Spatial methods for deriving crop rotation history

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Abstract

Benefits of converting 11 years of remote sensing classification data into cropping history of agricultural fields included measuring lengths of rotation cycles and identifying specific sequences of intervening crops grown between final years of old grass seed stands and establishment of new ones. Spatial and non-spatial methods were complementary. Individual-year classification errors were often correctable in spreadsheet-based non-spatial analysis, whereas their presence in spatial data generally led to exclusion of fields from further analysis. Markov-model testing of non-spatial data revealed that year-to-year cropping sequences did not match average frequencies for transitions among crops grown in western Oregon, implying that rotations into new grass seed stands were influenced by growers' desires to achieve specific objectives. Moran's I spatial analysis of length of time between consecutive grass seed stands revealed that clustering of fields was relatively uncommon, with high and low value clusters only accounting for 7.1 and 6.2% of fields.

Keywords: crop rotation; pre-crop; following crop.¹

¹ Abbreviations: PR, perennial ryegrass; TF, tall fescue; OG, orchardgrass; AR, Italian (or annual) ryegrass; WW, winter wheat; BENT, bentgrass; FF, fine fescue.

1. Introduction

Soundest agricultural policies would be those based on deepest understanding of relationships between management practices by individual farmers and environmental impacts across the broader landscape. Policy makers often extrapolate results of site-specific research, incomplete models, and sporadic monitoring efforts (CAST, 2014; Hansen et al., 2010; Mausbach and Dedrick, 2004; Mudgal et al., 2010; Mueller-Warrant et al., 2012; Natural Resources Conservation Service, 2009; Schnepf and Cox, 2007; Schonhart et al., 2009). While stated goals commonly include enhancing long-term sustainability of agriculture production, policies are often unscrutinized after implementation. We propose cost-effective remote-sensing approaches to evaluate behavior of agriculture at the landscape-scale as a way to quantify relationships among farming practices and ecosystem services. Our approach capitalized data already routinely collected (i.e., satellite and other remotely-sensed imagery, public records of agricultural production, and rules governing practices such as time out between successive stands of particular crops) through conversion into long-term records of cropping history in fields. Converted data could then be used as evidence for existence of various crop rotation practices and rationale for specific crop management decisions by farmers. Our methods represent long-term efforts to reliably convert raw data into higher level concepts. Recent validation of these procedures (Mueller-Warrant et al., 2016b) enabled us to interpret landscape-scale behavior of a major sector of agriculture in the U.S. Pacific Northwest (PNW), perennial grasses grown for seed. Similar studies are easier to conduct in Europe because cropping history data collected by regional governments is viewed as public information appropriate for study (Castellazzi et al., 2008; Leteinturier et al., 2006; Thenail et al., 2009; Steinmann and Dobers, 2013).

Rules for producing certified grass seed in the PNW mandate minimum periods of 2 to 6 years between successive established crops of the same kind, with immediate planting back to the same variety allowed in lower classes of certified seed (Anon., 2016). While grass seed certification standards typically do not specify minimum periods for changing from one crop kind to another, the required within-field observations and cleaned-seed sample tests for presence of other grasses force growers to take at least 1 to 2 years out before planting new stands. Previous efforts to analyze cropping sequence patterns in western Oregon succeeded in measuring durations of established grass seed stands in thousands of cases over an 11-year period for PR (*Lolium perenne* L.), TF [*Schedonorus arundinaceus* (Schreb.)], and OG (*Dactylis glomerata* L.), along with similar measurements of successive replantings of annual crops such as AR (*Lolium perenne* L. subsp. *multiflorum* {Lam} Husnot) and WW (*Triticum aestivum* L.) (Mueller-Warrant et al., 2016b). Transition frequencies between all pre-crops and following crops were also analyzed over that same period, independent of past or future field history. Extending this year-to-year cropping sequence data into full rotations from the end of one grass seed stand to the start of the next was desirable for several reasons. First, links from one grass seed stand to the next would produce knowledge of the number of years growers use to change their seed crops, a key variable for interrupting pest cycles and reducing populations of weeds, diseases, and invertebrates. Second, frequencies at which specific rotational crops appear in the years between two grass seed stands could determine whether growers choose certain crops for their anticipated benefits or merely randomly select them (Griffith et al., 2011; Mueller-Warrant et al., 2016b).

