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Wetland ecosystem services in California's Central Valley and implications for the Wetland Reserve Program

WALTER G. DUFFY[1] AND SHARON N. KAHARA

U.S. Geological Survey, California Cooperative Fish Research Unit, Humboldt State University, Arcata, California 95521 USA

Abstract. Primary ecosystem services provided by freshwater wetlands in the California Central Valley, USA, include water quality improvement, biodiversity support, and flood storage capacity. We describe these services for freshwater marshes, vernal pools, and riparian wetlands and the implications for wetlands restored under USDA programs in the Central Valley. California's Central Valley is a large sedimentary basin that was once covered by grasslands, extensive riparian forests, and freshwater marshes that today have been converted to one of the most intensive agricultural areas on earth. Remaining freshwater wetlands have been heavily altered, and most are intensively managed. Nitrogen loading from agriculture to surface and groundwater in the Central Valley was estimated to be 34.7×10^6 kg N/yr. Atmospheric deposition of nitrogen in the Central Valley was estimated to be 44.3×10^6 kg N/yr, of which $\sim 1.5 \times 10^6$ kg N/yr was introduced directly to wetlands. Our analysis indicates that wetlands enrolled in the USDA Wetland Reserve Program (WRP) may potentially denitrify the NO_3-N load from relatively unpolluted source water in <18 days, but the potential to denitrify the NO_3-N load from highly polluted source water is uncertain.

Water management strongly influences use, diversity, and abundance of avian fauna as well as other biota. Freshwater marshes in the region continue to support important populations of breeding and wintering waterfowl and shorebirds whose populations fluctuate seasonally. Avian diversity in the little remaining area of Central Valley's riparian wetlands is also high and influenced by stand maturity, heterogeneity, and diversity. USDA conservation practices that promote these characteristics may support avian diversity. Effects of USDA conservation practices on non-avian fauna are poorly understood and warrant further study.

Key words: birds; Central Valley, California; conservation programs; invertebrates; water quality; wetlands.

INTRODUCTION

Wetlands are among the most threatened ecosystems in the world (Millennium Ecosystem Assessment 2005). Globally, the surface area of wetland ecosystems has been estimated to be 8.6×10^6 ha, or $\sim 6\%$ of the earth's surface area (Mitsch and Gosslink 2000). Although limited in area, wetlands are prominent landscape features on most continents, are among the most productive ecosystems on earth (Kvet and Westlake 1998), and provide a variety of services to human societies. These services include biological diversity, recreation, surface and flood water storage, nutrient reduction, and carbon sequestration (Sahagian and Melack 1998, Millennium Ecosystem Assessment 2005, Batzer and Sharitz 2006, Bridgham et al. 2007). Despite providing these services, the worldwide loss and degradation of wetlands has been more rapid than for other ecosystems (Millennium Ecosystem Assessment 2005).

Wetland loss and degradation is a global phenomenon, but has been particularly acute in the United States, where almost half of the wetland area of the lower 48 states was lost by the mid-1980s (Tiner 1984). While wetland loss and degradation continue, recent assessments found the area of restored and created wetlands exceeded losses, resulting in a net gain of wetland area for the first time in over 50 years (Dahl 2005). Much of the recent gain in wetland area has occurred in agricultural landscapes. In the Central Valley of California (CVC), freshwater wetland area has increased from $\sim 153 \times 10^3$ ha in the mid-1980s (Frayer et al. 1989) to 198×10^3 ha today. Agricultural production of rice in the northern valley has also ameliorated some wetland loss. The primary reasons for wetland loss in the CVC, as in other parts of the world, have been conversion for agriculture and infrastructure development driven by human population growth (Millennium Ecosystem Assessment 2005). Water withdrawal, runoff of nutrients and pesticides, and introduction of alien species also contribute to degradation of CVC wetlands. By 2025, the population of California is expected to increase from its current 37×10^6 to $44–48 \times 10^6$ people or 19–30% (Public Policy Institute of California 2006). Population growth, exacerbated by

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[1] E-mail: Walter.Duffy@humboldt.edu

global climate change, will increase demand for water and land for agriculture and development, continuing to threaten wetlands in the CVC.

