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Changes in field-level cropping sequences: Indicators of shifting agricultural practices

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ABSTRACT

Farmers implement an assortment of management practices to ensure the sustainability, economic viability, and resilience of their operation. Dryland farming practices dominate in the semiarid regions of the US northern Great Plains, where historical practice has been to rotate small-grain cereals with whole-year summer fallow; however, pulse crops (e.g., lentils) have become increasingly common in these regions as an alternative to fallow. The area of fallow in northeastern Montana, for example, has decreased by one-third, while the area of pulse crops has increased more than five-fold. Our objectives were: (1) to characterize the principal cropping sequences in northeast Montana during the period of regional pulse crop adoption (2001–2012); and (2) to identify changes in the relative proportions of these sequences during the same period. We identified crops at the field-level by class (cereal, pulse, fallow, or cereal–fallow strips) for 2001–2012 using multitemporal Landsat imagery in conjunction with the cropland data layer, cadastral data, ground reference data, and local producers' records. The annual crop classifications were combined into a 12-character string for each field that represented the sequence of crop classes for 2001–2012. We then searched these strings for specific 2- and 3-year crop sequences with a string-matching algorithm. The most abundant sequences involved continuous cereal, block-managed cereal–fallow, and cereal–pulse. We also observed a steady decrease in the abundance of cereal–fallow sequences managed by strip-cropping that were coincident with increases in block-managed cereal–fallow sequences and with increases in pulse production. We conclude that, over the study's time frame, regional producers grew more cereal crops and fallowed fields less frequently, but did not appear to strongly adhere to specific sequences. Furthermore, strip-cropping as a management practice has declined substantially.

1. Introduction

The area of fallowed cropland in northeastern Montana has decreased by one-third in the past 15 years, while the area devoted to pulse crops has increased nearly five-fold (Lee, 2011). Pulses, leguminous crops grown for their edible seeds, were grown primarily on land formerly in cereal–fallow sequences, managed by strip-cropping (i.e., alternating 50 or 100 m wide strips) or in block-managed rotations and in idle fields returning to production following expired enrollment in the Conservation Reserve Program (CRP). Incorporating pulses into rotational sequences with the region's dominant crop – small grain cereals – improves the robustness and resilience of local agricultural systems (Zentner et al., 2001, 2002; Burgess et al., 2012). The identification of specific rotational sequences is important because they provide an insight into the general long-term sustainability of regional agriculture. Furthermore, determining the prevailing sequences can help establish which ones have been successful and, therefore, which sequences might be more likely to succeed in similar regions.

Management practices affect the sustainability, economic viability, and resilience of an operation. Management practices at the field-level include logistical (e.g., scheduling planting), crop management (e.g., fertilizer rates, water usage), crop (species and variety), cropping systems (e.g., sequences and rotations), and tillage systems (e.g., no till, conservation till, or traditional till) (Meinke and Stone, 2005). We focus on individual fields, because, in most instances, they represent the smallest and most fundamental decision unit for managers.

Climate plays a large role in determining whether a particular management practice is adopted locally and, if adopted, how

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prevalent the practice becomes. In semiarid regions, the established agricultural practices focus primarily on capturing, conserving, and effectively using water (Cochran et al., 2006). Dryland farming practices dominate the drier portions of the U.S. Northern Great Plains (NGP), such as northeastern Montana. Historical practice in these regions has been to rotate small-grain cereals with summer fallow, a practice that entered widespread use in the late 1930s as a means to manage soil water in regions where rainfall is a limiting resource (Cochran et al., 2006). Cultivating pulses as green manure recently has become an increasingly common alternative to summer fallow in rotations with cereals (Miller et al., 2006; O'Dea et al., 2013; Tanaka et al., 2010).

Cereal–pulse sequences include a cereal, typically spring or winter wheat (*Triticum aestivum* L.), durum (*Triticum turgidum* L.), or barley (*Hordeum vulgare* L.), and a pulse crop such as dry pea (*Pisum sativum* L.), lentil (*Lens culinaris* Medik.), dry bean (*Phaseolus vulgaris* L.), or chickpea (*Cicer arietinum* L.) (Lemke et al., 2007). These sequences provide many field-level benefits including: (1) biological nitrogen (N) fixation, thereby making additional N available to the succeeding crop and reducing fertilizer requirements; (2) substantially lower water requirements than cereals or alfalfa; (3) improved options for controlling weeds; (4) reduced insect and disease problems; (5) improved soil tilth and stability; (6) reduced soil erosion; and (7) improved yields and higher protein levels for the following cereal crop (Cochran et al., 2006; Lee, 2011; Peel, 1998).

Changes in the relative proportions of cereal–fallow (block-managed and strip-cropped) and cereal–pulse sequences have implications for farm productivity and profitability, as well as broader implications in terms of improved environmental quality and economic impacts on surrounding communities (Zentner et al., 2001, 2002). The pulse industry in the northeast Montana counties of Daniels, Roosevelt, Sheridan, and Valley has recently experienced rapid growth. This region cultivated less than 20,000 ha annually through 2003; however, production increased to more than 125,000 ha during the relatively short span of 2004–2006. The area devoted to pulse crops has stabilized since 2006 with little additional growth; however, other regions such as north-central Montana have experienced recent growth (NASS, 2013). The annual economic benefits to these counties have been substantial with more than $100 million directly attributed to the 2010 pulse crop (Lee, 2011). The lessons learned here can be useful to producers in other regions in which the pulse crop potential has yet to be fully realized. The objectives of this work were: (1) to characterize the principal cropping sequences in northeast Montana during the period of regional pulse crop adoption (2001–2012); and (2) to identify changes in the relative proportions of these sequences during the same period.

2. Materials and methods

2.1. Study area

The study area comprises the four most northeastern Montana counties of Daniels, Sheridan, Roosevelt, and Valley (Fig. 1). It is bounded by Saskatchewan to the north, North Dakota to the east, and the Missouri River to the south. Federal and state lands lie along much of the western border and are non-cropland. The region is characterized by low relief and has a semiarid climate (Padbury et al., 2002). Total precipitation averages just over 310 mm annually, occurring primarily as rain between April and September (WRCC, 2013). Maximum daily temperatures in July average 31 °C, while January maximum daily temperatures average −10 °C (WRCC, 2013). The dominant land cover types are shortgrass prairie and agriculture. Regional agricultural practices are primarily dryland systems (Tanaka et al., 2010), although center-pivot irrigation is not uncommon for producers in close proximity to the Missouri River. Agriculture consists largely of cereal crops, primarily spring wheat, and an increasingly substantial area of pulse crops throughout most of the region; however, relatively small amounts of other crops are grown within the Missouri River corridor (NASS, 2012).