The primary goals of this project were to: (1) develop raster and object-based methods for converting a previously published 11-year-long series of remote sensing landuse classifications into multi-year cropping history, (2) test spatial clustering of fields for years that intervening crops were grown between consecutive grass seed stands, and (3) categorize year-to-year transitions within crop rotations as either matching frequencies expected from single-step Markov models of independence or as indicating the presence of constraints on crop choice.

2. Methods

2.1 Background data

This research was conducted over 25,303 km² of the Willamette River basin and nearby drainages in north-western Oregon and south-western Washington from 2004 to 2014 as previously described in detail (Mueller-Warrant et al., 2011, 2015, 2016a, and 2016b). Ground-truth data of crop kind and stand establishment phase were collected during drive-by, roadside surveys of 3000 to 7000 fields per year, simplified into 57 landuse categories representing ~99% of the area. Remote sensing data sources included Landsat, Moderate Resolution Imaging Spectroradiometer (MODIS) 16-day composite, and Advanced Wide Field Sensor (AWiFS) satellites, National Aerial Imagery Program (NAIP) images, NASA nightlights data, and topography, all converted to 30 m pixels. The maximum likelihood classifier was used in remote sensing classifications of each specific combination of the number of cloud-free bands present in progressively smaller cloud-free areas as additional images were added to raster stacks. Resulting classification rasters were merged in order maximizing the number of bands used to classify each individual pixel. Known locations of 91,442 fields from Farm Service Administration - Common Land Units (CLU) facilitated majority-rule and second-place

reclassification of polygons. Further rule-based reclassification of the CLUs between majority-rule and second-place values were conducted to minimize year-to-year cropping sequence inconsistency and match ancillary data on crop production area by county. Classification accuracy over the 11-year period as the 57-class κ statistic for the final products of this research averaged 0.680 and 0.689 for training and validation datasets. Products of this prior research included measurements of stand duration of established perennial crops and non-spatial matrices of year-to-year transition frequencies between pre-crops and following crops.

2.2 Converting single year rasters into multi-year cropping sequences

The 57 classification categories of the earlier studies (Mueller-Warrant et al., 2016a; Mueller-Warrant et al., 2016b) were simplified to 39 categories of greatest importance to agriculture by merging three AR classes into a single category, combining all 13 forest classifications into one, and combining all five urban development classifications into one, while retaining all other classes. The 39-category landuse classification for 2009 was typical of those present in all 11 years (Fig. 1). The reduction to 39 classes allowed us to multiply rasters from six consecutive years by factors of 40 raised to powers of 0–5, adding them together to create single-valued summaries of all unique cropping sequences over periods from 2004–2009, 2005–2010, 2006–2011, 2007–2012, 2008–2013, and 2009–2014. We subtracted 2^{31} (2,147,483,648) during calculations to force all values into the ArcGIS™ Long Integer data type range (-2,147,483,648 to 2,147,483,647). Numbers of pixels associated with each value represented area in units of 0.09 ha for each unique landuse sequence. The 6-year summaries typically possessed ~200,000 unique classes, and could therefore only be viewed as stretched color or gray-scale representations (Fig. 2 and 3).

Techniques for extracting more easily understood information from the six separate 6-year-long cropping sequence rasters included value selection, raster algebra, and conversion from raster to vector data type within ArcGIS itself, along with export of attribute tables to external spreadsheets for more complex analyses. Selecting subsets of values in attribute tables allowed us to directly identify a wide variety of conditions of interest, including cropping sequences indicating the start of new perennial grass seed stands in specific calendar years, the end of old stands, and rotational crops grown during intervening years between consecutive grass seed stands. Additional raster algebra steps identified numbers of full rotation cycles from one grass seed crop stand to the next, as well as calendar year in which each new grass seed stand began (Fig. 4, 5, 6). Raster data were converted back to CLU polygons for identifying and analysing the number of intervening rotational crops grown between consecutive grass seed stands to measure the effect of time out of grass seed on spatial clustering of fields using Moran's I statistics. Alternately, number of fields present in raster data was estimated by setting minimum and maximum areas per field to 3 and 53 ha, counting additional fields as multiples of 27 ha (one standard deviation above average size).

