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ORIGINAL PAPER

Landsat-based monitoring of annual wetland change in the Willamette Valley of Oregon, USA from 1972 to 2012

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Abstract In Oregon's Willamette Valley, remaining wetlands are at high risk to loss and degradation from agricultural activity and urbanization. With an increased need for fine temporal-scale monitoring of sensitive wetlands, we used annual Landsat MSS and TM/ETM+ images from 1972 to 2012 to manually interpret loss, gain, and type conversion of wetland area in the floodplain of the Willamette River. By creating Tasseled Cap Brightness, Greenness, and Wetness indices for MSS data that visually match TM/ETM+ Tasseled Cap images, we were able to construct a complete and consistent, annual time series and utilize the entire Landsat archive. With an extended time series we were also able to compare annual trends of net change in wetland area before and after the no-net-loss policy established under Section 404 of the Clean Water Act in 1990 using a Theil-Sen Slope estimate analysis. Vegetated wetlands experienced a 314 ha net loss of wetland area and non-vegetated wetlands experienced a 393 ha net gain, indicating higher functioning wetlands were replaced in area by non-vegetated wetland habitats such as agricultural and quarry ponds. The majority of both gain and loss in the study area was attributed to gains and losses of agricultural land. After 1990 policy implementations, the rate of wetland area lost slowed for some wetland categories and reversed into trends of gain in wetland area for others, perhaps representative of the success of increased regulations. Overall accuracy of land use classification through manual interpretation was at 80 %. This accuracy increased to 91.1 % when land use classes were aggregated to either wetland or upland categories, indicating that our methodology was more accurate at distinguishing between general upland and wetland than finer categorical classes.

Keywords Remote sensing · Wetlands · MSS · Tasseled Cap · No-net-loss · Change detection

Introduction

Wetlands are some of the most important and valuable ecosystems on the planet. They are known to cleanse polluted waters, protect shorelines, recharge groundwater aquifers, buffer flood and drought severity, and provide unique habitat to a wide variety of plants and animals (Mitsch and Gosselink 2000). Even though wetlands are so important, the planet has lost roughly 50 % of its wetlands since 1900 (UNWWAP 2003;

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Nicholls 2004). In the U.S. specifically, 22 states have lost more than 50 % of their wetland area between the 1780s and the 1980s (Dahl 1990) with losses continuing into the twenty first century (Dahl 2011). The majority (87 %) of freshwater wetland loss in the U.S. is attributed to agricultural conversion (Hefner and Brown 1984), and in states where agriculture is a significant source of economic output, remaining wetlands are increasingly threatened. In Oregon, agriculture is the second largest industry behind technology and accounts for an estimated 12 % of all jobs in the State (Searle 2012). The State thusly places substantial importance in its land use planning goals on the preservation of agricultural land (Bernasek 2006). Oregon's Willamette Valley accounts for the majority of agricultural output with 53 % of the valley bottom classified as agricultural land (Morlan et al. 2010). Agriculture, combined with 70 % of the State's population residing in the valley, places Willamette Valley wetlands in a dangerous setting.

Wetlands of the Willamette Valley have a long history of disturbance, alteration and removal. The valley was once comprised of extensive wet prairies and abundant riparian forests along the Willamette River floodplain. However, over the past 150 years, these ecosystems have been greatly reduced in area and connectivity (Daggett et al. 1998; Baker et al. 2004; Christy and Alverson 2011). Urbanization, agricultural activities, logging, and channelization of the Willamette River have reduced the valley's wetlands up to 57 % of their original range, with a 98 % loss of wet prairies and a 72 % loss of floodplain riparian forest (Taft and Haig 2003; Oetter et al. 2004; Christy and Alverson 2011). Today, with 70 % of the State's population residing in the valley and 96 % of the valley privately owned, monitoring the abundance and arrangement of wetlands and other critical habitats have become a top priority to planners and conservationists (Morlan 2000, Baker et al. 2004; Oregon Department of Fish and Wildlife 2006).

Following the federal goal of "no-net-loss" of wetland area enacted under Section 404 of the Clean Water Act in 1990 (USACE and EPA 1990), Oregon has since attempted to monitor and regulate wetland losses due to disturbance and modification of the State's remaining wetlands by aiming to decrease wetland losses and replace disturbed wetlands through mitigation. Mitigation is the attempt to alleviate the destruction of wetlands by replacing an existing wetland or its functions by creating a new wetland, restoring a former wetland, or enhancing or preserving an existing wetland (Votteler and Muir 2002). Following policy implementations, several studies have examined the efficacy of wetland conservation in the Willamette Valley through the State of Oregon's wetland strategy by evaluating policy compliance through investigation of permit requirements associated with the no-net-loss standard, by examining trends and patterns in permitting and compensatory mitigation records, and two-date change detection of spatial wetland patterns and extent through wetland classification of aerial photography (Kentula et al. 1992; Bernert et al. 1999; Morlan et al. 2010; Christy and Alverson 2011).

The U.S. also has its own wetland mapping protocol to aid in monitoring wetland trends. Run under the U.S. Fish and Wildlife Service, The National Wetlands Inventory (NWI) was designed to produce detailed maps and status reports of the characteristics and extent of the nation's wetlands (Wilen and Bates 1995). These maps are established through a mixture of stereoscopic color infrared photographs to identify and delineate wetlands (emphasizing color, texture, and pattern), fieldwork, and ancillary cover class maps such as soils and land use (Wilen et al. 1996). While it is critical to the success of the no-net-loss wetland conservation strategy that wetlands be mapped and monitored, the NWI has been found to be variable in its accuracy (with low categorical and spatial accuracy), contain high errors of omission, and of coarse temporal resolution, with some maps over two decades old (Stolt and Baker 1995; Kudray and Gale 2000). Agencies and individuals attempting to explore changes and trends in wetlands using aerial imagery are often limited in their temporal scope by the availability of NWI maps or aerial imagery. Moreover, the two-date, decadal interval change detection approaches used are too coarse a temporal grain to allow for insight into finer temporal-scale trends in wetland change and disturbance before and after specific policy implementations and environmental events (such as floods).

Utilizing Landsat satellite imagery to aid in federal wetland mapping was initially proposed and tested by the Federal Geographic Data Committee, but found to lack the needed spatial resolution for classification detail and wetness designation that aerial photography provided (Federal Geographic Data Committee 1992).

However, for monitoring regional-scale processes over longer time periods at a finer temporal resolution, Landsat satellite imagery has several advantages over aerial photography. Landsat now has over 40 years of freely available, high quality annual imagery (offering the longest running time series of systematically collected remote sensing data) and a spatial resolution that has yielded accurate classifications of many specific land use types and land use change (Cohen and Goward 2004). Dense (at least annual), multi-decadal Landsat time series imagery is becoming the norm for change detection in forested landscapes and should be explored for use in other ecosystems and land cover and use types such as wetlands.

Most work in wetland change detection using satellite imagery (from a variety of different sensors) has been done using automated classification techniques (Baker et al. 2007; Adam et al. 2010). While there are numerous advantages with automated analyses, a considerable issue with the common approach of deriving independent classifications for separate years and then comparing them to derive change is that the independent errors from each map are compounded, yielding a significantly greater error in the change domain.

The majority of wetland mapping using Landsat data has been single-date classification, two-date change detection, or short-term (0–5 years) change detection using annual images (Johnston and Barson 1993; Lunetta and Balogh 1999; Baker et al. 2007; Wright and Gallant 2007; Frohn et al. 2009; Huang et al. 2014), but dense time series algorithms for temporally and categorically detailed characterization of changes in wetlands is inevitable (Kayastha et al. 2012). However, accurate results will likely remain elusive during the development and testing phases, and there is an urgent need to begin to characterize wetland changes using dense Landsat time series interpretations across large, important wetland areas such as the Willamette Valley.

