Late 20th Century Land Change in the Central California Valley Ecoregion

Ben Sleeter
U.S. Geological Survey, Menlo Park, CA

Abstract

This research challenges two general assumptions of land-cover change in California's Central Valley ecoregion. They are (1) the primary land-cover change occurring in urbanization of agricultural lands, and (2) that the ecoregion experienced a rapid decline in farmland between 1973 and 2000. Our findings indicate that while urbanization is significant, it is secondary to conversions occurring between agriculture and rangelands (grasslands/shrublands). Furthermore, we estimate that farmland increased in area over the study period, expanding from 71.6% of the ecoregion in 1973 to 72.4% in 2000, a net increase of 357 km^2. New agricultural lands were often found at the ecoregion periphery in the form of nut orchards and grapes, indicating a general shift away from traditional low-risk and low-value field crops to high-risk and high-value specialty crops. Rangeland is estimated to have declined by nearly 20%, from 19.2% of the ecoregion in 1973 to 15.4% in 2000, while developed lands increased from 6.5% to 9.0% over the same time period. Changes between agriculture and rangeland accounted for over 70% of all estimated change, while changes directly associated with urbanization accounted for approximately 14% of all identified land-cover change. Across all land-cover classes, we estimated that 12.4% of the ecoregion changed from one land-cover type to another during the 27-year study and that the period of highest change was between 1973 and 1980. Many drivers may explain these results, including the influence of regional climate variability and drought. This research suggests that drought, if severe enough over an extended number of years, has the potential to significantly influence rates and types of regional land-cover change. Understanding these coupled human-environment relationships has implications for monitoring biogeochemical systems, natural resources, and ecosystem services at local to regional scales.

Introduction

Since the early 1970s, space-borne satellite imaging has facilitated the understanding of complex socio-environmental systems. The ability to analyze large amounts of spectral information regarding landscape condition has enabled researchers to gain perspective of earth-surface processes at multiple spatio-temporal resolutions. Space-borne imaging systems have been used to study Earth systems, including atmospheric and climate processes, ocean surface conditions, and quantification of landscape composition. Furthermore, there is an extensive body of scientific literature describing methods and efforts to detect and quantify land-use and land-cover change (LULCC) at various spatial and temporal scales. Despite the widespread use and acceptance of satellite remote-sensing techniques, there is generally a lack of comprehensive and consistent spatio-temporal information on the rates and types of LULCC.

In 1999 the National Research Council issued a report titled *Measures of Environmental Performance and Ecosystem Condition*, which emphasized a need for data on land-use and land-cover change (NRC 1999). In 2000 an NRC report titled *Ecological Indicators for the Nation* identified land use as the single largest driver of ecological change (NRC 2000). In 2000, at the request of the National Science Foundation, the NRC was tasked with identifying the grand challenges in Environmental Science and determined land-use dynamics to be one of eight grand challenges within the context of environmental problems. The NRC report identified LULC changes as "…major contributors to global climate change, to the loss of global biotic diversity, and to the reduced functioning of ecosystems and the essential services they provide to humans" (NRC 2001). Furthermore, the NRC identified important areas for research, the first being development of long-term, regional databases for land uses, land covers, and related social information (NRC 2001). Foley et al. (2005) contend that changes in land use have necessitated consumption of an increasing share of global resources at the potential expense of the capacity of ecosystems to sustain food production, maintain water and forest resources, regulate climate and air quality, and ameliorate infectious diseases.

While changes in LULC are generally recognized as having important influences on climate and air quality at multiple scales (Foley et al. 2005) with direct linkages to the fluid global systems of the biosphere (Turner and Meyer 1991), the role of LULCC and variability in altering regional temperatures, precipitation, vegetation, and other climate variables has been mostly ignored by the Intergovernmental Panel on Climate Change (Pielke 2005). Feddema et al. (2005) conclude that most significant regional climate effects are associated directly with land-cover conversions in mid-latitude and tropical areas and demonstrate that land-cover effects can significantly alter regional climate outcomes associated with global warming. Their results demonstrate the importance of including LULCC in forcing scenarios for future climate-change studies. Undertaken at various spatial and temporal scales, research in LULCC is needed to improve understanding of patterns and dynamics that affect the structure and function of Earth systems consistent with global environmental change (Rindfuss et al. 2004).

In response to the need for regional information describing LULCC, the U.S. Geological Survey (USGS) and U.S. Environmental Protection Agency (EPA) developed a regionally consistent approach, using an analysis framework based on EPA Level III Ecoregions (Omernik 1987; EPA 1999), to determine the rates, causes, and consequences of late 20th century LULCC for the conterminous United States (Loveland et al. 2002). This article describes efforts to detect, quantify, and describe LULCC change in the Central California Valley ecoregion (Central California Valley or "Central Valley") (Omernik 1987; EPA 1999).

Central California Valley ecoregion

The Central Valley is an elongated alluvial valley running north to south in excess of 650 km, with an average width of approximately 50 km (Figure 1). Agriculture is the dominant land cover found in the ecoregion and comprises approximately 70% of total land area (Vogelmann et al. 2001). Six of California's top eight agricultural counties are found at least partially within the Central Valley and are all located in the southern portion of the ecoregion (USDA 2008a). Major commodities produced in the Central Valley include milk and cream, grapes, almonds, cattle and calves, tomatoes, cotton, walnuts, and rice. California leads the nation in production of nearly 80 crops, including almonds, American Pima cotton, grapes (raisin, table, and wine), alfalfa, lettuce, lemons, milk, olives, tomatoes, and walnuts (USDA 2008a). California has led the nation every year since 1948 in agricultural cash receipts, recording $31.7 billion in 2005 (Sumner, Bervejillo, and Kuminoff 2003; USDA 2008b). A thorough discussion of the evolution of California agriculture can be found in Olmstead and Rhode (2003).