Several U.S. Department of Agriculture (USDA) programs encourage landowners to conserve or restore wetlands and surrounding uplands. Of these, the Wetland Reserve Program (WRP) is directly focused on wetland conservation. This program provides financial incentives to landowners who agree to restore, protect, or enhance wetlands. The goal of this program is to increase ecosystem services provided by restored wetlands. However, no formal scientific evaluation of the effects of WRP conservation practices in the CVC in providing ecosystem services has been undertaken.

Our objective is to illustrate some key ecosystem services potentially provided by WRP wetlands in the CVC. We reviewed literature and synthesized information relevant to wetland ecosystem services in the CVC. This review focuses primarily on freshwater marshes, since these habitats comprise most of the habitats enrolled in the WRP in the CVC. Information on wetland ecosystem services provided by freshwater marshes in the CVC is imbalanced, with considerable literature available for waterbirds and lesser information available on invertebrates and nutrient reduction. WRP wetlands have not previously attracted the attention of research because these wetlands are on private lands where access is limited and because the program is relatively young. More than half of WRP easements in the CVC were enrolled after the year 2000. With these limitations, we synthesized trends in implementation of WRP wetlands, and, through inference, discuss potential increases in wetland ecosystem services resulting from the WRP.

California's Central Valley

The CVC is an elongated sedimentary basin ~640 km long, 88 km wide, and covering an area of 5.4×10^6 ha (Fig. 1; Fayer et al. 1989). It is often subdivided into the Sacramento River Valley in the north and San Joaquin and Tulare Valleys in the south. Topography is relatively flat throughout the valley, with elevation ranging from 120 m in the north and south to below sea level near San Francisco Bay (Schoenherr 1992). Boundaries of the valley are not precisely defined since valley grasslands grade into oak–grassland savannas of the foothills everywhere except the south where deserts border the CVC. The climate of the valley is Mediterranean with warm, dry summers and mild, wet winters. Air temperature varies little throughout the valley, with average July highs being 37.1°C in both Bakersfield and Red Bluff, while average December lows in Bakersfield (2.9°C) are only slightly warmer than in Red Bluff (2.3°C). Annual precipitation, however, exhibits a distinct gradient and ranges from 16 cm in Bakersfield and 46 cm in Sacramento to 92 cm in Red Bluff. Throughout the valley, >90% of annual precipitation falls as rain during November–May. However, runoff of the Sierra Nevada snowpack historically contributed a proportionately greater volume of water to the southern CVC than to the northern portion. Unlike rainfall, snowmelt runoff volume was also greatest in early summer (Fig. 2). Native habitats in the CVC were predominantly grasslands dominated by bunchgrasses, with extensive riparian forests and freshwater marshes.

Wetlands in the CVC are primarily freshwater marshes with either seasonal or semipermanent hydrologic regimes, riparian wetlands, or vernal pools. Most can be classified using Cowardin et al. (1979) as palustrine wetlands of different water regimes (e.g., seasonal, semipermanent). Freshwater wetlands once covered ~1.6×10^6 ha or 30% of the CVC. The largest freshwater wetland area in California was associated with Tulare, Buena Vista, and Kern Lakes (Frayer et al. 1989). These lakes contained as much as 178×10^3 ha of wetland and deepwater habitats, although the amount varied seasonally and annually due to climatic conditions. Historically, freshwater marshes in the Sacramento Basin were fed by flooding during winter precipitation, while marshes in the San Joaquin Basin were fed by flooding during snowmelt runoff, resulting in distinct differences in the timing of flooding (Fig. 2). Freshwater marshes in other parts of the CVC were flooded by rivers that seasonally inundated large areas. Vernal pools refer to temporary wetlands with shallow surface depressions in areas of poorly drained soils that retain surface water during winter precipitation, surface flows, or subsurface flows (Smith and Verrill 1998). The area of these wetlands in the CVC in recent years varies from ~107 to 286×10^3 ha (Frayer et al. 1989, Newbold 2002).

