Measuring Adoption Intensity of Weed Resistance Management Practices using Data Envelope Analysis with Principal Components

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Public Policies, Research and the Economics of Herbicide Resistance Management

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Motivation

- Herbicide resistant weeds are a problem and spreading
- Lots of reasons why has this problem has occurred
- Lots of reasons why we should be concerned
- Lots of ideas about what we should do about it
- Lots of reasons why it will be difficult to address

- Basic Management Principle: Measure to Manage
  - You cannot manage what you do not measure!
- My Goal Today: Present a method to measure farmer adoption of weed resistance management practices based on method we use to measure agricultural sustainability

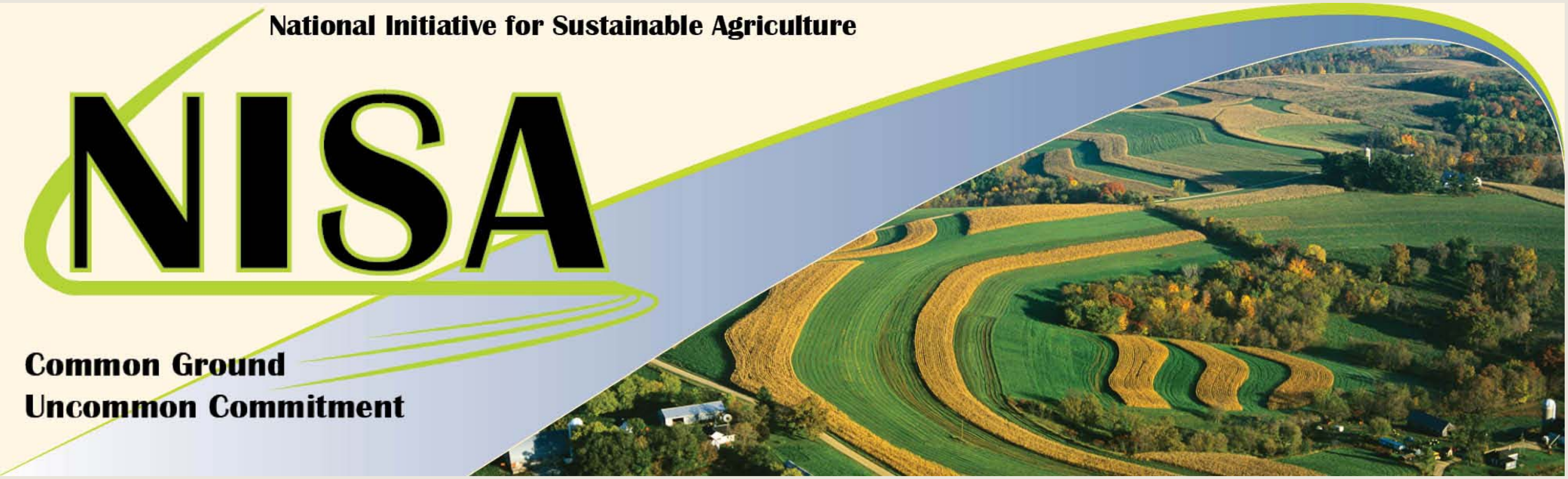
Lots of Problems in Ag

- Double food production by 2050 (Tillman et al. 2011)
- Can already detect negative impacts of climate change on aggregate crop yields (Lobell et al. 2011)
- Dead zones will continue: Legacy N and P will pollute surface waters for decades, even if ag disappeared (Sebilo et al. 2013; Jarvie et al. 2013; Finlay et al. 2013)
- From 2006-2011, 1.3 million grassland acres converted to crops on the Great Plains (Wright & Wimberley 2013)
- Soil Erosion: “Losing Ground” (Cox et al. 2011)
- Groundwater declines (India, CA, Ogallala, etc.)
- Herbicide resistant weeds just one of the many problems
- **Solution: Agricultural Sustainability!**

Making Ag Sustainability Practical

- Lots of grand ideals, media events, colorful graphics, papers, reports, conferences, presentations, …
- How do you make Ag Sustainability practical?
- What do you measure? How do you measure it?
- Sustainability is multi-dimensional: How do you capture the tradeoffs?
- A first step is measuring farmer adoption of best management practices (BMPs) that have demonstrated positive outcomes
- Herbicide resistance management practices are just a special case of this more general problem

- Several active projects at UW in ag sustainability
  - Cranberry, soybeans, sweet corn, green beans, potatoes, plus whole farm
- National Initiative for Sustainable Agriculture (NISA): http://nisa.cals.wisc.edu/
- **Developed an index of BMP adoption intensity for agricultural sustainability that also applies to adoption of weed resistance management practices**



The Rest of the Presentation

1. Describe the General Measurement Problem
2. Describe the Analysis Method: Data Envelope Analysis with Principal Components
3. Present empirical results for weed BMP adoption among U.S. corn, soybean, and cotton growers
4. Summarize regression analysis to explore the determinants of weed BMP adoption intensity

The General Problem

- Conduct a survey and have data on farmer adoption of numerous practices
  - Weed BMPs for managing herbicide resistance
    - Our survey has 10 practices and we add 3 more
    - Norsworthy et al. (2012) has 12 practices
  - Sustainable Ag practices
    - Cranberry: ~20 practices, Soybean: ~70 practices, Sweet Corn & Green Bean: ~100, Whole Farm: ~200
    - Insect, disease, weed, soil, nutrient, water/irrigation mgmt, natural areas/biodiversity, employee mgmt, professional development, record keeping/planning, energy/GHG/recycling, community involvement, …

The General Problem

- Practice adoption highly correlated and/or interrelated:
  - Complementary and Competitive practices: scouting for insects, diseases, & weeds; RR adoption and use of residual herbicide or multiple modes of action
- Commonly use Categorical/Discrete measures
  - Do you use this practice: Yes/No
  - How often do you use this practice: Always, Often Sometimes, Rarely, Never
- Main point: Adoption data consists of many variables, some discrete, many correlated

Data Envelope Analysis with Principal Components

1. Principal Component Analysis (PCA) to reduce number of variables and transform variables to positive continuous variables with little loss of information
2. Data Envelope Analysis (DEA) to create composite index measuring how intensely each farmer adopts practices

- Output:
  - Score between 0 and 1 for each farmer measuring BMP adoption intensity relative to peers
  - Distribution of scores describes BMP adoption intensity of the grower population
  - Way to measure changes over time at individual grower level and for a grower population