2.2. Data

2.2.1. Satellite imagery

Landsat images for 2001–2006 and 2012 were obtained from the Earth Resources Observation and Science Center (EROS). Three Landsat scenes were required for full coverage of the study area: Path 36, Row 26 (36/26); Path 36, Row 27 (36/27); and Path 35, Row 26 (35/26). We used a mid-season mosaic (∼mid-July) and a late-season mosaic (∼mid August) from each year to better capture phenological variation and improve classification. Obtaining cloud-free images of the study area required using imagery from two sensors: the Thematic Mapper (TM) aboard Landsat 5 (2001–2006) and the Enhanced Thematic Mapper Plus (ETM+) aboard Landsat 7 (2001–2006, 2012) (Table 1). The ETM+ images from 2003 onward have data gaps caused by the permanent failure of its scan-line corrector (SLC) (see e.g., Markham et al., 2004); images with these data gaps are known as SLC-off images. Due to the positions of the three overlapping Landsat scenes relative to the study region, data loss due to SLC-off gaps has been estimated at approximately 15% or less (Long et al., 2013).

2.2.2. Ground reference data

Ground reference data from 525 locations were collected during July 2012. The locations were randomly chosen from fields identified as agriculture and that were viewable from public rights-of-way. We recorded location and class (Cereal, Pulse, or Other). Cereal–fallow strip-cropping is not an uncommon practice, particularly in the western portion of the study area; these fields were typically classified as 'cereal'. Some reference sites were unusable because they were: (1) not accessible; (2) not agriculture; (3) duplicate observations of the same field; or (4) cloud covered in both mid-season and late-season images. The final dataset used 434 of the ground reference sites; 278 (64%) were cereal crops, 86 (20%) sites were pulse crops, and 70 (16%) were something else (typically CRP land or, much less frequently, some other crop such as alfalfa). These percentages are similar to regional data from the US Department of Agriculture (USDA) (NASS, 2012).

2.2.3. The cropland data layer

The cropland data layer (CDL) is a geo-referenced raster-based data layer denoting specific agricultural cover types (e.g., wheat, lentil, or corn). It was developed by the USDA's National Agricultural Statistical Service (NASS) primarily to assist in determining seasonal area estimates for major commodity crops (Johnson, 2013; NASS, 2013). The CDL has been used in a wide range of agricultural (e.g., Scheffran et al., 2007; Schultz et al., 2007; Kutz et al., 2012) and environmental (e.g., Linz et al., 2004; Hagen et al., 2005) studies. The CDL extends back to 1997 and is based on medium-resolution satellite data with extensive ground reference data (Boryan et al., 2011; Han et al., 2012). Coverage of the conterminous US for 2008–2012 is complete, while coverage for 1997–2007 depends on the state. Coverage for Montana, for example, dates to 2007, while neighboring North Dakota extends back to 1997.

The CDL is created from a variety of inputs. Imagery inputs are multitemporal and derive from several satellite-based sensors. The list of sensors depends on the year; the CDLs in this study were based on: (1) the Advanced Wide Field Sensor (AWiFS) (2007–2010); (2) TM (2008–2011); (3) Moderate Resolution Imaging Spectroradiometer (MODIS) 16-day NDVI (Normalized

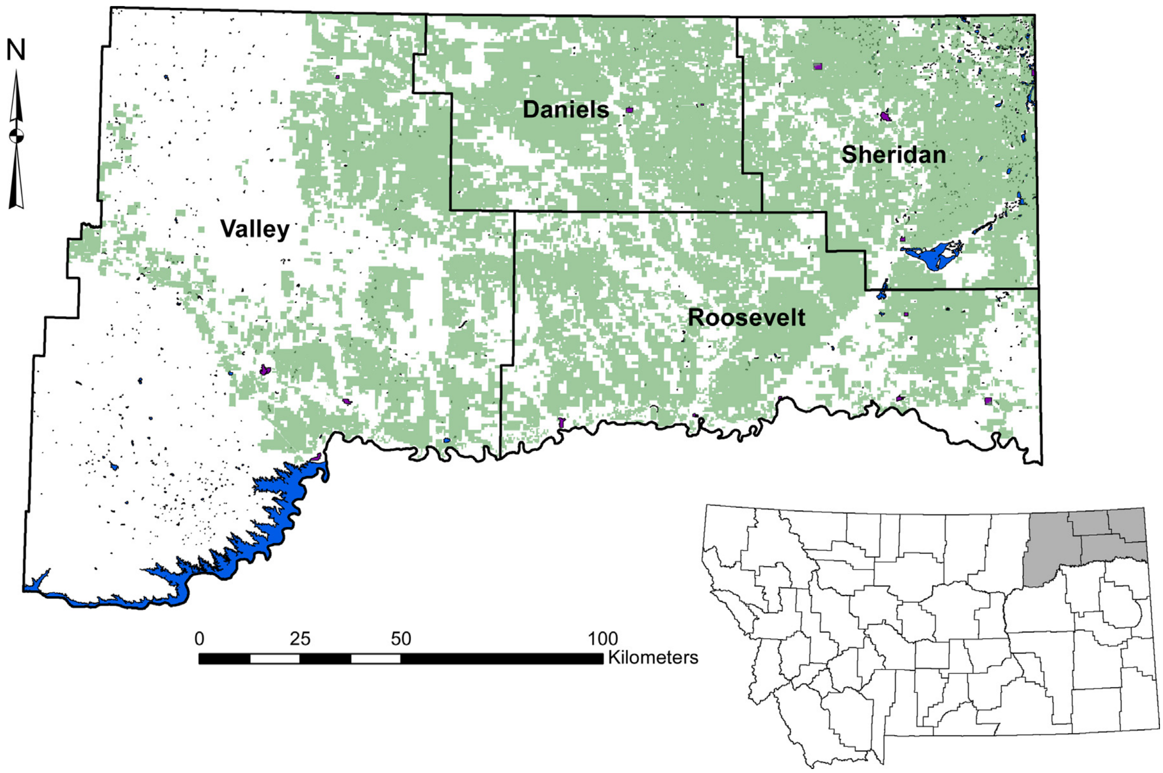

Fig. 1. The study area encompassed the northeastern Montana counties of Daniels, Roosevelt, Sheridan and Valley. Agricultural areas, as defined in this study, are indicated by shading in the larger map.

Differenced Vegetation Index) composite (2007, 2009); and (4) the SLIM-6 sensor aboard the DEIMOS-1 satellite (2011–2012) and the UK-DMC-2 satellite (2012) (Boryan et al., 2011; NASS, 2013). Additional inputs to the CDL included the National Elevation Dataset (NED), the National Land Cover Database (NLCD), and the USDA Farm Service Agency (FSA) Common Land Units (CLU), which are the ground reference data (Boryan et al., 2011; Johnson, 2013; NASS, 2013). Spatial resolution is either 30 m (2008, 2010–2012) or 56 m (2007, 2009) and depends on which sensors were used.