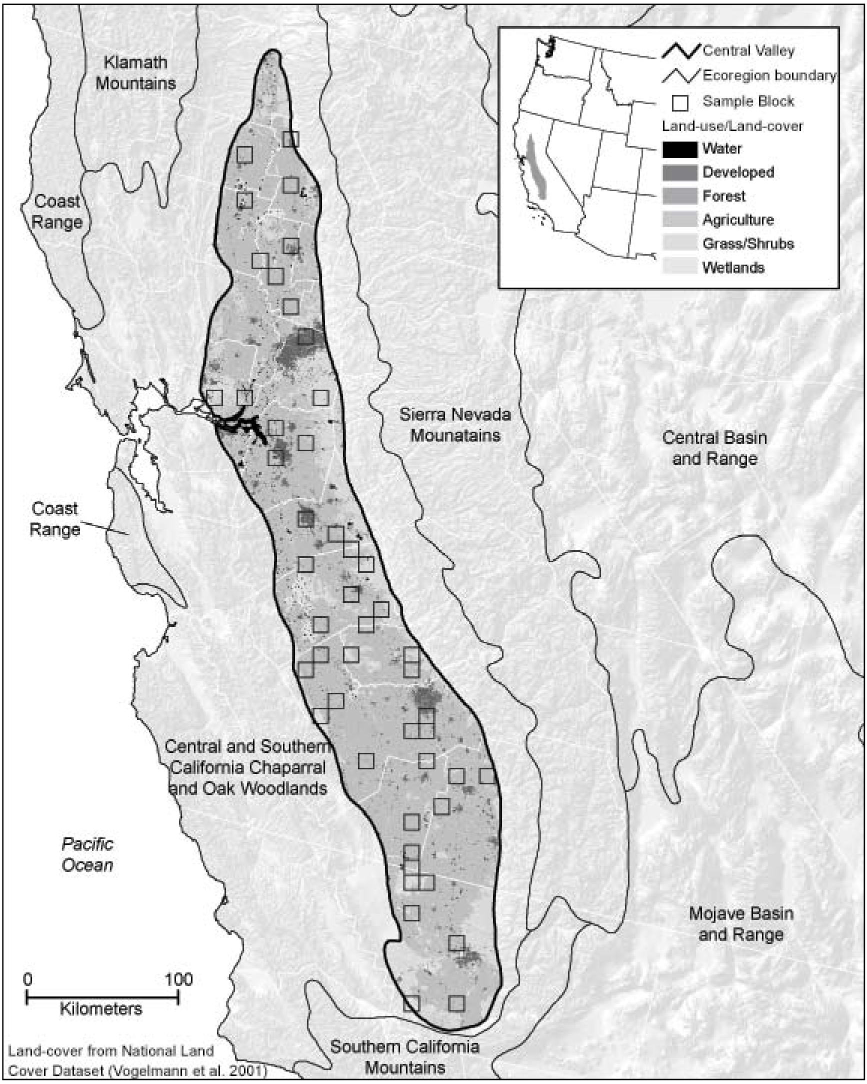


Figure 1.—Location map of the Central California Valley ecoregion, with ecoregion (Omernik 1987) and stratum boundary. Ecoregion stratum boundary is defined as the extent of all 10 km grid cells assigned to the Central California Valley ecoregion. Also present are the 48 randomly selected 10 km x 10 km sample blocks used for analysis in this research project.

The Central Valley is surrounded by the Oak Woodlands ecoregion (Figure 1). The transition between these two regions is characterized by gently sloping foothills dominated by grasslands and oak savannah (Figure 2). Due to the generalization of ecoregional boundaries,

Figure 2.—The transition area between the Central California Valley and Central and Southern California Chaparral and Oak Woodlands ecoregions (Omernik 1987). This region is characterized by gently rolling hills, typically dominated by grasslands and oak savannahs. (Photograph by Christian Raumann, 18 May 2006.)

there are numerous areas where grassland-oak woodland savannahs are found within the Central Valley ecoregion, although they are not the primary landscape naturally occurring to the region. In these areas, livestock grazing has been the traditional land use, along with irrigated and dry-land cropping. Agriculture that does have a presence at the ecoregion periphery includes citrus, nut crops such as almonds and walnuts, and vineyards.

Grasslands/shrublands are not limited to the Central Valley ecoregion periphery, and at one time, prior to European settlement, they dominated the ecoregion's land cover. While agricultural development and expansion since the mid-19th century has largely removed most of the native grasslands, wetlands, and desert shrubs common to the ecoregion, the U.S. Fish and Wildlife Service manages numerous wildlife refuges and wildlife management areas where grasslands still exist (Figure 3).

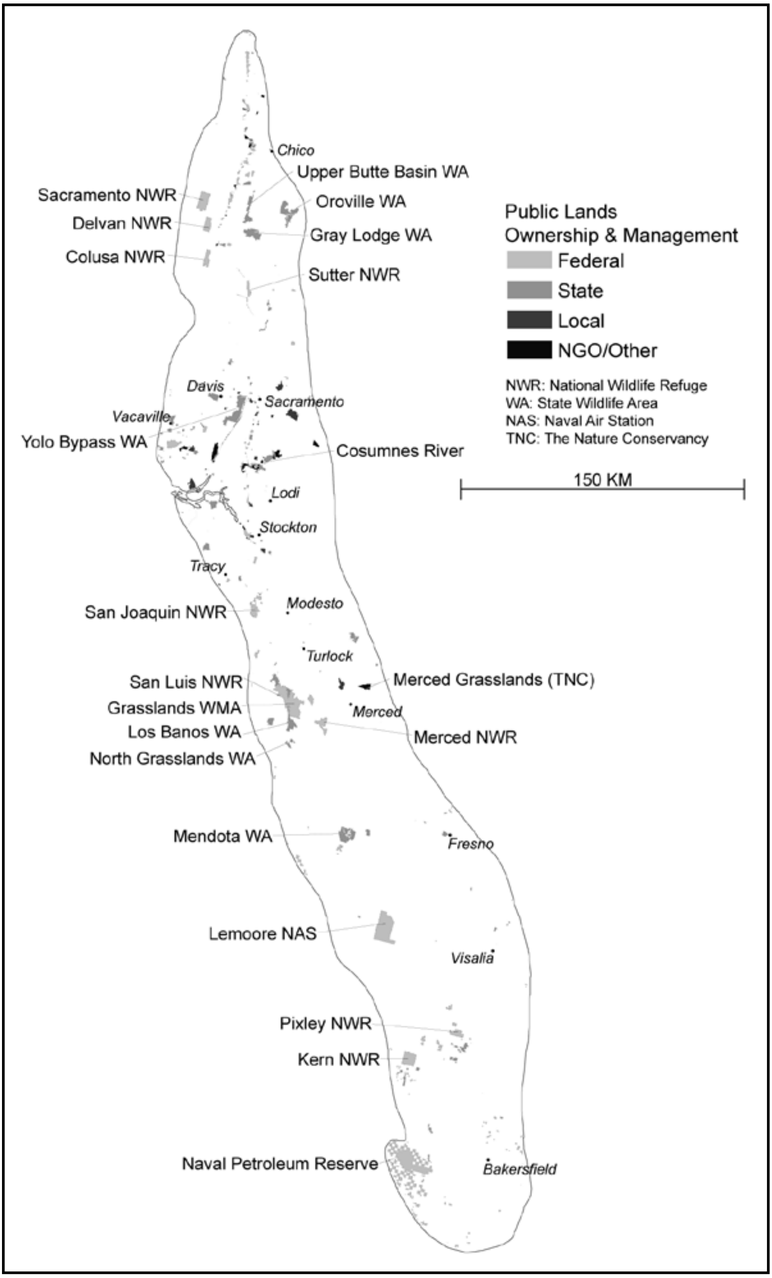


Figure 3.—State and federally managed wildlife and other "natural" areas within the CCV ecoregion. Organizations representing waterfowl interests, such as Ducks Unlimited and the California Waterfowl Association, also play an active role in management of wetlands and other critical wildlife habitat areas.

Developed land uses in the Central Valley have been increasing since gold was discovered at Sutter's Mill in 1848. There are two major developed corridors in the region, both following the major transportation routes through the ecoregion. Highway 99, running north to south along the eastern edge of the ecoregion connects Bakersfield, Fresno, Modesto, Stockton, and Sacramento, while Interstate 80 joins Sacramento, Davis, Vacaville, and Fairfield with the San Francisco Bay Area. Significant growth has also occurred at Los Banos, which serves as a commuter shed for San Jose and Silicon Valley. U.S. Census estimates that in 2000, more than five million people resided in the ecoregion, adding more than a million residents in every decade since 1970 (U.S. Bureau of Census 2008) (Figure 4).

Methods

The Land Cover Trends project (referred to as "Trends") was developed to answer fundamental questions about the rates, causes, and consequences of land-cover change at a regional scale for the conterminous United States, while providing a baseline for future regional land-cover change research (Loveland et al. 2002). While other projects provide a data product or "snap shot" of land cover at a single interval (e.g., National Land Cover Dataset [Vogelmann et al. 2001]), the objective of Trends is to establish a temporal framework that is applied consistently across the nation for the purpose of comparative analysis, so as to understand the spatial and temporal variability associated with land change. Ideally, a wall-to-wall mapping effort would have been undertaken to accomplish this goal of providing LULCC information for the nation. However, such an approach, carried out at a regional scale, would be too costly and time prohibitive. To overcome these obstacles, a sampling approach was employed, using an ecoregion framework, to categorize local to regional landscape change (Stehman, Sohl, and Loveland 2003). Trends provides estimates of land-cover composition and change at the regional scale through the identification of local processes. Following is a brief description of the Trends methodology. For a complete description, see Loveland et al. (2002), Stehman, Sohl, and Loveland (2003), and Sohl, Gallant, and Loveland (2004).

