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Dynamics of Utah's agricultural landscapes in response to urbanization: A comparison between irrigated and non-irrigated agricultural lands

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ABSTRACT

In the literature on how urbanization affects agricultural landscapes, little attention has been focused on differentiating and comparing the changes in irrigated agricultural landscapes to non-irrigated agricultural landscapes. Additionally, there have been few applications of landscape metrics for understanding agricultural landscape changes. The objectives of this study were to: (1) analyze and compare the changes of both irrigated and non-irrigated agricultural lands in a rapidly growing region; (2) identify the spatial patterns and hotspots of these changes; and, (3) examine the spatial relationships between changes in agricultural landscapes and urban development. We adopted landscape metrics and gradient analysis to assess where and how agricultural landscape changes occurred in northern Utah over the past 30 years. A revised urban gradient was also developed to detect the changes of agricultural landscapes in relation to new urban development. We found that irrigated agricultural lands were more affected by urban development than non-irrigated agricultural lands, with evidence of more patches, more irregular patch shapes, and less connectivity among patches. This study contributes not only to the existing literature on the dynamics of both irrigated and non-irrigated agricultural lands in relation to urban development, but also helps fill the gap of scant applications of landscape metrics and urban gradient analysis in agricultural areas. Most importantly, such a comprehensive examination of Utah's agricultural landscapes will serve as part of the scientific foundation for informing land use policy in the region, as well as provide lessons for other places that are facing similar agricultural land conversion challenges.

1. Introduction

Under the pressure of urbanization, globally many agricultural lands have been converted to urban uses or are under the threat from urban development (Foley et al., 2005). This is certainly the case in large parts of the western United States (Brown, Johnson, Loveland, & Theobald, 2005; Daniels, 1999). Particularly, irrigated agricultural lands are extremely vulnerable to urbanization and have made up a great amount of agricultural land loss in the region (American Farmland Trust, 1986; Baker, Everett, Liegel, & Van Kirk, 2014). This is because in the arid American West, under the rising competition to acquire water resources and water rights, irrigated agricultural land conversion is often driven more by water use conversions than land use conversions per se (Baker et al., 2014). Some scholars have argued that where agricultural water supplies are available is where growth is likely to occur (Tarlock & Lucero, 2002; Baker et al., 2014). Furthermore, researchers have found that fragmentation and conversion of irrigated agricultural lands posed a variety of challenges to food production, ecosystem functions, as well as social equity (Brown et al., 2005; Manjunatha, Anik, Speelman, & Nuppenau, 2013). Conversion of irrigated agricultural lands to urban development, in particular, has serious impacts on regional water management and planning (Kuminoff, Sokolow, & Sumner, 2001; Utah Governor's Water Strategy Advisory Team, 2017).

Some scholars have argued that irrigated agricultural lands conversions compared with non-irrigated agricultural lands conversions, due to the different underlying processes, often result in more fragmented and less aggregated landscapes (Baker et al., 2014; Lucero & Tarlock, 2003; Riebsame, Wescoat, & Morrisette, 1997; Tarlock & Bates, 2008). However, in the literature on analyzing how urbanization affects overall agricultural landscapes, little attention has been focused on differentiating and comparing the changes in irrigated agricultural

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landscapes to changes in non-irrigated agricultural landscapes (Baker et al., 2014; Riebsame et al., 1997). Therefore, there is a knowledge gap concerning the dynamics of agricultural landscapes in terms of where and how irrigated compared to non-irrigated agricultural lands transition to other uses. Information on the processes and impacts of agricultural lands conversions is useful for land and water policy and planning decisions.

When it comes to the methods of studying landscape changes under urbanization, landscape metrics have proven successful in revealing the general patterns of landscape transformations (Mcgarigal, Cushman, Neel, & Ene, 2002; Turner, 1990). Moser et al. (2002) and Schaller et al. (2012) suggested landscape metrics could also efficiently reveal the more specific changes in agricultural landscapes. Surprisingly, there have been few applications of landscape metrics in agricultural landscape studies. Uuemaa, Mander, and Marja (2013) found that in the 128 studies using landscape metrics for landscape pattern analysis, only seven studies dealt with agricultural areas. Among these seven studies, two of them adopted landscape metrics to measure landscape fragmentation (Pôças, Cunha, & Pereira, 2011) and plant species richness (Moser et al., 2002). In two other examples, landscape metrics were used to evaluate the impacts of policy options on agricultural landscapes (Berger & Bolte, 2004; Colson, Bogaert, & Ceulemans, 2011). Su, Jiang, Zhang, and Zhang (2011) and Su, Xiao, and Zhang (2012) used landscape metrics to analyze the varying spatial relationships between agricultural landscape patterns and urbanization. None of these studies, however, made the distinction between irrigated agricultural lands and non-irrigated agricultural lands.

McDonnell and Pickett (1990) suggest that gradient analysis can be a very useful tool to study the influence of urbanization on ecosystems. An urban gradient is a way to organize and view urbanization in space (Zeng, Sui, & Li, 2005). It is generally measured by the distance of land to an urban core; the closer it is to the urban core, the more urbanized it is (McDonnell et al., 1997; McDonnell & Pickett, 1990). In environmental studies, urban gradient analysis has proven successful to quantify landscape changes in elements such as resources, community compositions, and ecological functions by the degree of urbanization (McDonnell et al., 1997; McDonnell & Pickett, 1990). Combined with landscape metric analysis, urban gradient analysis has demonstrated power to aid in characterizing changes of landscape patterns in relation to urbanization (Blair, 1996; Luck & Wu, 2002; Weng, 2007).

In this study we adopted landscape metrics and urban gradient analysis to examine the dynamics of agricultural landscapes in response to urbanization, and applied this approach to a regional case study in Northern Utah. The objectives of this project were to: (1) analyze and compare the changes of both irrigated and non-irrigated agricultural lands; (2) identify the spatial patterns and hotspots of these changes for both irrigated and non-irrigated agricultural lands; and, (3) examine the spatial relationships between changes in agricultural landscapes and urban development. This study contributes not only to the existing literature on dynamics of both irrigated and non-irrigated agricultural lands in relation to urban development, but also helps fill the gap of scant applications of landscape metrics and urban gradient analysis in agricultural areas. Most importantly, a comprehensive examination of Utah's agricultural landscapes will serve as part of the scientific foundation for informing land use policy in the region, as well as provide lessons for other places that are facing similar agricultural land conversion challenges.

2. Materials and methods

2.1. Study area

Our study area is situated in the northern part of Utah (Fig. 1), covers about 25000-km^2 and has more than 2 million inhabitants. It is made up of four river basins: Bear River Basin, Weber River Basin, Jordan River Basin, and Utah Lake Basin. It also encompasses Utah's most urbanized region, the Wasatch Range Metropolitan Area (WRMA). WRMA is where 80% of Utah's population resides and where future growth is most likely to occur (Utah Foundation, 2014a). Between 1982 and 2012, over 160-km^2 of Utah's agricultural lands were converted to urban development (Farmland Information Center, 2016). Most of these conversions took place in the four river basins of our study area due to fast urban growth in the WRMA (Farmland Information Center, 2016). Rising concerns about securing food supply, maintaining open space, and sustaining rural lifestyles have evoked agricultural lands protection sentiments and efforts in Utah (Utah Department of Agriculture and Food, 2012; Envision Utah, 2014; Utah Governor's Water Strategy Advisory Team, 2017). Additionally, due to a growing population and changing climate, agriculture, which is the biggest water use sector in the region, is facing increasing competition from the rapidly growing WRMA municipalities and industries seeking to acquire water (Utah Foundation, 2014b).

2.2. Land use data

We used Water-Related Land Use Datasets of Years 1986 and 2015 for our analysis (Fig. 1). These datasets were obtained from the Utah Division of Water Resources. The Water-Related Land Use Datasets are digitized spatial vector data. These datasets document the land use types in the region, which include: irrigated agricultural lands, non-irrigated agricultural lands, wet/open water areas, and urban areas. Land use classification and irrigation use classification were done by the staff of the Utah Division of Water Resources through remote sensing, land survey, and ground truth verification. These datasets were originally created to provide Utah decision makers and water managers with land-related water use information for determining regional water budgets. Agricultural land use, and particularly if the land was irrigated or not, has been an important component of the database. Those digitized datasets date back to Year 1986, and the most recent ones are in 2015. Consequently, it is ideal for application in this research study, which examines changes in agricultural landscapes over the nearly three decades between 1986 and 2015.

2.3. Landscape metric analyses

Although a variety of landscape metrics have been devised to measure the spatial patterns of landscapes, researchers have revealed that many of these metrics are correlated and redundant, as well as hard to interpret (Cushman, McGarigal, & Neel, 2008; Riitters et al., 1995; Torrens, 2008). But there are several metrics proven to be independently effective and easy to interpret (see Riitters et al., 1995; Torrens, 2008; Cushman et al., 2008 for further details). Based on these prior findings, for this study we selected four class-level metrics (i.e., metrics that apply to land use classes): Aggregation Index (AI), Total Area (CA), Number of Patches (NP), and Perimeter-Area Ratio (PARA). Definitions and their associated landscape interpretations and calculations are listed in Table 1.