Classification accuracies for the CDL are reported by NASS for each state by year and are typically 80–95% (producer's and user's) for the major crops (NASS, 2013). These are state-wide accuracies; however, there are regional variations in accuracy that are not captured by this assessment. The state-wide accuracy report for the 2012 Montana CDL claims an overall accuracy of 73.8%; but when we assessed the accuracy of the study area portion of the CDL using our own ground reference data (434 observations), we found an overall accuracy of 92.6% ($\kappa = 0.86$). This is likely due to high class accuracies of the study area's major crop classes (fallow ~93%, cereals ~87%, pulses ~70%). There is some concern that the CDL tends to underestimate area when calculations are based on pixel counts (Johnson, 2013), but we employ an object-oriented approach (discussed momentarily), which largely avoids this bias. We therefore found the CDL to be a reliable source of ancillary data.

2.2.4. Ancillary vector data

We also used ancillary vector data: the Montana cadastral framework and the Montana land cover framework, both available from the Montana State Library's Geographic Information Clearinghouse. The cadastral framework is a geodatabase of private (taxable) and public (tax exempt) land parcels, which generally delineate agricultural fields. The land cover framework is a geodatabase of land cover classes as defined by the 2001 NLCD and identifies, among other things, agricultural land. We used the cadastral framework from June 2012 and the May 2010 land cover framework (MSL, 2012).

Table 1
Dates and sensors for the Landsat imagery used in the study.

Year	Mid-season		Late-season	
	Dates[a]	Sensors[b]	Dates	Sensors
2001	5 August (217)/6 August (218)	ETM+/TM	21 August (233)/22 August (234)	ETM+/TM
2002	23 July (204)/24 July (205)	ETM+/TM	23 August (229)/24 August (236)	ETM+/ETM+
2003	18 July (199)/19 July (200)	TM/ETM+	11 August (223)/12 August (224)	ETM+/TM
2004[c]	12 July (194)/13 July (195)	ETM+/TM	21 July (203)/14 August (227)	ETM+/TM
			13 August (226)/29 August (242)	ETM+/ETM+
2005	8 July (189)/15 July (196)	ETM+/ETM+	1 Sep (244)/2 Sep (245)	ETM+/TM
2006	11 July (192)/18 July (199)	ETM+/ETM+	19 August (231)/28 August (240)	ETM+/ETM+
2012	11 July (193)/18 July (200)	ETM+/ETM+	12 August (225)/19 August (232)	ETM+/ETM+

[a] Julian dates are in parentheses.
[b] TM is the Thematic Mapper (Landsat 5); ETM+ is the Enhanced Thematic Mapper (Landsat 7).
[c] The 2004 late-season required a different pair for the east (path 35) and west (path 36) halves of the mosaic because of excessive clouds.

2.3. Data preparation

2.3.1. Creating the 'fields' layer

We began by intersecting the cadastral layer, which delineates land ownership boundaries (fields), with the NLCD layer. This step eliminated all land parcels from the cadastral layer that lay in regions not defined as agricultural. We sought land parcels of 16.2 ha (40 acres) or larger to define agricultural fields. This minimum field size was chosen for two reasons – it allowed us to easily remove small land parcels (e.g., residential lots) from the cadastral layer, and it helped to focus our analyses on major producers. The median agricultural field in the study area was 65 ha in area, and the 16.2 ha minimum eliminated less than 1% of agricultural land. Consequently, the cadastral layer was modified by deleting all fields less than 16.1 ha; allowing for small variations in minimum-sized fields. Some fields, particularly the smaller ones, were located entirely within the 2012 ETM+ data gaps; these fields were also deleted from the cadastral layer. Fields that were located partially within a data gap were eliminated if they consisted of less than 40 pixels; this was to ensure a large enough sample size of pixels such that any field-based statistical measure (e.g., mean spectral value of the red band) would be representative of the entire field. The modified cadastral layer was designated the 'fields' layer and comprised 13,145 agricultural fields.

2.3.2. Creating the CDL mosaics

The CDL data were obtained from the USDA via the CropScape web-based interface. Annual data are provided as TIFF (tagged image file format) images clipped to an area of interest (AOI). We downloaded the CDL data for the study area (Montana counties Daniels, Roosevelt, Sheridan, and Valley) for 2007–2012, as well as neighboring Divide and Williams counties in North Dakota for 2001–2006 (the North Dakota CDLs were needed to facilitate classification for 2001–2006 (see Section 2.5)). The individual county files were combined into regional mosaics by year. CDL data were thematic rasters and comprised 255 classes, the vast majority of which were not present in the study area. We combined these 255 classes into four by recoding the thematic classes for each of the regional mosaics: (1) cereals (barley, durum wheat, spring wheat, winter wheat, rye, oat, and other small grains); (2) fallow (fallow/idle cropland); (3) pulse (chickpea, lentil, and pea); and (4) other (all remaining classes).

2.3.3. Image pre-processing

Level-one terrain-corrected (L1 T) Landsat images were acquired from the USGS via the EarthExplorer web-based interface. Invalid pixels, caused by line dropout or slight shifts in the position of the data gaps per band, were removed. We employed a multitemporal approach to improve subsequent classification and constructed a mid-season and a late-season mosaic for each year. Complete coverage of the study area required imagery from different dates. Since differences in atmospheric conditions or solar angles affect the amount of reflected radiation, radiometric normalization was required.

Mosaics were produced in several steps. First, we directly combined the two Path 36 images (36/26 and 36/27) into the 'west' image without radiometric normalization because these images were from the same day. The third image (35/26), the 'east' image, was from a different date since consecutive Landsat orbits are not adjoining, necessitating radiometric normalization. We combined the east and west images by using the overlapping regions to derive a linear regression model with the western image as the reference, adjusting the values in the east image, and then creating a mosaic using the west and the adjusted east images. Clouds and their shadows were a persistent problem in nearly every year in this study, particularly in the mid-season, and were identified with a supervised classified algorithm and a binary (cloud/shadow or no cloud/shadow) mask created for each mosaic. We used these binary masks to eliminate pixels containing clouds or cloud shadows.

Changes in spectral values from mid- to late-season capture important phenological differences and have proved to be important variables for crop classification (Long et al., 2013). We, therefore, created a differenced mosaic by subtracting the late-season mosaic from the mid-season one. Next, the mid-season, late-season, and the differenced mosaics were stacked and cleaned by removing pixels with a zero in any layer. Zeros represented pixels with no data, due to either data gaps or to clouds and shadows, and this step ensured that the remaining pixels had data for all layers. The final step was to clip the stacked mosaics to the fields layer.

2.4. Determining field-level crop class (2007–2012)

We used the CDL and the cadastral layer to determine crop class at the field-level for 2007–2012. The CDL mosaics were converted to thematic rasters with four classes during the data preparation phase; however, the mosaics were still pixel-based. Classification at the pixel level is challenging because monoculture fields are often classified as multiple classes; however, classification algorithms can operate on groups of contiguous pixels (object-oriented) as well as individual pixels (pixel-based). Object-oriented classification is most appropriate when the landscape can be delineated into meaningful homogeneous regions, ideal for agricultural fields (e.g., Forster et al., 2010). Several studies have concluded that object-oriented approaches to classification produce better results than pixel-based approaches (e.g., Pedley and Curran, 1991). Transforming the pixel-based CDL layers to a collection of fields with a single classification required four basic steps: (1) creating crop class-specific versions of the CDL; (2) segmentation of these layers; (3) data extraction; and (4) classification.