Human influence on CVC habitats dates back thousands of years. Although impacts on natural resources by Native American Indians are not well documented, >500 tribes are recorded in California, and each tribal group harvested natural resources and many manipulated habitats to maintain wildlife or native plant populations (Paddison 1999). The first agricultural impacts in the CVC were the introduction of Mediterranean weeds and large herds of domesticated livestock by Spanish settlers who colonized the state in 1769 (Paddison 1999). Early agricultural development was often located in riparian wetlands where irrigation was not required. This development accelerated through the mid-1800s and, when coupled with sedimentation from gold mine tailings, forever altered riparian wetlands of the CVC (Isenberg 2005). Conversion of wetlands to agricultural production became widespread in the 1850s and continued through the 1920s (Frayer et al. 1989). By 1920, 70% of the wetland area in the CVC had been modified by levees, drainage, and local water diversion projects. More recent analyses estimated 95% of wetlands in the CVC had been lost, as well as 98% in riparian habitat, and 64% of grasslands (Central Valley Joint Venture 2006).

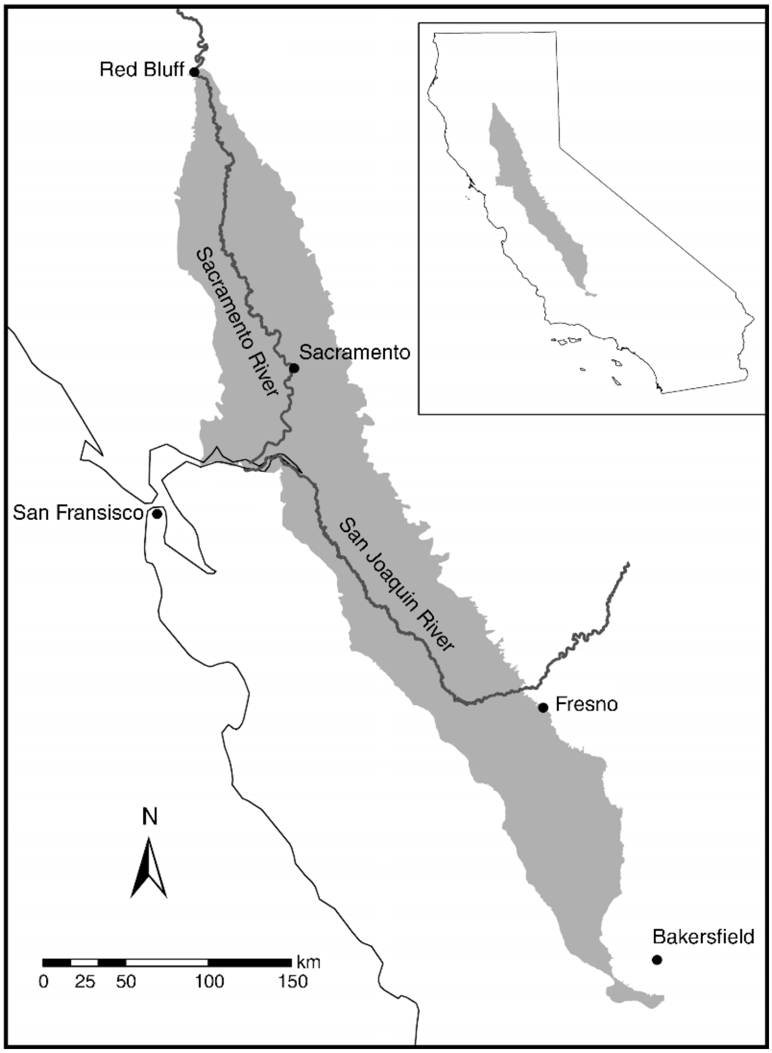

FIG. 1. Map of California, USA, with the Central Valley offset.

Today, the vast majority of land in the CVC (94%) is privately owned, including important wildlife habitats such as wetlands, riparian forest, and grasslands (Hickey et al. 2008). Agricultural development in the CVC is intensive, with $\sim 3.0 \times 10^6$ ha (56%) of the valley classified as irrigated or nonirrigated farmland (Table 1; Newbold 2002). Cotton, almonds, corn, rice, silage, grapes, and tomatoes occupy $>1.3 \times 10^6$ ha of the total agricultural land. Agriculture development in the CVC has only been possible because a massive water distribution system that transfers water from the north to arid central and southern parts of the state. Water withdrawals in California were recently estimated to be 53.5×10^9 m^3/yr (Hutson et al. 2001), roughly equal to the water storage capacity in the entire state (Great Valley Center 2005). In the CVC, water withdrawals over recent wet and dry years have averaged 35.7×10^9 m^3/yr or 67% of the state total (Great Valley Center