To quantify the spatial variability of landscape patterns across the whole study area, a moving-window sampling strategy was used. Briefly, a moving window analysis places a window with specified size and shape over each focal cell, computes the selected landscape metric, and returns the metric value back to the focal cell. Therefore, each window around a focal cell is treated like a sub-landscape, and the metric value returned to the focal cell represents the patterns within this sub-landscape (McGarigal et al., 2002).

Kupfer (2012) commented that moving window combined with landscape metrics is effective at capturing the landscape neighborhood effects. However, window size is highly influential to the final results of metric analysis (McGarigal et al., 2002; McGarigal & Marks, 1995). Therefore, we conducted a preliminary test to investigate the effects of window size on metric analysis in our study. Four different window sizes were employed and tested: 0.5-km × 0.5-km, 1-km × 1-km, 5-

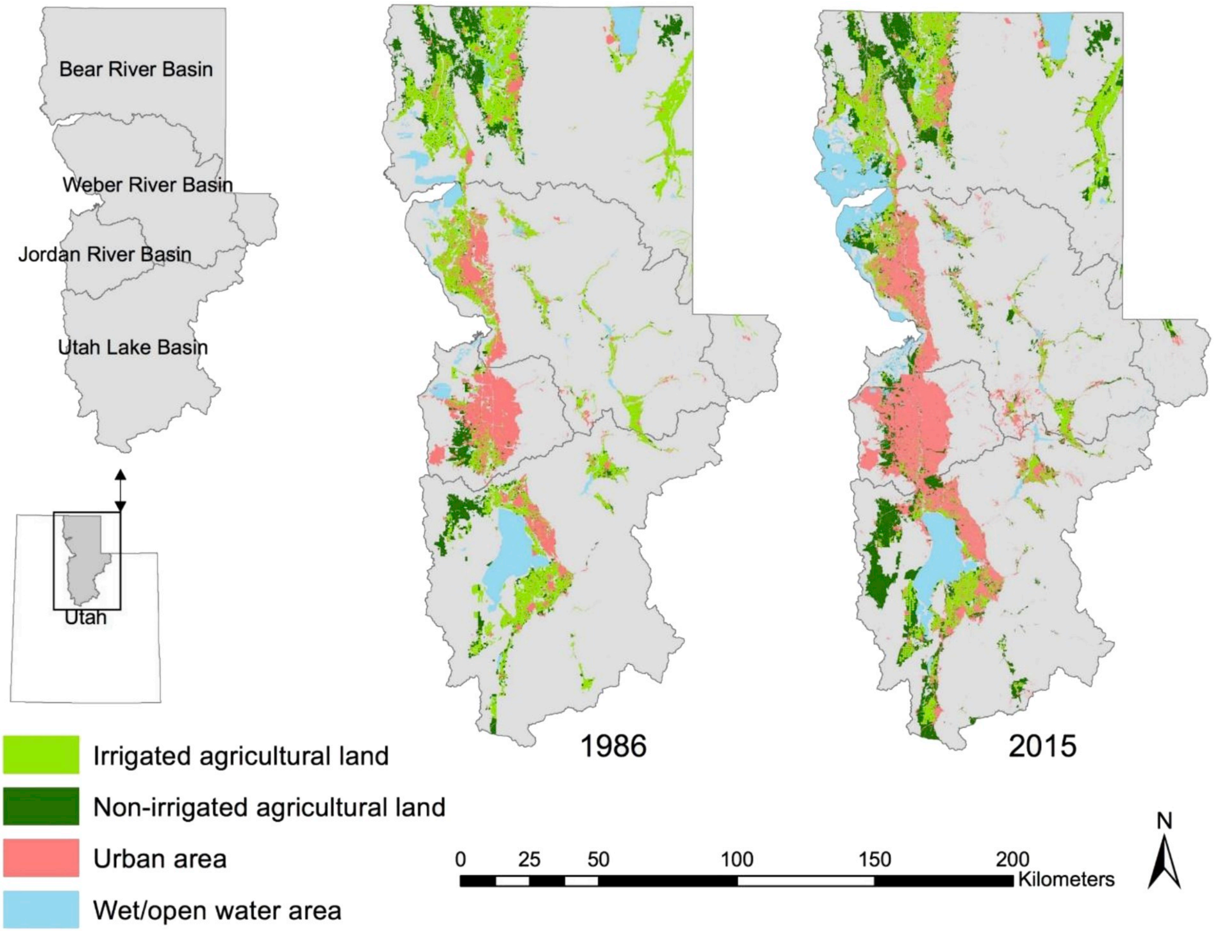

Fig. 1. Wasatch Range Metropolitan Area (WRMA) and its land uses in 1986 and 2015.

km × 5-km, and 10-km × 10-km. We found that window sizes of 1-km × 1-km performed the best in aggregating and retaining neighborhood characteristics (related research with similar findings have been discussed by Luck & Wu, 2002; Wagner & Fortin, 2005; Yeh & Huang, 2009; Su et al., 2011).

We used FRAGSTATS (version 4.2) (McGarigal, Cushman, & Ene, 2012) to measure landscape patterns. Data of irrigated and non-irrigated agricultural lands from 1986 to 2015 for the entire WRMA region were extracted from the Water-Related Land Use Dataset, then converted into raster format with 30-m resolution to fit FRAGSTATS's requirements. Each of the selected four landscape metrics (i.e., AI, CA, NP, PARA) were analyzed independently and applied to both irrigated and non-irrigated agricultural lands separately. Outputs of moving window analysis through FRAGSTATS are raster maps. A total of four raster maps were generated to represent the spatial patterns for one land use type (either irrigated or non-irrigated agricultural lands) at one point in time (either year 1986 or year 2015). For a set of these four raster maps, each of them represents the values of one of the four landscape metrics (i.e., AI, CA, NP, PARA), respectively, on a per grid cell basis across the study area at a given year.

2.4. Analysis of changes in agricultural landscapes over time

The resulting raster maps from landscape metric analysis allowed us to calculate the changes of landscape patterns between 1986 and 2015 for both irrigated and non-irrigated agricultural lands. Because landscape patterns are measured by four landscape metrics independently, to calculate the change under each landscape metric, we simply subtract the raster map of year 1986 from the 2015 raster map (see Fig. 2). Therefore, for each type of land use (i.e., irrigated and non-irrigated agricultural land), four new raster maps were produced to indicate the change of the values of each of the four landscape metrics from 1986 to 2015. These changes can be represented as positive values, meaning the value of a given landscape metric has increased at a given location over time, or as negative values, meaning the value of a given landscape metric has decreased at a given location over time.

For each land type (i.e., irrigated and non-irrigated agricultural land), Local Indicators of Spatial Association (LISA) analysis was used to analyze the spatial association of these changes under each of these four landscape metrics (i.e., AI, CA, NP, PARA) (see Fig. 2). As a result, four types of significant spatial changes at a 95% confidence interval were determined by LISA: High-High Cluster, Low-Low Cluster, High-Low Outlier, and Low-High Outlier (see Fig. 2). A High-High Cluster is an area that is surrounded by areas with high positive values, but its own values are significantly ($P < 0.05$) higher than its surrounding areas in general. High-High Cluster indicates a concentration of significant positive high values. In our study, this result reflects an area that underwent a significant increase of values under one particular landscape metric (change of the value of a given landscape metric > 0, $P < 0.05$), thus we call it "hotspots of increase." The reverse is true for Low-Low Cluster. A Low-Low Cluster is a concentration of significantly lower negative values in relation to surrounding low values, hence, we correspondingly called these clusters "hotspots of decrease." In this study we defined both High-High Clusters and Low-Low Clusters as "hotspots of changes." High-Low Outlier and Low-High Outlier suggests that the cluster has a significant High-Low or Low-High relationship with neighboring land (see Anselin (1995) for further detail). Both High-Low and Low-High Outliers are insightful to detect where land use

Table 1
Landscape metrics, their definitions, and calculation equations.

Metric	Description/calculation scheme/utilities	Equation	Range	Unit:
Aggregation Index (AI)	Measures the degree of aggregation of patches. Compact clusters of patches are considered to be more aggregated.	$\text{AI} = \frac{g_{ij}}{max \rightarrow g_{ij}}(100)$ g_{ii} = number of like adjacencies (joins) between pixels of patch type (class) i based on the single-count method. $max \rightarrow g_{ij}$ = maximum number of like adjacencies (joins) between pixels of patch type (class) i based on the single-count method.	$0 \leq \text{AI} \leq 100$	None
Total Area (CA)	Measures landscape composition; specifically, how much of the landscape is comprised of a particular patch type.	$CA = \sum_{j=1}^{n} a_{ij}\left(\frac{1}{10,000}\right)$ a_{ij} = area (m^2) of patch ij.	$\text{CA} \geq 0$	Hectare
Number of Patches (NP)	Measures the extent of subdivision or fragmentation of the patch type.	$NP = n_i$ n_i = number of patches in the landscape of patch type (class) i.	$\text{NP} \geq 1$	None
Perimeter-Area Ratio (PARA)	Measures the variability in patch shape complexity, where shape is defined by perimeter-area relationships.	$PARA = \frac{p_{ij}}{a_{ij}}$ P_{ij} = perimeter (m) of patch ij. a_{ij} = area (m^2) of patch ij.	$\text{PARA} \geq 0$	None

Note: All equations are adopted from McGarigal et al. (2002).

changes are significantly dissimilar to neighboring land, exhibiting unusual spatial patterns. LISA analysis was performed using GeoDa 1.8 software (Center for Spatial Data Science, The University of Chicago, 2016).