Conversion from raster data to spreadsheet format assumed there would be far fewer than the ~4 GB of potential 6-year cropping sequences. Even the ~200,000 observed cropping sequences had to be subdivided by grass seed crop [AR, PR, OG, TF, BENT (*Agrostis stolonifera* L. and *A. capillaris* L.), or FF (*Festuca rubra* L. aggregate)] bracketing the multi-year sequences of interest before export from ArcGIS. Additional steps after import into spreadsheets included reorganizing and simplifying the data by year within the 6-year periods. While many of the same

types of selections could be made in either the spatial data format of ArcGIS or the non-spatial format of a spreadsheet, in practice the spreadsheet environment was better suited for identifying the large numbers of crop rotations present and testing assumptions necessary to correct relatively minor sequence errors, such as those frequently present during the establishment year of new perennial grass seed stands.

2.3 Recognizing full crop rotations from previous grass seed crops

Detection of newly established grass seed stands was the fundamental step in the process of extracting full crop rotations from multi-year cropping sequence data. This step was followed by looking back in time to identify the specific crops grown from 1 to 6 years earlier, searching for the most recently grown previous grass seed crop of the same or different kind. Typical output from spreadsheet summaries of multi-year cropping sequences beginning newly established stands of PR or TF in any particular year ranged from 1000 to 2000 unique cropping sequences bridging the period back to the end of previous grass seed crop stands (data not shown). Data from neighbouring pairs of 6-year summaries (e.g., 2004 – 2009 and 2005 – 2010) were linked by identifying all cases in the later period matching a given sequence present earlier, extending the crop rotation period being analysed to 7 years.

The dominant cropping sequences for each year starting new grass seed stands were inspected for logical consistency of transitions into new grass seed crops, and either removed from further analysis when no simple explanation for the logical errors existed or corrected when reasonable interpretations were possible. For example, if WW in some year was followed by established PR the next year, it was likely that wheat stubble and growth of volunteer seedlings in a new fall

planting of PR led to confusion with established PR during classification. Indeed, such fields sometimes posed challenges to trained personnel during drive-by, roadside collection of ground-truth data. Transitions needing correction matched some of the more common classification errors detected in the original 11-years of landuse data (Mueller-Warrant et al., 2011 and 2015). The end products of corrections made to crops in the transition period into new grass seed stands in general duplicated cropping sequences already present at high frequency (data not shown). A total of 36 PR and 116 TF fields had to be omitted from further analysis because their cropping sequences were too ambiguous. The crop rotations themselves were too numerous for inclusion in this manuscript.

2.4 Cropping sequence chi-square tests for deviation from single-step Markov model

Chi-square tests were used to determine whether specific year-to-year transitions matched frequencies of a simple single-step Markov model, with expectations based on the average of 10 individual year-to-year measurements of frequencies of the 3,249 potential transitions among all 57 landuse classes (Mueller-Warrant et al., 2016b). Because situations were never encountered in which the overall significance of a group of transitions was changed by how the infrequent cases were handled, we have simply omitted them in setting Markov expectation values.

3. Results and Discussion

3.1 Spatial properties of cropping sequences.

Distinct spatial differences in landuse were present across the region (Fig. 1). AR production was concentrated in the southern half of the Willamette River valley, primarily on the east side of the river. FF was mainly produced east of Salem, OR, in the Silverton Hills. Locations of forests and

urban development in all 11 years were similar to that shown for 2009. When converted into 6-year-long landuse sequences, areas with stable classifications (e.g., continuous urban development, forests, or pasture) appeared as white, while the rest of the ~200,000 cropping sequences displayed as varying gray-scale values, needing further selection and simplification to become intelligible (Fig. 2 and 3).