We created field-based objects in which objects were assigned to the class corresponding to the majority of the extant pixels from the CDL. The only exception to this scheme is when the proportion of cereal and fallow were nearly equal, in which the fields were classified as cereal–fallow strips. This process resulted in six final classes: cereal (C), fallow (F), pulse (P), other crops or non-agricultural land (O), cereal–fallow strip-cropping (S), and no data or missing (M). The single-letter class identifiers were necessary for subsequent analysis with string matching algorithms; hereafter, we refer to these class identifiers. The accuracy of this procedure was evaluated by comparing the derived field-level classifications to the 2012 ground reference data and to local producers' records for 2007–2012.

2.5. Determining field-level crop class (2001–2006)

Montana CDL layers were not available for 2001–2006; therefore, a separate procedure was developed to determine crop class at the field-level for these years. We took advantage of two key facts: (1) the footprint for our Landsat imagery encompassed Divide and Williams counties in North Dakota, immediately adjacent on the eastern border of the study area; and (2) CDL data existed for these North Dakota counties for 2001–2006.

We began with an unsupervised classification (36-classes) of the Landsat imagery, since we had no ground reference or CDL data for the study area. We then used the CDL data from the two North Dakota counties as an overlay. This allowed us to identify each of the 36 unsupervised classes, based on pixels, as C, F, O, or P. These classified pixels were aggregated at the field-level. The classified image at this point was a thematic raster with four classes and subsequent processing was as described in the previous section. Accuracy was evaluated by processing the 2012 imagery with

Table 2
Definition of cropping sequences.

Length	System	Sequences[a]
2-year rotations	Monoculture	CC, FF, PP
	2-class rotations	CP/PC, CF/FC, SS, PF/FP, SC, FS/SF
3-year rotations	Monoculture	CCC, FFF, SSS, PPP
	2-class rotations	CCF/CFC/FCC, CCP/CPC/PCC
	3-class rotations	CFP/CPF/FCP/FPC/PCF/PFC

[a] Sequences are shown with all permutations. C, cereal; F, fallow; P, pulse; S, strip-cropped.

this method and comparing the derived field-level classifications to the 2012 ground reference data and to local producers' records for 2012. We made the necessary assumption that, if the method was successful for 2012, it would be successful for other dates, since no reference data was available to test this assumption.

2.6. String construction and pattern determination

The annual crop classifications were combined into a 12-character string representing the sequence of classes (e.g., CFCFCFCCPCCP) for each field in the study. There were 106 fields classified as M (missing data) for at least one year in the 2001–2012 sequence. We were able to recover 37 of these by examining the classification for the remaining years. If a field was the same class for all years in which we had data, we assumed that the missing year was the same class. If, for example, a field was missing a class for 2005 and all of the other years were O (OOOOMOOOOOOO), then we felt confident that 2005 was also O and replaced the M with O in the string. We only recovered missing data in this manner and made no attempts to infer any patterns for fields with missing data. The remaining 69 fields with missing data were removed from the dataset, leaving a total of 13,076 fields with complete sequences.

We then searched these strings for specific *a priori* 2- and 3-year sequences (e.g., CP, see Table 2) using the Biostrings package (Pages et al., 2013) in the statistical program R (R Development Core Team, 2011). Identifying 2- and 3-year sequences within longer sequences is problematic because every 2-year sequence is embedded within 3-year sequences, which are embedded within 4-year sequences, and so forth (see Hennessy, 2006, for a mathematical discussion). This embedded relationship creates ambiguities when we try to assign a field in a particular year to a specific sequence. The third year, for example, in the 4-year string CC**F**C is fallow; but, this field might represent the first year of a FC sequence, the second year of a CF sequence, the third year of a CCF, or one of the many other possibilities. In any specified year, a field is simultaneously in several sequences.

A common approach to characterize changes in cropping sequences is to partition the data into non-overlapping blocks (e.g., Plourde et al., 2013). The string CCFCFP, for example, can be considered as three 2-year sequences (CC, FC, and FP), or as two 3-year sequences (CCF and CFP) under this scheme. This approach avoids ambiguity by assigning years to specific blocks. If our example, CCFCFP, represented 2001–2006 and we used 2-year blocks, then 2003 is the first year in a FC sequence. Partitioning the data into non-overlapping blocks ignores the notion that fields are simultaneously in several sequences. An alternative to non-overlapping blocks is to use an *n*-year moving window – a rotation-conditioned lag operation (Hennessy, 2006). With a 2-year moving window, the string CCFCFP is considered as five 2-year sequences (CC, CF, FC, CF, and FP), while a 3-year moving window yields four 3-year sequences (CCF, CFC, FCF, and CFP).

We looked at the data in *two* different ways. We used a 2-year moving window (2001–2002, 2002–2003, . . ., 2011–2012) to identify and characterize the principal 2-year sequences, and similarly structured windows to characterize 3-year sequences. We summarized all sequences in terms of area and the number of fields involved and identified changes in these sequences by identifying increases and decreases in abundance over time. We also identified changes in area over time for the individual classes (C, F, P, and S) and total productive agricultural land.

3. Results

3.1. Individual classes

Total productive agricultural land in the region increased by approximately 180,000 ha between 2001 and 2012, driven by increases in area devoted to cereal (C) and pulse (P) crops (Fig. 2a). Cereals increased from 380,000 ha to 580,000, a substantial increase (Fig. 2b). Pulse crops increased from 20,000 ha to 1,10,000 ha (Fig. 2c). Cereal–fallow strip-cropping (S), in contrast, decreased substantially in area, from 2,10,000 ha to 80,000 ha (Fig. 2e). Fallowed cropland (F) maintained a constant trend across the study's time frame, but this is due to a doubling of fallow in 2011 during an excessively wet spring that interfered with planting in the region; the area of fallow had been decreasing throughout 2001–2010 (Fig. 2d). The plots for C and F exhibit a moderately strong inverse relationship ($r = -0.59$), which consists of synchronized patterns of alternating highs and lows that typically move in opposition to one another (Fig. 2f). Fallow reached highs in 2002 and 2011; both years were characterized by above average spring precipitation (WRCC, 2013).

The mean field size increased for all classes between 2001 and 2012. Most of these increases were modest: the average size of cereal fields increased by 3 ha, fallow fields had a 10-ha increase on average, cereal–fallow strip-cropped fields increased an average of 10 ha, and pulse fields increased by an average of 22 ha. These increases were accompanied by overall increases in the number of fields, area, and proportion of land in production. Mean area of the strip-cropped fields increasing while the total area of strip-cropping decreased suggests that smaller fields were preferentially converted to block management, perhaps as a trial prior to full conversion of all fields.