In the study presented here we use annual Landsat time series to quantify wetland losses and type conversions to a large and important western U.S. wetland ecosystem. Further, we extend the analysis back through the complete Landsat archive, examine wetland area gained, and focus on ecology- and policy-specific contextual information to both aid in wetland identification and interpret the significance of observed changes. We used a methodology that applies long-standing and accurate geovisual cognition approaches associated with manual aerial photointerpretation to dense Landsat time series (Cohen et al. 2010). Our objectives are to:

(1) Quantify and characterize spatial and ecological trends in annual wetland change through gain, loss, and conversion in the Willamette Valley; (2) Evaluate the effect of the no-net-loss federal wetland conservation policy change enacted in 1990 on trends in net wetland area; and (3) Describe a new methodology that reaches back through the over 40-year Landsat archive to map fine-scale wetland and related land-use changes from 1972 to 2012.

Visual interpretation of Landsat time series to derive accurate change information is not new. Cohen et al. (1998) compared this technique against use of multi-date aerial photos and polygon spatial databases and found that the three approaches yielded nearly identical results in the context of accuracy assessment. More recently, Cohen et al. (2010) developed the TimeSync methodology to validate and calibrate change detection maps derived using automated algorithms with annual Landsat time series (Kennedy et al. 2010). TimeSync is based on visual, contextual interpretation of plot-level disturbance and recovery sequences throughout a pixel's (or plot's) spectral trajectory and has already been successfully used with early Landsat data (Pflugmacher et al. 2012).

Although the spatial resolution of Landsat data is considerably less than that of aerial photos, at the patch level (multiple 30 m pixels) Landsat data should provide a capability for accurate characterization of wetland change. For the pre-Thematic Mapper (TM) era (before 1982) we rely on integration of Multispectral Scanner (MSS) data to complete the time series, which may require a larger minimal mapping unit (multiple 60 m pixels) for accurate interpretations. Additionally, the spectral quality is sub-TM level, which could reduce the quality of interpretations. We informally examine the difference in quality of interpretations from MSS and TM and the latter sensor ETM+ (Enhanced TM+) to provide insights into the value of MSS in this context.

Methods

Study area

At approximately 14,400 km^2, the Willamette Valley Ecoregion (Omernik 1987) lies between the Coast Range Mountains to the west and the Cascade

Mountains to the east (Fig. 1). The valley ranges from 32 to 64 km wide and 195 km in length with elevations varying between 4 and 122 m. Climate in the Willamette Valley consists of mild, wet winters and hot, dry summers with most precipitation falling in the coldest months between fall and early spring. Annual precipitation totals vary depending on elevation. Eugene, for example, sits at 110 m above sea level and receives an annual average precipitation of 117 cm while Portland, at 7 m, receives 94 cm (Taylor and Bartlett 1993). Average high temperatures in the valley range from 3 to 5 °C in the coldest months to 25–30 °C in the summer and average lows are generally between −1 and 2 °C in winter and 10–13 °C in summer with a growing season (days between freezing temperatures) ranging between 110 and 180 days depending on location (Taylor and Bartlett 1993).

To focus our change detection effort on areas with the highest probability of containing historic and present wetlands, a floodplain inundation map was used (Fig. 1). Developed by River Design Group (RDG) in Corvallis, OR, this map estimates the extent of the floodplain inundation area associated with the two-year discharge of the main stem Willamette River by utilizing 1-m lidar data and "bath tub" hydrologic modeling (River Design Group 2012). The map extends from the confluence of the Middle Fork and Coast Fork Willamette River in the City of Eugene in the south to Willamette Falls near Oregon City to the north. This map was selected for the ecological importance of a regulated two-year inundation discharge for floodplain wetlands. We theorized that a two-year inundation flood frequency represents the spatial extent within which wetlands could potentially persist (if they do not already) if not obstructed through agricultural or urban land alteration. Historically, the Willamette Valley wetlands were located predominantly along the Willamette and Columbia River floodplains (Christy and Alverson 2011). Our objectives place a specific emphasis on *wetland* change detection in the Willamette Valley and we used historical context to target our efforts to the lowlands of the Willamette Valley ecoregion where the probability of wetland occurrence is relatively high (Morlan et al. 2010).

Image pre-processing

To compile a complete time series, we collected annual summer date Landsat images of the study area from 1972 to 2012. These data included both MSS World Reference System (WRS) 1 path/row 50/29 images from 1972 to 1983 and TM and ETM + WRS 2 path/row 46/29 images from 1984 to 2012, with all data processed to L1T (terrain-corrected and radiometrically calibrated; http://landsat.usgs.gov/Landsat_Processing_Details.php). The geometric accuracy of MSS L1T data was less than desirable for time series analysis (~120 m RMSE for some images). To increase geometric accuracy, we individually co-registered MSS images to a reference TM image using an automated, correlation-based identification of image "tie points" with a maximum RMSE of 30 m and a first-order polynomial transformation (Kennedy and Cohen 2003; Pflugmacher et al. 2012). To match the spatial resolution of the TM and ETM+ images for standardized interpretation, we resampled the MSS images to 30 m pixel size using a nearest neighbor approach.

The orthogonal Tasseled Cap (TC) transformation has been widely used for change detection because of its usefulness in revealing changes in vegetation (Dymond et al. 2002; Parmenter et al. 2003; Hui et al. 2009; Kennedy et al. 2010; Pflugmacher et al. 2012). The TM TC transformation of the six Landsat TM reflectance bands results in three vegetation indices known as brightness, greenness, and wetness (Crist and Cicone 1984). Since the Willamette River floodplain is predominantly a mosaic of agricultural land with scattered natural vegetation, we chose the TC transformation, in part, because it has shown to be particularly useful in capturing differences in natural versus cultivated vegetation (Lobser and Cohen 2007). Additionally, a combination of the brightness and wetness indices is correlated with moisture content, giving supplementary insight to wetland disturbance and land use change distinction between wetland and upland vegetation (Crist and Cicone 1984; Nielsen et al. 2008). Lastly, by reducing the image data to three bands, valuable spectral and textural information is more parsimoniously displayed on a computer screen, allowing for easier manual interpretation of annual change. See Appendix 1 for details on our conversion of tasseled cap coefficients for MSS data.

Manual interpretation of wetland loss and gain

To manually interpret annual wetland losses and gains associated with land use change, a specific workflow was implemented for consistency and quality

