers	0.0020	0.0005	5.0000
6	Y23_14	0.0019	0.0004	5.0000
7	Y22_3_Steward	0.0002	0.0000	5.0000
8	Y20_3abcd_scale	0.0000	0.0000	5.0000
9	Y20_3e	0.0000	0.0000	5.0000
10	Y20_4acde_scale	0.0000	0.0000	5.0000
11	Y20_4b	0.0000	0.0000	5.0000
12	Y20_5abcdefghi_sum	0.0000	0.0000	5.0000
13	Y20_6abcdefghijk_sum	0.0000	0.0000	5.0000
14	Y20_9	0.0000	0.0000	5.0000
15	Y20_11acdgi_scale	0.0000	0.0000	5.0000
16	Y20_12_Econ_capacity	0.0000	0.0000	5.0000
17	Y20_12_Agron_efficacy	0.0000	0.0000	5.0000
18	Y20_13_Stewardship_motive	0.0000	0.0000	5.0000
19	Y20_13_Regulatory_motive	0.0000	0.0000	5.0000
20	Y20_13_Social_motive	0.0000	0.0000	5.0000
21	Y20_14	0.0000	0.0000	5.0000
22	Y20_15	0.0000	0.0000	5.0000
23	Y20_18	0.0000	0.0000	5.0000
24	Y20_19	0.0000	0.0000	5.0000
25	Y20_CC_Beliefs	0.0000	0.0000	5.0000
26	Y20_23abdl_scale	0.0000	0.0000	5.0000
27	Y20_23i	0.0000	0.0000	5.0000
28	Y20_25cfi_scale	0.0000	0.0000	5.0000
29	Y20_26a	0.0000	0.0000	5.0000
30	Y20_26b	0.0000	0.0000	5.0000
31	Y20_34	0.0000	0.0000	5.0000
32	Y20_36	0.0000	0.0000	5.0000
33	Y21_8_Soil_health	0.0000	0.0000	5.0000
34	Y21_11_4R_Info_ag	0.0000	0.0000	5.0000
35	Y21_11_4R_Info_social.media	0.0000	0.0000	5.0000
36	Y21_13q	0.0000	0.0000	5.0000
37	Y21_13s	0.0000	0.0000	5.0000
38	Y21_13t	0.0000	0.0000	5.0000
39	Y21_13u	0.0000	0.0000	5.0000
40	Y21_13v	0.0000	0.0000	5.0000
⋮				

Each row corresponds to one covariate `var`, evaluated by permuting its values across individuals (holding the fitted MTM fixed) and recomputing the weighted multinomial log-loss. The column Δ`logloss_mean` reports the average increase in weighted log-loss relative to the unpermuted baseline, $\Delta\mathcal{L} = \mathcal{L}_{\pi(\texttt{var})} - \mathcal{L}_{\text{base}}$, where larger values indicate greater predictive contribution of that covariate to transition outcomes. The column Δ`logloss_sd` is the standard deviation of $\Delta\mathcal{L}$ across `nperm` random permutations. Covariates are sorted in descending order of Δ`logloss_mean`; variables near the top are most influential for predicting cover-crop transition probabilities under the MTM.

Table 32: Permutation-importance ranking of covariates for the Markov Transition Model (MTM) from year block (2022, 2023) to year block (2023, 2025).