3.2. Two-year sequences

Two-year monoculture sequences comprised 28–48% of the fields, depending on the year, while multi-class rotational sequences accounted for the remaining 52–72%. Plots of monoculture sequences indicate that the number of fields involved in a specific monoculture sequence (CC, FF, and PP) varied across the time frame. Cereal (CC), for instance, experienced a minimum in 2005–2006, and peaked three years later during 2008–2009 (Fig. 3a). Continuous fallow (FF) was typically quite low (<5000 ha) during the study, but peaked dramatically in 2010–2011 (Fig. 3b). Continuous pulse sequences (PP) were likewise uncommon (<10,000 ha) except for a brief period during 2005–2007; yet, these PP sequences comprised less than 1% of all fields (Fig. 3c). There was an increase in fallow and a drop in cereal production for 2010–2011 and 2011–2012. These relationships persisted for all sequences, regardless of whether we measured by the number of fields or by area. Hereafter, unless specifically noted, results and comments will apply equally to the number of fields as well as their area. We did not consider fields in continuous cereal–fallow strip-cropping (SS) as monoculture sequences, but rather a form of cereal–fallow rotations, which are discussed shortly.

Plots of multi-class rotational sequences illustrate, as in the monoculture sequences, that the number of fields involved in rotations varied. The most notable trends were the nearly ten-fold increase in the number of fields in cereal–pulse (CP/PC) sequences (Fig. 4a) and the substantial decline in the number of cereal–fallow sequences (Fig. 4c) managed by strip-cropping (SS). Cropping sequences involving fallow increased for periods that included 2011. Cereal–fallow (CF/FC) sequences, for instance, were declining, but increased when 2011 was included (Fig. 4b). Fields in other configurations of cereal–fallow sequences (SC and FS/SF) were less common (Fig. 4e and f). The number of SC sequences generally increased over the study's time frame. The SC, and to lesser degree the SF, sequences mark the transition in management practices away from strip-cropping. These transitions were more frequent in the 2003–2004 and the 2006–2007 time frames. Pulse–fallow (PF/FP) sequences were generally not common, but they did exhibit a small rise early in the study (2003–2007) and again in 2011 (Fig. 4d).

3.3. Three-year sequences

Monoculture sequences based on a 3-year moving window comprised 22–42% of the fields in production, while multi-class rotational sequences accounted for the remaining 58–78%. Continuous 3-year cereal sequences (CCC) were frequent, but less abundant than the 2-year sequences (CC). The CCC sequences followed the same general pattern of relative abundance (Fig. 5a) as did the CC sequences. Continuous fallow (FFF) and pulse (PPP) were very uncommon, with less than 15 fields for either sequence (Fig. 5b and c). Extended cereal–pulse rotations (CCP, CPC, and PCC) exhibited the same dramatic rise in abundance as in the 2-year sequences, from 335 fields in the 2001–2003 time frame to 2416 fields in 2010–2012 (Fig. 6a). Extended cereal–fallow rotations (CCF, CFC, and FCC) also mirrored the 2-year sequences, slightly declining until 2011 was included in the window (Fig. 6b). Cereal–fallow

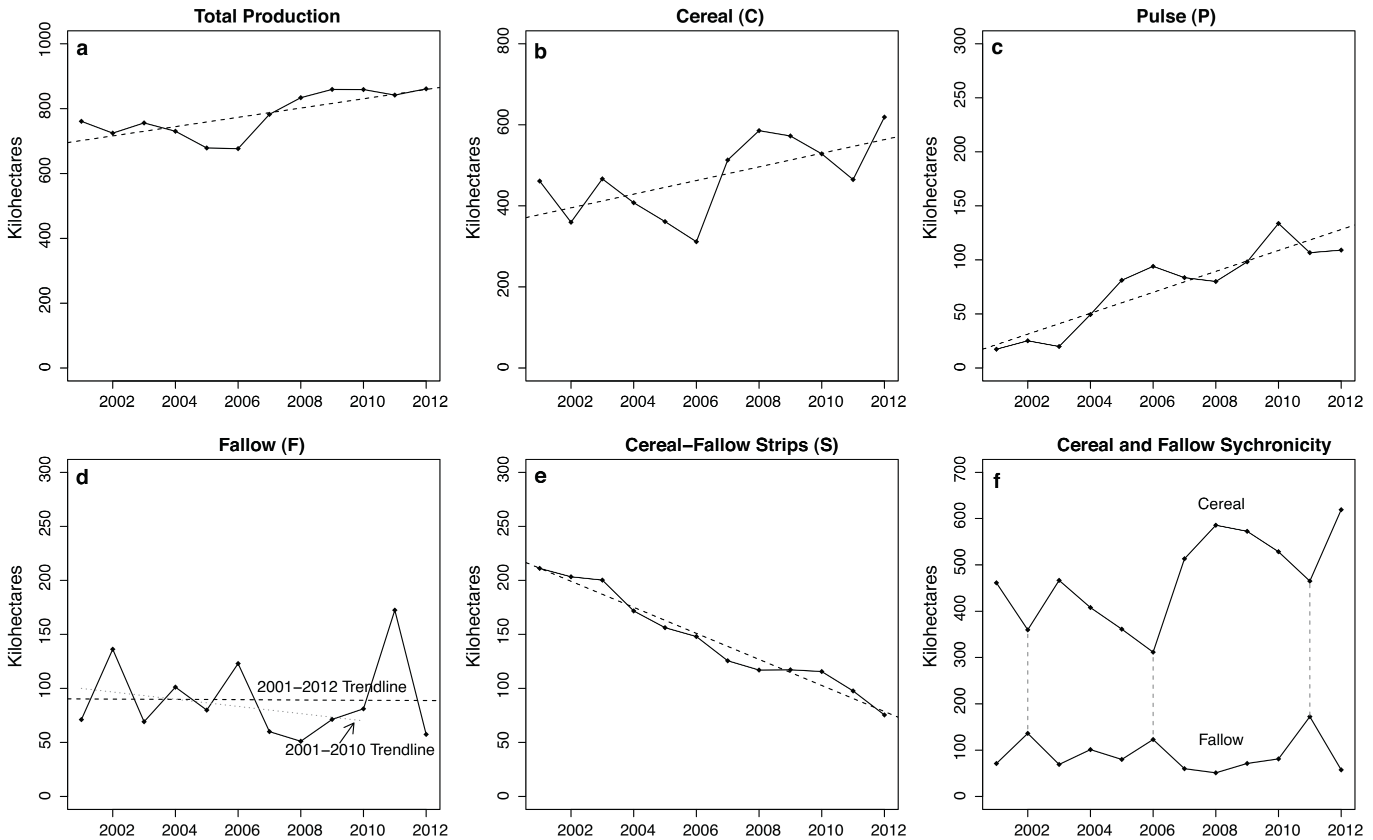

Fig. 2. Area on an annual basis (2001–2012) devoted to: (a) total agricultural production; (b) cereal (C) crops; (c) pulse (P) crops; (d) fallowed (F) fields; (e) cereal–fallow strip-cropped (S) fields; and (f) cereal and fallow plotted together to illustrate the synchronicity.

rotations managed by continuous strip-cropping (SSS) steadily declined throughout the study's time frame, decreasing by 70% (Fig. 6d). We also considered 3-year pulse–cereal–fallow sequences (PCF, PFC, CPF, CFP, FCP, and FPC). These sequences were less common, but not trivial–typically less than 2% of all fields, (Fig. 6c). PCF sequences typically constituted less than 300 fields; however, there was an increase to 440 fields for the 2009–2011 window (Fig. 6c), which is likely due to the large number of fallow fields in 2011.