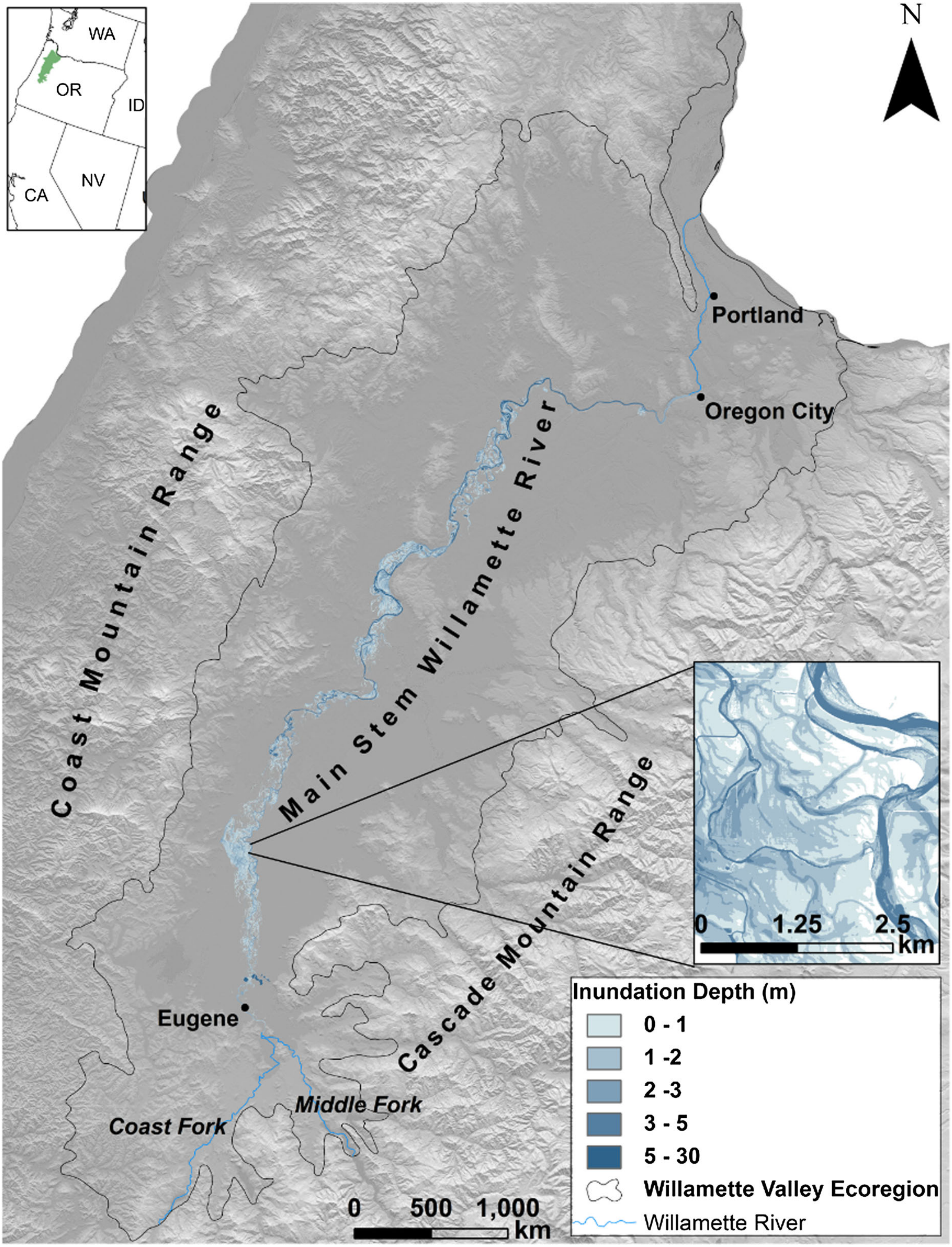

Fig. 1 Map of the Willamette Valley Ecoregion with the Main Stem Willamette River 2-year inundation floodplain

assurance (see Appendix 2). The interpreter had extensive experience with TimeSync-based visual vegetation disturbance detection using Landsat TC time series and spent additional time visually training and calibrating on TC color patterns within known wetlands. For increased interpretation functionality, we spatially segmented the study area into 40 different subareas, each a 255 × 255 pixel block (7650 m × 7650 m in size), that spanned the entire inundation study area (Fig. 2).

Similar to the U.S. Fish and Wildlife Service's Technical procedures for conducting status and trends of the Nation's wetlands (Dahl and Bergeson 2009), we used a consolidated, modified version of the Cowardin wetland classification system in order to accommodate the use of Landsat Tasseled Cap imagery as our primary data source (Cowardin et al. 1979). Water chemistry, water depth, soil inundation and detailed differences in vegetative species cannot necessarily be assessed reliably from the imagery data alone and detailed classifications reliant on these characteristics were not possible. Cowardin et al. (1979) defines deepwater habitats (deep, permanent water bodies such as lakes and rivers) separately from wetlands. While specific structural and functional differences exist between wetlands and deepwater habitats, the Willamette River and its tributaries, as well as floodplain ponds and lakes, hold significant hydrological and ecological value in the context of our study area and objectives (Shaffer and Ernst 1999; Taft and Haig 2003) and were classified as wetlands (Ramsar Convention Bureau 1991; Ferren et al. 1995; Semeniuk and Semeniuk 1997).

Wetland land use classes included emergent vegetation, lacustrine, riparian vegetation, and riverine (Table 1). We adapted upland vegetation land use categories from the Anderson land use classification system (Anderson et al. 1976), and included agricultural, upland vegetated, and urban categories (Table 1). Although some changes spanned multiple years, only the first year of detection was used in annual analysis of wetland change.

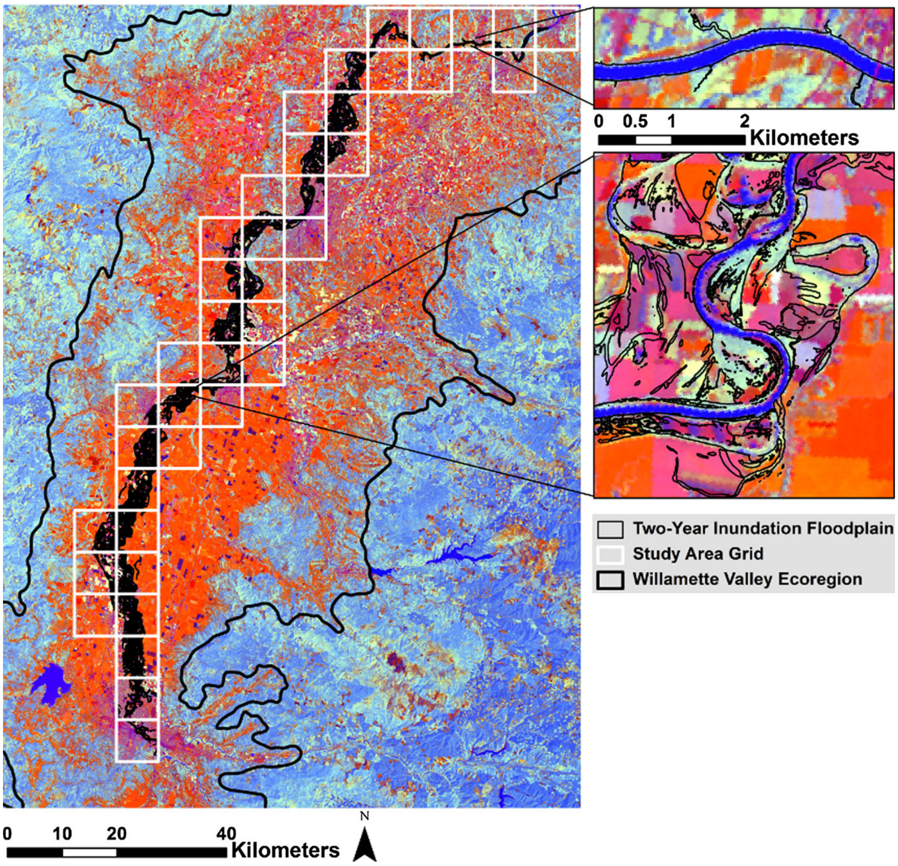

Fig. 2 Map of inundation study area spatially segmented into 40 different subareas, each a 255 × 255 *pixel block* (7650 m × 7650 m in size). The extent of the inundation study area was varied depending on spatial context of the Willamette River. In metropolitan areas (*top right*) the floodplain was restricted to a small margin along the river. In agricultural areas (*bottom right*), the floodplain extended far beyond the riverbank

Table 1 Land use categories used in wetland land use change interpretations

Land use category	Description
Emergent vegetation (wetland)	Vegetated land that includes non-woody, perennial, rooted herbaceous hydrophytes associated with wetlands such as marshes, bogs, fens, or wet prairies. This category is a combination of the Cowardin et al. (1979) Palustrine system and the emergent vegetation associated with Riverine and Lacustrine systems
Lacustrine (wetland)	Non-vegetated land that includes permanently flooded lakes, reservoirs, and ponds as defined by Cowardin et al. (1979) Lacustrine deepwater system
Riparian vegetation (wetland)	Vegetated land that includes scrub-shrub and forested wetlands associated with Cowardin et al. (1979) Riverine, Lacustrine, and Palustrine systems
Riverine (wetland)	Non-vegetated land with running water or a substrate associated with a stream or river such as rock, cobbles, gravel, or sand associated with the Cowardin et al. (1979) Riverine deepwater system
Agriculture (upland)	Mixed land associated with the attributes of Anderson's Agricultural Land class
Upland vegetated (upland)	Non-wetland vegetated land associated with the Anderson et al. (1976) Rangeland and Forested Land class
Urban (upland)	Non- or partially-vegetated land associated with the Anderson et al. (1976) Urban land use class

Accuracy assessment

Accuracy of our Landsat time series interpretations was checked in several ways. First, as already described, all wetland loss and gain interpretations and land use and wetland class interpretations were checked against high spatial resolution true-color aerial and satellite images in Google Earth. Second, we conducted fieldwork to compare our interpretations of current land use and wetland type, with the assumption that accuracy of these interpretations was consistent through time. Fieldwork was conducted in June, 2013 at the tail end of the region's wet season. This was when water associated with ephemeral wetlands was still present and the growing season had commenced, permitting identification of wetland vegetation.