Non-Negative Polychoric PCA

- Non-Negative: Restrict PCA so weight matrix **U** has all positive weights (preparing for DEA)
- Use polychoric correlation for discrete variables rather than typical Pearson's correlation
- Data $\mathbf{X} \in R^{V \times N}$ v = 1 to V variables k = 1 to N farms
- Divide each observation x_{vk} by each variable's st. dev. σ_v to form normalized data matrix $\mathrm{X} \in R^{V \times N}$
- New data $\mathbf{Y} = \mathbf{U}^{\mathrm{T}}\mathrm{X}$, where $\mathbf{Y} \in R^{I \times N}$ is matrix of retained PC's i = 1 to I and $\mathbf{U} \in R^{V \times I}$ is the PCA weight matrix

Non-Negative Polychoric PCA

- Dong et al. (2013) gives details for solving for **U**

$$\max_{\mathbf{U}} \frac{1}{2} \| \mathbf{U}^{\mathrm{T}} \mathbf{X} \|_F^2 - \frac{\alpha}{4} \| \mathbf{I} - \mathbf{U}^{\mathrm{T}} \mathbf{U} \|_F^2 \ , \quad \text{subject to} \quad \mathbf{U} \geq 0$$

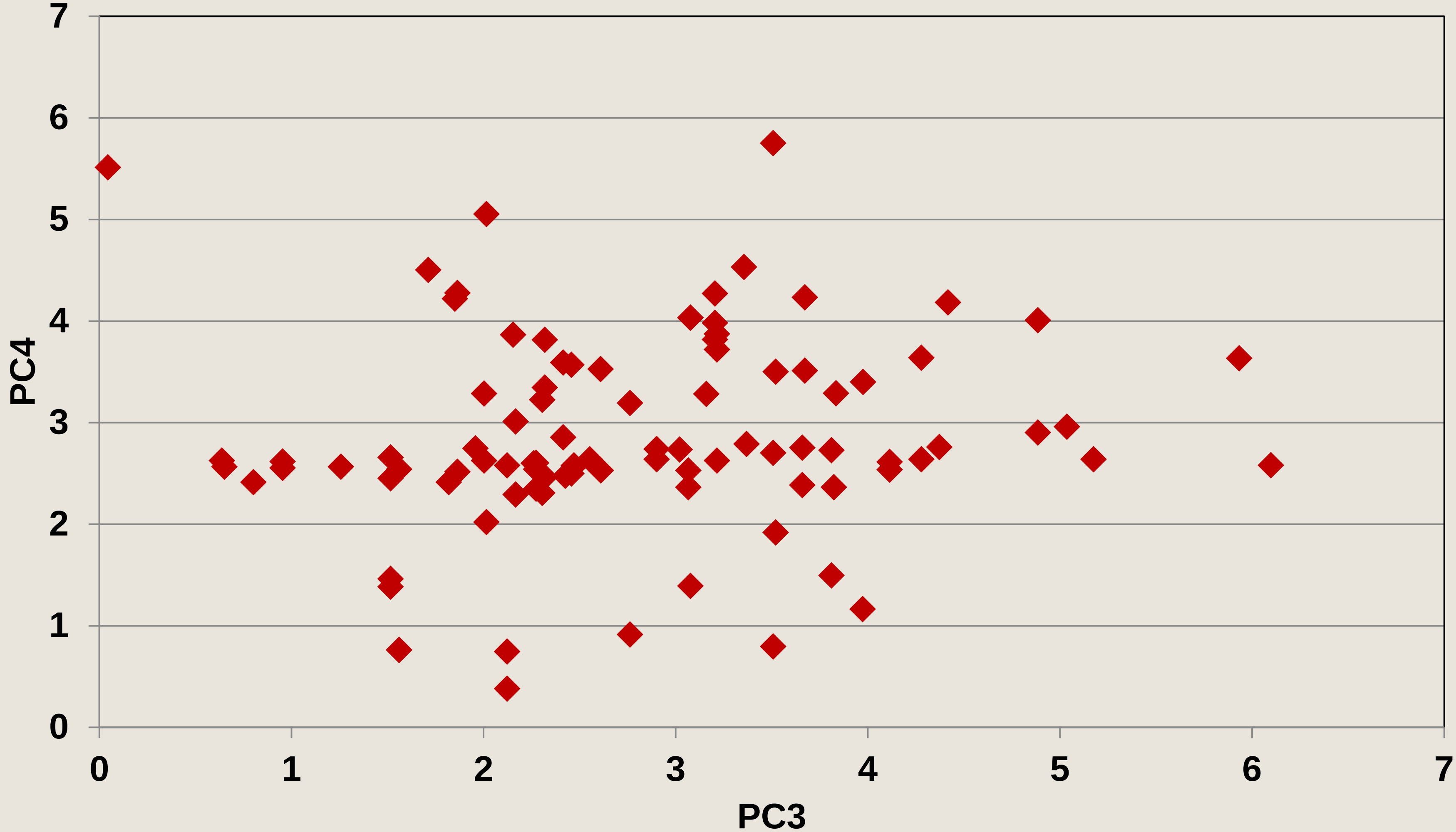
- $||\cdot||^2$ = Squared Frobenius norm = sum of squared elements
- Fairly intense optimization process
- With 70 PC’s and 300+ observations = 2 days on PC for each choice of number of PCs to retain

Cranberry Example PCA weight matrix **U** with elements u_{iv}

	% Ac Scout	Hired Scout	Times Scout	Dist Travel	Cultrl Practc	Soil Test	Tissue Test	Weathr Station	Soil Moistr	Irrg Unifm Test	Nut Mgmt Plan	Consrv Plan	Recycle	Emply Insrnc	Emply Retrmt	Safety Trng
PC1	**1.014**	0	0.001	0	0.025	0	0	0	0.008	0.003	0	0	0	0	0	0
PC2	0	0.051	**1.012**	0	0	0	0.020	0	0	0.002	0	0	0.016	0	0.000	0
PC3	0	0	0.009	0.034	0	0	0	**0.958**	**0.339**	0	0	0	0	0	0	0
PC4	0.001	0	0	0.012	0.035	0	0	0	0.062	**1.011**	0.007	0.026	0	0	0	0
PC5	0	0	0	0	0	0.080	**0.605**	0	0.091	0	**0.822**	0.023	0	0	0	0
PC6	0	0.078	0	**0.431**	0	0	0.018	0	0	0	0	0	0.017	**0.914**	0	0
PC7	0	0	0	0	0	0.029	0.003	0	0.069	0	0	**0.728**	**0.708**	0	0	0
PC8	0	0.008	0	0	0	0	0.011	0.001	0	0	0	0	0.017	0.022	**1.014**	0.019
PC9	0	**0.353**	0	0	**0.496**	**0.417**	0	0	0.050	0	0	0	0	0	0	**0.707**