4. Discussion

4.1. Total production and monoculture sequences

An increase in the mean field size for *all* target classes (C, F, P, and S) suggests that additional fields were added to production between 2001 and 2012. This increase in the total area under production is illustrated in Fig. 2a and is indicative of regional agricultural extensification. Increases in total production are likely primarily due to considerably large areas returning to production following CRP enrollment. Regional reductions of 10.3% in the amount of CRP mirror the decreasing trend at the national level following areal caps on CRP in the 2008 Farm Bill (Fargione et al., 2009; Lee, 2011).

Cereal production varied substantially during 2001–2012, but had an overall increasing trend. Maximum production was in 2012, while minimum production was in 2006 and coincided with a peak in the number of fields enrolled in CRP (Lee, 2011). Cereal abundance is inextricably linked to the abundance of fallow, and the observed increasing trend for regional cereal production is associated with a decreasing trend in fallow. This suggests that either continuous cereal cropping was increasingly common or that block-managed alternate year cereal–fallow sequences were less common. Our data indicate that both situations occurred, but

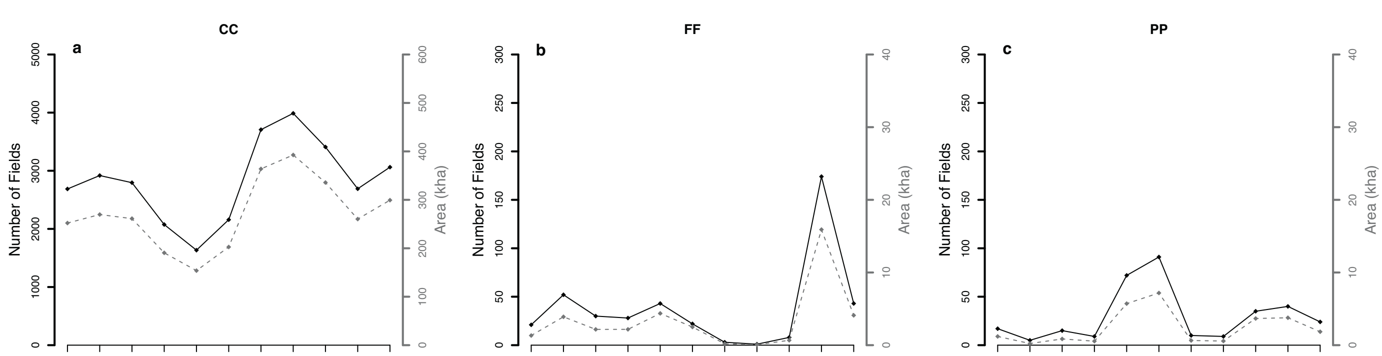

Fig. 3. Abundance of 2-year monoculture sequences in number of fields (black solid line) and in area (gray dotted line) for: (a) cereal–cereal (CC); (b) fallow–fallow (FF); and (c) pulse–pulse (PP). The horizontal axis is a 2-year moving window such that, for example, '02 = 2001–2002, '03 = 2002–2003.

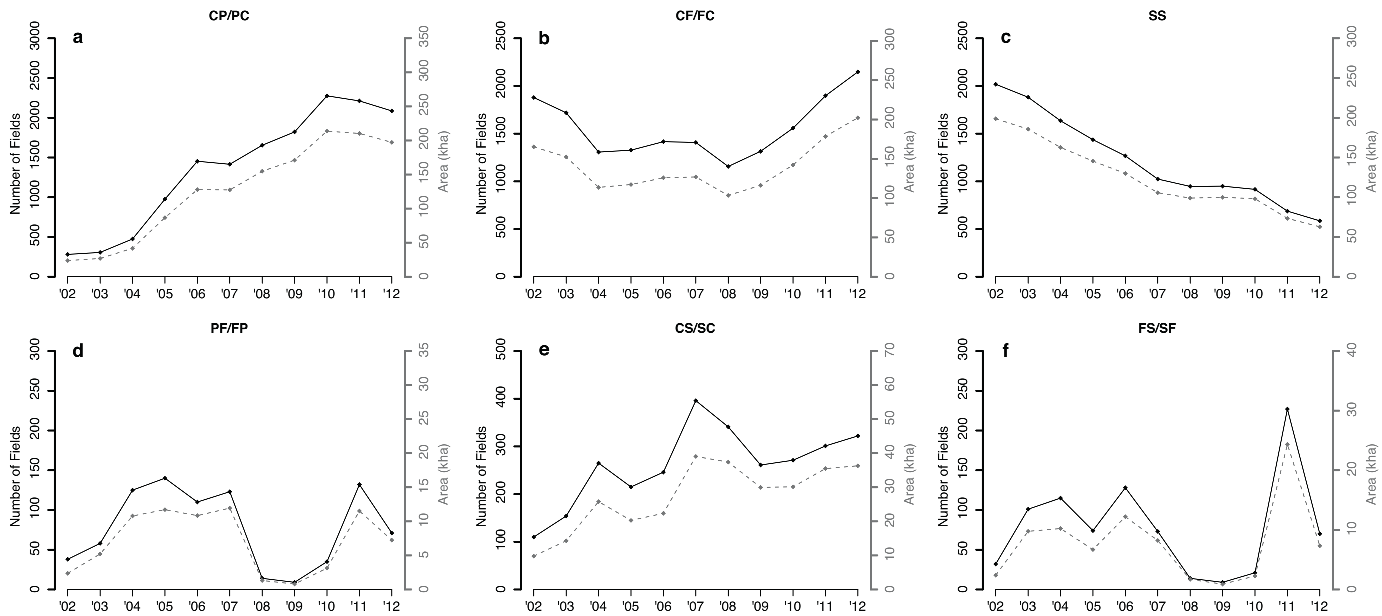

Fig. 4. Abundance of 2-year rotational sequences in number of fields (black solid line) and in area (gray dotted line) for: (a) cereal–pulse (CP/PC); (b) cereal–fallow (CF/FC); (c) continuously strip-cropped (SS); (d) pulse–fallow (PF/FP); (e) cereal–strip-cropped (SC); and (f) fallow–strip-cropped (FS/SF). The horizontal axis is a 2-year moving window such that, for example, '02 = 2001–2002, '03 = 2002–2003.

continuous cereal production was the stronger trend. We found that the abundance of the 2-year continuous cereal sequences (CC) tended to increase over time, but the 3-year sequences (CCC) remained essentially unchanged.