	var	Δ_logloss_mean	Δ_logloss_sd	nperm
1	Y25_27q	0.0314	0.0053	5.0000
2	Y25_26_Compaction_mgmt_prac	0.0215	0.0057	5.0000
3	Y25_25b	0.0211	0.0068	5.0000
4	Y25_27p	0.0197	0.0050	5.0000
5	Y25_27o	0.0112	0.0021	5.0000
6	Y25_27h	0.0102	0.0025	5.0000
7	Y25_27j	0.0074	0.0041	5.0000
8	Y25_27r	0.0011	0.0004	5.0000
9	Y22_2_Opinion_leader	0.0000	0.0000	5.0000
10	Y22_3_Productivist	0.0000	0.0000	5.0000
11	Y22_3_Steward	0.0000	0.0000	5.0000
12	Y22_16_Trusted_entities	0.0000	0.0000	5.0000
13	Y22_16_Private_entities	0.0000	0.0000	5.0000
14	Y22_16_Public_entities	0.0000	0.0000	5.0000
15	Y22_17a_Trauma	0.0000	0.0000	5.0000
16	Y23_14	0.0000	0.0000	5.0000
17	Y23_15	0.0000	0.0000	5.0000
18	Y23_16	0.0000	0.0000	5.0000
19	Y23_17	0.0000	0.0000	5.0000
20	Y23_18	0.0000	0.0000	5.0000
21	Y23_19	0.0000	0.0000	5.0000
22	Y23_20_N_mgmt_prac	0.0000	0.0000	5.0000
23	Y23_20_EoF_prac	0.0000	0.0000	5.0000
24	Y23_20_Other_prac	0.0000	0.0000	5.0000
25	Y23_20s	0.0000	0.0000	5.0000
26	Y23_20t	0.0000	0.0000	5.0000
27	Y23_20u	0.0000	0.0000	5.0000
28	Y23_20v	0.0000	0.0000	5.0000
29	Y23_21_Agron_efficacy	0.0000	0.0000	5.0000
30	Y23_21_Econ_capacity	0.0000	0.0000	5.0000
31	Y23_33	0.0000	0.0000	5.0000
32	Y23_35	0.0000	0.0000	5.0000
33	Y24_3_Satisfaction	0.0000	0.0000	5.0000
34	Y24_4	0.0000	0.0000	5.0000
35	Y24_6	0.0000	0.0000	5.0000
36	Y24_7_Stress	0.0000	0.0000	5.0000
37	Y24_21_NRS_support	0.0000	0.0000	5.0000
38	Y24_21_NRS_barriers	0.0000	0.0000	5.0000
39	Y24_22_Conservation_advisor	0.0000	0.0000	5.0000
40	Y25_25c	0.0000	0.0000	5.0000
⋮				

Table 33: Summary of the directions of associations between covariates and transition outcomes on the log-odds scale from year block (2020, 2021) to year block (2022, 2023).

	term	2	3	4
1	(Intercept)	-3.076	-4.388	-4.033
2	S=2	1.256	1.482	0.505
3	S=3	2.149	3.259	2.412
4	S=4	0.191	2.286	3.042
5	Y23_20_N_mgmt_prac	0.240	0.240	0.240
6	Y23_17_level1	0.000	0.000	0.759
7	Y23_20v	0.188	0.188	0.288
8	Y23_20u	0.123	0.123	0.123
9	Y21_24_CC_barriers	0.000	0.000	-0.056
10	Y23_14_level1	0.000	0.000	0.075
11	Y22_3_Steward	0.000	0.000	0.003
12	Y20_11acdgi_scale	0.000	0.000	0.000
13	Y20_12_Agron_efficacy	0.000	0.000	0.000
14	Y20_12_Econ_capacity	0.000	0.000	0.000
15	Y20_13_Regulatory_motive	0.000	0.000	0.000
16	Y20_13_Social_motive	0.000	0.000	0.000
17	Y20_13_Stewardship_motive	0.000	0.000	0.000
18	Y20_14	0.000	0.000	0.000
19	Y20_15_level1	0.000	0.000	0.000
20	Y20_18_level1	0.000	0.000	0.000
21	Y20_19	0.000	0.000	0.000
22	Y20_23abdl_scale	0.000	0.000	0.000
23	Y20_23i	0.000	0.000	0.000
24	Y20_25cfi_scale	0.000	0.000	0.000
25	Y20_26a	0.000	0.000	0.000
26	Y20_26b	0.000	0.000	0.000
27	Y20_34	0.000	0.000	0.000
28	Y20_36_level1	0.000	0.000	0.000
29	Y20_3abcd_scale	0.000	0.000	0.000
30	Y20_3e	0.000	0.000	0.000
31	Y20_4acde_scale	0.000	0.000	0.000
32	Y20_4b	0.000	0.000	0.000
33	Y20_5abcdefghi_sum	0.000	0.000	0.000
34	Y20_6abcdefghijk_sum	0.000	0.000	0.000
35	Y20_9_level1	0.000	0.000	0.000
36	Y20_CC_Beliefs	0.000	0.000	0.000
37	Y21_11_4R_Info_ag	0.000	0.000	0.000
38	Y21_11_4R_Info_social.media	0.000	0.000	0.000
39	Y21_13q	0.000	0.000	0.000
40	Y21_13s	0.000	0.000	0.000
⋮				