2.5. *Analysis of changes in agricultural landscapes over time in relation to urbanization*

A revised urban gradient was developed to detect the changes of agricultural landscapes in relation to urbanization in this study. Differing from a traditional urban gradient which is depicted from the urban center, this study explores the gradient of urban impacts from new development. Specifically, we created 1-km, 3-km, 5-km, and 10-km buffer distances from new urban development between 1986 and 2015. The reason to use new development between 1986 and 2015 for building the gradient is to highlight and emphasize the influence of new urban development on agricultural land conversion. We first plotted the distribution of land use along the gradient for both year 1986 and year 2015. This enabled us to compare the changes of land use composition in each buffer zone. We also plotted the distribution of the total area of the two types of hotspots (hotspots of increase, and hotspots of decrease) identified by LISA analysis within each distance buffer zone. The analytic objective here is to examine the spatial relationships between these hotspots and new urban development. Put differently, the analysis specifically examines how far or close these hotspots are to new urban development. Such analysis was designed to test the hypothesis that agricultural areas that are close to new urban development are more subject to the effects of urbanization by seeing if most of the hotspots of changes were located close to new urban development.

3. Results

3.1. *General description of agricultural landscapes and urban development*

From 1986 to 2015, the total amount of agricultural lands increased from 3054-km^2 to 3323-km^2. However, the total amount of irrigated agricultural lands in the WRMA decreased approximately 22% from 2154-km^2 to 1685-km^2, while non-irrigated agricultural lands increased approximately 82% from 900-km^2 to 1638-km^2 (Table 2). It is noticeable that over this time, WRMA urban areas grew expansively by 90% or 1080-km^2 from 1196-km^2 to 2276-km^2 (Table 2 and Fig. 1). Among the 1189-km^2 of newly urbanized areas during this period, about 38% (447-km^2) was formerly irrigated agricultural lands, 12% (142-km^2) was formerly non-irrigated agricultural lands, and about 50% (600-km^2) was "other," a category consisting of mostly rangelands. There were also many observed land conversions of irrigated agricultural lands to non-irrigated land (238-km^2) and of non-irrigated land to irrigated land (103-km^2) (Table 2). It is important to recognize that agricultural landscape changes cannot be simplistically taken as a process of losing lands to urban development. Rather, there are active transitions between irrigated agricultural lands and non-irrigated agricultural lands, as well as agricultural land conversions to other uses and vice versa.

The WRMA study area as a whole has shifted from an agricultural-dominated landscape to a highly-urbanized landscape as reflected in changes of total areas (CA) in various land use categories (Fig. 3). Additionally, at this regional scale, patches within each of the three land use types (urban, irrigated agricultural lands, and non-irrigated agricultural lands) have all become less aggregated (AI) and more irregular and complex in shape (PARA). It is interesting to note that, while the total area (CA) of irrigated agricultural lands has decreased, its total patch number (NP) has increased. This indicates that average patch size of irrigated agricultural lands could potentially be smaller. Combined with signs of less aggregation among patches (decreasing AI) and increasing shape complexity (increasing PARA values), it is evident that irrigated agricultural landscapes have become more fragmented.

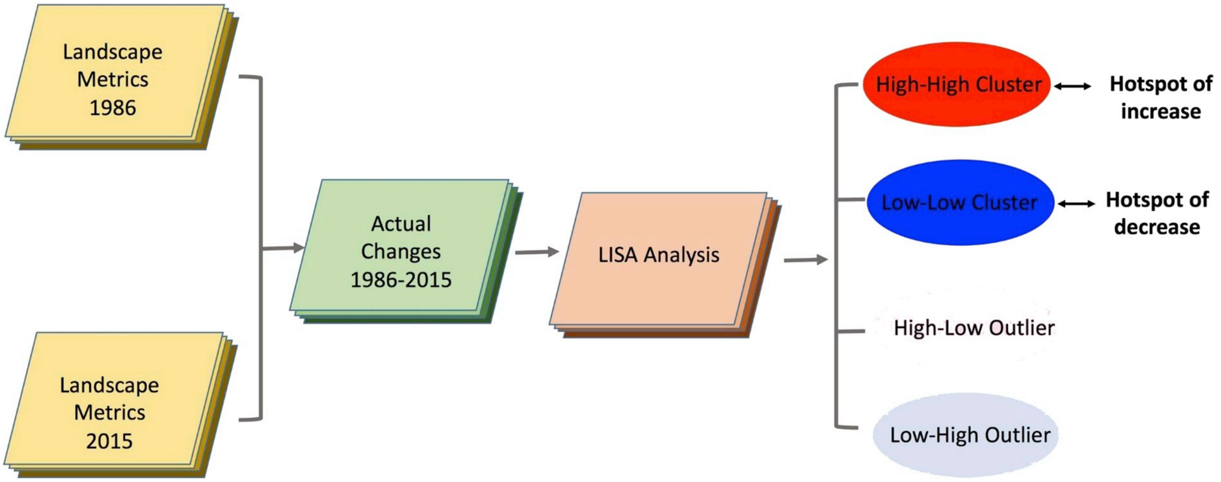

Fig. 2. Methodological diagram of analyzing the changes of spatial patterns of agricultural landscapes.

3.2. Changes of agricultural landscape patterns between 1986 and 2015

Results of landscape metric analysis using a 1-km × 1-km moving window sampling strategy are presented in Appendix A for irrigated agricultural lands and Appendix B for non-irrigated agricultural lands. These figures are effective visuals to understand the landscape patterns at each specific location across the whole study area at the beginning and end of the nearly three-decade period. For example, one can see that the northwestern and southwestern parts of the study area were dominated by irrigated agricultural lands and aggregated areas in both years 1986 and 2015 (Appendix A, second CA panels). The majority of non-irrigated agricultural lands also were located in the southwestern side and in a small part of the northwestern side of the study area (Appendix B, second CA panels).

The values of actual change between 1986 and 2015 for each landscape metric are shown in Fig. 4 (irrigated agricultural landscapes) and Fig. 5 (non-irrigated agricultural landscapes). For irrigated agricultural lands (Fig. 4), CA values have widely declined across the Weber River Basin and Jordan River Basin, indicating a general loss of irrigated agricultural lands in these two river basins. However, in the Bear River Basin and Utah Lake Basin, the changes of irrigated agricultural lands were more complex. Our results show that while the central part of the Utah Lake Basin experienced a decrease of irrigated agricultural lands, the western side and southern tip of Utah Lake have seen an increase in irrigated agricultural lands. CA results in the Bear River Basin are even more intricate as decreases and increases of irrigated agricultural lands are mixed together in the region. Overall, irrigated agricultural lands have become more dispersed (decreases of AI) across the whole study area. In the west areas of Bear River Basin, Weber River Basin, and Utah Lake Basin, irrigated agricultural lands have become patchier (increases in NP). Additionally, patch shapes (PARA) of irrigated agricultural lands have become more irregular and complicated across the entire WRMA region.

For non-irrigated agricultural lands (Fig. 5), we observed an overall increase of CA and NP across the four river basins, although certain places in the northwestern part of Bear River Basin, south part of Jordan River Basin, and northern part of Utah Lake Basin did experience loss of non-irrigated agricultural lands. This is consistent with the data presented in Table 2, which show that non-irrigated agricultural lands went up from 900-km^2 to 1638-km^2 from 1986 to 2015. In contrast with irrigated agricultural lands, non-irrigated agricultural lands have become more aggregated (increase of AI). As with irrigated agricultural lands, the shapes of patches of non-irrigated agricultural lands became more irregular and complex across the region.

3.3. Spatial patterns and hotspots of agricultural landscape changes

Results of LISA analysis further illustrate the spatial association of these changes for each landscape metric (see Fig. 6 and Fig. 7). These results help to identify where changes are significantly similar to or different from neighboring areas. For irrigated agricultural lands, most of the clusters and outliers are distributed in the Bear River Basin (Fig. 6). Table 3 summarizes the total areas of High-High Clusters and Low-Low Clusters in each river basin. It is clear that the Bear River Basin has the most hotpots (High-High Clusters and Low-Low Clusters) of agricultural landscape changes. Fig. 6 shows that in the northwestern part of the Bear River Basin, hotspots of irrigated agricultural lands loss (CA clusters in blue representing Low-Low Clusters) is accompanied by increase of patch numbers (NP clusters in red representing High-High Clusters) and more complicated patch shapes (PARA clusters in red representing High-High Clusters). This result suggests the irrigated agricultural lands located within these Bear River Basin hotspots have become more fragmented. Meanwhile, several CA outliers were found sporadically in the same northwestern part of the Bear River Basin. These outliers had a high value of landscape metrics while surrounded by low value neighbors. It is hard to explain the stories behind what might have caused these outliers solely relying on landscape metrics. But as one can see, the irrigated landscape in the Bear River Basin is very complex and diversified.

For non-irrigated agricultural lands, hotspots of landscape changes were generally located in the Bear River Basin and Utah Lake Basin areas (Fig. 7 and Table 3). In the northeast part of the Bear River Basin,

Table 2
Land use transition matrix for the WRMA region (unit: km^2).