Because the majority of the Willamette River floodplain is privately owned and not accessible by public roads, the number of possible polygons to visit was narrowed to 67. Once in the field, only 45 sites were publically accessible. Sites were located in the field using a recreation grade GPS and checked against imagery from Google Earth and maps. At each visited location, land use and wetland class were noted. For all locations visited, a site was marked as correctly interpreted if the majority of the polygon contained the correct wetland and/or land use class.

Wetland change

To characterize temporal trends in wetland loss and gain, we calculated amount of wetland gain and loss, and net change (gain–loss), for each of the 40 annual intervals of the time series from 1972 to 2012. This was done across the four wetland types and separately for each type. Wetland gain and loss were defined by wetland land use change not associated with wetland-to-wetland (e.g. riparian to emergent) conversion. Wetland-to-wetland conversion can be an ecologically significant transition, but as it represents a net neutral change in wetland area it was not included in gain and loss calculations.

For insight into the land use transitions associated with wetland loss and gain, and transitions among wetland-to-wetland types, we organized our data into relevant transitions tables. One table highlights wetland loss, one highlights wetland gain, and the third shows wetland type conversion. Because we did not interpret upland-to-upland type conversion in our analyses we did not combine all transitions into a single table.

In addition to examining the categorical changes in wetland area lost and gained, we also sought to explore the possible effects of the no-net loss policy change on the rate at which net wetland area changed over the study period. First, we calculated the annual, cumulative sum of net change in area for each wetland type and across all wetland types and plotted it over time. To determine if there were trends related to the no-net-loss policy change, we first split our annual net change data into two periods to represent the years prior to federal policy mandating no-net-loss ("pre-policy", 1972–1989) and the period after ("post-policy", 1990–2012). Time series analysis of the rate of change of net wetland area was calculated using the Theil-Sen (TS) Slope estimate analysis (Theil 1950; Sen 1968). TS is a non-parametric linear regression method that estimates the slope of a dataset by calculating the median slope of all pair-wise sample points in the forward direction. This analysis yielded a pre-policy and post-policy slope for each wetland type and for all wetland categories combined. The slope values indicate the strength of a trend in the change in net area for each wetland category. If the slope had a negative sign for a given time period, a trend in net loss was observed, and visa versa. A permutation test (Good 2000) with 10,000 iterations was used to create a *p* value that represents the significance of the difference between the pre- and post-policy TS slopes. The one-sided p-value is calculated as the proportion of sampled permutations where the difference between pre- and post-policy change was greater than or equal to the observed slope difference for the difference between the two slopes.

Results

Wetland loss, gain, and type conversion across the full study period

Within the two-year inundation floodplain of the main stem of the Willamette River (approximately 28,890 ha), only a small fraction of the area underwent wetland gain, loss, or type conversion between 1972 and 2012. Adding the totals from all loss (442 ha, Table 2), gain (521 ha, Table 3), and type conversion (289 ha, Table 4), we observed that 1252 ha of total wetland change occurred between 1972 and 2012, which represents 4.3 % of the study area.

Across the full study period, emergent wetlands experienced the second greatest decrease in area, 85 ha or 19 % of total wetland area lost (Table 2). Emergent wetlands had the lowest increase in area, 45 ha or 8.6 % of total wetland area gained (Table 3) among the four wetland types. This translates to a 40.5 ha net loss in emergent wetland area (Table 5). Of the total emergent wetland area lost, 41.5 % was from conversion to agriculture and 58.5 % from conversion to urban land use (Table 2). Of total emergent wetland area gained, 100 % came from conversion from agricultural land use (Table 3).

Gain in lacustrine wetlands was proportionally the largest among the four types at 67 % (348 ha) of total gains (Table 5), with losses being the smallest at 1 % (5.1 ha) of total wetland area lost, next to riverine wetland for which there was no loss (Table 5). Lacustrine wetlands experienced 68 times more gain in area compared to loss, resulting in a 343 ha net gain in area (Table 5). Of the 5.1 ha of lacustrine area lost, 39 % came from conversion to agricultural land use and 61 % from conversion to urban land use (Table 2). Of the total lacustrine wetland area gained, 81 % was attributed to conversion from agricultural land use and the remaining 19 % came from conversion from urban land use (Table 3).

Loss in riparian wetlands was the largest decrease in area among the four wetland types, accounting for 80 % (352 ha) of all wetland area lost (Table 5). Although riparian wetlands had the second largest increase in area with 15 % (78 ha) of total wetland area gained (Table 3), losses in area were 4.5 times greater than gains resulted in a net loss of 274 ha (Table 5). From the riparian wetland area lost, 83 % came from conversion to agricultural land use and 17 % from conversion to urban land use (Table 2). Of the total riparian wetland area gained, 95 % came from conversion from agricultural land use, 4 % from conversion from urban land use, and 1 % (0.8 ha) from conversion from upland herbaceous land (Table 3).

While gain in riverine wetlands area accounted for only 9.6 % of total wetland area gained (Table 5), this wetland category experienced no losses during the study period (Table 2) resulting in a net gain of 50 ha (Table 5). Of the riverine area gained, 100 % came from conversion from agricultural land (Table 3).

Within the full study period and across all wetland types, the study area experienced 1.1 times more gain than loss in wetland area, resulting in a net gain of 78 ha (Table 5). Conversion to agricultural land use was the main cause of wetland area lost for all individual categories and accounted for 74 % all wetland area lost across all categories (Table 2). Conversion to urban land use was the second highest cause of wetland area lost and accounted for 26 % of area lost across all categories (Table 2). Conversion from agricultural land to wetland was the leading land use change across gains and losses (449.8 ha) and resulted in 86 % of all wetland area gained, with the

Table 2 Loss of wetland area (ha), by type, to the three upland land use classes

Starting wetland class (ha)	Ending upland class (ha)			
	Agriculture	Upland vegetation	Urban	Total
Emergent	35.3	0	49.8	85.1
Lacustrine	2	0	3.1	5.1
Riparian	291.1	0	60.9	352
Riverine	0	0	0	0
Total	328.4	0	113.8	442.2

Table 3 Gain of wetland area (ha), by type, from the three upland land use classes

	Ending wetland class (ha)				
Starting upland (ha)	Emergent	Lacustrine	Riparian	Riverine	Total
Agriculture	44.6	281.4	73.9	49.9	449.8
Upland vegetation	0	0	0.8	0	0.8
Urban	0	66.6	3.4	0	70
Total	44.6	348	78.1	49.9	520.6

Table 4 Type conversion of one wetland category to another

Starting wetland class (ha)	Ending wetland class (ha)				
	Emergent	Lacustrine	Riparian	Riverine	Total
Emergent	0	*19.3*	0	*2.6*	21.9
Lacustrine	*49.9*	0	*13.8*	0	63.7
Riparian	33.8	*22.6*	0	*89.1*	145.5
Riverine	*17.2*	1.4	*39.4*	0	58.0
Total	100.9	43.3	53.2	91.7	289.1

Italicised indicate a conversion from vegetated wetland category to non-vegetated wetland category, or from non-vegetated wetland to vegetated wetland

Table 5 Wetland area gain and loss across the 40-year interval period of observation

Wetland type	Area gained (ha)	Percent of total gain	Area lost (ha)	Percent of total loss	Net change (ha)
Emergent	44.6	8.6	85.1	19.2	−40.5
Lacustrine	348.0	66.9	5.1	1.15	342.9
Riparian	78.1	15.0	352.1	79.6	−273.9
Riverine	49.9	9.6	0.0	0.0	49.9
Total	520.5	100.0	442.2	100.0	78.3

remaining gain attributed to conversion from urban land use at 13 % and less than 1 % from conversion to upland herbaceous (Table 3).