- Final PCA Output: For each farmer k: $y_{ik} = \Sigma_v u_{iv} x_{vk}$
- Example: PC1 = 1.014 x %AcresScouted + 0.025 x UseCulturalPractices + ... (weighted average)
- PC1 and PC2: Pest scouting practices
- PC3 and PC4: Irrigation practices
- PC5: Nutrient management

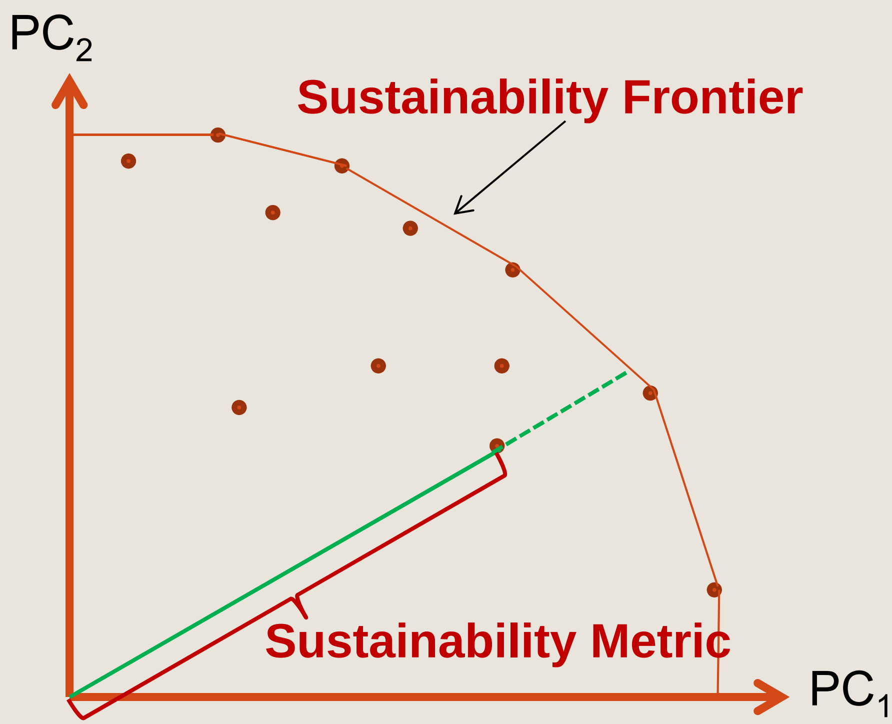
Cranberry Example: PC4 (irrigation uniformity testing) vs. PC3 (weather station & soil moisture monitoring)



Data Envelope Analysis (DEA)

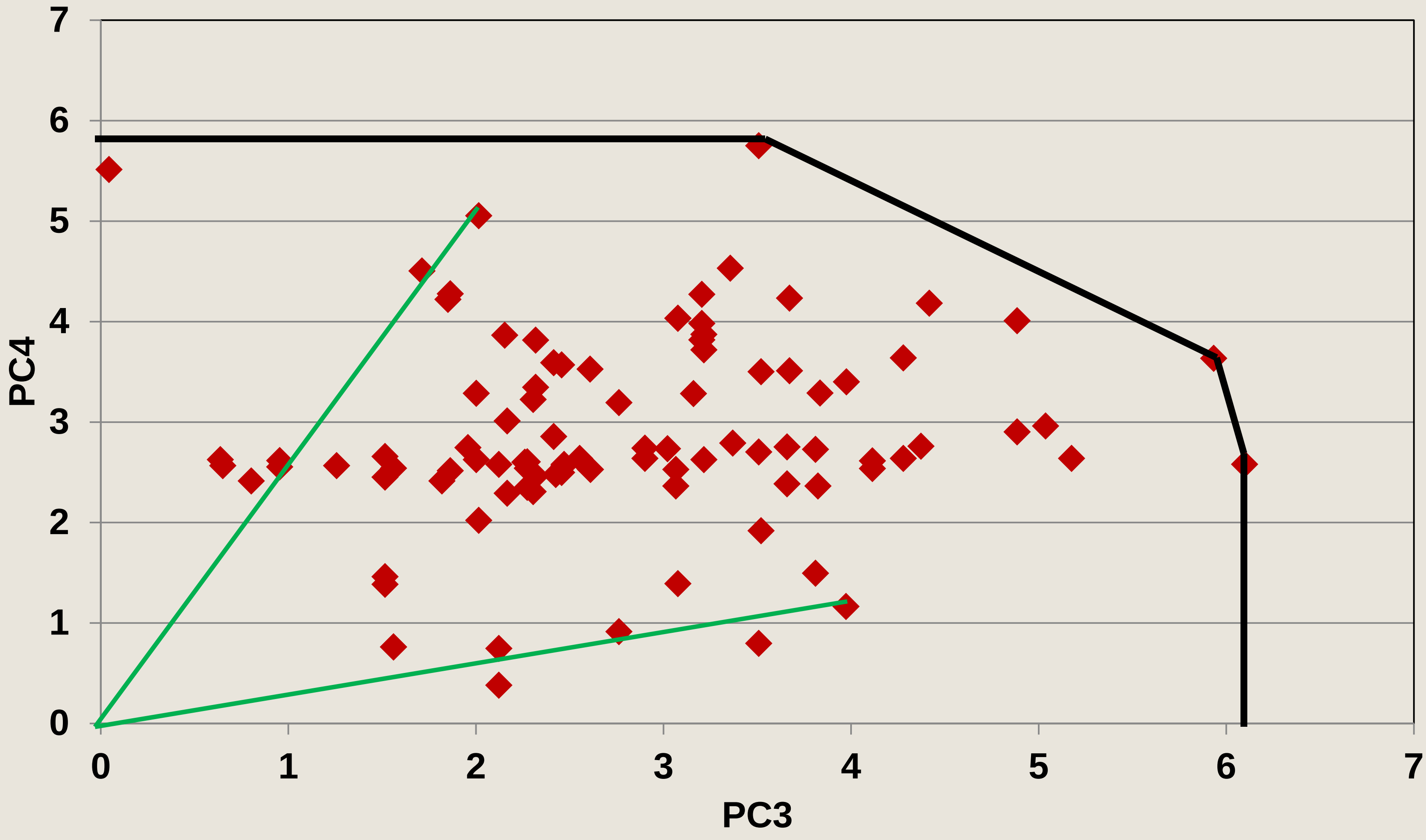
- DEA widely used to rank or score individuals, companies, countries in a variety of contexts
- Creates index number ranking each unit relative to peers
- Too many variables reduces discriminating power
- Correlation among variables creates bias
- Discrete variables imply non-interpretable combinations
- Technically use input-oriented, constant returns to scale DEA with multiple outputs and a single dummy input of 1 for all farms, which requires all data to be positive
- Use non-negative polychoric PCA to pre-process data to reduce dimensions, remove correlation, and make data positive and continuous
- Common-weight DEA to increase discriminating power