A key step toward realizing that desired state was identifying the years in which new grass seed stands first appeared, which in turn allowed detection of full crop rotation cycles from old grass seed stands to new ones. Over 93% of the area had no detectable crop rotations from old to new grass seed stands, while 1, 2, or 3 full rotation cycles between grass seed crops were present in 5.32, 1.35, and 0.06% of the area (Fig. 4). Single rotation cycles into new grass seed stands (green to blue-scale display) occurred on a yearly average of 0.59% of the area, ranging from a low of 0.45% in 2005 to a high of 0.77% in 2013. The most common two-rotation-cycle (yellow to red-scale) case had new grass seed stands starting in both 2008 and 2013, occurring on 0.11% of the area. Zooming into areas of concentrated grass seed production in Linn and Marion Counties (Fig. 5 and 6) provided clearer views of the situation. First, the high spatial heterogeneity in numbers of crop rotation cycles and specific years in which new crop stands began production matched what would be expected for a mature industry with a wide range of crop kinds and stand ages managed by large numbers of growers prior to the start of our landuse classification project. Second, the occasional similarity in starting years for new crop stands in fields grown in close proximity to one another corresponded to grower reports that they often manage several physically distinct fields as single production units. Third, these maps emphasized that our data management techniques had indeed produced meaningful summaries of

cropping sequence data. Although these maps did not include any of the cropping sequence corrections to apparent grass seed planting year that were developed in the non-spatial spreadsheet analysis, the density of fields was high enough to provide good spatial coverage.

Conversion from raster to CLU field-based representation of the data allowed use of various spatial tools for analyzing patterns, while simultaneously spotlighting the reduction in coverage as further logical requirements for potential crop rotations were imposed (Fig. 7 versus Fig. 5 and Fig. 8 versus Fig. 6). Excluded from object-based maps of the numbers of years of intervening crops grown between consecutive grass seed stands were all the cases in which no complete crop rotation cycles were found because only a single grass seed stand had been present during the 11 years. Also excluded were cases lacking full multi-year consistency in terms of which particular grass seed crop was present, something that had often been successfully dealt with in the non-spatial spreadsheet analysis. Despite cases omitted for these and other similar reasons, numbers of fields were still large enough to test spatial clustering and detect outliers (Fig. 9 and 10). Moran's I tests were conducted for fields rotating into PR and TF both separately and jointly, and the pooled results were presented because nearly identical selections of fields were classified into all five categories (non-significant, high values in high-valued clusters [HH], low values in low-valued clusters [LL], high value outliers in low-value clusters [HL], and low value outliers in high-value clusters [LH]) by either method. Using a $P \leq 0.05$ significance level, 81.6% of grass seed fields across the entire Willamette Valley showed no clustering in the number of years of intervening crops present between consecutive grass seed stands. Significant HH and LL clustering was present in 7.1 and 6.2% of fields, while significant HL and LH outliers were present in 1.9 and 3.1% of fields. Loosening requirements to $P \leq 0.1$

237 and 0.2 significance levels only selected an additional 4.4 and 10.7% of fields, clearly showing
238 the absence of spatial clustering for years of intervening crops in the large majority of cases. AR
239 was excluded from this analysis because it was almost always replanted year after year into the
240 same fields for approximately as long as our classification data covered, and so would have
241 appeared as LL clustering if viewed as having 0 years of intervening crops between each AR
242 stand and otherwise would seldom have qualified as the new grass seed crop in a rotation.
243 Possible causes for clustering in length of intervening rotational crops grown between
244 consecutive grass seed stands present in some fields may include: (1) management preferences of
245 growers whose collection of fields often span similar distances, (2) spatial variation in soil type
246 and physical properties, and (3) the spatial distribution of weeds that respond favorably to
247 treatments available in some of the rotational crops.

3.2 Presence of constraints on transitions between pre-crops and following crops

In the period spanning 2 years to 1 year ahead of full establishment of new grass seed crop stands, pre-crop to following crop transitions reflected the different approaches growers used for establishing TF versus PR. In TF, 585 out of 834 fields were spring-planted, while in PR 740 out of 835 fields were fall-planted (data not shown). Pre-crop to following crop transitions in progressively earlier pairs of years revealed additional details about methods growers used to prepare fields for eventual establishment of grass seed crops. In the interests of space, we have chosen to only present full tables of transition results for periods from 3 years to 2 years (Tables 1 and 2) and from 4 years to 3 years (Tables 3 and 4) prior to full establishment of new stands.