Although the study area saw a net gain in total wetland area, gains and losses were not distributed evenly across wetland types. Vegetated wetlands (emergent and riparian) had individual net losses across the study period and when combined, had an overall net loss of 314 ha (Table 5). Non-vegetated wetlands (lacustrine and riverine) had individual net gains in wetland area across the study period and when combined, had an overall net gain of 484 ha (Table 5). Therefore, while calculations across all wetland types aggregate to a net gain in wetland area, this is the result of vegetated wetland area being replaced with non-vegetated wetland area relative to net wetland area changed.

Although, not representative of net gain or loss in wetland area, there was a significant amount of wetland type change within the individual wetland categories (Table 4). The largest conversion between wetland types was riparian wetland area converted to riverine wetland (89.1 ha). This was followed by, in descending order of area converted, lacustrine to emergent, riverine to riparian, riparian to emergent, riparian to lacustrine, emergent to lacustrine, riverine to emergent, lacustrine to riparian, emergent to riverine, and riverine to lacustrine. Combined, vegetated wetlands (emergent and riparian) gained 120.3 ha from conversion from non-vegetated wetlands (lacustrine and riverine) and lost 133.6 ha to non-vegetated wetlands, resulting in a net loss of 13.3 ha for vegetated wetlands to non-vegetated wetlands. Therefore, in both conversion to and from both upland and wetland land use types, vegetated wetlands show a net loss of area.

Annual change, pre- and post-policy

All four wetland types, as well as all wetland types combined, had different trends in annual net change in wetland area from the pre-policy and post-policy eras (Table 6; Fig. 3). In the pre-policy era, net change in emergent wetlands resulted in a negative TS slope of 3.48, representing a trend in which the study area lost 3.48 ha more net emergent wetland area than it gained per year (Table 6). Post-policy, this trend reversed with a positive TS slope, signifying a trend in which emergent wetlands gained 1.38 ha more wetland area than lost per year. While emergent wetlands experienced a reversal of the negative pre-policy trend into a positive post-policy one, the positive trend observed post-policy is less than half the strength of the preceding negative trend and, thusly, did not completely reverse trend in net losses in wetland area that occurred pre-policy.

The pre-policy TS slope for riparian wetlands was the strongest and most negative across all wetland types for both pre- and post-policy years, with a net loss of 9.32 ha of wetland area annually (Table 6). The post-policy trend was still negative, but weaker, with a net loss of 3.59 ha of riparian wetland per year. Although the negative post-policy trend in net wetland area was 61 % weaker than the pre-policy trend, is still the second strongest of all negative trends across all wetland types and both eras, indicating these wetlands are still losing area at a high annual rate, even after policy implementation.

Across all wetland types combined, the study area experienced a net loss of 2.59 ha of wetland area per year in the pre-policy era of 1972–1989 (Table 6). In the post-policy years, this trend was reversed into a stronger, positive trend of a net gain of 3.29 ha of all wetland area per year from 1990 to 2012. However, similar to analysis of the wetland loss, gain, and type conversion across the full study period, the pre- and post-policy trends observed across all wetland types are the result of an imbalance between vegetated and non-vegetated wetland types. The strong, positive annual trend observed in post-policy lacustrine wetlands tips the post-policy trend across all wetland types into the positive spectrum, despite a weak positive trend from emergent wetlands, a strong negative trend in riparian wetlands, and no trend from riverine wetlands. Removing lacustrine and riverine wetlands, vegetated wetlands had a very strong negative trend and lost −13.3 ha of net wetland area annually in the pre-policy era. Post-policy, the trend in net change in wetland area was still negative but weaker with 2.31 ha of net wetland area lost annually.

Error analysis

Error matrices for the seven land use categories, based on the field visits to 45 change polygons yielded an overall accuracy of 80 % (Table 7). With our methodology, we overestimated riparian, agricultural, and lacustrine land use types most frequently with errors of commission of 25, 28, and 40 % respectively. Urban, emergent, upland vegetation, and riverine land use types all had 0 % errors of commission. We underestimated agricultural, urban, and upland land use types most frequently with errors of omission at 13, 40, and 100 % respectively and errors of omission equaling 0 % for all other land use types. Examining our ability to distinguish only between wetland and upland land use types, overall accuracy was 91.1 % and omission and commission rates were low (Table 8). The

Table 6 Calculated Theil–Sen (TS) slope for cumulative net change in wetland area for pre-policy (1972–1989) and post-policy (1990–2012) time series for each wetland category and all wetland categories combined

Wetland type	Pre-policy TS slope	Post-policy TS slope	p value
Emergent	−3.48	1.38	0.006
Lacustrine	8.82	4.45	0.15
Riparian	−9.32	−3.59	0.057
Riverine	1.59	0	0.13
All	−2.59	3.29	0.26
Vegetated only	−13.32	−2.14	0.004

Also shown are p value for the significance of the difference between the two slopes

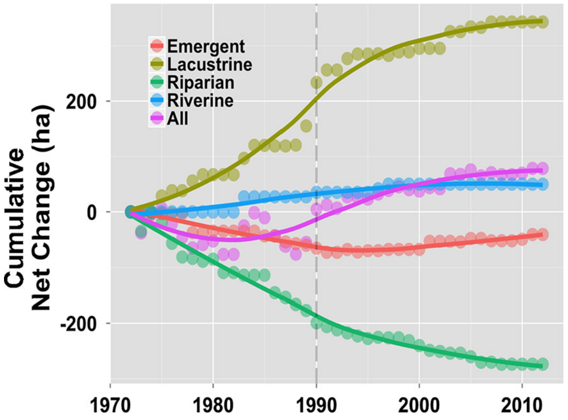

Fig. 3 Cumulative, annual change in net area for individual wetland categories as well as all wetland categories combined. *Dashed line* at 1990 represents no net loss federal policy implementation

aggregated wetland land use category had both the highest error of omission (13 %) and commission (22 %), indicating it was more difficult to classify compared to upland categories, which had 0 % errors of omission and commission.

Discussion

Globally, wetlands have been recognized as some of the most valuable providers of essential ecosystem services such as water quality regulation, groundwater recharge, erosion control, natural hazard mitigation, and carbon storage (de Groot et al. 2012, Russi et al. 2013). Despite their importance, the planet has lost roughly 50 % of its wetlands since 1900 (UNWWAP 2003) through effects such as agricultural conversion, irrigation, pollution, urbanization, and climate change with recent loss in areas such as East Asia up to 1.6 % a year (Gong et al. 2010).

To combat wetland loss nationally, the U.S. strives for no-net-loss of wetland area through Section 404 of the Clean Water Act. In Oregon, wetland mitigation is regulated through the Department of State Lands (ODSL) with several other agencies involved in wetland regulation and some areas implementing more intensive goals at the watershed, city, or community-scale (ODSL 2011). The Willamette Valley is particularly dense in localized wetland conservation goals with some agencies operating at the sub-city level.

To achieve a broader view of ecological and spatial changes in Willamette Valley wetlands, we employed a new methodology that reaches back through the over 40-year Landsat archive to map fine-scale wetland land-use changes. First, we were able to quantify and characterize trends in annual wetland change through gain, loss, and conversion in the Willamette Valley from 1972 to 2012, and, subsequently, evaluate the effect of the no-net-loss federal wetland conservation policy enacted in 1990, on annual trends in net wetland area.