Ecoregion Stratification

EPA Level III Ecoregions of the United States (Omernik 1987; U.S. Environmental Protection Agency 1999) were chosen to stratify the conterminous U.S. into primary reporting units. Ecoregions are char-

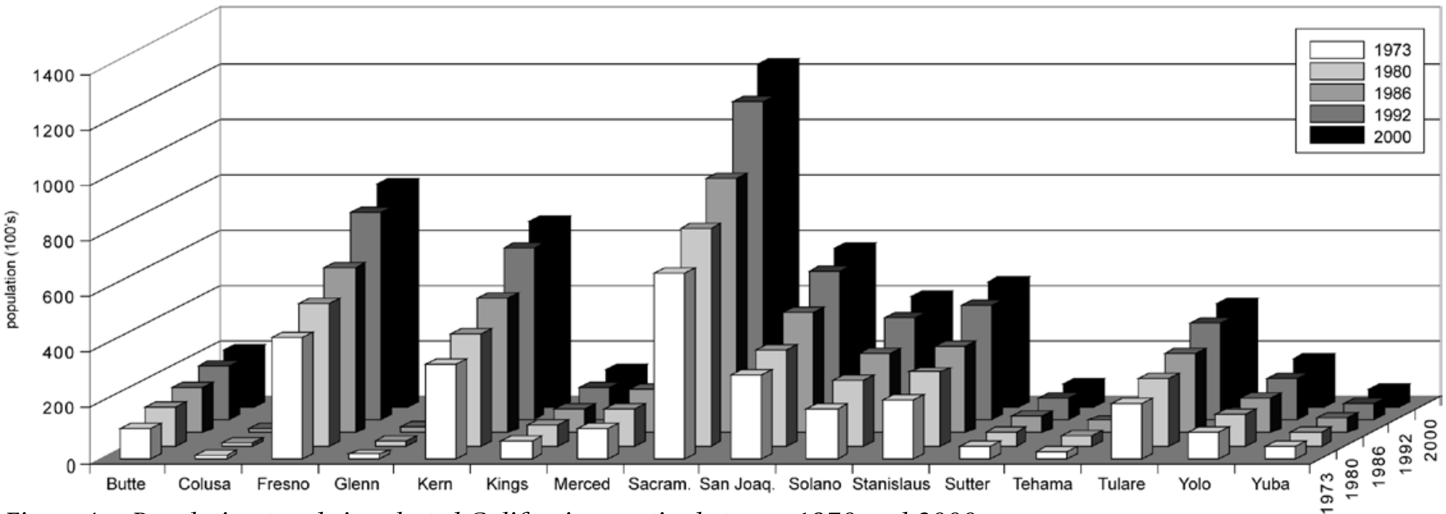


Figure 4.—Population trends in selected California counties between 1970 and 2000.

acterized by the range and availability of resources and thus reflect areas of relative homogeneity corresponding well with patterns of land cover, urban settlement, agricultural variability, and resource-based industries (Gallant et al. 2004). While other stratifications exist, Omernik ecoregions were chosen because they incorporate primary land use into the identification of regional boundaries (Omernik 1987; Loveland et al. 2002; Gallant et al. 2004).

Sampling Design

A pure panel sampling design was used where selected samples were the same for all time periods (Fuller 1999; Stehman, Sohl, and Loveland, 2003). Spatially, a stratified one-stage cluster sample was used where the clusters were 10 km by 10 km spatial units (hereinafter called “10 km blocks”). Within each 10 km block, features equal to or larger than a minimum unit of 60 m by 60 m were mapped. The 10 km blocks serve as the primary sampling unit (PSU), and the 60 m pixels serve as secondary sampling units (SSU). A fixed grid of 10 km blocks was overlain across the conterminous United States. Ten-kilometer blocks were then stratified geographically using EPA Level III Ecoregions and assigned to an ecoregion based on center-point location. The collection of 10 km blocks assigned to an ecoregion, or “stratum,” corresponds closely, but not exactly, to the irregular shape of the ecoregion boundary. For this reason, we report results in this article for the stratum (i.e., the extent of all blocks assigned to an ecoregion; hereinafter Central Valley stratum or stratum) as opposed to the ecoregion. Next, a random sample of PSUs is selected with the *a priori* goal of estimating LULCC at ± one percent for an 85% confidence interval (Loveland et al. 2002).

Based on ecoregion size and expected LULC change and variability, sampling for the Central California Valley ecoregion consisted of 48 sample blocks (out of a total population of 458) (Figure 1). In addition to being randomly selected, sample blocks were assigned to image interpreters at random to reduce interpretative bias. Upon completion of interpretation of all sample blocks for an ecoregion, a consistency check was performed to identify illogical conversions followed by a peer review of mapping work. When compared to complete area coverage efforts, sampling is often the preferred method due to reduced costs, timely reporting, and comparable levels of uncertainty (Cochran 1977; Sohl, Gallant, and Loveland 2004). For a complete discussion of uncertainty associated with the Land Cover Trends sampling approach and uncertainty associated with a census approach, see Stehman (2005).

Data Sources

Five dates of Landsat imagery were used as reference images for detection of LULC change. Due to the cost typically associated with collection of these data at a national scale, several existing databases were leveraged to minimize data acquisition expenditures and ensure relatively high-quality, cloud-free scenes. Temporal center points were identified based on availability of existing Landsat data collections, namely the North American Landscape Characterization (NALC) Program (Sohl and Dwyer 1998) and the Multi-Resolution Land Characteristics (MRLC) Consortium (Loveland and Shaw 1996). NALC data holdings consisted of three dates of Landsat MSS imagery centered on 1973, 1986, and 1992. These data were re-sampled to a 60 m spatial resolution and projected to an Albers conical equal area projection. MRLC data consists of Landsat TM and ETM imagery at a 30 m spatial resolution centered on years 1992 and 2000. To supplement the imagery available from these two national programs and ensure a consistent 6- to 8-year temporal interval, a new data acquisition was made for Landsat MSS centered on year 1980. The new 1980 MSS images were also referenced to the Albers projection with a pixel resolution of 60 m. Terrain correction was applied to each new 1980 image to ensure proper co-registration between image dates. The final Trends Landsat database then consisted of images centered typically ± 2 years of 1973, 1980, 1986, 1992, and 2000 (Table 1).

Table 1: Landsat database used for Land Cover Trends research project.

INTERVAL	LANDSAT SENSOR	DATABASE	SPATIAL RESOLUTION
1973	MSS	NALC	60 meter
1980	MSS	New Acquisition	60 meter
1986	MSS	NALC	60 meter
1992	MSS; TM	NALC; MRLC	60 meter; 30 meter
2000	ETM	MRLC	30 meter

Classification Approach

The National Land Cover Dataset (NLCD) (Vogelmann et al. 2001) was chosen to serve as a reference product to derive an initial land-cover classification. The NLCD data was recoded from its original 21 Anderson level II classes to a modified Anderson level I scheme to meet LULC change mapping needs (Anderson et al. 1976). For the southwest region, NLCD level I overall accuracy was 85% with a standard error of 2% (Wickham et al. 2004). The 11 broad land-cover classes chosen were: water, developed or built-up, mining, barren, forest, grasslands and shrublands (rangeland), agriculture, wetlands, perennial snow and ice, mechanical disturbance (timber cutting and scraping and leveling of land prior to development), and non-mechanical disturbance (fire, storms, pest-infestations etc.).