For transitions into year-2 following crops coming from year-3 pre-crops leading to new stands of PR, there were 10 significant following crops, a total of 30 associated pre-crops over all of the significant following crops, and 86 non-zero observations out of 300 possible transition types, with 97% of the original number of fields retained (Table 1). As expected, the transitions into year-2 following crops coming from year-3 pre-crops were dominated by cases leading up to fall-plant PR (Table 2). The four most abundant year-2 following crops were fall-plant PR with 740 fields, WW with 115 fields, winter fallow/unknown summer crop with 77 fields, and established FF with 35 fields, with the latter case primarily consisting of continuation of established FF from year-3 pre-crop to year-2 following crop. The three most abundant year-3 pre-crops were winter fallow/unknown summer crop with 325 fields, WW with 242 fields, and established PR with 122 fields. The 85 fields for the specific transition from year-3 pre-crop established PR to year-2 following crop fall-plant PR likely corresponded to seed certification rules for planting PR back to the same variety immediately after destroying the old PR stand.

The three next most common pre-crops were beans (*Phaseolus vulgaris* L.), established FF, and established clover (*Trifolium pratense* L., and *T. repens* L.), present in 68, 57, and 34 fields, respectively. Their over-abundance compared to Markov model expectations suggested the presence of benefits from these transitions.

For transitions into year-2 following crops coming from year-3 pre-crops leading to new stands of TF, there were nine significant following crops, a total of 26 associated pre-crops over all of the significant following crops, and 92 non-zero observations out of 300 possible transition types, with 97% of the original number of fields retained (Table 2). As expected, the transitions into year-2 following crops coming from year-3 pre-crops were dominated by cases leading up to spring-plant grass seed and fall-plant TF (Table 7). The three most abundant year-2 following crops were spring-plant grass seed (581 fields), fall-plant TF (241 fields), and winter wheat (103 fields).

For transitions into year-3 following crops coming from year-4 pre-crops leading to new stands of PR, there were 20 significant following crops, a total of 24 associated pre-crops over all of the significant following crops, and 142 non-zero observations out of 480 possible transition types (Table 3). A total of 1032 fields remained in the list of transitions violating expectations of the Markov model when pooled over all pre-crops within individual following crops, or almost 98% of those initially present in the year-1 following crop coming from year-2 pre-crop transitions.

The transitions into year-3 following crops coming from year-4 pre-crops included many cases in which the year-4 pre-crop had been established PR along with many other cases that were in the midst of transitions from previous seed crops to new stands of PR. The four most abundant year-

3 following crops were winter fallow/unknown summer crop with 328 fields, WW with 244 fields, established PR with 122 fields, and beans with 68 fields. The same three pre-crops that were the most common in the year-3 pre-crop to year-2 following crop transitions were still the most common in year-4 pre-crop to year-3 following crop transitions. Comparing year-4 pre-crop transitions in Table 3 to year-3 pre-crop transitions in Table 1, there were nearly four times as many instances (39 versus 10 cases) in which the pre-crop was established TF, suggesting a strong preference for at least 2 years from end of a previous TF stand to planting of new PR.

For transitions into year-3 following crops coming from year-4 pre-crops leading to new stands of TF, there were 18 significant following crops, a total of 25 associated pre-crops over all of the significant following crops, and 133 non-zero observations out of 450 possible transition types (Table 4). A total of 1030 fields remained in the list of transitions violating expectations of the Markov model when pooled over all pre-crops within individual following crops, or almost 98% of those initially present in the year-1 following crop coming from year-2 pre-crop transitions. The transitions into year-3 following crops coming from year-4 pre-crops included many cases in which the year-4 pre-crop had been established TF. The four most abundant year-3 following crops were winter fallow/unknown summer crop (405 fields), winter wheat (133 fields), established TF (127 fields), and spring-plant grass seed (62 fields).

4. Conclusions

Years of intervening rotational crops between consecutive grass seed stands showed only modest tendencies for spatial clustering of fields, suggesting the presence of a mix of competing factors in growers' decisions concerning how long to stay out of grass seed production. Growers did not

randomly select rotation crops between successive grass seed stands. Instead, their choices were deliberately made up to 5 years before eventual planting of new stands of PR or TF seed crops. WW was the most common intervening crop in rotations into PR. Unknown summer annuals were the most common intervening crop in rotations into TF when either 1 or 4 years were available for intervening crops, while WW was the most common when either 2 or 3 years were available.

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393 organization in farms to crop-mosaic patterning at local landscape scales. *Agriculture,*
394 *Ecosystems and Environment*, 131, pp. 207-219.