Year 1986	Year 2015	Irrigated agricultural lands	Non-irrigated agricultural lands	Urban	Other	Total
	Irrigated agricultural lands	1,335	238	447	134	2,154
	Non-irrigated agricultural lands	103	575	142	80	900
	Urban	41	32	1,087	36	1,196
	Other	206	793	600	18,958	20,557
	Total	1,685	1,638	2,276	19,208	24,807

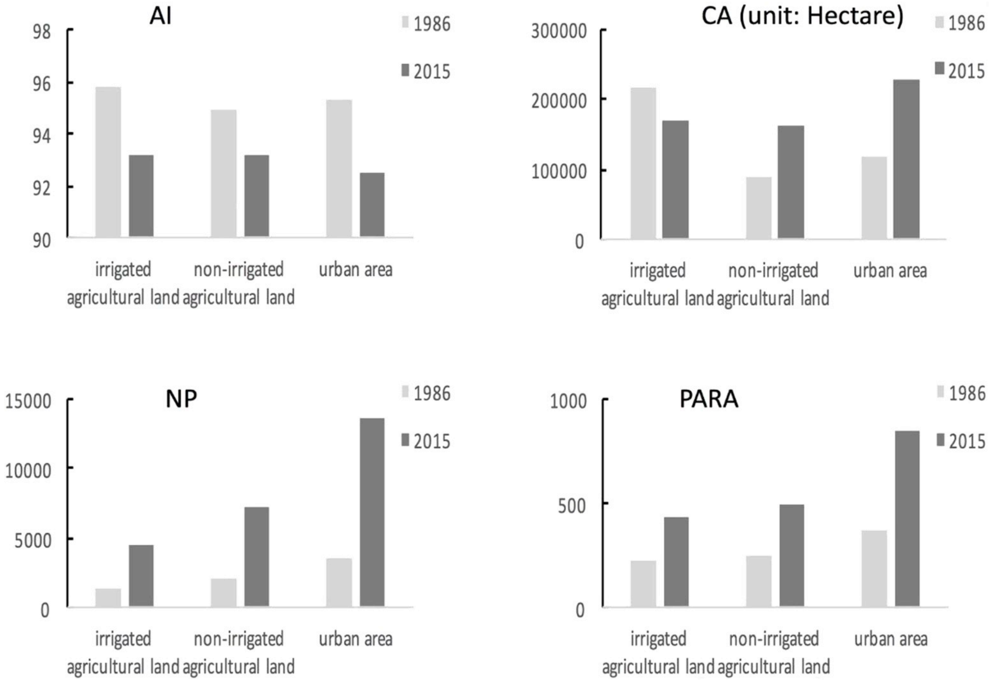

Fig. 3. Synoptic changes of landscape metrics in the WRMA study area.

hotspots of increase of non-irrigated agricultural lands (CA clusters in red) are roughly in the same locations as hotspots of AI. This means that the area of non-irrigated agricultural lands has grown bigger and more aggregated. Combined with a decrease of NP, non-irrigated agricultural landscapes in the northeast part of the Bear River Basin displayed a consolidation pattern. On the contrary, in the northwest part of the Bear River Basin, hotspots of increase in non-irrigated agricultural lands (CA clusters in red) were generally overlaid with hotspots of increase in NP. However, patches have grown more compact and patchier based on hotpots of AI and NP. Although both the northeast and northwest parts of the Bear River Basin have undergone an increase of total areas of non-irrigated agricultural lands, the two regions displayed very different landscape change patterns. In the southern tip of the Utah Lake Basin, a decrease in patch numbers and shape complexity on non-irrigated agricultural lands is a significant observation.

3.4. Changes of agricultural landscape in response to urbanization

Gradients of new development between 1986 and 2015 are shown in Appendix C. It is visually compelling to recognize that most of the new urban development in the study area is concentrated on the west side of the Jordan River Basin and Weber River Basin and on the north side of the Utah Lake Basin. Appendix D shows the amount of irrigated and non-irrigated agricultural lands in each gradient distance at years 1986 and 2015. We see that within the areas where new development took place between 1986 and 2015, about 400-km^2 of irrigated agricultural lands and more than 100-km^2 of non-irrigated agricultural lands have vanished. This result is consistent with our findings in Table 2. The majority of the irrigated and non-irrigated agricultural lands are located within 1 km distance of these new development areas. We found that while cities in our study areas are experiencing conversion of irrigated agricultural lands to new development, the total amount of irrigated agricultural lands that is within 1-km distance to new development basically remained the same. Our results also indicate that the gain of non-irrigated agricultural lands between 1986 and 2015 was mostly located within 1-km distance to new development. These results suggest that cities also see conversion of other nearby land uses to non-irrigated agricultural lands.

Hotspots of irrigated agricultural landscape changes between 1986 and 2015 were all located within 5-km distance to newly urbanized areas, while hotspots of non-irrigated agricultural landscape changes were all located within a 10-km radius of the newly urbanized areas (Fig. 8). However, for both irrigated and non-irrigated agricultural lands, most of the hotspots of landscape changes between 1986 and 2015 were located within 1-km distance of the newly urbanized areas. This finding indicates that the 1-km distance to new development is the threshold where agricultural landscapes have changed significantly (Fig. 8). Outside the 1-km distance threshold, the total areas of hotspots in each zone decreased dramatically.

4. Discussion

4.1. Changes of agricultural landscapes in the study area

Although the total amount of agricultural lands increased from 1986 to 2015, the amount of irrigated agricultural lands has decreased more than 20%. Simply aggregating irrigated and non-irrigated agricultural lands together could potentially be misleading and mask the land use transitions within agricultural lands. We found that irrigated agricultural lands and non-irrigated agricultural lands present very different patterns and trends in terms of landscape changes in our study area. Irrigated agricultural land changes show clear signs of fragmentation, signified by increasing amounts of smaller patches, greater patch isolations, and more irregular patch shapes. In contrast, the total amount of non-irrigated agricultural lands increased and patches of non-irrigated agricultural lands became more aggregated. Those major findings demonstrate the need to distinguish irrigated and non-irrigated agricultural lands when analyzing changes in agricultural landscapes, or when conducting land and water use planning involving agricultural conversion and conservation.

Factors driving such change processes can vary. First, the distribution pattern of agricultural land and urban areas influences the conversion of agricultural land. Generally, irrigated agricultural lands are close to existing development and more suitable for development, whereas, non-irrigated lands are usually located more remote from urban areas or on harder-to-develop hillsides. This kind of spatial

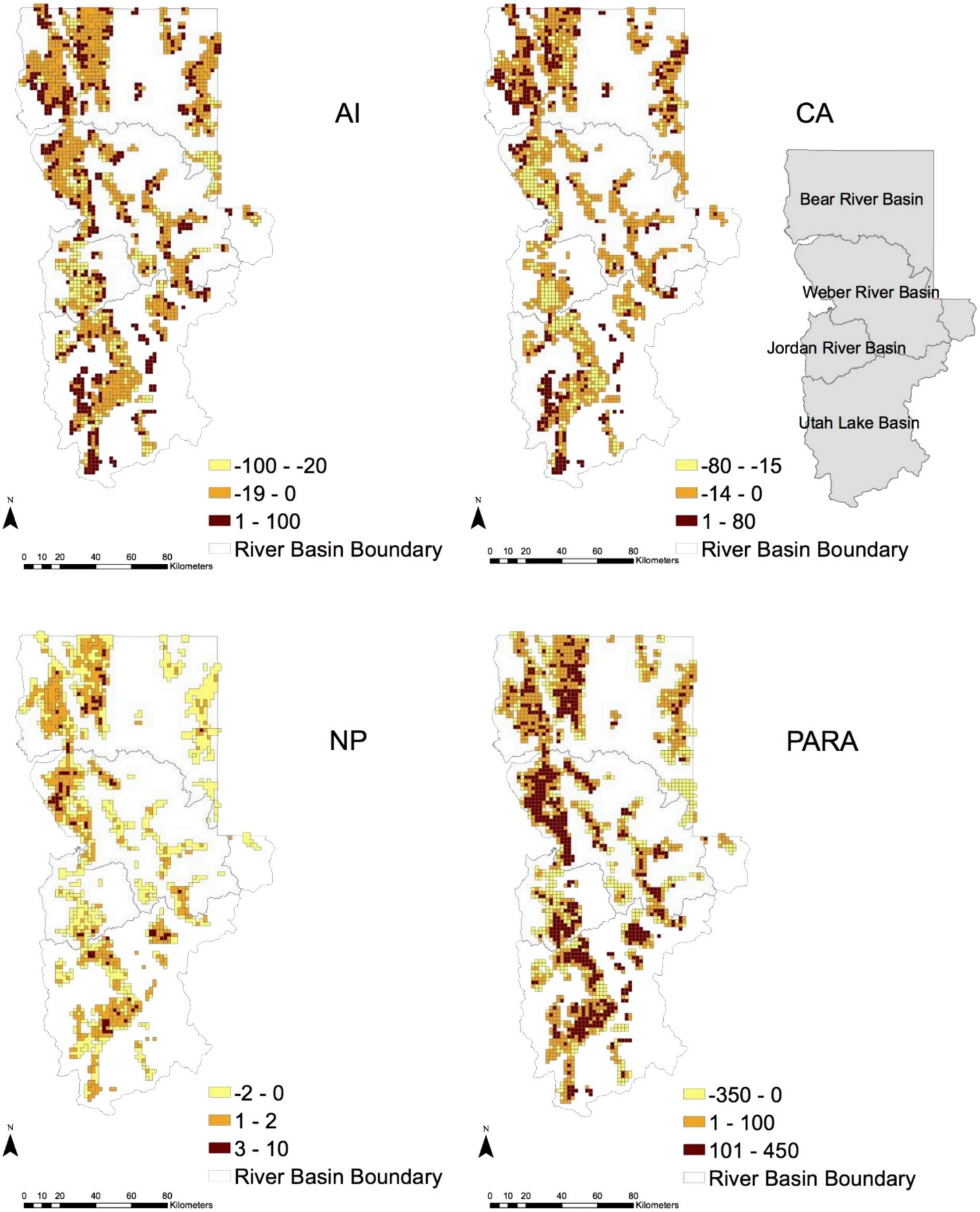

Fig. 4. Actual change of values for each landscape metric of irrigated agricultural lands between 1986 and 2015.