Direction on log-odds for the Markov Transition Model (MTM) with destination level $Y = 1$ as the reference category. Each row corresponds to a model term (`term`), including the intercept, initial-state indicators ($S = 2, 3, 4$; with $S = 1$ as the reference so its effect is 0), and covariates (with categorical covariates represented by separate dummy variables such as `_level`ℓ, relative to their baseline level). Columns `2`, `3`, and `4` report the estimated coefficients $\hat{\eta}_m(\texttt{term})$ in the baseline-category multinomial logit: $\log\{\Pr(Y = m \mid S, X)/\Pr(Y = 1 \mid S, X)\}$ for $m \in \{2, 3, 4\}$. A positive value in column m indicates that increasing the term (or being in that category/level) increases the log-odds—and hence the odds—of transitioning to destination level m relative to destination level 1, holding other predictors fixed; a negative value indicates a decrease. The odds ratio for a one-unit change in a numeric covariate (or for a dummy level vs baseline) is $\exp(\hat{\eta}_m)$.

Table 34: Summary of the directions of associations between covariates and transition outcomes on the log-odds scale from year block (2022, 2023) to year block (2023, 2025).

	term	2	3	4
1	(Intercept)	-3.136	-4.448	-4.667
2	S=2	1.223	1.492	0.652
3	S=3	0.424	1.665	1.796
4	S=4	-0.027	1.354	2.851
5	Y25_27q	0.221	0.221	0.221
6	Y25_26_Compaction_mgmt_prac	0.545	0.545	0.545
7	Y25_25b	0.000	0.000	0.010
8	Y25_27p	0.094	0.094	0.173
9	Y25_27o	0.070	0.070	0.128
10	Y25_27h	0.109	0.109	0.109
11	Y25_27j	0.098	0.098	0.098
12	Y25_27r	0.013	0.013	0.013
13	Y22_16_Private_entities	0.000	0.000	0.000
14	Y22_16_Public_entities	0.000	0.000	0.000
15	Y22_16_Trusted_entities	0.000	0.000	0.000
16	Y22_17a_Trauma	0.000	0.000	0.000
17	Y22_2_Opinion_leader	0.000	0.000	0.000
18	Y22_3_Productivist	0.000	0.000	0.000
19	Y22_3_Steward	0.000	0.000	0.000
20	Y23_14_level1	0.000	0.000	0.000
21	Y23_15_level1	0.000	0.000	0.000
22	Y23_16_level1	0.000	0.000	0.000
23	Y23_17_level1	0.000	0.000	0.000
24	Y23_18	0.000	0.000	0.000
25	Y23_19	0.000	0.000	0.000
26	Y23_20_EoF_prac	0.000	0.000	0.000
27	Y23_20_N_mgmt_prac	0.000	0.000	0.000
28	Y23_20_Other_prac	0.000	0.000	0.000
29	Y23_20s	0.000	0.000	0.000
30	Y23_20t	0.000	0.000	0.000
31	Y23_20u	0.000	0.000	0.000
32	Y23_20v	0.000	0.000	0.000
33	Y23_21_Agron_efficacy	0.000	0.000	0.000
34	Y23_21_Econ_capacity	0.000	0.000	0.000
35	Y23_33	0.000	0.000	0.000
36	Y23_35	0.000	0.000	0.000
37	Y24_21_NRS_barriers	0.000	0.000	0.000
38	Y24_21_NRS_support	0.000	0.000	0.000
39	Y24_22_Conservation_advisor	0.000	0.000	0.000
40	Y24_3_Satisfaction	0.000	0.000	0.000
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