Manual interpretation was used to partition land cover into one of 11 land-cover classes, based on the Anderson Level I classification system (Anderson et al. 1976). Interpretation of Landsat imagery was facilitated with the use of ancillary data such as aerial photographs, topographic maps, and other spatially explicit sources of information. The 1992 NLCD (Vogelmann et al. 2001) was used as a land-cover reference point. While NLCD provides a decent starting point for LULCC mapping, it is not appropriate in its original form for use at the local scale. Due to the "speckled" nature of NLCD, interpreters commonly had to clean up the product or start with an entirely new land cover interpretation, which LULCC mapping was based upon. Image interpreters used the 1992 Landsat TM image, as well as other ancillary data sources such as aerial photographs, to derive a suitable land-cover product for the 1992 date. Once land cover was mapped for the 1992 period, interpreters forward- and backward-classified LULCC for the remaining four dates. This was accomplished by comparing Landsat images from successive dates and visually identifying areas of LULCC. Upon completion of mapping, change estimates were generated using post-classification comparison of LULC products from the multiple dates.

Sample block change products provide estimates of land-cover change with defined bounds of uncertainty in three different categories. *Net change* is the difference in area of a land-cover class between time *t* and *t-1*. *Gross change* is the total area that changed (i.e., gains plus losses) in a given land-cover class between time *t* and *t-1*. The third type of change is *conditional gross change*. For example, of the area that was classified as developed in time *t*, how much of that area was agriculture in time *t-1*, how much of that area was grasslands/shrublands in time *t-1*, etc.? Formulas to estimate net, gross, and conditional gross change and corresponding margins of error can be found in Stehman, Sohl, and Loveland (2003).

Results

Spatial Area Change

Gross spatial area change (or "footprint") for the Central California Valley ecoregion, meaning the percent of stratum area that changed land-cover type at least one time between 1973 and 2000, was estimated at 12.4% of stratum area (5,670km^2) with a margin of error of 3.0% (±1,351 km^2) for an 85% confidence interval (Table 2).

Table 2: Gross spatial area change, 85% confidence interval, standard error, and relative error for the Central California Valley ecoregion.

			MARGIN OF ERROR (85% CI)				
	FOOTPRINT OF CHANGE	% of ECOREGION	+/- (%)	LOWER BOUND	UPPER BOUND	STANDARD ERROR	RELATIVE ERROR
(1973–2000)	*ALL CHANGE*	*12.4%*	*3.0%*	*9.4%*	*15.3%*	*2.0%*	*16.3%*
	1 Change	9.3%	2.0%	7.3%	11.2%	1.3%	14.4%
	2 Changes	2.5%	1.3%	1.3%	3.8%	0.9%	34.5%
	3 Changes	0.6%	0.2%	0.3%	0.8%	0.2%	27.2%
	4 Changes	0.0%	0.0%	0.0%	0.0%	0.0%	36.2%

Most locations changed only once (74.8% of gross change; 4,241 km^2). Multiple changes (i.e., pixels changing two, three, or four times) accounted for the remaining 25.2% of gross change, or 1,429 km^2. Table 2 shows the breakdown of estimated spatial area change with associated margins of error, lower and upper bounds, and standard and relative error. Relatively low standard error indicates high levels of confidence in gross spatial area change estimates.

Gross Change by Interval

Gross change was also estimated for each temporal interval. The period 1973 to 1980 had the highest estimated change, with 5.7% of the stratum (2,615 km^2) changing from one land-cover type to another between the two dates. The 1980 to 1986 interval was estimated at 3.3% (1,498 km^2); the 1986 to 1992 interval at 3.0% (1,388 km^2); followed by the 1992 to 2000 period at 4.1% change (1,873 km^2). Net change estimates, margins of error, lower and upper bounds, standard error, and relative error can be found in Table 3.

Table 3: Estimated change by temporal period, 85% confidence interval, standard error, relative error, and estimated normalized average annual change given as both percent of stratum area and in square kilometers.

% stratum		85% CONFIDENCE INTERVAL					
	% of ECOREGION	+/- (%)	LOWER BOUND	UPPER BOUND	STANDARD ERROR	RELATIVE ERROR	AVERAGE ANNUAL %
1973 to 1980	5.7%	1.4%	4.3%	7.1%	1.0%	17.1%	0.8%
1980 to 1986	3.3%	0.8%	2.4%	4.1%	0.6%	17.6%	0.5%
1986 to 1992	3.0%	1.2%	1.8%	4.3%	0.8%	27.5%	0.5%
1992 to 2000	4.1%	1.3%	2.8%	5.4%	0.9%	22.4%	0.5%

km^2		85% CONFIDENCE INTERVAL					
	ECOREGION AREA	+/- (km^2)	LOWER BOUND	UPPER BOUND	STANDARD ERROR	RELATIVE ERROR	AVERAGE ANNUAL km^2
1973 to 1980	2615	655	1960	3266	1.0%	17.1%	376
1980 to 1986	1498	385	1113	1882	0.6%	17.6%	247
1986 to 1992	1388	559	829	1951	0.8%	27.5%	234
1992 to 2000	1873	614	1260	2482	0.9%	22.4%	234

Due to the varying lengths of temporal intervals, temporal comparison of change estimates was accomplished by calculating average annual estimates of change for each period. This is accomplished by simply dividing the estimated change rate by the length of the temporal interval. Average annual change was highest between 1973 and 1980, at an estimated 0.8% (376 km^2) per year, while the following three intervals remained relatively constant at 0.5% (247 km^2) per year for the 1980 to 1986 period and 0.5% for both the 1986 to 1992 and 1992 to 2000 intervals (231 km^2 and 231 km^2, respectively).

To determine whether there was a statistically significant difference between change estimates for the four temporal intervals, a Wilcoxon test (Wilcoxon 1945) was used to determine to what extent the difference in mean rank of change estimates is significant. Statistically significant differences were observed where $P<0.05$, that is, the probability that the observed difference could be the result of random fluctuations in the variables (i.e., estimates of change in two intervals), indicating that estimates of change for the 1973 to 1980 interval were in fact different from the other three intervals, while comparison of the last three intervals does not reveal any statistical difference. This indicates that the rate of gross change was relatively stable between 1980 and 2000, showing very little variability between temporal periods.

Net Change

Change in individual land-cover types, or net change, is measured at the stratum scale. The land-cover class with the largest change was the grasslands/shrublands class, with an estimated loss of 1,775 km^2. That is, 19.2% of the stratum was grasslands/shrublands in 1973 and decreased to 15.4% by 2000 (Table 4). The second largest net change was an estimated increase of 1,124 km^2 of developed lands (2.5% of stratum area) over the 27-year study period. Agriculture is estimated to have accounted for 71.6% of stratum area in 1973, increasing to 72.4% of stratum area in 2000. Net changes for each LULC class by temporal center point with associated margins of error can be found in Table 4. While net change is an important measure of change across the stratum, it is important to note that it does not reflect the dynamic nature of change over time. Only changes in the developed class followed a typical linear trend, increasing in area in each interval. The agricultural and grassland/shrubland classes experienced significant amounts of gains and losses within each interval and are masked by the net change values.

Testing for statistical significance of LULCC trends over the entire 27-year study period was done for two types of trends, linear and quadratic. A Wilcoxon test (Wilcoxon 1945) was applied to each LULC class to obtain probabilities of the trend being the result of random fluctuations of the percent land cover estimates. The developed, mechanical disturbed, and grassland/shrubland classes were statistically significant linear trends, with $P<0.05$. The grassland/shrubland class was also significant as a quadratic trend, at a significance level of $P<0.05$. The agriculture class was significant as a quadratic trend, at a significance level of $P<0.10$. Trends in LULCC over the study period were not significant in any of the other classes at the $P<0.10$ level, meaning trends in minor land-cover classes could not be measured with any statistical certainty, although those

Table 4: Land cover class estimates for each class in each date presented in percent of stratum and in absolute area (km²).