correlation between intensive agricultural land (e.g. irrigated land) and urban areas has been observed since the early development of urban areas. Second, social economic factors also direct new development to the surrounding lands of the existing urban areas. As influenced by local land markets and dictated by city and county government growth policies across the United States, new development is generally confined to the fringes of expanding cities and other urban areas (Brueckner, 2000). This makes irrigated agricultural lands, which are largely located within proximity to existing urban areas, very susceptible to be developed. Third, the price gap of agricultural lands for agricultural production and for development is generally large, consequently, economic incentive is another driver for landowners to sell those lands (Brown et al., 2005). Last, recent research has identified that urban encroachment disrupts canal-based irrigation and makes it difficult for agricultural landowners to manage irrigation (Baker et al., 2014; Cox & Ross, 2011; Hicks & Peña, 2003), which could potentially discourage agricultural landowners to continue to farm near urban development. These and many other factors combine to make irrigated agricultural

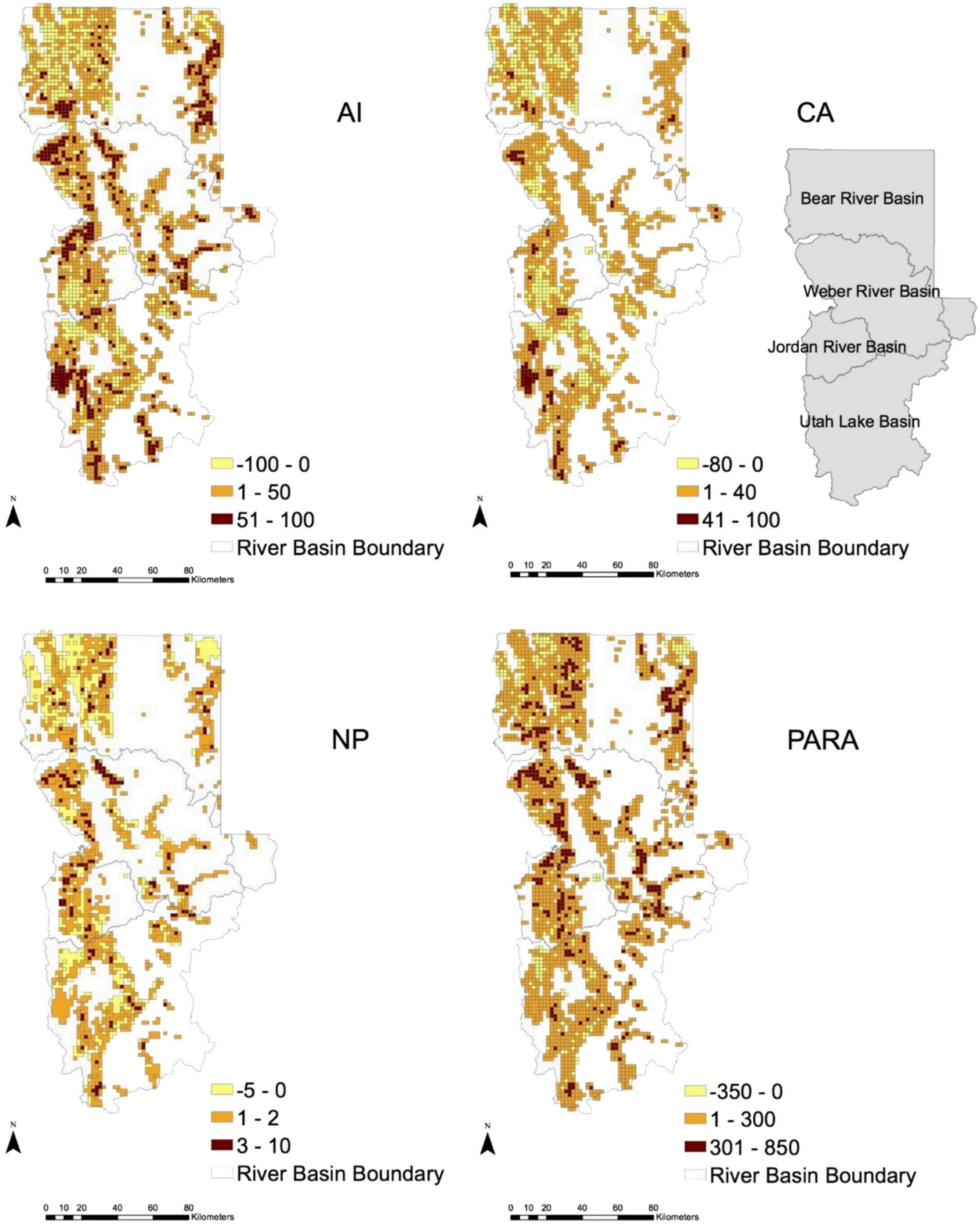

Fig. 5. Actual change of values for each landscape metric of non-irrigated agricultural lands between 1986 and 2015.

lands more vulnerable to urban development and resulted, in this case study, in those lands becoming more fragmented under the pressure of urban encroachment. On the other hand, the increase and aggregation of non-irrigated agricultural lands might be attributed to landowners who change irrigation practices on the land or shift their farming operations to a more remote area to expand their operation and solidify their lands (Kuminoff et al., 2001). This is not just happening in the United States. Other studies also have shown that prime agricultural lands which are usually irrigated agricultural lands, are more likely to be converted to urban uses in other countries (Deng, Huang, Rozelle, & Uchida, 2008; Yeh & Li, 1999).

We also found variations in terms of changes in agricultural landscapes across the four river basins. Despite the fact that all four basins have experienced changes in both irrigated and non-irrigated agricultural lands (Figs. 4 and 5), the most significant changes (hotspots of changes) for both types of agricultural lands were in the Bear River

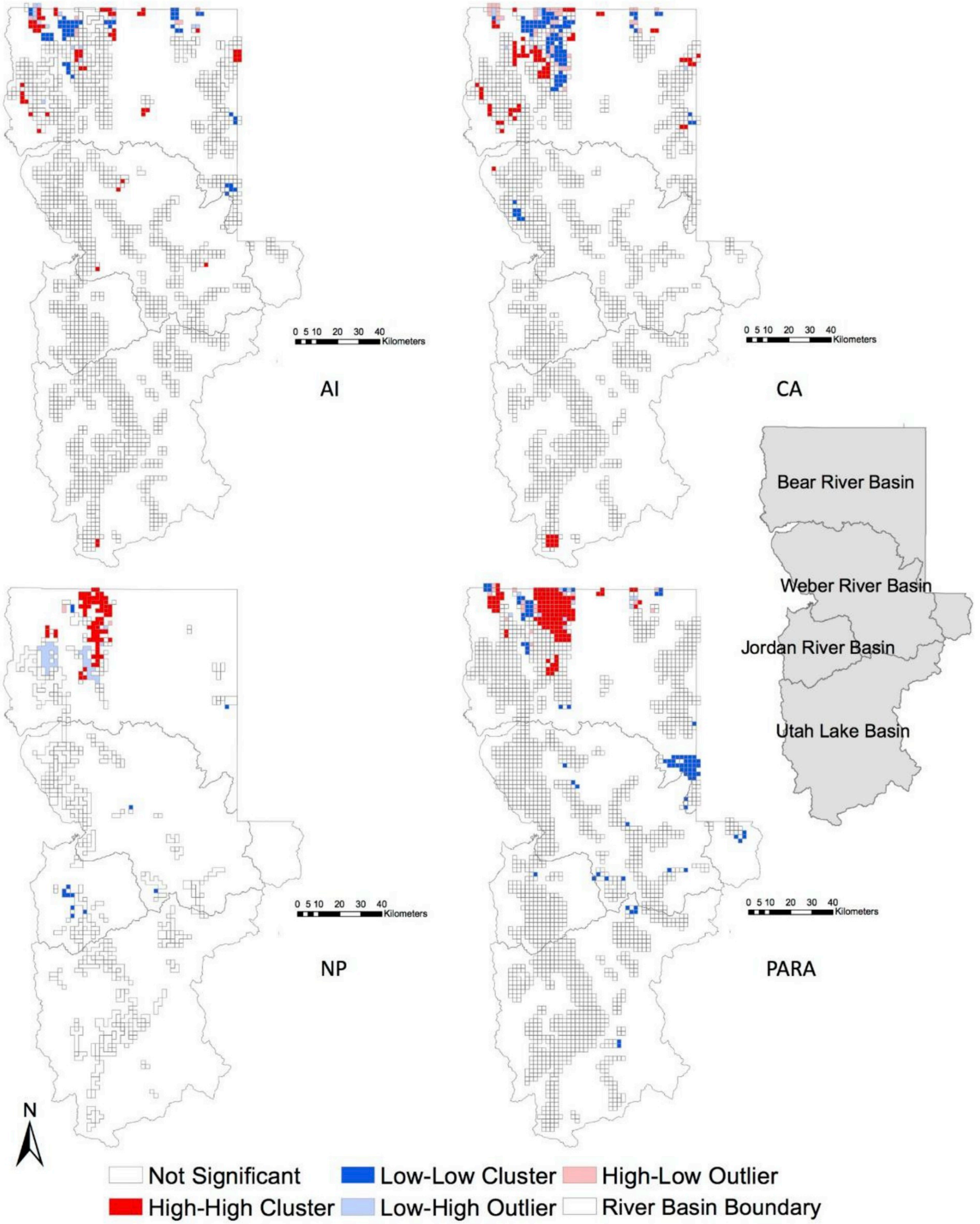

Fig. 6. Spatial patterns of changes in irrigated agricultural landscapes between 1986 and 2015.