Wetland loss

The largest decrease in wetland area across all wetland types combined was attributed to conversion to agricultural land with a loss of 328 ha (74 % of total loss). As noted, the Willamette Valley places high value on its agricultural industry. Extensive loss of wetland area to agricultural expansion is consistent with previous studies that have examined wetland

Table 5 Error matrix for all land use categories based on wetland loss and gain polygon classifications validated in the field

Observed land use	Predicted land use								
	Emergent	Lacustrine	Riparian	Riverine	Agriculture	Upland vegetation	Urban	Column total	Error of omission (%)
Emergent	2.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0
Lacustrine	0.0	3.0	0.0	0.0	0.0	0.0	0.0	3.0	100.0
Riparian	0.0	0.0	6.0	0.0	0.0	0.0	0.0	6.0	0.0
Riverine	0.0	0.0	0.0	3.0	0.0	0.0	0.0	3.0	0.0
Agriculture	0.0	1.0	1.0	0.0	13.0	0.0	0.0	15.0	13.3
Upland vegetation	0.0	0.0	1.0	0.0	0.0	0.0	0.0	1.0	100.0
Urban	0.0	1.0	0.0	0.0	5.0	0.0	9.0	15.0	40.0
Row total	2.0	5.0	8.0	3.0	18.0	0.0	9.0	45.0	
Error of commission (%)	0.0	40.0	25.0	0.0	27.8	0.0	0.0		

Table 8 Error matrix for aggregated wetland and upland land use categories based on loss and gain polygon classifications validated in the field

Observed land USE	Predicted land use			
	Upland	Wetland	Column total	Error of omission (%)
Upland	27	4	31	12.9
Wetland	0	14	14	0
Row total	27	18	45	
Error of commission (%)	0	22.2		

trends in the Willamette Valley and is likely attributed to the continuing expansion of agricultural production and commerce in the valley (Bernert et al. 1999; Morlan et al. 2010). To compound this, regulatory monitoring of spatial and ecological wetland changes within private agricultural settings is not straightforward. A study of regulatory compliance of wetland change in the Willamette Valley from 1982 to 1994 conducted by ODSL found that 81 % of all unauthorized wetland changes were attributed to agricultural conversions. Further, they found that no wetland changes due to agricultural conversions that required a permit were authorized by OSDL permit (Shaich 2000). Both Section 404 of the Clean Water Act and the ODSL operate on a complaint driven enforcement program of unauthorized agricultural wetland change. While some activity using heavy equipment closer to urban areas may be visible to the public, wetland change activities on expansive agricultural land in sparsely populated areas are less likely to be observed and reported (Shaich 2000). This lends great value to studies such as this one that use remote sensing to monitor wetland losses.

The next largest decrease in wetland area across all wetland types was conversion to urban land use, which accounted for 26 % (114 ha) of all wetland lost to upland conversion. The population of Willamette Valley has increased by 11.6 % in the past decade alone (State of Oregon 2012). With increase in population, comes an increase in urbanization and development. Even though urbanization poses an increased threat to Willamette River floodplain wetlands, our study observed less urban conversion than agricultural. Conservation efforts through Oregon's Statewide Planning goals (Macpherson and Paulus 1973) aim to protect floodplain wetlands and agricultural land from urbanization and could explain why more wetlands were lost to agricultural conversion compared to urbanization and development.

Wetland gain

For each individual wetland type and across all wetland types combined, conversion from agriculture resulted in the largest increase (86.5 %) in wetland area for the full study period. Almost all wetlands observed in our two-year inundation study area were directly adjacent or closely connected to an agricultural field, making these fields spatially and ecologically relevant for connecting current wetlands to future restored wetlands. Gain in wetland area can occur both naturally or purposefully through official mitigation and restoration or creation from land owners or groups not affiliated with government agencies. Nearly all (96 %) of vegetated wetland area gain was attributed to conversion from agriculture. For emergent and riparian wetlands, agricultural fields in the Willamette Valley are well suited for wetland restoration, enhancement, or creation. Since these fields were likely prairie or wet prairie ecosystems in the past, relic soil and hydrologic conditions may remain for potential recapture of wetland ecosystem function through restoration (Wold et al. 2011). Streams running through agricultural land offer additional opportunity for riparian wetland restoration, creation, and enhancement. Along with programs such as the Wetland Reserve Program that offer private landowners the opportunity to protect, restore, and enhance wetlands on their agricultural property (United States Congress 1990), many other land trust organizations in the Willamette Valley have begun to buy private agricultural land either outright or as easements with the goal of future wetland restoration (Wold et al. 2011).

Conversion from agricultural land to lacustrine wetlands accounted for 54 % of all wetland area gained. The majority of agricultural land converted to lacustrine wetlands appeared to be from anthropogenic activities and the construction of on-farm ponds. While these temporary ponds do have the potential to be ecologically significant for Willamette Valley plant and wildlife species, they function far below that of a wetland with natural vegetation and hydrology and without exposure to agricultural disturbance (Lippert and Jameson 1964; Dahl 2006; Pearl et al. 2005). We also observed permanent ponds created on agricultural land as the result of heavy flooding where inundation levels never receded entirely, leaving behind small ponds directly adjacent to river.

All increase in riverine wetland area came from agricultural conversion. Riverine wetlands had three distinct time periods that accounted for all gain in area: 1983, 1990, and 1996–1997 and resulted from observed incision or erosion of channel banks and agricultural fields directly adjacent to the river. Increase in discharge from high precipitation events could create cases in which the river overtakes a channel bank for a gain in area. The 1996 precipitation event, in particular, was a notable 100-year flood event of the Willamette River resulting from a rain-on-snow precipitation event (Colle and Mass 2000) and created rearrangement of river course on a small scale and, from our observations, took several years to stabilize. Natural channel relocation has great potential for wetland restoration in the Willamette Valley. Managers can use flood events that naturally reclaim historic floodplain area from upland land use and increase channel complexity and connectivity as guidance to better focus habitat restoration efforts where they would be most effective.

In addition to riverine area gained from agricultural land, 89 ha of riparian wetland area was converted to riverine wetland area over the full study period through the same mechanisms as riverine conversion of agricultural land. Riparian forests along the Willamette River have seen a net increase in stand maturity over the past several decades attributed to an increase in flood control measures (Gutowsky 2000). This suggests that during periods of increased inundation and discharge of the Willamette River, riparian forests are vulnerable to capture by the flooded channels. Additionally, our observed loss of riparian wetlands to both riverine and agricultural conversion and a continued annual net loss of riparian wetlands suggest that riparian forests along the Willamette River are being spatially compressed from both sides into narrow strips that when lost are not replaced in area. Due to their smaller size, these smaller, narrow stands are more susceptible to complete riverine conversion during periods of heavy inundation.

Both riparian and lacustrine wetlands had an increase in wetland area resulting from conversion from urban land use. For lacustrine wetlands, the majority of this conversion either came from ponds created on private residences and golf courses or from partially developed or barren land converted to quarry land with quarry ponds. As they stand, these ponds offer little wetland habitat. However, future reclamation of quarry ponds into higher functioning wetlands is possible (Kondolf 1993).

Ecological and spatial trends of wetland change

We found that before State and Federal policy implementations, all wetlands experienced annual loss of area with emergent and riparian wetlands decreasing at an even higher annual magnitude. After policy implementation in 1990 and through 2012, loss of wetland area across all wetland types was not just slowed, but reversed into a trend of annual gain across all wetlands (Table 6; Fig. 3). However, like trends seen across the entire study period, individual wetland types were affected differently by policy implementation.

Across all wetland types and individually, it appears that wetland conservation policies were effective at slowing loss of wetland area and in some cases, were able to facilitate trends in annual gain. This is consistent with an increase in mitigation permits associated with Willamette River received by ODSL after 1990 compared to 1972–1989 (Fig. 4). An increase in permits can be seen as a representation of regulations imposed and enforced on wetland area changed, and limitations on illegal or unregulated wetland change.