* Linear trend significance. P values less than 0.05 indicate significance at the alpha=0.05 level.
** Linear trend significance. P values less than 0.10 indicate significance at the alpha=0.10 level
^{t} Quadratic trend significance. P values less than 0.05 indicate significance at the alpha=0.05 level.
^{tt} Quadratic trend significance. P values less than 0.10 indicate significance at the alpha=0.10 level.

%	WATER		DEVELOPED*		MECH. DIST.*		MINING		BARREN		FOREST		GRASS/ SHRUB*^{t}		AGRICUL- TURE^{tt}		WETLAND	
	%	85% CI	%	85% CI	%	85% CI	%	85% CI	%	85% CI	%	85% CI	%	85% CI	%	85% CI	%	85% CI
1973	0.7%	0.3%	6.5%	3.1%	0.0%	0.0%	0.2%	0.1%	0.0%	0.0%	0.3%	0.1%	19.2%	5.1%	71.6%	5.8%	1.4%	1.0%
1980	0.7%	0.3%	7.2%	3.4%	0.1%	0.0%	0.2%	0.1%	0.0%	0.0%	0.3%	0.1%	17.7%	4.9%	72.3%	5.7%	1.6%	1.1%
1986	0.8%	0.5%	7.6%	3.5%	0.1%	0.0%	0.2%	0.2%	0.0%	0.0%	0.3%	0.1%	16.7%	4.7%	72.8%	5.6%	1.7%	1.2%
1992	0.7%	0.3%	8.2%	3.7%	0.1%	0.1%	0.2%	0.2%	0.0%	0.0%	0.3%	0.1%	17.3%	5.0%	71.5%	5.8%	1.7%	1.2%
2000	0.9%	0.5%	9.0%	3.8%	0.2%	0.1%	0.2%	0.2%	0.0%	0.0%	0.3%	0.1%	15.4%	4.4%	72.4%	5.6%	1.7%	1.2%
Change	0.2%		2.5%		0.1%		0.0%		0.0%		0.0%		-3.9%		0.8%		0.3%	

km²	WATER		DEVELOPED*		MECH. DIST.*		MINING		BARREN		FOREST		GRASS/ SHRUB*^{t}		AGRICUL- TURE^{tt}		WETLAND	
	km²	85% CI	km²	85% CI	km²	85% CI	km²	85% CI	km²	85% CI	km²	85% CI	km²	85% CI	km²	85% CI	km²	85% CI
1973	299	142	2984	1438	17	9	79	64	2	0	156	60	8806	2345	32803	2666	655	458
1980	328	151	3280	1553	29	18	86	64	2	0	147	60	8097	2221	33116	2597	715	499
1986	358	206	3462	1603	24	14	86	69	2	0	146	55	7641	2148	33324	2546	758	536
1992	322	156	3740	1681	36	27	90	73	3	0	145	55	7933	2276	32764	2670	768	545
2000	411	215	4108	1740	74	37	95	78	2	0	142	55	7031	2034	33160	2551	777	559
Change	112		1124		57		16		0		-14		-1774		357		122	

minor classes combined accounted for less than 2.5% of the entire ecoregion area.

Common Conversions

An understanding of where changes in LULC are coming from and going to can be obtained by examining the most common land-cover conversions. The most common conversion was 3,334 km^2 of grasslands/shrublands converting to agriculture, followed by 1,965 km^2 of agriculture converting to grasslands/shrublands, 684 km^2 of agriculture changing to developed, and 366 km^2 of grasslands/shrublands converting to developed. Combined, these four changes accounted for 86.1% of all estimated change in the stratum. The most common conversions were also calculated for each temporal interval and are presented in Table 5.

In three of the four temporal intervals, grassland/shrublands converting to agriculture was the largest individual conversion, accounting for nearly 50% of all estimated change. While this particular conversion was common in all temporal intervals, it was less common between 1986 and 1992, when it was outpaced by agriculture converting to grassland/shrublands (Figure 5). During this interval, agriculture to grassland/shrublands accounted for an estimated 48.6% of all change (675 km^2), while grassland/shrubland converting to agriculture dropped to 19.5% of total estimated change (271 km^2) (Figure 6). Rainfall records from the same temporal interval indicate a period of long-term, below-average annual precipitation that is believed to have had significant impacts on land use.

During all temporal periods, change from agricultural to developed consistently ranked in the top three land-cover conversions. This conversion was closely followed by grassland/shrublands changing to developed. Over the course of the entire 27-year study period, we estimate 684 km^2 of pasture and/or cropland changed to developed uses, while an additional 366 km^2 converted from grassland/shrubland to developed. The intervals with the highest average annual increase in developed were 1986–1992 and 1992–2000, with an estimated 0.10% of the stratum area (45.8 km^2) changing to developed uses every year. Table 6 shows the total estimated area converted to developed uses from all other classes for each of the four temporal periods.

Table 5: Top five land cover conversions (area), margin of error, and standard error for each interval and overall.

Period	From class	To class	Area changed (km²)	Standard Error (km²)	85% CI +/- (km²)	% of ecoregion	% of all changes
1973–1980	Grass/Shrub	Agriculture	1305	316	462	2.8%	49.9%
	Agriculture	Grass/Shrub	748	240	351	1.6%	28.6%
	Agriculture	Developed	177	64	94	0.4%	6.8%
	Grass/Shrub	Developed	106	51	75	0.2%	4.1%
	Agriculture	Wetland	71	63	92	0.2%	2.7%
	Other classes	Other classes	208	n/a	n/a	0.5%	8.0%
			2615			5.7%	100.0%
1980–1986	Grass/Shrub	Agriculture	734	188	275	1.6%	49.0%
	Agriculture	Grass/Shrub	316	122	176	0.7%	21.1%
	Agriculture	Developed	98	35	52	0.2%	6.5%
	Grass/Shrub	Developed	71	29	43	0.2%	4.7%
	Agriculture	Water	57	47	68	0.1%	3.8%
	Other classes	Other classes	222	n/a	n/a	0.5%	14.8%
			1498			3.3%	100.0%
1986–1992	Agriculture	Grass/Shrubs	675	314	460	1.5%	48.6%
	Grass/Shrub	Agriculture	271	81	119	0.6%	19.5%
	Agriculture	Developed	160	53	77	0.3%	11.5%
	Grass/Shrub	Developed	101	33	49	0.2%	7.3%
	Water	Agriculture	44	39	58	0.1%	3.2%
	Other classes	Other classes	137	n/a	n/a	0.3%	9.9%
			1388			3.0%	100.0%
1992–2000	Grass/Shrub	Agriculture	1024	366	536	2.2%	54.7%
	Agriculture	Developed	249	99	146	0.5%	13.3%
	Agriculture	Grass/Shrub	225	69	101	0.5%	12.0%
	Grass/Shrub	Developed	89	32	46	0.2%	4.8%
	Agriculture	Mech. Disturbed	62	26	37	0.1%	3.3%
	Other classes	Other classes	224	n/a	n/a	0.5%	12.0%
			1873			4.1%	100.0%
Overall:							
1973–2000	Grass/Shrub	Agriculture	3334	792	1160	7.3%	45.2%
	Agriculture	Grass/Shrub	1965	656	960	4.3%	26.6%
	Agriculture	Developed	684	198	289	1.5%	9.3%
	Grass/Shrub	Developed	366	123	181	0.8%	5.0%
	Agriculture	Wetland	165	145	213	0.4%	2.2%
	Agriculture	Water	136	88	129	0.3%	1.8%
	Agriculture	Mech. Disturbed	112	45	65	0.2%	1.5%
	Grass/Shrub	Water	99	41	61	0.2%	1.3%
	Water	Agriculture	77	33	49	0.2%	1.0%
	Water	Grass/Shrub	59	40	59	0.1%	0.8%
	Other classes	Other classes	377	n/a	n/a	0.8%	5.1%
			7374			16.1%	100.0%

Figure 5.—Large area of natural grassland/shrubland just north of Kern National Wildlife Refuge in northern Kern County. It was common for parcels in this area to change between natural covers and irrigated agriculture during our study period. (Photograph by Benjamin Sleeter, 18 September 2004.)