DEA for Adoption Intensity (Theory)



- Farmer practice adoption gives PC1 and PC2
- Plot these points: Each farmer is a point
- DEA Frontier: outer envelope of points
- Distance from origin to point measures practice adoption intensity relative to frontier
- Max score = 1.0
- Min score = 0.0

Cranberry Example PC4 vs. PC3



Common-Weight DEA

Average deviation

$$\text{Minimize } h(d_k, \omega_i, z) = t \frac{1}{K} \sum_{k=1}^{K} d_k + (1-t) z$$

Max deviation over all k

$$\text{subject to } S_k^b - \sum_{i=1}^{I} \omega_i y_{ik} = d_k,\ d_k \geq 0,\ z - d_k \geq 0\ \forall k,\ \omega_i \geq \varepsilon\ \forall i,\ z \geq 0.$$

Common-weight DEA score

Basic DEA score

$$\text{Maximize } S_k^b(\omega_{ik}) = \sum_{i=1}^{I} \omega_{ik} y_{ik}$$

$$\text{subject to: } \sum_{i=1}^{I} \omega_{ik} y_{ik} \leq 1\ \forall k,\ \omega_{ik} \geq \varepsilon\ \forall k$$

- $0 \leq t \leq 1$ weights average and max deviation in objective
- Vary t from 0 to 1 by 0.01 and solve for optimal scores, then average scores for a grower over all solutions

$$\bar{S}_k = \frac{1}{T} \sum_{t=0}^{1} S_{kt} = \frac{1}{T} \sum_{t=0}^{1} \sum_{i=1}^{I} \omega_{it} y_{ik} = \sum_{i=1}^{I} \bar{\omega}_i y_{ik}$$

Average DEA weight

$$\bar{\omega}_i = \frac{1}{T} \sum_{t=0}^{1} \omega_{it}$$

Combine Weights from PCA and DEA

- PCA is weighted average of original data
- DEA score is a weighted average of the PC's
- Combine the weights to get score in terms of the original variables measuring grower practice adoption

standard deviation

original variable

$$\bar{S}_k = \sum_{v=1}^{V} \sum_{i=1}^{I} (\bar{\omega}_i u_{vi} / \sigma_v) x_{vk} = \sum_{v=1}^{V} w_v x_{vk}$$

Average DEA weight

PCA weight

final weight

- Main Point: Can express farmer score as a weighted average of their responses, where weights are endogenous

Weed BMP Data

- Telephone survey of 400 corn, 400 soybean and 400 cotton famers from main producing states
  - At least 250 acres of target crop
  - Surveyed during Nov-Dec 2007
  - Questions on 2007 and plans for 2008
  - Weed management with RR focus
  - Funded by Monsanto
- Published various conference papers, plus journal papers Hurley et al. 2009a, 2009b, 2009c, Frisvold et al. 2009

Weed Management Survey

- General Grower and Operation Information
- 2007 Production Practices
- Weed BMP Use
- Factors Influencing Herbicide Choices
- 2008 Production Plans
- Economic questions to derive WTP estimates

Weed Resistance Management BMPs

- Scout fields before a herbicide application
- Scout fields after a herbicide application
- Start with a clean field, using a burndown herbicide application or tillage
- Control weeds early when they are relatively small
- Control weed escapes and prevent weeds from setting seeds
- Clean equipment before moving between fields to minimize weed seed spread
- Use new commercial seed that is as free from weed seed as possible
- Use multiple herbicides with different modes of action during cropping season
- Use tillage to supplement weed control provided by herbicide applications
- Use the recommended application rate from the herbicide label

Soybean Data	Frequency of Adoption (% of Respondents)				
Practice	Never	Rarely	Sometimes	Often	Always
Scout fields before a herbicide application	1.1	1.6	10.3	31.7	55.4
Scout fields after a herbicide application	1.3	2.9	14.5	32.5	48.8
Start with a clean field, using a burndown herbicide application or tillage	9.8	5.5	12.9	15.3	56.5
Control weeds early when they are relatively small	0.3	1.3	10.6	36.9	50.9
Control weed escapes and prevent weeds from setting seeds	2.4	3.7	14.0	31.7	48.3
Clean equipment before moving between fields to minimize weed seed spread	34.8	26.1	18.5	10.0	10.6
Use new commercial seed that is as free from weed seed as possible	1.1	0.3	1.9	5.5	91.3
Use multiple herbicides with different modes of action during the season	18.5	20.1	33.3	14.5	13.7
Use tillage to supplement weed control provided by herbicide applications	37.2	23.0	24.5	7.7	7.7
Use the recommended application rate from the herbicide label	0.5	0.3	3.7	21.1	74.4

Augmented Data

- Added 3 continuous variables
- % RR target crop acres following non-RR crop
- % target crop acres treated with burndown herbicide
- % target crop acres treated with residual herbicide

Soybean Data	Mean	St. Dev.	Minimum	Maximum
%RRPostNonRR	51.0	43.6	0.0	100.0
%Burndown	34.7	43.7	0.0	100.0
%Residual	21.9	38.1	0.0	100.0

Results Analyzing Each Crop Separately

- PCA: Mostly to remove correlation and convert to positive continuous variables
- Retained 11 PC's that captured 89%, 88% and 90% of variance of original soybean, corn and cotton data
- DEA: Varied t from 0 to 1 by 0.01 steps, found 20, 15 and 9 unique solutions for soybean, corn and cotton
- Calculated practice-specific weights, plus properties of the score distribution