397 Table 1. Observed transitions into 10 following crops in rotation year-2 coming from 30 pre-
 398 crops in rotation year-3 for perennial ryegrass.

No.	Year-3 pre-crop description	Year-2 following crop identified by number†									
		3	4	13	16	19	30	35	40	41	43
		(number of fields)									
1	Bare ground in fall not any other class	38		239	41	1		5			1
2	All AR (includes 12 and 44)	1		22	1						
3	Spring-plant new GS crop stands		4	5							
4	Established PR	7		85	14		5	5		6	
5	Established OG	1									
6	Established TF			3	3		3			1	
7	Pasture	1		5	1	1					
8	Established clover			19	9				6		
9	Established mint			2							
10	Haycrop			1							
11	All forest landuse classes	4		5		1					
13	Fall-plant PR	2	1	16	1		1	1			
15	Fall-plant clover			9	1	1					
16	WW	4		198	34		1	1	1	1	2
17	Meadowfoam			11	2						
18	Established BENT	2		6							
19	Established FF	1		17	2	31	5				1
23	Established alfalfa			1							
26	Caneberry	1									
27	Corn and sudangrass			6	2						
28	Nursery crops	2		4	2					1	
30	Fallow	5		6							
31	All urban landuse classes			1							
35	Beans	6		61	1						
36	Flowers			5							1
40	Other fall-plant/no-till grass seed crops								1		
41	Spring-plant peas or other unidentified	1		4			1			1	
43	New planting alfalfa or vetch			5	1						
55	<i>Brassicaceae</i>			4							
56	Strawberry	1									
	Totals	77	5	740	115	35	16	12	8	10	5

399 †The 20 other year-2 following crops were omitted.

400

401

402 Table 2. Observed transitions into nine following crops in rotation year-2 coming from 26 pre-
 403 crops in rotation year-3 for tall fescue.

No.	Year-3 pre-crop description	Year-2 following crop identified by number†								
		3	6	14	16	17	28	30	40	41
		(number of fields)								
1	Winter fallow/unknown summer crop	276		62	36		10		2	2
2	All AR (includes 12 and 44)	22		33	1	2			3	
	Spring-plant new grass seed stands	36	19	6	1					
4	Established PR	8		5	4	1				
5	Established OG			1		3		1		
6	Established TF	55	17	39	12	1		1		1
7	Pasture	3		1						
8	Established clover	11		6	5				1	1
9	Established mint	1		2						
10	Haycrop	5		1		1			1	
11	All forest landuse classes			1						
13	Fall-plant PR	15		3	1		1			
14	Fall-plant TF	11	15							
15	Fall-plant clover	10	1	3	1		1			
16	Wheat and oats	32		57	31		2	5	1	
17	Meadowfoam	5		4						
18	Established BENT	1		1						
27	Corn and sudangrass	6		1	2		1			
28	Nursery crops	4		5	1		3	1		
30	Fallow	47		1	1		1			
31	All urban landuse classes		1	1	1					
35	Beans	17		5	1					
36	Flowers	1		1						
41	Spring-plant peas or other unidentified	9			1					
43	New planting alfalfa or vetch	5		2	3					
55	<i>Brassicaceae</i>	1			1					
	Totals	581	53	241	103	8	19	8	8	4

404 †The 23 other year-2 following crops were omitted.

405 Table 3. Observed transitions into 20 following crops in rotation year-3 coming from 24 pre-crops in rotation year-4 for perennial
 406 ryegrass.