Basin (Figs. 6 and 7). Additionally, changes within the Bear River Basin are diversified, with hotspots and outliers mixed across the northwestern side of the basin. This analysis is useful for better characterizing significant changes in the agricultural landscapes across the regional study area. Such information can be used by researchers as a way to focus more detailed analyses and by agricultural conservation practitioners to target and prioritize potential places for various types of agricultural actions and programs.

4.2. Changes of agricultural landscapes in relation to urbanization

Urbanization has affected Utah's agricultural lands use patterns over the last three decades. About half of the new urban development from 1986 to 2015 in the study area was from agricultural lands conversion (Table 2). Our results demonstrate most of the hotspots of changes in agricultural lands were located close to new development, which means that new development is at least spatially associated with agricultural

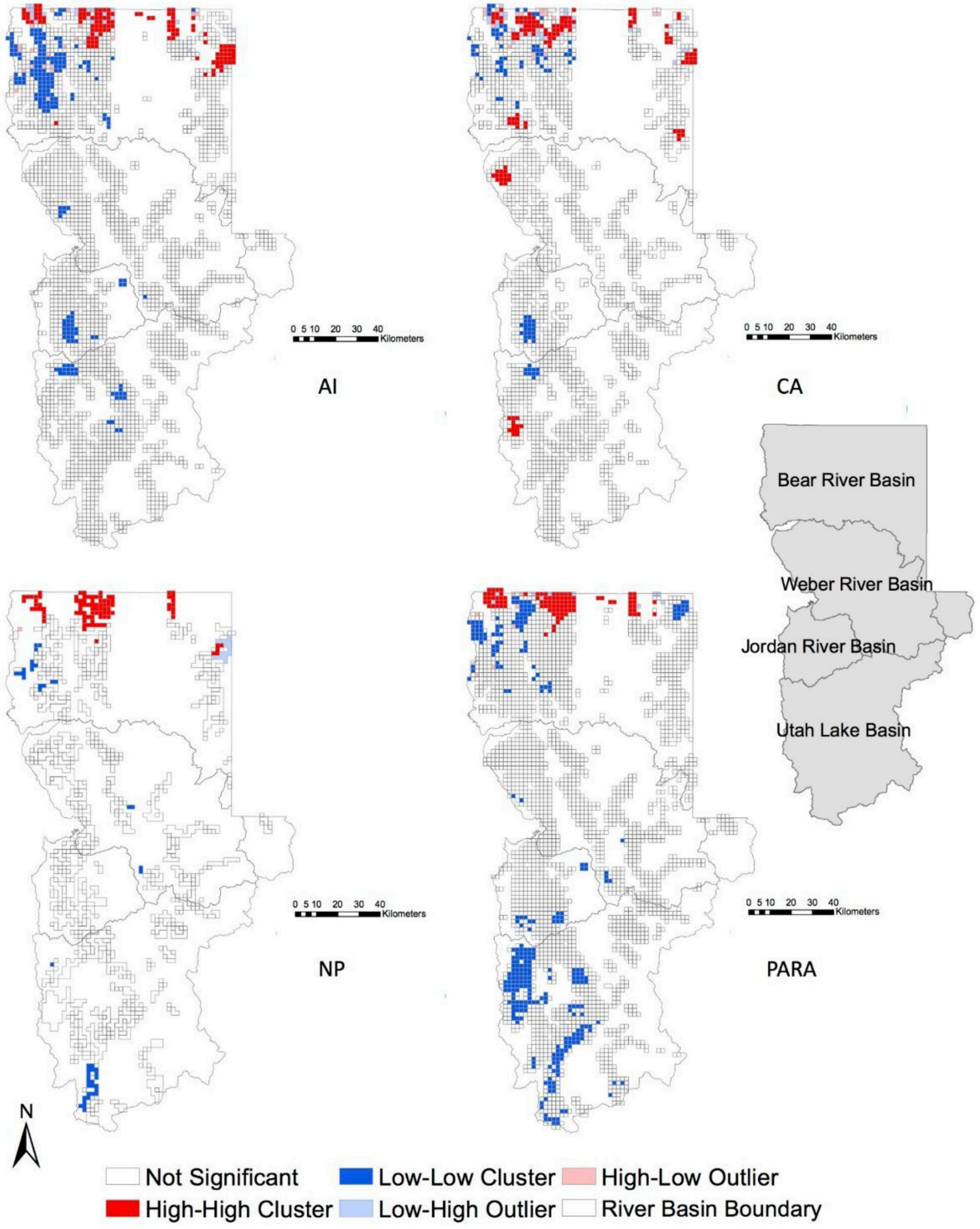

Fig. 7. Spatial patterns of changes in non-irrigated agricultural landscapes between 1986 and 2015.

landscape changes (Figs. 6 and 7). These results support the theory of Daniels (1999) that increasing urbanization decreases the stability of and affects the structure of agricultural landscapes. In addition, other studies have shown that the proximity to new urban development can be a powerful predictor of agricultural landscape changes. This finding is also supported by other researchers, such as Su et al. (2011) and Yeh and Huang (2009). Specifically, our results suggest that 1-km distance to new urban development is a threshold where agricultural landscapes would be significantly affected by new urban development (Fig. 8). This information can be useful for land use planners or agricultural conservationists to anticipate urbanization pressures and potential changes to agricultural lands (Dredge, 1995).

4.3. Implications of agricultural landscape changes

The potential implications of agricultural lands fragmentation have

Table 3
Summary of the total areas of hotspots in each river basin (unit: km^2).

Basin Name	Metric	Irrigated Agricultural Lands		Non-irrigated Agricultural Lands	
		High-High Cluster	Low-Low Cluster	High-High Cluster	Low-Low Cluster
Bear River Basin	AI	186	216	452	529
	CA	265	334	403	222
	NP	284	12	364	69
	PARA	483	233	355	381
Weber River Basin	AI	16	2		28
	CA	4		61	
	NP				16
	PARA		44		28
Jordan River Basin	AI				117
	CA			48	85
	NP				
	PARA		7		81
Utah Lake Basin	AI	8			109
	CA	36			40
	NP				101
	PARA		24		721

been studied by other researchers with respect to the increasing economic challenges of engaging in agricultural enterprises and the potential loss of the environmental benefits that agricultural lands can support (e.g., Baker et al., 2014; Manjunatha et al., 2013). Most pertinent to our study area and to Utah, conversion of irrigated agricultural lands to urban development poses severe challenges to Utah's regional water management (Utah Governor's State Water Strategy Advisory Team, 2017). It is widely accepted that conversion from agricultural lands to urban development significantly alters groundwater recharge (Barron, Barr, & Donn, 2013; Han, Currell, Cao, & Hall, 2017). It generally takes many years for aquifers to reach a new equilibrium with respect to the hydrological changes induced by the urbanization processes (Han et al., 2017; Zipper, Soylu, Kucharik, & Loheide, 2017), which in turn affect groundwater level, quality and flow regimes (Barrett et al., 1999; Foster, 2001).

Furthermore, as indicated by many other studies, once the percentage of impervious area in a watershed reaches 30%, stream health is degraded and stormwater management encounters greater difficulties (Arnold & Gibbons, 1996). For instance, based on the Water-Related Land Use Datasets used in this study, we found that in the Jordan River Basin (2038-km^2), impervious surface has increased from 507-km^2 (accounting for 25% of the total lands) in 1986 to 815-km^2 (40% of the total lands) in 2015. In addition, regional news coverage suggests WRMA urban communities are confronting greater challenges in terms of flooding, stormwater management, and water quality control.

New spatial configurations of irrigated agricultural landscapes, non-irrigated agricultural landscapes, and urban development generally entail changes in water uses that require different types of management approaches. With agricultural lands gradually diminishing, many areas in the Bear River Basin have experienced declining agricultural water use and increasing municipal and industrial water use (Utah Association of Conservation Districts & Utah Department of Agriculture and Food & Natural Resources Conservation Service, 2011). Although agriculture likely will continue to be the major water use sector, under anticipated conversions of additional agricultural lands and the associated transfer of agricultural water use to residential, commercial, or environmental water uses, the capacity and efficiency of water infrastructure in both urban and agricultural environments will be strained to meet changing water use patterns (Utah Association of Conservation Districts & Utah Department of Agriculture and Food & Natural Resources Conservation Service, 2011). Agricultural landscape changes pose challenges not only to the availability of land resources but also to the associated water management (Roos, 2016; Utah Governor's State Water Strategy Advisory Team, 2017).