Montana led the nation in lentil and pea production in 2011 (Lee, 2011). Northeast Montana is the state's premier pulse producing region, and we observed that pulse production increased six-fold between 2001 and 2012. Pulses accounted for a small amount of cropland in the study area, approximately 22,000 ha per year, during 2000–2003. Pulse crops began a dramatic rise in 2004, which peaked in 2010 at approximately 34,000 ha. Our data closely match those from national and state-level agencies (Lee, 2011; NASS, 2012). Pulse crops reportedly were grown primarily on land that previously had used fallow as a management practice (Lee, 2011). The field-level benefits of pulse crops are mainly beneficial to the successive cereal crop; therefore, continuous pulse sequences (PP or PPP) were uncommon. Two-year pulse sequences (PP) were rare except for the 2005–2006 and 2006–2007 windows, but they never exceeded 100 fields. The 3-year sequences (PPP) were very infrequent.

Continuous fallow (FF or FFF) is an uneconomical practice, and we found it infrequently throughout the first 10 years of the study. It is possible that some of the fields in 2- or 3-year fallow sequences were misclassified as fallow when they were more likely strip-cropped fields. Two-year sequences (FF) averaged 3400 ha during 2001–2010, while 3-year sequences averaged only 390 ha. We observed a quadrupling of continuous fallow sequences (FF and FFF) above their respective averages for time frames that include 2011. This increase is because many producers were unable to seed their fields in 2011 as they struggled with below average temperatures and precipitation as much as 400% above normal (NOAA, 2011). Many fields were, therefore, unintentionally fallowed; we see this quite clearly in the data as increases in the number of fallow fields (Fig. 2d) and in the number of FF sequences (Fig. 3b).

4.2. Cereal–fallow sequences

The rotation of crops as a beneficial agricultural practice has been known to farmers for thousands of years, yet historical trends in agricultural production have been to increase cropping intensification and simplify rotations. Formal investigations with dryland crop rotations began at least as early as 1908 when the Montana Agricultural Experiment Station initiated a series of experiments with continuous cropping systems and various rotations (Atkinson et al., 1917). Much of this work involved land brought under cultivation for the first time after breaking native prairie sod. Our results

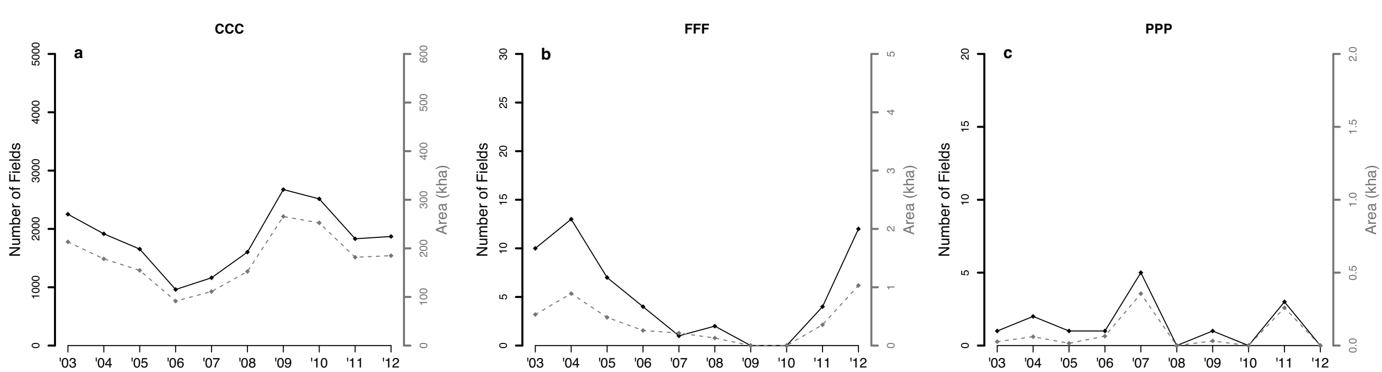

Fig. 5. Abundance of 3-year monoculture sequences in number of fields (black solid line) and in area (gray dotted line) for: (a) continuous cereal (CCC); (b) continuous fallow (FFF); and (c) continuous pulse (PPP). The horizontal axis is a 3-year moving window such that, for example, '03 = 2001–2003, '04 = 2002–2004.

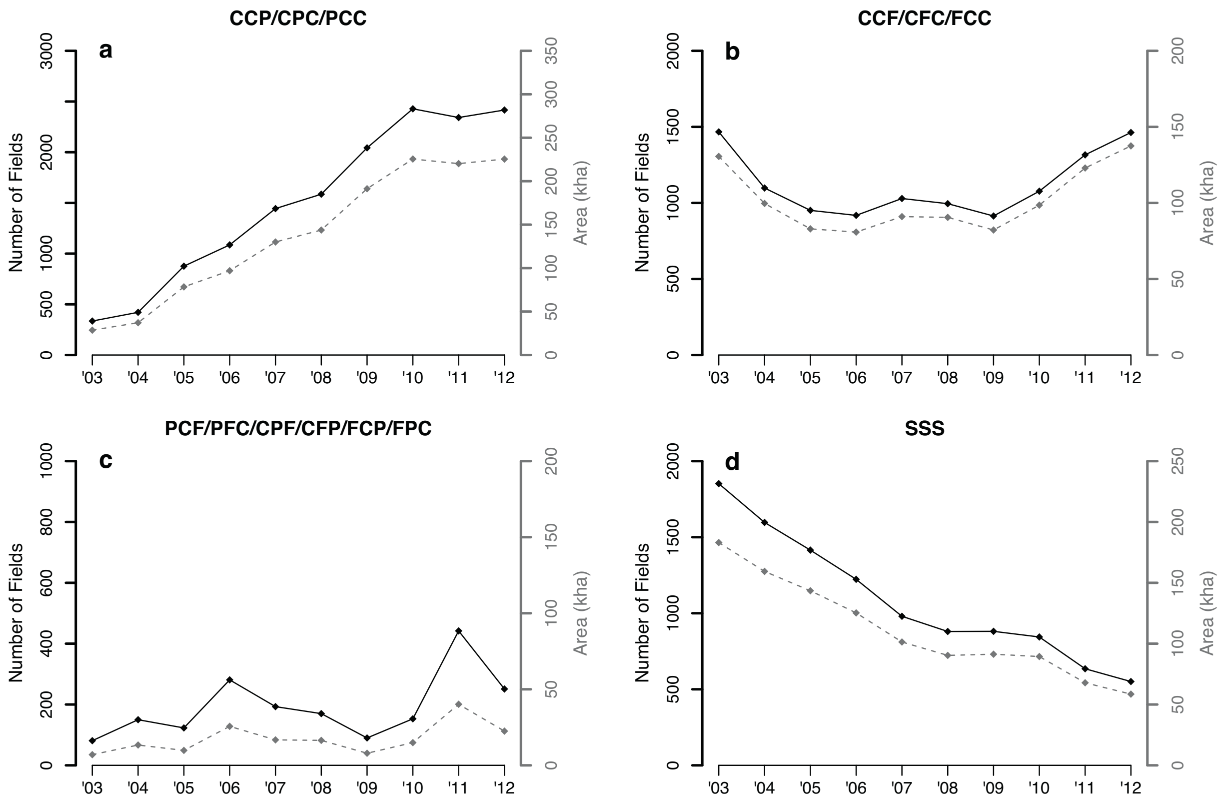

Fig. 6. Abundance of 3-year rotational sequences in number of fields (black solid line) and in area (gray dotted line) for: (a) cereal–cereal–pulse (CCP/CPC/PCC); (b) cereal–cereal–fallow (CCF/CFC/FCC); (c) pulse–cereal–fallow (PCF/PFC/CPF/CFP/FCP/FPC); and (d) continuously strip-cropped (SSS). The horizontal axis is a 3-year moving window such that, for example, '03 = 2001–2003, '04 = 2002–2004.