Practice	Soybean	Corn	Cotton
Scout fields before a herbicide application	0.0218	0.0002	0.0078
Scout fields after a herbicide application	0.0245	0.0337	0.0177
Start with a clean field, using a burndown herbicide application or tillage	0.0041	0.0001	0.0005
Control weeds early when they are relatively small	0.0316	0.0371	0.0496
Control weed escapes and prevent weeds from setting seeds	0.0002	0.0003	0.0016
Clean equipment before moving between fields to minimize weed seed spread	0.0184	0.0009	0.0000
Use new commercial seed that is as free from weed seed as possible	0.0525	0.0942	0.0632
Use multiple herbicides with different modes of action during the season	0.0002	0.0008	0.0004
Use tillage to supplement weed control provided by herbicide applications	0.0003	0.0000	0.0002
Use the recommended application rate from the herbicide label	0.0910	0.0826	0.1005
% RR area planted following a non-RR crop	0.0218	0.0004	0.0000
% planted area treated with a burndown herbicide	0.0003	0.0006	0.0338
% planted area treated with a residual herbicide	0.0002	0.0001	0.0000

Weights and Marginal Effects

- Weights can be used to see which practices most increase grower adoption intensity scores, ceteris paribus
- Practices coded 0, 1, 2, 3, and 4 for Never, Rarely, Sometimes, Often, Always
  - Weight is how much grower score would increase with increasing adoption by moving up one step on the scale
- Other practices coded as percentages
  - Weight is how much grower score would increase with increasing adoption by 1 % point

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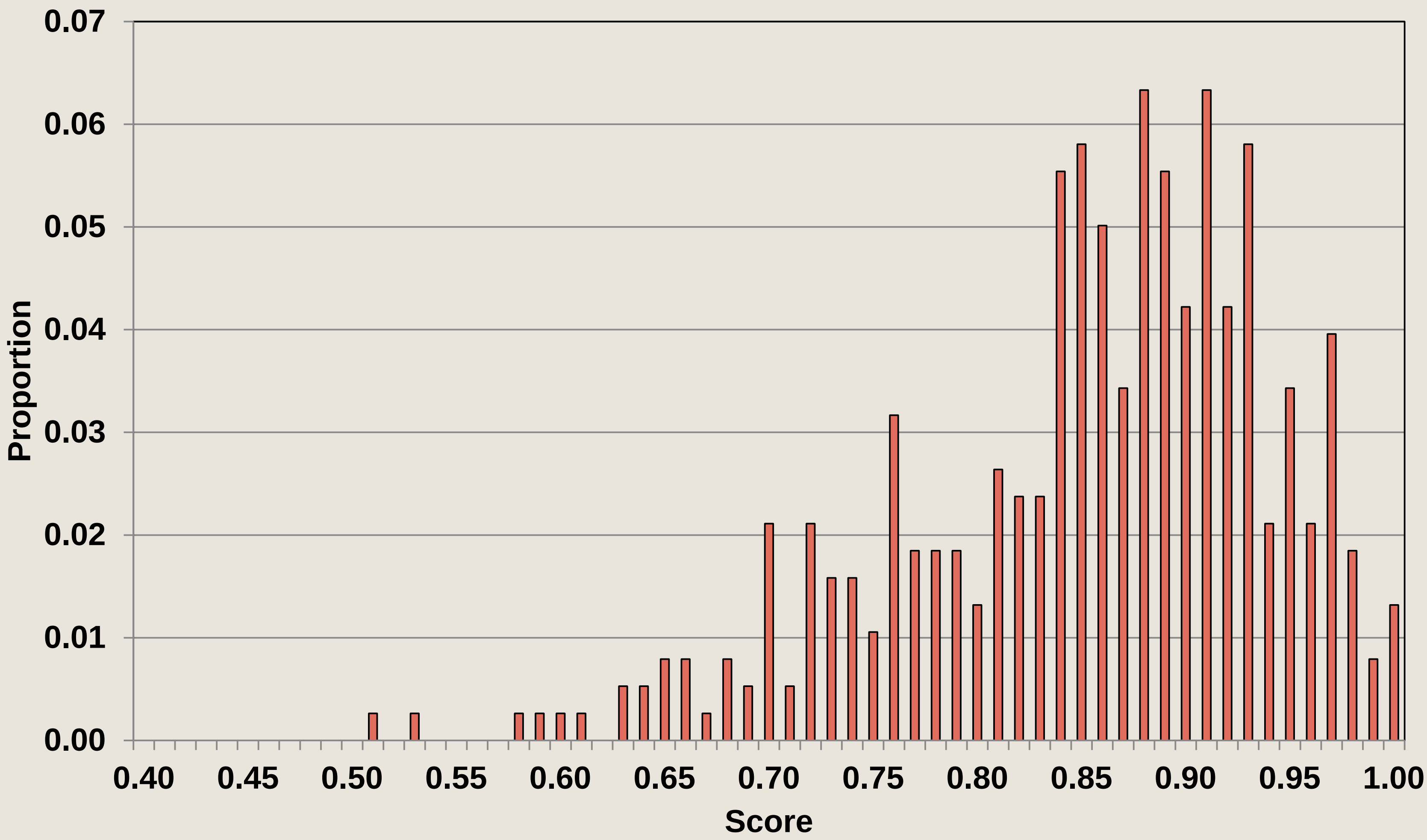
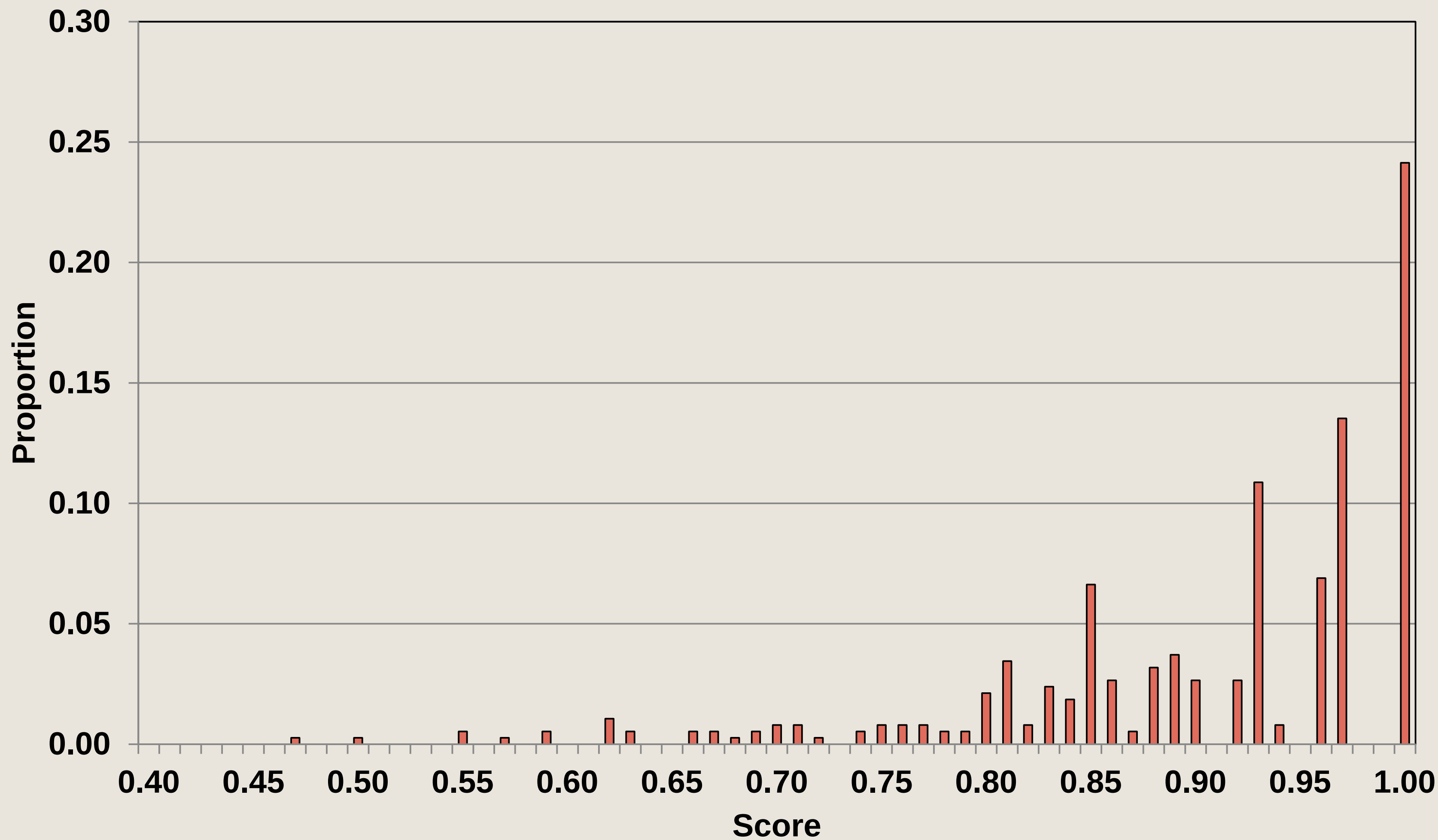
Statistics for Adoption Intensity Scores