4.4. *Using landscape metrics to assess agricultural landscape changes*

Landscape metrics have proven effective in aiding assessment of the patterns and changes occurring in agricultural landscapes in the WRMA study area. By understanding the changes of agricultural lands at a large regional landscape scale, landscape metrics are complementary to the more detailed census of agriculture farmland survey methods. Traditional farmland surveys track changes of agricultural lands at the individual farm level, and it is often challenging to comprehend how cumulative changes in individual farms affect and are being affected by the patterns and functions of their surrounding landscapes (Vaz, De Noronha, & Nijkamp, 2014). In this regard, landscape metrics can be a useful means to identify spatial changes in agricultural landscapes.

However, landscape metrics may not be efficient to understand and explain the drivers of these changes. These shortcomings are present in our study. For example, we identified hotspots and outliers of agricultural lands changes throughout the region and focused on changes in the Bear River Basin, but it is difficult to explain what caused these changes at these specific locations solely based on landscape metrics analyses. Neighborhood agricultural practices may influence the irrigation decisions on individual locations in the hotspot areas, and various reasons may account for decisions on irrigation practices in outlier areas.

In addition, we found that relying on land use data at two points in time may fail to capture certain finer-scale temporal changes in agricultural landscapes. In our study, we observed that there was a fair amount of land use transitions occurring between irrigated agricultural lands and non-irrigated agricultural lands between 1986 and 2015 (Table 2). Certainly the process of land conversion between irrigated and non-irrigated agricultural lands during the period of 1986–2015 is not fully captured, as we only used two temporal snapshots of agricultural landscapes to look at longer-term cumulative changes. Data availability limited our capability to utilize landscape metrics in revealing finer agricultural landscape change processes in this study.

Last, we think agricultural lands fragmentation should be understood and addressed from both the spatial and township/tenure standpoints. Sklenicka (2016) argued that agricultural land ownership has a significant influence over the patterns and functions of agricultural landscapes. High farmland ownership fragmentation may result in parcel sizes too small to maintain the economy-of-scale for traditional farming and often leads to greater land degradation (Sklenicka, 2016). Our analysis verified fragmentation of irrigated agricultural lands within the study area. We think that tracking the changes of ownership behind these land use changes will provide additional valuable insights to understand the drivers of these changes and is an area for future research. Also, echoing Sklenicka (2016), we think that efforts to defragment current irrigated agricultural landscapes needs to be addressed from the land ownership perspective as well.

5. Conclusion

This study adopted landscape metrics and a revised gradient analysis to analyze landscape changes in both irrigated agricultural lands and non-irrigated agricultural lands in relation to urban development for the Wasatch Range Metropolitan Area. It provides a detailed assessment of where and how agricultural landscape changes occurred in northern Utah over the past 30 years. We found that irrigated agricultural lands were more affected by urban development than non-irrigated agricultural lands, with evidence of more patches, more irregular patch shapes, and less connectivity among patches. Fragmentation of irrigated agricultural landscapes poses challenges to some of the region's land and lifestyle preservation goals and to water management. We conducted this work with the goal of providing useful information for predicting the likely influences of urban development

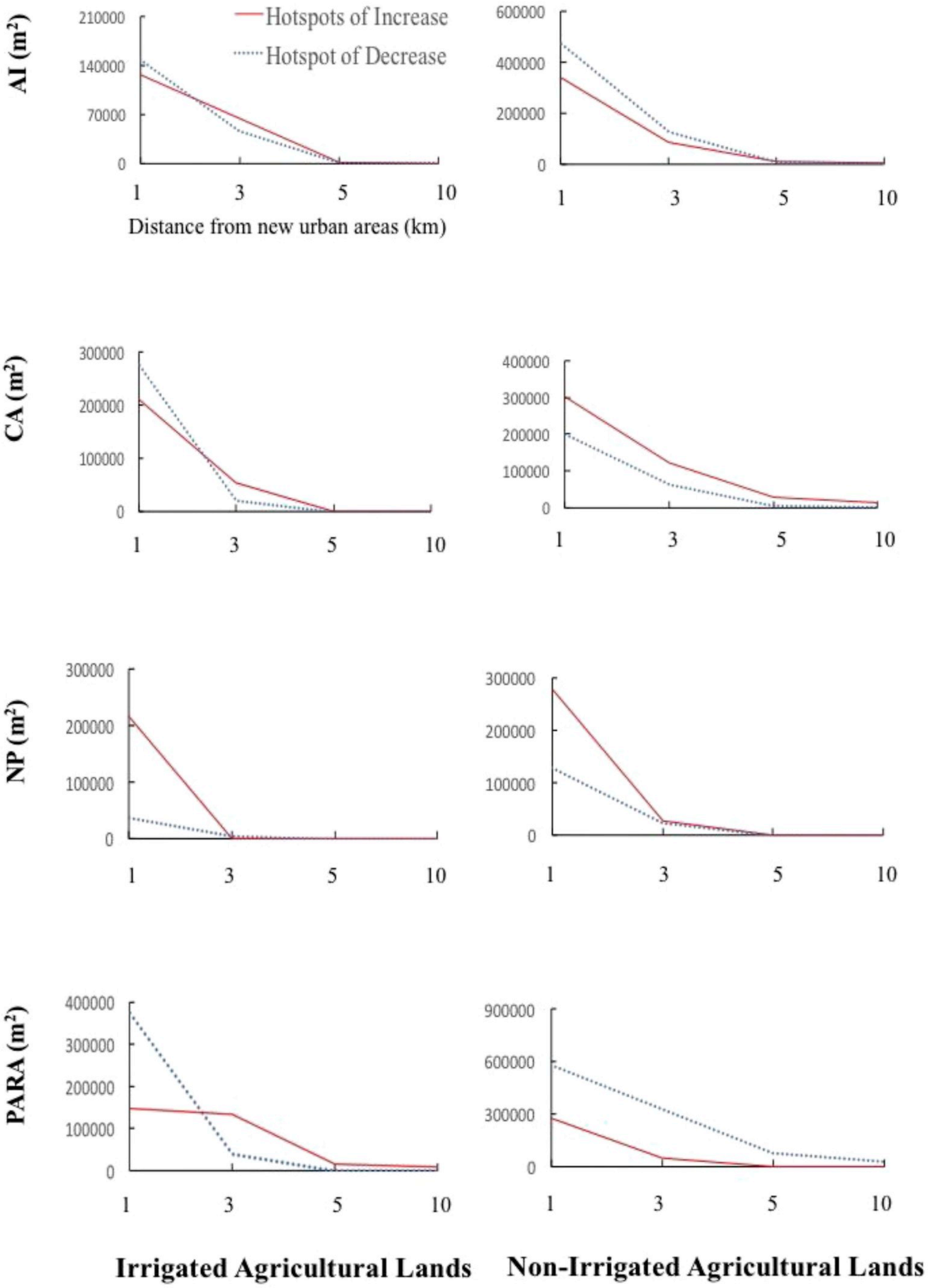

Fig. 8. Hotspots of WRMA agricultural landscape pattern changes between 1986 and 2015 in relation to new urban development (left column is irrigated agricultural lands while right column represents non-irrigated agricultural lands).

on agricultural landscapes, as well as for identifying hotspots for agricultural landscape changes that might be places for focused preservation or planning efforts to prevent further agricultural land fragmentation as part of the State of Utah's strategy to support sustaining the agricultural sector.

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Appendix A

Landscape patterns of irrigated agricultural lands at 1-km scale, with year 1986 in the upper row and 2015 in the lower row.