No.	Year-4 pre-crop description	Year-3 following crop identified by number†																			
		1	2	3	4	6	7	8	11	13	15	16	17	19	27	28	30	35	36	41	43
		(number of fields)																			
1	Bare ground in fall not any other class	105		2			1	1		6	1	39	1		8	5	1	28		4	
2	All AR (includes 12 and 44)	2	13							1	3	2	2								
3	Spring-plant new grass seed stands	1			2	1						1							1		
4	Established PR	77	2	1	95		3	1		4	3	68	6	1			5	24	1		4
6	Established TF	10	3		1	6						13	1				1	3		1	
7	Pasture	2			1	1	1		1			2					1		1		
8	Established clover							14			2	6								1	
10	Haycrop	2										2									
11	All forest landuse classes	1							15					1							
13	Fall-plant PR	8	1		16			1				5						2			
15	Fall-plant clover	1						23				5						1			
16	WW	44	4	5	2	1	2			5	3	66	3			3	1	2		1	2
17	Meadowfoam	2		1			1														
18	Established BENT	11			1						1	3						3			
19	Established FF	6			2				1			14		54					3		
27	Corn and sudangrass	1	1									2			1	1					
28	Nursery crops	2				1										1		1			
30	Fallow	2		1				2		3		2					1	1			
31	All urban landuse classes	2																			
35	Beans	39			1		1			1		7			1			3			
36	Flowers	2							1		1	3		2			1				
41	Spring-plant peas or other unidentified				1					1											
43	New planting alfalfa or vetch	2										3									
55	<i>Brassicaceae</i>	5								1		1									
	Totals	328	24	10	122	10	9	42	18	22	14	244	13	58	10	10	11	68	6	7	6

407 †The 10 other year-3 following crops were omitted.

408 Table 4. Observed transitions into 18 following crops in rotation year-3 coming from 25 pre-crops in rotation year-4 for tall fescue.

No.	Year-4 pre-crop description	Year-3 following crop identified by number†																	
		1	2	3	4	5	6	8	10	13	14	15	16	27	28	30	35	41	43
		(number of fields)																	
1	Winter fallow/unknown summer crop	134	2	30	3			1	1	8	6		18	6	2	3	9	3	
2	All AR (includes 12 and 44)	36	46	2			4				2	4	2		2	22		3	
3	Spring-plant new grass seed stands	3		1	1		20						1			1			
4	Established PR	30	3		9	1						1	5			5	5	1	
5	Established OG		1			4										1			
6	Established TF	45	2	1			102		3		5		28	2		8	5		2
7	Pasture	1							1										
8	Established clover	15		2				7			3	3	13	1		2			
9	Established mint	1																	
10	Haycrop	3											1				1		
13	Fall-plant PR	11		2	3		1					2					1		
14	Fall-plant TF																		
15	Fall-plant clover	9		3	1			18		1	1		5			1		1	
16	Wheat and oats	80	4	1					2	5	4	5	43	1	7	5			7
17	Meadowfoam	1	1	6												1		1	
25	Filberts														1				
27	Corn and sudangrass	2																1	
28	Nursery crops	6																	
30	Fallow	7		10						3	2					1			
31	All urban landuse classes	1			1							1	1						
32	Vineyards	1	2																
35	Beans	12						1				1	6				3		
36	Flowers			1											1				
41	Spring-plant peas or other unidentified	7		3					1	3	3		7			1		1	
43	New planting alfalfa or vetch								1				3		1				1
	Totals	405	61	62	18	5	127	27	9	20	26	17	133	10	14	51	24	11	10

409 †The 14 other year-3 following crops were omitted.

List of figures

Figure 1. Landuse in 2009 after reclassification from 57 into 39 categories.

Figure 2. Multi-year landuse sequence, 2004 to 2009, gray-scale for 186,393 values.

Figure 3. Multi-year landuse sequence, 2009 to 2014, gray-scale for 275,541 values.

Figure 4. Number of crop rotation cycles and starting year of each new grass seed stand. Years are displayed using green to blue, yellow to red, and gray scales for cases of 1, 2, or 3 cycles.

Figure 5. Number of crop rotation cycles and starting year of each new stand, Linn County.

Figure 6. Number of crop rotation cycles and starting year of each new stand, Marion County.

Figure 7. Years of intervening crops in rotations between grass seed stands, Linn County.

Figure 8. Years of intervening crops in rotations between grass seed stands, Marion County.

Figure 9. Moran's I clustering of intervening crop length, Linn County. Red, orange, blue, turquoise, and gray denote HH, HL, LH, LL, and non-significant clustering.

Figure 10. Moran's I clustering of intervening crop length, Marion County. Red, orange, blue, turquoise, and gray denote HH, HL, LH, LL, and non-significant clustering.

X 1 + X 40 + X 1600 + X 64000 + X 2560000 + X 102400000

Cropping sequences from 2009 to new PR in 2013 can be further limited to just cases where 2009 was end of an old grass seed stand. Multiple options are used for sequence period, year starting new PR stand, and year ending previous grass seed crop. Tables are then exported and opened in spreadsheet format.