Although Oregon has had more intensive wetland regulations since 1990, we found that for both our 40-year study period, and since 1990 wetland conservation policies, vegetated wetland area was lost at a greater rate than, and was replaced by, non-vegetated wetlands. Other studies investigating both Willamette Valley wetlands and national wetlands have found the same trend with an increase in shallow, non-vegetated and open water ponds and lakes (Bernert et al. 1999; Morlan et al. 2010; Dahl 2006). Along with loss in area to upland land use, we also observed net loss of vegetated wetlands from conversion to non-vegetated wetlands. Thus, it is important to recognize that conversion of one type of wetland to another either directly or through mitigation might represent a net loss of ecosystem services and function.

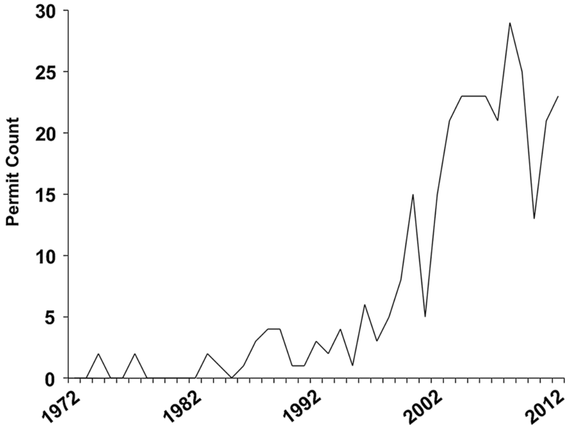

Fig. 4 Number of wetland mitigation permits submitted to the State of Oregon associated with the Main-Stem Willamette River. *Source* Oregon Department of State Lands (2013)

Willamette Valley vegetated wetland habitats hold substantial ecological significance for many plant and wildlife species (Floberg et al. 2004; Primozich and Bastasch 2004). If higher ecologically functioning wetlands are lost and replaced in area with lower quality wetlands, mitigation does not represent a net neutral change in wetland function. This adds to the overwhelming consensus in the literature that states the no-net-loss policy has failed in regards to both to no net loss of wetland area and no net loss of wetland function, as wetlands destroyed are not always replaced with equally valuable habitat types (Turner et al. 2001).

Spatial extent is another issue to consider when evaluating trends in wetland area. Our study area was a subset of the Willamette Valley, defined by the main-stem Willamette River two-year inundation floodplain as determined by 1 m lidar hydrologic modeling. Oregon's wetlands are officially regulated on a statewide-scale with conservation goals to monitor at finer-scales such as city, county, and watershed. Hectare for hectare we do not know which, if any, gain in wetland area we observed was meant to replace wetland area lost that we observed or which was subject to regulatory permits. While there are over two dozen wetland mitigation banks within the Willamette Basin, only one was located within our study area. Therefore, we must consider that wetland area destroyed in our study area could have been compensated with mitigation banks elsewhere. This raises the issue of spatial extent in relation to compensatory wetland mitigation; if a wetland is destroyed in a particular area, managers should consider the spatial and ecological bounds of where to rebuild, restore, or enhance elsewhere.

Areas of both gain and loss were often clustered through space and time. Many of the sites that experienced change in one decade also saw change in all or other decades as well (Fig. 5). Even with Oregon's increasing population, only 13 % of observed wetland loss occurred within city-defined urban growth boundaries (UGB). However, while UGBs appeared to buffer wetland loss within their borders, 72 % of the remaining loss occurred within just 1 km of a UGB and nearly all (98 %) was observed on private land. Oregon's Statewide Planning goals may protect wetlands within official UGBs, but efforts towards loss prevention and detection should be spatially directed toward private land within Oregon's unincorporated communities (areas that lie outside the urban growth boundary of any city (Macpherson and Paulus 1973)) that contain valuable wetland area.

Mapping annual wetland change with landsat imagery

Our accuracy assessment of wetland land use change was polygon-based as opposed to pixel-based and was only able to capture 12 % of our interpretations due to access restrictions associated with private land. Overall accuracy of land use classification through gain and loss polygons was at 80 %. This accuracy increased to 91.1 % when land use classes were aggregated to either wetland or upland categories, indicating that our methodology was more accurate at distinguishing between general upland and wetland than finer categorical classes. Both accuracies are on par with other studies examining Landsat's capability to accurately classify wetland land use (Sader et al. 1995; Hewitt 1990; Harvey and Hill 2001). Although interpretations were continuously checked through Google Earth imagery (Cohen et al. 2010), the low sample size and restricted nature of our accuracy assessment yields results that should be considered alongside their limitations.

Assessing Landsat's entire time series was crucial for evaluating long-term trends in our study area. MSS imagery (1972–1983) is underutilized, if not discounted, in recent studies that use Landsat imagery for temporal analysis (Sloan 2012) due to a perceived inconvenience and increased labor associated with pre-processing (Maxwell and Sylvester 2012). Comparing wetland change polygons captured and drawn using MSS imagery (1972–1983) to those captured with TM/EMT+ imagery (1984–2012), we found that MSS polygons had a slightly higher median (4.6 ha compared to 2.7 ha) but a smaller range than TM polygons (0.5–55.0 ha compared to 0.3–70.1 ha). A

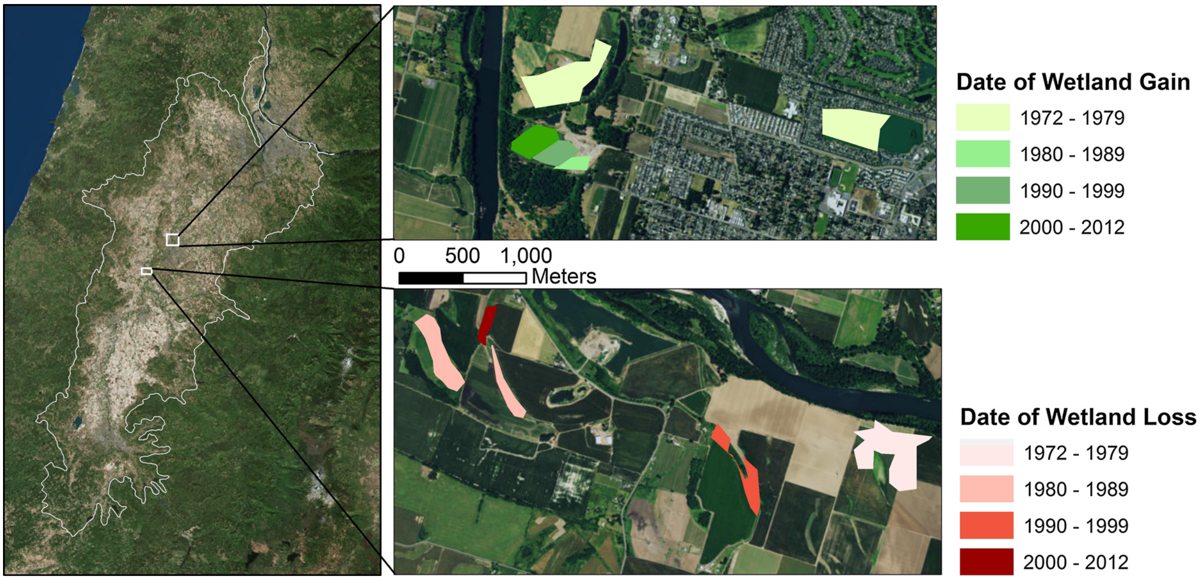

Fig. 5 Map showing sites within the study area where gain and loss of wetland area was observed in all four decades in the study period

single 30 m square pixel and a 60 m square pixel represent 0.09 and 0.36 ha respectively. The minimum polygon captured from TM imagery (0.3 ha) is only slightly smaller than the minimum single-pixel polygon you could capture using MSS data and does not represent a large spatial or informational gap between the two data sets. We can also not factor out other variables that could affect the size of wetland change polygons observed such as climate, policy, or other natural and anthropogenic factors.