Statistic	Soybeans	Corn	Cotton
Average	0.848	0.899	0.889
St. Dev.	0.090	0.102	0.113
Minimum	0.504	0.462	0.412
25% Quartile	0.801	0.843	0.844
50% Quartile	0.863	0.927	0.920
75% Quartile	0.911	0.964	0.966

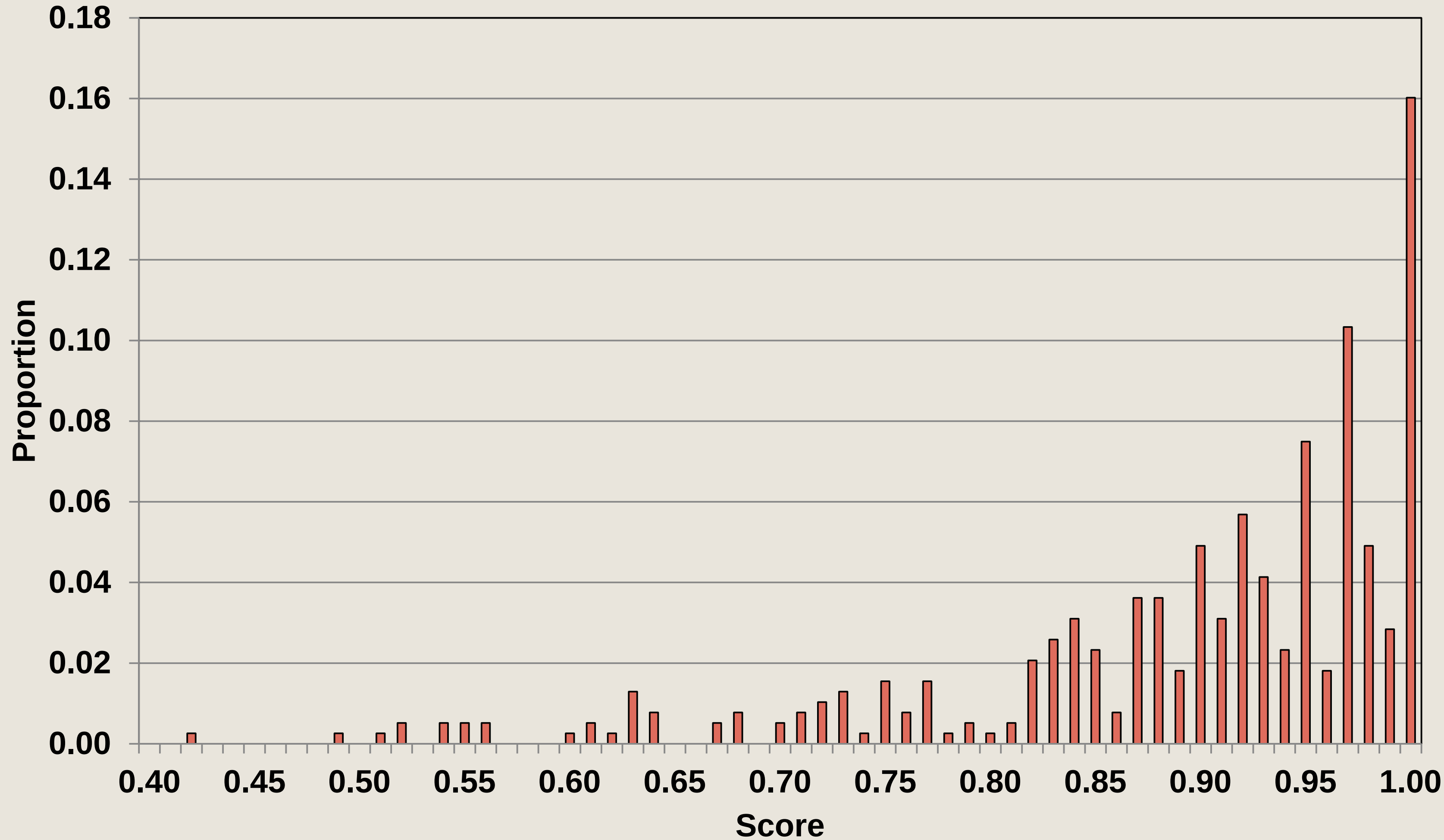
Histogram of Soybean Adoption Intensity Scores