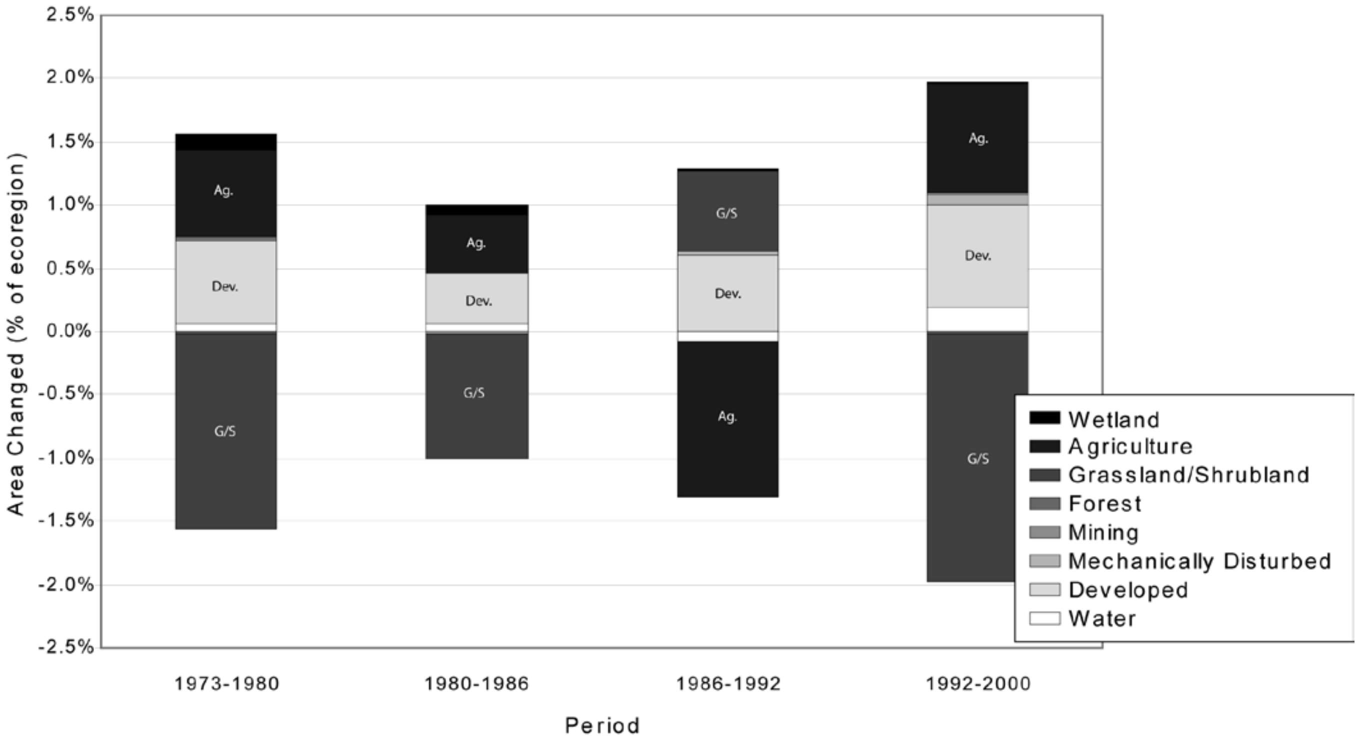


Figure 6.—Net changes in selected land-cover classes for the four temporal intervals. Agriculture had a net increase in each of the four intervals, with the exception of 1986–1992, where losses in agricultural lands outpaced gains. Trends in the grassland/shrubs class followed an inverse relationship and between 1986 and 1992 gains outpaced losses. Significant increases in development were estimated for each of the four intervals.

Table 6: Estimates of change to developed uses.

INTERVAL	% CHANGE	km^2	STANDARD ERROR	RELATIVE ERROR	+/- 85% CI	LOWER BOUND	UPPER BOUND
1973–1980	0.65%	296.0	0.22%	34.36%	0.33%	0.32%	0.97%
1980–1986	0.40%	181.8	0.13%	32.64%	0.19%	0.21%	0.59%
1986–1992	0.61%	278.5	0.16%	26.57%	0.24%	0.37%	0.84%
1992–2000	0.80%	368.3	0.31%	38.01%	0.44%	0.36%	1.25%

Discussion

Changes in Agriculture

One hypothesis of this research was that land-cover change in the CCV_S was unidirectional, with most change taking the form of urbanization of agricultural lands. Urbanization in the Central Valley has long been considered the single greatest threat to the region (Moore 1998; Vink 1998; Sokolow 1998; Charbonneau and Kondolf 1993). Results from this research project support the hypothesis that agricultural lands are being converted to new development; however, this particular transition was not the most commonly observed change. Furthermore, we estimate a net increase in agricultural lands in the ecoregion between 1973 and 2000 (Table 4). This conclusion is supported by findings in Hart (2003) and Johnston and McCalla (2004). From a land-area perspective, the conversion of agricultural lands to developed uses is secondary to the changes occurring between grassland/shrublands (rangelands) and agricultural landscapes (Figure 7).

Four scenarios generally explain the observed conversions between grassland/shrublands and agriculture. They are:

- Cycling of agricultural lands in and out of production
- Loss of agricultural productivity due to environmental conditions (e.g., drought, desertification, increased salinazation, water availability, etc.)
- Removing parcels from agricultural production in advance of development (results in a multi-step process)
- Development of traditional agricultural lands and relocation of agriculture to ecoregion periphery

Planned and unplanned rotation of fields can result in mapped conversion between these two land-cover sectors, while seasonal and annual idling of cropland may also result in "false-positive"

Figure 7.—Large expanse of grape vines located just east of Montpelier, California, and 17 km east of Turloch, California, in Stanislaus County. Since 1970 the region has seen a large increase in land used for viniculture. (Photograph by Benjamin Sleeter, 19 September 2004.)

detections of land conversion. However, these changes are believed to account for a very small amount of the total agriculture change, considering a patch would have to have the time to develop a robust vegetative cover that was spectrally similar to naturally occurring vegetation. Idle lands with no vegetative cover are always classified as agriculture. Degradation of marginal agricultural lands due to a lack of fresh water, lack of drainage, the presence of a high water table, and salinization of soil and ground water resources can also result in loss of agricultural production (Schoups et al. 2005) and are often expressed as a change from agriculture to grassland/shrubland covers. Research by Schoups et al. (2005) has shown that, for some lands in the San Joaquin Valley, irrigated agriculture may not be sustainable due to salinization of soils.

At a much smaller scale, urbanization was also responsible for converting agricultural lands to grassland/shrublands. Often occurring at the periphery of existing urban areas, urbanization not only converts agricultural lands to developed uses but also resulted in the transitional conversion of agricultural lands to grasslands/shrublands, which in subsequent years would eventually transition to developed uses.