The high temporal resolution (one image per year) of our image data not only yielded insight into annual trends of wetland gain and loss, but was also crucial to interpretation of wetlands using Landsat data. Landsat data does not provide the same spatial resolution as aerial imagery, making it more difficult to classify finer categorical wetland and land use classes. To make up for this informational deficiency, we augmented our analysis with high temporal resolution. While our methodology showed Landsat's successful capacity to distinguish between wetland and upland land use types for the purposes of change detection, there are several notable deficiencies. Landsat's spatial resolution limited our ability to distinguish between wetland classes at a finer-scale, such as Cowardin subclasses (Cowardin et al. 1979) or hydrogeomorphic (HGM) classification (Brinson 1993), and led to an aggregation into coarser land use classes. Although annual monitoring of broad wetland classes is a good first step, those interested in gain and loss of specific ecological functions require more detailed cover class information for future studies.

Resulting from the imminent need to develop a methodology that utilizes Landsat imagery to monitor annual wetland change, and the accuracy associated with manual classification, we chose to use visual interpretation instead of an automated approach. However, an automated approach has the potential for increased efficiency, reliability, and repeatability and is necessary if this type of change detection is to be implemented on a larger-scale (Hui et al. 2009). The temporal, spectral, and spatial variability of wetlands, along with the inability to detect specific wetland criteria such as soil inundation period, makes them difficult to detect and classify. It is often challenging to distinguish the boundaries between vegetation habitat types and ensure capture of wetlands (as delineated from the field) rather than "wetland-like" habitats (Schmidt and Skidmore 2003; Zomer et al. 2009; Adam et al. 2010). Ecological variability, combined with the frequent occlusion of wetland vegetation by the reflectance spectra of soil, atmospheric, and hydrologic regimes often associated with these ecosystems, automated classification becomes even more complicated (Guyot et al. 1990; Yuan and Zhang 2006).

Inclusion of intra-annual Landsat images could additionally help improve classification of annual wetland change detection. Wetlands are a land condition, not exclusively cover, and are, therefore, subject to both intra- and inter-annual variations based on hydrology, precipitation, and other climatic factors which could result in false-change detections when using annual imagery (Schroeder et al. 2011). Zhu et al. (2012) developed the Continuous Monitoring of Forest Disturbance Algorithm (CMFDA) and subsequently the Continuous Change Detection and Classification (CCDC) algorithm (Zhu and Woodcock 2013) that use all available cloud-free Landsat pixels in for any usable image (even those with high cloud cover) to characterize forest disturbance (CMFDA) and land cover change (CCDC). The temporal resolution of a single Landsat sensor is 16 days, and this increases to 8 days when utilizing Landsat 5 and 7 (now 7 and 8). CMFDA and CCDC algorithms were created for capturing land cover change, but the concept could be applied for classifying temporally variable wetlands. Inclusion of wet season imagery together with growing season imagery could help to both distinguish between wetland classes and wetlands from upland cover classes and help in classifying and monitoring seasonally and annually variable wetlands such as farmed wetlands. Addition of every clear pixel in monitoring change detection could also give insight to the trends in intra-annual ecosystem variability and link them to policy changes or changing climatic factors.

The launch of Landsat Program's newest satellite, Landsat 8, in February of 2013 holds additional promise in interpreting more complex and detailed wetland classification using Landsat data. The new satellite's Operational Land Imager (OLI) sensor is an upgrade in radiometric resolution with 12-bit quantization (4096 potential grey levels) compared to 8-bit (256 grey levels) in previous sensors (http://landsat.usgs.gov/

landsat8.php). Enhanced signal to noise performance will allow improvements in classification of land cover dynamics and should be explored for more detailed mapping of distinct wetland ecosystems.

Conclusions

By evaluating wetland change from 1972 to 2012 in the Willamette River two-year inundation floodplain using annual Landsat imagery we found that:

- Despite wetland conservation laws dating back to the 1960s, wetlands in our study area experienced annual loss, gain, and type conversion across the entire study period.
- Federal and State laws in 1990 mandating no-net-loss of wetland area helped to slow the rate of annual loss of wetland area as well as create trends in annual gain in area for some wetland types with change in wetland area slowing even more significantly for all wetland types near the end of the study period.
- Higher functioning vegetated wetlands (emergent and riparian) experienced greater loss and less gain than and were replaced in area by non-vegetated (lacustrine and riverine) both before and after stricter policy regarding wetland conservation.
- Manual interpretation of MSS and TM/ETM + Landsat Tasseled Cap imagery worked well for capturing annual change in wetland area for broader wetland categories.
- Little spatial detail was sacrificed by using MSS data and 12 years of important annual data was gained through its use.
- Temporal context through annual imagery, ancillary data layers, and Google Earth were valuable and necessary for manual interpretation of wetland change in a spectrally and temporally dynamic agricultural setting.

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Appendices

Appendix 1

Here we describe in detail our methods for converting tasseled cap coefficients for MSS data.

We used TC coefficients for TM reflectance factor data (Crist and Cicone 1984) for both the TM and ETM+ data (Cohen et al. 2003) after first deriving surface reflectance for each TM and ETM+ image using LEDAPS (Masek et al. 2006). There is no similar set of coefficients for MSS reflectance factor data, requiring a calibration of the MSS data to the TM/ETM+ time series. To integrate MSS data with TM/ETM+, we used random forest regression (Breiman 2001) to predict TM TC brightness, greenness, and wetness (y-variables) directly from the MSS band 1–4 spectral data (x-variables) with coincidently acquired Landsat 4 MSS and Landsat 5 TM images from 1987 (Main-Knorn et al. 2013). The derivation of pseudo-wetness for MSS data is new, and was chosen over the derivation of TC angle (Gómez et al. 2012; Pflugmacher et al. 2012) for our study because we wanted to maintain the wetness index from TM/ETM+ for our time series. When evaluating the goodness of fit for the predicted TC coefficients, we examined scatterplots for general correlation, but put most emphasis on image appearance consistency both within the MSS images themselves and compared to the TM/ETM+ images through time. Although imperfect, the results were more than sufficient for consistent visual interpretation across the time series. Once the time series was compiled, we applied a two-standard deviation stretch to each image to enhance visual image contrast.

Appendix 2

Here we describe our workflow and methods to manually interpret annual wetland losses and gains associated with land use change.

During interpretations of a given subarea, three software applications were open: TimeSync (Cohen et al. 2010), ArcMap, and Google Earth. TimeSync and ArcMap were complementary in their use. Within TimeSync the 41 annual Landsat TC image “chips” for the subarea were simultaneously displayed, and was thus best for interpretation of wetland gain and loss and land use change (given ArcMap does not have this functionality). Additionally, within ArcMap were two data layers that assisted in the interpretation process by spatially limiting the interpretations, including the 1 m lidar inundation map and a shapefile of the main stem of the Willamette River and its tributaries within the floodplain created from the Pacific Northwest Hydrogaphy Framework's Oregon Water Courses shapefile. Within Google Earth were historic image snapshots of each subarea and the inundation map (defined by kmz files), which assisted in confirming and identifying wetland gain and loss and land use change within the relevant interpretation area. The availability and temporal resolution of historical imagery in Google Earth varied depending on location.

We interpreted the study area one subarea at a time moving east to west from south to north. Wetland gain was interpreted as new wetland land use derived from a different land use category and loss was any wetland area that was converted to a different land use during the time period defined by the Landsat time series. Wetland-to-wetland conversion was also interpreted and classified as wetland area that was converted to a different wetland type (e.g. riparian to emergent). When interpreting change polygons, three attributes were selected from drop down menus in the attribute table: date when change was first detected, starting land use, and ending land use.

Area and perimeter of each drawn polygon were calculated within ArcMap. Our workflow required an average of 39 min per subarea, ranging between 10 and 90 min, with the biggest factors being the geometric area of the floodplain located within the subarea and the number and complexity of wetland losses and gains.

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