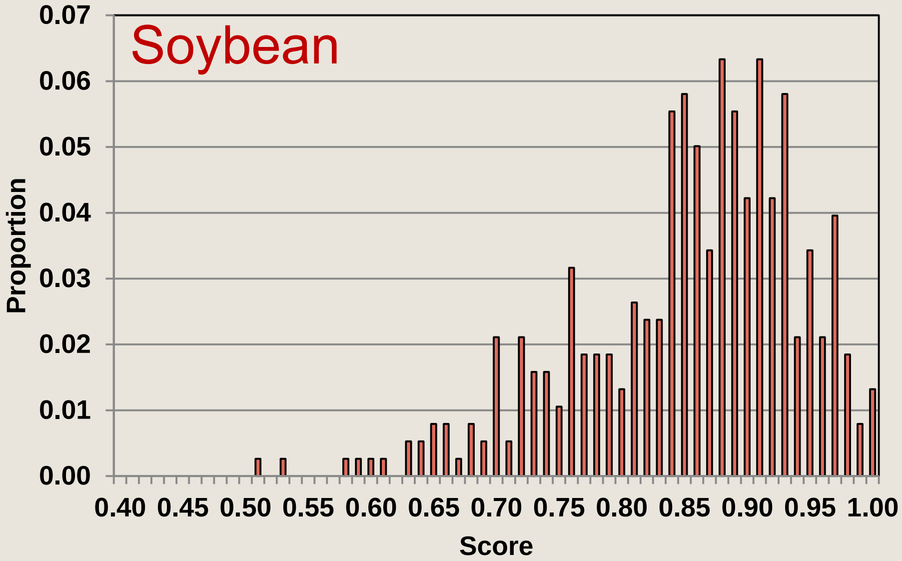


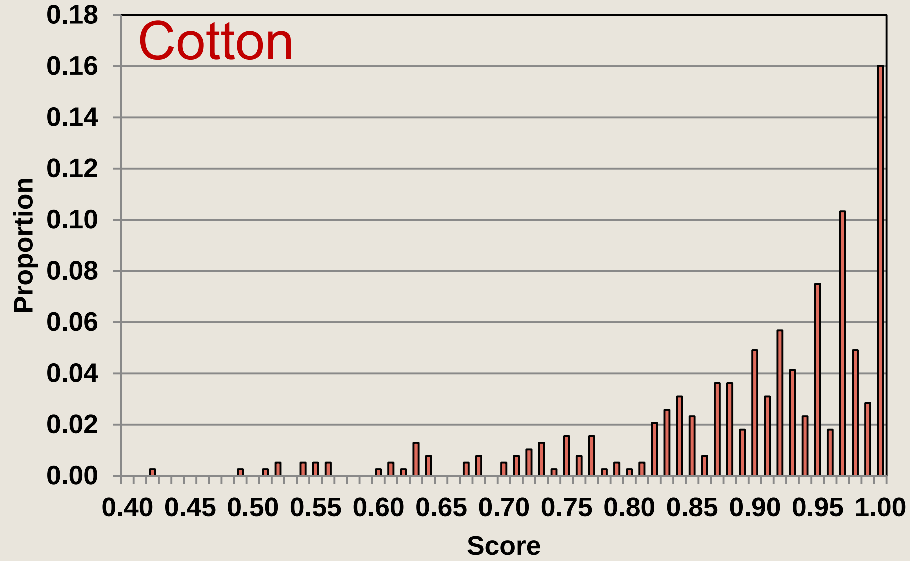
Histogram of Corn Adoption Intensity Scores