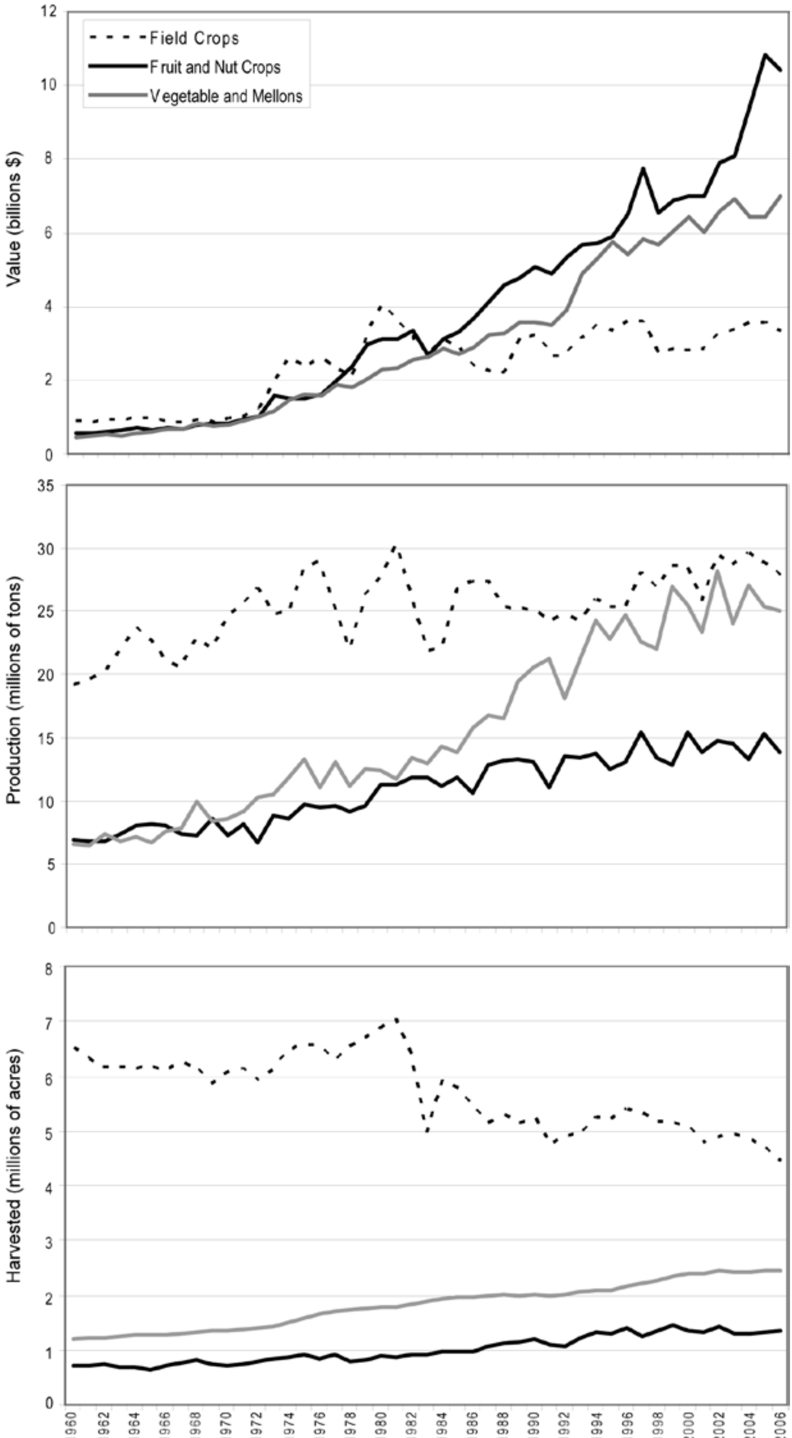
Perhaps the most obvious explanation of the fluctuations between agriculture and grassland/shrublands is the dynamic nature of farming in the ecoregion. As development continues to convert farm lands to new urban uses, agriculture is relocating to the periphery of the ecoregion and into the Central and Southern Chaparral and Oak Woodlands ecoregion, bringing large amounts of marginal lands into agricultural production (Charbonneau and Kondolf 1993). This represents a major shift for the ecoregion and the State of California in general, as farmers continue the transition away from traditional field crops such as alfalfa and grains and invest in higher-risk and higher-value crops such as fruits and nuts (USDA 2008; Johnston and McCalla 2004; Blank 2000) (Figure 8).

Irrigation of marginal lands at the ecoregion periphery carries some amount of concern regarding the attenuation of non-point source water-quality impacts (Charbonneau and Kondolf 1993), although the increased use and technological advancement of drip irrigation systems has the potential to limit impacts to water quality. Drip irrigation use has increased from less than half of 1% of all irrigated land in 1972 to nearly 33% in 2001 (Orang, Snyder, and Matyac 2005). This corresponds to a shift away from field crops to a substantial increase in orchards and vineyards. Orang, Snyder, and Maytac (2005) estimated that irrigated orchards increased from about 15% to 31% of all irrigated land in California since 1972; vineyards increased from about 6% to 16% over the same time period; and field crops decreased from about 67% to 42% (Figure 9). Additionally, the transfer from field crops to perennial crops also has the potential benefit of increasing carbon sequestration in California. Kroodsma and Field (2006) estimate that between 1980 and 2000, California agriculture sequestered 0.7 Tg C/yr with perennial crops accounting for more than 50% of the total, mostly due to the production of woody biomass and the low-till nature of their soils. The authors conclude that adopting low-till and improved pruning techniques has the potential to nearly double the amount of carbon sequestered by California agriculture.

An intriguing result of our research was the temporal nature of change between agricultural and grassland/shrubland land-

Figure 8.—Young citrus orchard in the foreground, contrasted by an older orchard in the background, 11 km north of Visalia, California, in Tulare County. Citrus is a major crop type found near Visalia. The boundary between the CCV and SCCCOW ecoregions is located approximately 10 km to the east. (Photograph by Benjamin Sleeter, 19 September 2004.)

Figure 9 (next page).—Three major crop types in California agriculture with area (acres), amount harvested (tons), and value ($) plotted since 1960. From 1960 to 1980, field crops accounted for the greatest amount of harvest land, the highest amount of production, and even the highest value. Between 1980 and 2006, field crops have remained relatively stable in value while production has increased on a declining amount of harvested land. Fruit and nut crops and vegetables and melons have gradually increased in the amount of land harvested, while production and value have both shown substantial increases. This amounts to increased efficiency across all crop types, while specialty and high value crops continue to occupy a greater share of the landscape.



Field Crops
Fruit and Nut Crops
Vegetable and Mellons
Value (billions $)
Production (millions of tons)
Harvested (millions of acres)
0
2
4
6
8
10
12
5
15
20
25
30
35
1
3
7
1960
1962
1964
1966
1968
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006

scapes. As noted earlier, gains in agriculture outpaced losses in all intervals, with the exception of 1986–1992. This interval happens to coincide with a period of extended drought in California (Figure 10) in which many farmers had to cut back their acreage under production, due to a lack of available irrigation water (USDA 1991). Should California enter into another period of prolonged drought, as is evidenced in the paleoclimate record (Stine 1994), significant areas of arid farmland currently being irrigated could potentially be converted to grassland/shrubland, due to a scarcity of water resources. Impacts of long-term climate could potentially result in high costs to California agriculture, although there is significant uncertainty associated with future projections and their associated impacts in the Central California Valley (Cash and Zilberman 2003). More research is needed to further quantify the relationship between LULCC in the ecoregion, the presence of persistent drought, and regional climate variability.

Urbanization and Development

Urbanization and impervious cover increased significantly in the ecoregion and serve as catalysts for change in other sectors, even though these changes are not the most significant in terms of area converted. Between 1973 and 2000 we estimate an additional 1,124 km^2 of new developed lands were added to the ecoregion, with most new conversions occurring near cities and at the periphery of existing infrastructure. It is estimated that between 1970 and 2001, California's population increased by 42% to 34.0 million people (U.S. Census Bureau 2008). During the same time, the population of Central California Valley counties[1] increased by nearly 51% to 5.58 million people, or approximately 16% of the state's total population (U.S. Census Bureau 2008). Sacramento, Fresno, Kern, and San Joaquin counties each accounted for at least 10% of the ecoregion's population in 2001, with Sacramento the highest at 22.7% (1.27 million people) (Figure 4).