indicate that, for northeastern Montana, the trend to increase cropping intensification has continued, but the trend to simplify rotations is reversing.

Fallow decisions in dryland farming conditions are fundamentally issues of soil water management, but they function within the confines of economic considerations. Cereal production is highly responsive to soil moisture at planting time and precipitation during the growing season. Producers, unfortunately, have no control over precipitation, but soil moisture can be influenced by fallowing decisions. Fallowing cereal fields in alternate years is a long-standing practice, which was described in 1703 as "a very ancient piece of husbandry" (Mortimer, 1703). Researchers (e.g., Burt and Allison, 1963; Verburg et al., 2012) have recommended that producers base fallow decisions on soil moisture at planting time, rather than considering continuous cereal or strict CF sequences as the only options. We found cereal–fallow sequences, regardless of form – basic (CF) or extended sequences (CCF/CFC/FCC), to be common, but not consistent in area or in the number of fields. Consequently, rigid adherence to continuous cropping or rotational sequences by producers in the study area does not seem likely. All cereal–fallow sequences tended to decrease in abundance though 2010, but rebounded in response to the large number of fields fallowed in 2011.

4.3. Cereal–fallow sequences managed by strip-cropping

There was a substantial decrease, nearly three-fold, in the abundance of cereal–fallow sequences managed by strip-cropping. Producers moved away from strip-cropping, converting those fields to other cereal–fallow sequences or to pulse production. Transitions away from strip-cropping were persistent throughout the study's time frame (Fig. 2e) and are apparent by noting increases in the frequency of SC and SF sequences. These two sequences mark the transition in management practices away from strip-cropping and we observed spikes in 2003–2004 and in 2006–2007 (Fig. 4e).

Reductions in strip-cropping practices during the study likely stem from three factors: (1) decreased vulnerability to insect damage; (2) increases in no-till practices; and (3) increases in pulse production. The management of cereal–fallow sequences by blocks (alternating years of cereal and fallow in a field) instead of strips reduces vulnerability to damage from the wheat stem sawfly (*Cephus cinctus* Norton), a major insect pest. Sawfly damage to fields is primarily limited to the edges; transitioning from strips to blocks considerably reduces the extent of edges (e.g., Weiss and Morrill, 1992). Strip-cropping is foremost a management practice to reduce soil erosion, primarily due to wind (e.g., Weiss and Morrill, 1992). No-till practices inject seeds directly into the previous year's stubble, which substantially reduces soil erosion without affecting productivity. No-till management is the majority tillage practice regionally, with estimates between 50% and 90% (e.g., Watts et al., 2009; Hansen et al., 2012). No-till practices also reduce fallow by efficient use of moisture–crop residues ease the loss of soil moisture due to evaporation and increase infiltration by slowing runoff and trapping snow (e.g., Scholten, 1988). The final factor is dramatic increases in the number of fields in cereal–pulse sequences. Pulse crops replace fallow in traditional cereal–fallow sequences since they have substantially lower water requirements (Cochran et al., 2006). Cereal–pulse sequences can, therefore, supplant cereal–fallow sequences that are managed by strip-cropping.

4.4. Pulse sequences

Formal recommendations in favor of cereal–pulse sequences instead of cereal–fallow can be found more than 300 years ago (e.g., Mortimer, 1703). Our data show a substantial rise in the number of fields involved in cereal–pulse sequences (CP/PC and CCP/CPC/PCC), which peaked in 2010 with Montana's record pulse crop (Lee, 2011). Since 2010, these cereal–pulse sequences have accounted for approximately 17% of all agricultural fields in the study.

Pulse–fallow sequences (PF/FP) were uncommon, since pulse often replaces fallow in cropping sequences. Nonetheless, small numbers of pulse–fallow sequences were observed in 2004–2007 and in 2011. We also considered 3-year pulse–cereal–fallow sequences (PCF/PFC/CPF/CFP/FCP/FPC). These sequences were likewise uncommon and tended to remain steady at approximately 14,000 ha, except for 2011. These sequences were not abundant for the same reason as pulse–fallow. The 2011 results are likely an anomaly, as noted previously, where numerous fallow fields represented missed planting windows.

5. Conclusion

We sought to identify and characterize changes in the principal cropping sequences during the period of pulse crop adoption (2001–2012) in northeast Montana, which we summarize below.

- The amount of cropland in active production increased, largely from declining CRP participation.
- The production of cereals increased overall, but was highly variable. The increases were closely associated with equivalent decreases in fallow. Continuous cereal and cereal–fallow sequences increased, but continuous cereal was the stronger trend – potentially due to improvements in soil water management through the adoption of no-till practices. Producers grew more cereal and fallowed fields less often but did not appear to strongly adhere to specified sequences – it is more likely that producers responded to soil moisture levels when deciding whether to plant a crop or to fallow the field.
- The prevalence of strip-cropped cereal–fallow sequences decreased substantially, particularly in the eastern portion of the study area. Notable decreases occurred in 2004 and 2007, which were coincident with increases in block-managed cereal–fallow sequences and with increases in pulse production. Producers that continued with cereal–fallow sequences tended to convert to block management rather than strip-cropping.
- Pulse production increased dramatically, primarily on previously fallowed fields. Pulse crops were nearly always in sequences with cereals; continuous pulse and pulse–fallow sequences were rare. Producers replaced a substantial amount of fallow with pulse crops.
- Excessive precipitation in 2011 caused farmers to unintentionally fallow many of their fields. This tripled the amount of fallow and altered sequences.

We examined the 12-year record of field-level crop classes in two different ways, as 2-year sequences and as 3-year sequences. The most prevalent 2-year sequences were continuous cereal, cereal–fallow, and cereal–pulse. The extended versions of these same sequences dominated when we considered the data as 3-year sequences: continuous cereal (CCC), cereal–fallow (CCF), and cereal–pulse (CCP), along with their permutations. Continuous strip-cropping, a previously established cereal–fallow sequence, has declined rapidly.

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