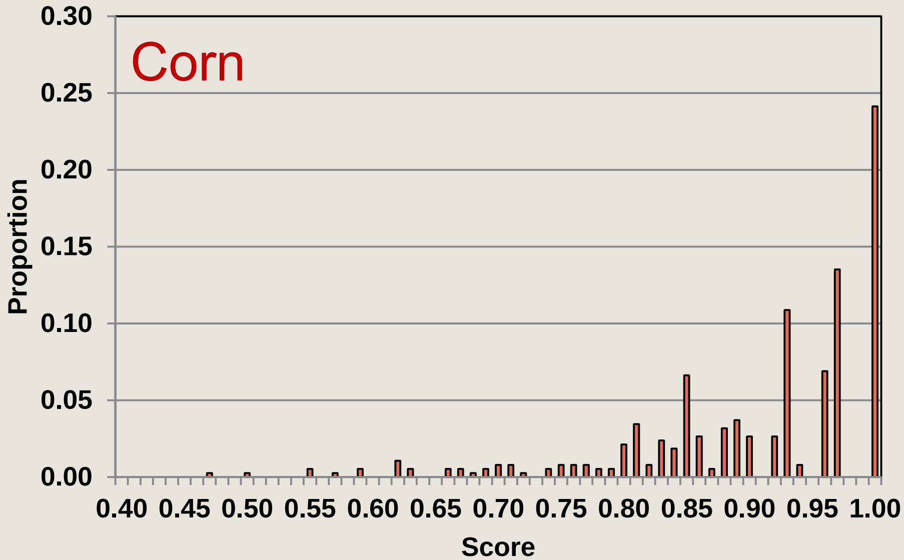


Histogram of Cotton Adoption Intensity Scores







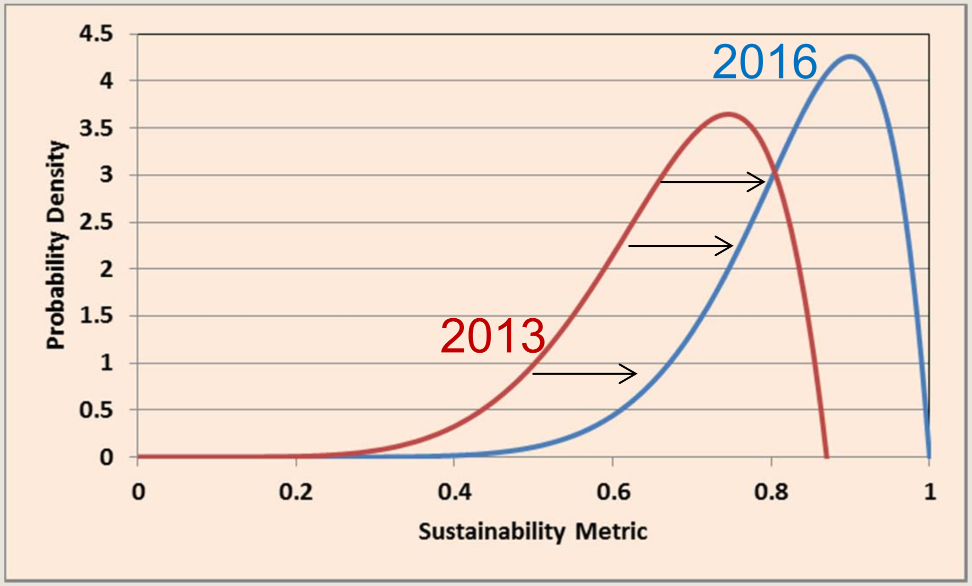


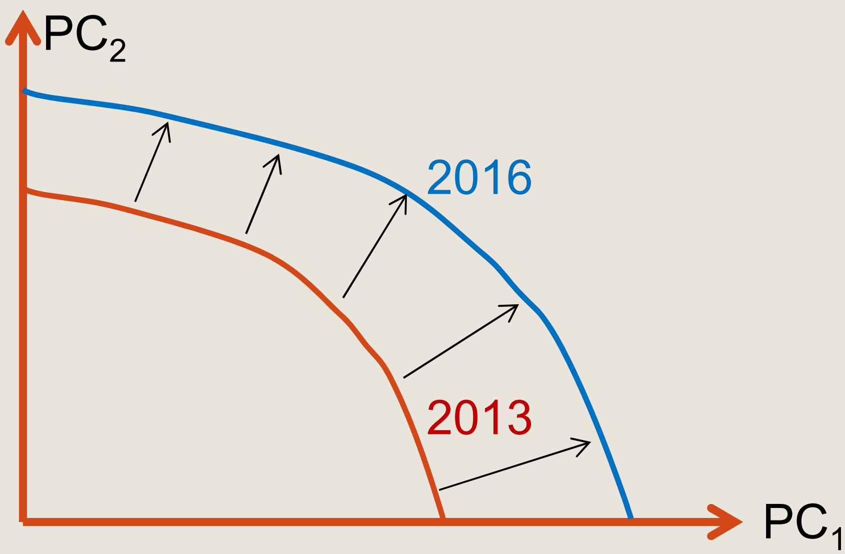
- All three crops have group on lower tail: "**Laggards**"
- All three crops have group on frontier: "**Leaders**"
- More heterogeneity among soybean growers
- Corn and cotton "unusually" concentrated on frontier from other cases

Uses of Scores and Weights

- Measure to Manage: Scores measure BMP adoption intensity relative to peer group
- Set baseline/benchmark and targets
- Set research and outreach priorities to help laggards improve and leaders push frontier out
  - Practices and types of growers to focus on
- Track changes over time, to see how individual growers or grower populations are doing
- Compare older and newer populations to see if a group as a whole is getting better

Tracking Changes, Making Comparisons





- Redo data collection and analysis and measure improvement over time by shift in score distribution and in frontier

- Developing an Ag Sustainability program for grower groups
- Exploring using ARMS data to link adoption intensity to profit

Regression Analysis of Scores

- Use regression to explore factors driving BMP adoption
- Regress individual grower score on other variables included in the survey
- Truncated Regression: Scores must be between 0 and 1
- Farm and Farmer Characteristics: Farm Size, % Owned, Education, Experience, Livestock, Crop Diversity, State, % Deviation from Mean County Yield, County Yield CV
- Weed Management: % Custom Application, Control Costs, Value RR, PC's of Herbicide Concerns
- Resistance: County has Resistant Weeds, % Counties in CRD with Resistance, Concerned about Resistance

Variable	Soybean	Corn	Cotton
Operator has college or advanced degree (Yes=1, No=0)			
Years managing farming operation			
Hectares of target crop plant in 2007			
% operated land owned by farmer			
% herbicide applications made by custom applicator			0.115
Coefficient of variation for county average yield			
% farm average yield deviates from county average			
Raise commercial livestock (Yes=1, No=0)			
Herfindahl index of crop diversity		-0.0953	
Self-reported average cost ($US/ha) to control weeds		0.000389	
Self-reported additional value ($US/ha) from planting RR crop in 2007			
Herbicide resistant weeds reported in county (Yes=1, No=0)		0.0764	
% counties in crop reporting district with herbicide resistant weeds	-0.00171		
Herbicide resistant weeds is most important weed management concern (Yes=1, No=0)			
Herbicide Concerns PC1	0.0137		-0.0109

Results Discussion

- Soybean: Higher BMP adoption intensity if
  - Fewer counties in CRD with resistance
  - PC1: More concern about human health and environment when choosing herbicides
- Corn: Higher BMP adoption intensity if
  - Less crop diversity/More crop specialization
  - Higher costs for weed control
  - Resistance reported in county
- Cotton: Higher BMP adoption intensity if
  - More Custom Application
  - PC1: Less concern about human health and environment when choosing herbicides

Summary and Conclusions

- DEA with PC: one way to measure BMP adoption intensity for a variety of applications: IPM, IWM, sustainability, …
- Measure to manage
  - Set baseline/benchmark and targets
  - Set research and outreach priorities
  - Identify practices and grower types to focus on
  - Track changes over time for impact assessment

Caveats and Future Research

- Relative Measure, so peer group matters
  - If all farmers low adopters, still score high
- Should connect to Outcomes: practices must be “good” practices or “best management practices”
  - Science/research to guide BMPs for survey
- Income and income risk not in this measure
  - How does a higher score impact Profit? Risk?
  - Considering using ARMS data to explore
- Process still takes a long time, need to streamline it

Acknowledgments

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Thank You For Your Attention!
Questions or Comments?

The Three Spheres of Sustainability

People, Profits & Planet

Triple Bottom Line

Producing crops and livestock for human use while simultaneously pursing environmental, economic, and social goals (NRC 2010)

Adopted from the 2002 University of Michigan Sustainability Assessment

Sustainability is no longer "Alternative Ag" but has become Mainstream!

- Most food/ag companies and commodity & ag groups have sustainability programs and/or initiatives
  - McDonald's, Cargill, Unilever, WalMart, Del Monte, PepsiCo/FritoLay, Sysco, …
  - National Corn Growers Association, United Soybean Board, National Association of Wheat Growers, National Potato Council, …
- Everyone's talking about sustainability!!!