The majority of new developed lands take the form of suburban subdivisions, new commercial and industrial development, and to a more limited extent, exurban growth such as ranchettes. Housing

[1] Central Valley counties were interpreted to include all counties that have their centroid within the stratum and other counties that have a large portion of their population located within the ecoregion stratum. Counties include Butte, Colusa, Fresno, Glenn, Kern, Kings, Merced, Sacramento, San Joaquin, Solano, Stanislaus, Sutter, Tehama, Tulare, Yolo, and Yuba.

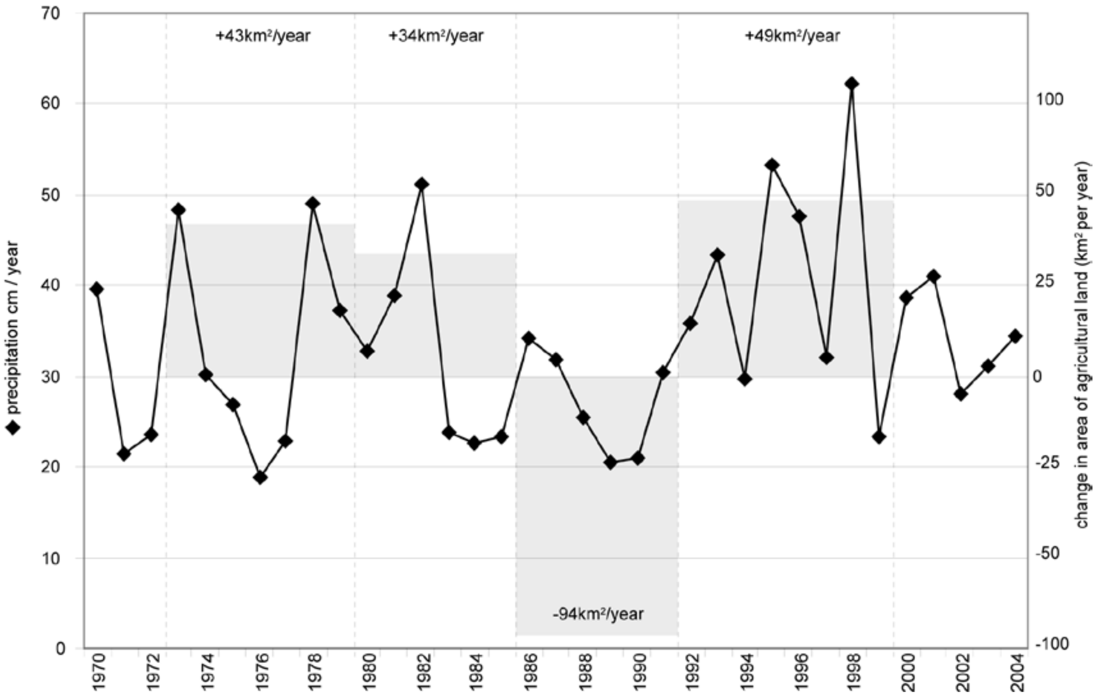


Figure 10.—Average annual precipitation (PRISM Group) and net changes in the agricultural class since 1970 for the CCV ecoregion. Net increases in agriculture were realized in three of the four temporal intervals. Only the 1986 to 1992 period resulted in a net loss of agricultural lands (-94 km2/yr). This period coincides with a period of extended drought in California, with a dry period extending back to 1983.

for the region's rapidly increasing population is the primary driver of new development. Sites where growth in suburban development was found include samples near Bakersfield, Fresno, Stockton, Modesto, and Sacramento, among others (Figure 11). Typically, these samples experienced relatively high rates of change to "developed," while other, more rural samples experienced little to no change in this sector. Occasionally, exurban development was captured and was generally confined to more rural settings. With respect to land-area conversions, exurban development was not a major land-use change observed in this region.

Growth in the developed landscape is occurring for a number of different reasons, although it continues to be heavily influenced by the major urban areas found just outside the ecoregion. The San Francisco Bay Area and Los Angeles, both part of the Southern and Central California Chaparral and Oak Woodlands ecoregion, continue to influence the landscape in the Central California Valley as people leave the urban centers in search of more affordable hous-

Figure 11.—Construction of a new suburban development just outside Fowler, California, in Fresno County. (Photograph by Benjamin Sleeter, 19 September 2004.)

ing. Cities such as Bakersfield, Tracy, Stockton, and Modesto often serve as commuter cities for those working in major metropolitan regions. California has also realized a surge in population due in part to in-migration from other states and Mexico. The large increase in population has resulted in a high demand for housing throughout the state. The Central Valley was particularly well suited to absorb a large share of this growth, due to the availability of relatively inexpensive land and its proximity to jobs and services. Gersmehl (1997) illustrates how realized capital gains alone in 1988 were estimated at $28 billion—the same magnitude as all agriculture in California.

In the future, the balance between agriculture and urban (developed) needs is sure to be high on the list of issues facing policy makers. The use of conservation easements is one tool that has already been employed in California to preserve farmland from urbanization (Sokolow and Lemp 2002; Johnston and Carter 2000). As more and more farmland is replaced by urban and developed uses in some portions of the ecoregion, and the boundary (edge) between the two competing land uses changes, conflicts between residential uses and agriculture have the potential to become an increasing problem for local and regional managers (Sokolow 2003). However, the use of easements is largely based on the general assumption that farmland in California is on a rapid decline and is at risk from urbanization. In keeping with findings from Hart (2003), we have shown this not to be the case in the Central California Valley ecoregion, as agricultural lands have shown a net increase between 1973 and 2000.

The underlying question begs asking: Why are people coming to California in such large numbers? To truly understand what drives LULCC, we must understand the linkages between socioeconomic systems and local to regional land-use decision-making. Lambin et al. (2004) indicate that the primary drivers of LULCC are local responses to economic opportunities and constraints. These same economic and policy-driven opportunities and constraints for new land uses are created by local to national markets and are increasingly influenced by globalization (Lambin et al. 2004). Additional research is needed to connect the remotely sensed observations presented in this paper with shifting market forces presumed to be driving local to regional land-use decisions in the Central California Valley ecoregion.

Conclusion

Since 1973 the Central California Valley has experienced a modest amount of change. We estimate that between 1973 and 2000, 12.4% of the ecoregion changed from one cover type to another. Over the same period, the amount of developed lands in the ecoregion increased from 6.5% to 9.0% of the ecoregion stratum, or 1,122 km^2. Results also reveal that contrary to popular belief, agriculture increased in area from 71.6% to 72.4%, mostly in the form of irrigated orchards and vineyards at the ecoregion periphery. The 1986 to 1992 interval was the only period where agriculture had a net decline and corresponds to a period of prolonged drought in California. Given the establishment of a historical context of LULCC, more research can now begin to quantitatively link drivers and consequences of change with these results, with the objective of providing accurate projections of land cover under varying management and environmental conditions. Identification of linkages between the human and environmental systems and remotely sensed observations represents a critical gap in knowledge of land-change science—a gap that will require significant resources to overcome (Rindfuss et al. 2004). The creation of a regional database of the rates, types, and dynamics of LULCC is a first start at bridging this information gap. As linkages are demonstrated, future projections of LULC could have significant usefulness for global and regional climate modeling, biogeochemical cycling, natural resource management, and urban/suburban land-use planning.

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