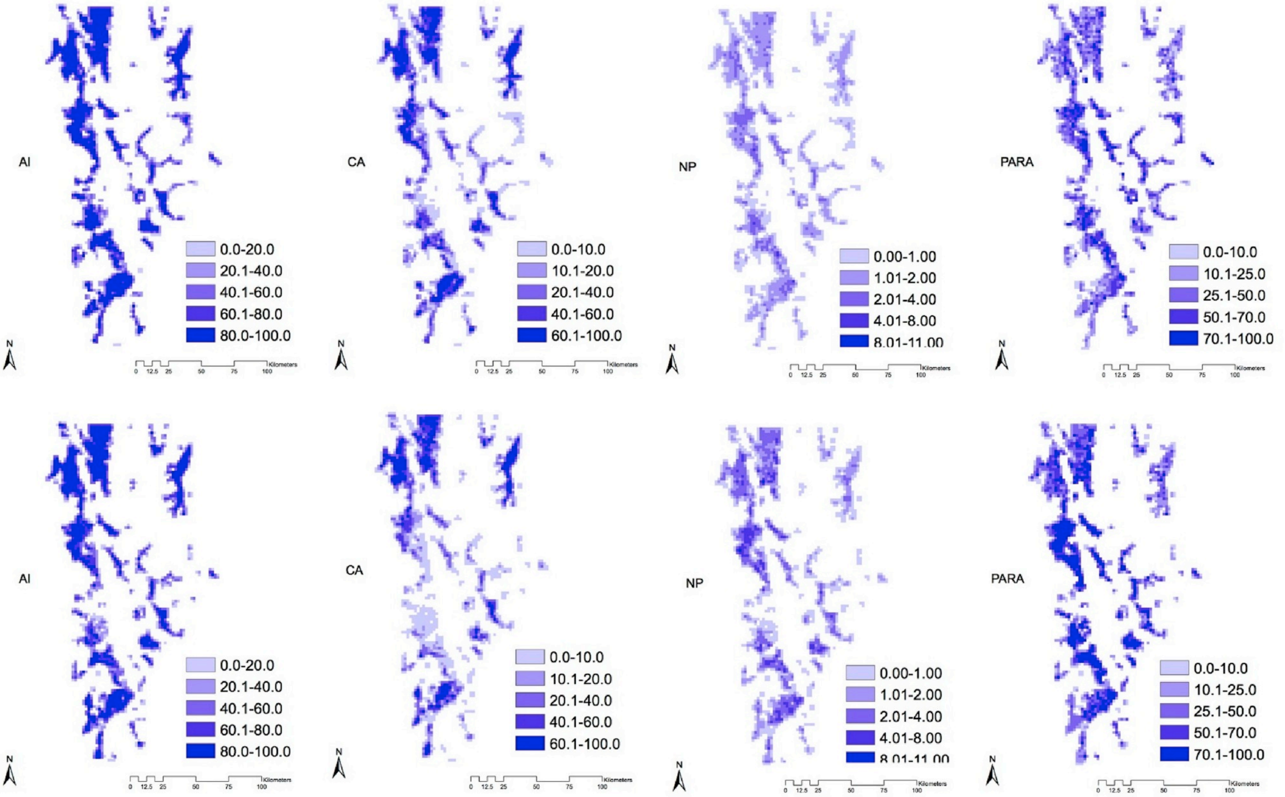

Fig. A1.

Appendix B

Landscape patterns of non-irrigated agricultural lands at 1-km scale, with year 1986 in the upper row and 2015 in the lower row.

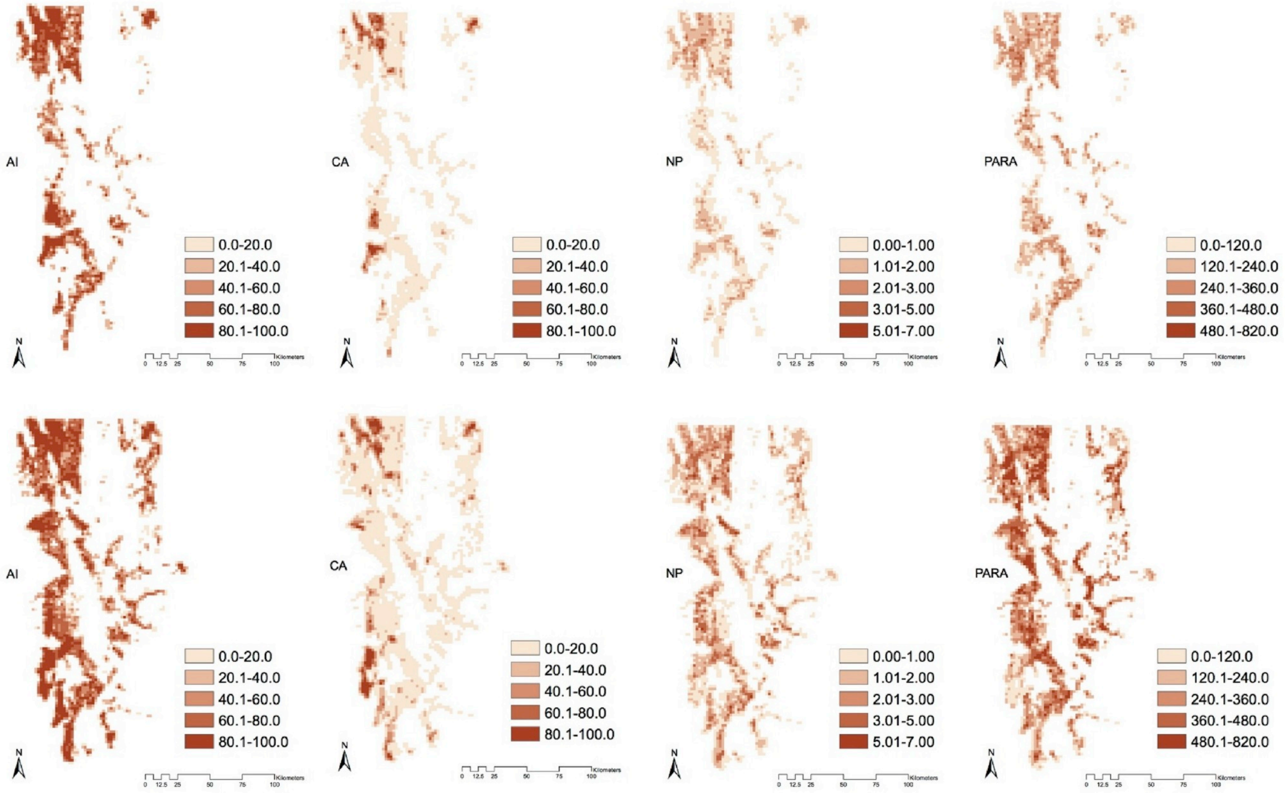

Fig. A2. 2

Appendix C

Gradients of new development between 1986 and 2015.

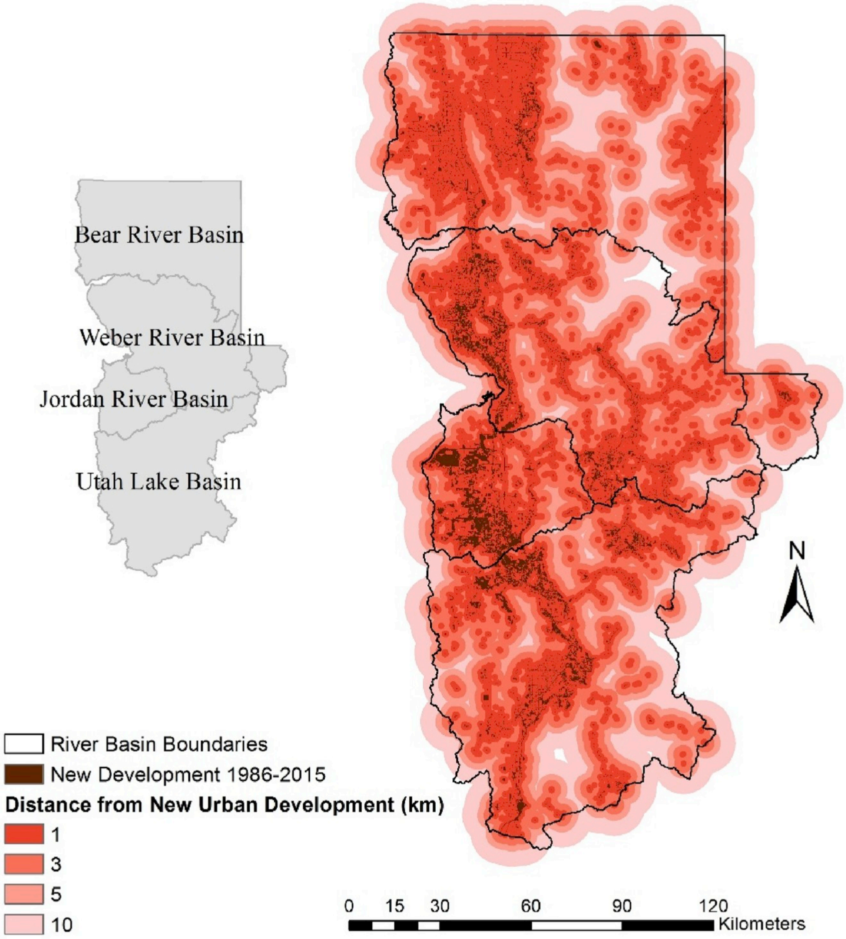

Fig. A3. 3

Appendix D

Distributions of irrigated (IR) and non-irrigated (NI) agricultural lands in relation to new development (1986–2015) in the WRMA.

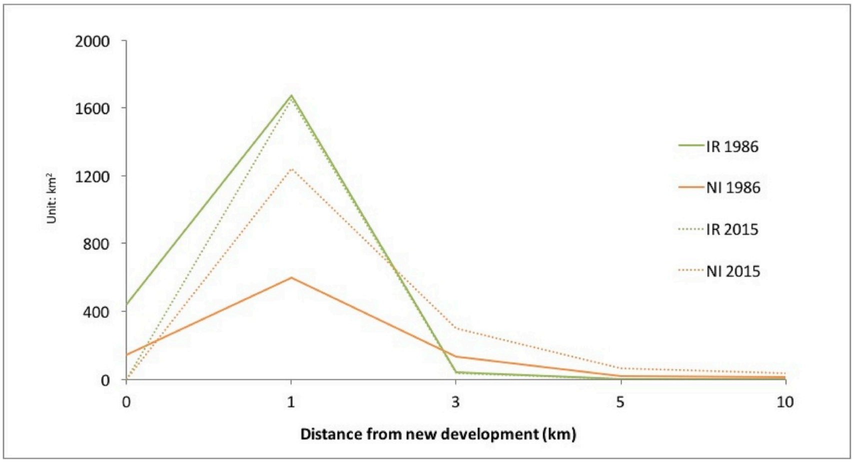

Fig. A4. 4

Appendix E. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2019.02.006.

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