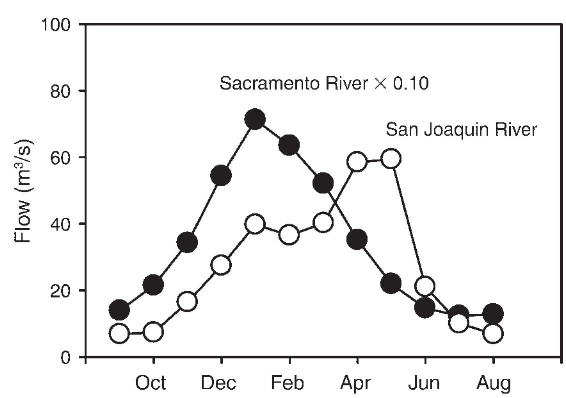

FIG. 2. Mean monthly flow in the San Joaquin River at Mendota, California, during 1940–2005 and in the Sacramento River at Red Bluff during 1892–1943. Sacramento River data presented are 10% of actual values for scale and to emphasize seasonal timing of flow.

TABLE 1. Current area and percentage of predominant land cover categories in the Central Valley of California (CVC), USA.

Land cover category	Area (ha)	Area (%)
Wetlands and deepwater habitats	305 451	5.7
Palustrine	83 185	1.5
Riparian	43 630	0.8
Vernal pool	107 000	2.0
Estuarine intertidal	23 935	0.4
Deepwater habitats	47 701	0.9
Grasslands	1 294 304	24.0
Forests	345 102	6.4
Chapparal/scrub	179 053	3.3
Urban lands	338 500	6.3
Agriculture lands	3 028 192	56.2
Total	5 383 602	100.0

Note: Sources of data to compile this table include Newbold (2002), California State University–Chico (2003), and Central Valley Joint Venture (2006).

2005). Most of the water used in the CVC (92.9%) is used in agricultural production.

Throughout the United States, USDA-funded conservation programs have successfully secured millions of acres of important wildlife habitat and continue to provide technical and financial support for their management. In the Lower Mississippi Alluvial Valley and the Prairie Pothole Region, these programs are responsible for the protection of breeding, migration, and wintering habitat for waterfowl and other nongame grassland birds (Reynolds et al. 2001, King et al. 2006). In the CVC, most of the agricultural land areas enrolled in USDA conservation programs are either enrolled in the Environmental Quality Incentives Program (EQIP) or receive technical assistance through the Conservation Technical Assistance Program (Table 2). The proportion of agricultural land enrolled in WRP is small; however, many Farm Bill conservation programs implement conservation practices that maintain, enhance, or restore wetlands. Thus, benefits to wetland conservation from different USDA conservation practices are difficult to infer from program titles. The two most common conservation practices employed within the WRP in the CVC between 2000 and 2006 were Wetland Restoration and Wetland Wildlife Habitat Management (Table 3). Many USDA conservation programs have existed for a decade or longer and enrolled large areas of the landscape in the CVC.

Widespread wetland conversions to agriculture, urban expansion, and disruption of natural hydrological processes in the CVC have resulted in unprecedented losses in species diversity and abundance (Fredrickson and Laubhan 1995). Since its inception, WRP restoration activities have focused primarily on the creation of heterogeneous micro- and macro-topography features such as islands, ponds, and swales in previously flat, laser-leveled fields. Although the resulting seasonal and semipermanent wetlands are thought to benefit wildlife, effects have yet to be comprehensively evaluated. Conservation plans applied on easement lands are comprised of USDA conservation practices, and all projects must comply with conservation practice criteria in order to receive financial assistance. Specific activities and habitat design follow the recommendations of USDA technical guides and are dependent on soils, geomorphology, and water availability. Current restoration goals revolve around enhancing habitat for nesting and migrating waterfowl and shorebirds, as well as invertebrates and plants associated with vernal pools. Riparian buffer enhancement and tree-planting practices have also been initiated to provide habitat for riparian songbirds. Management goals rarely implicitly include non-avian species; however, as sites mature they may provide benefits for a more diverse assemblage of fish, amphibians, reptiles, and mammals.

Today, >90% of wetlands in the CVC are managed, and two-thirds of managed wetlands are in private ownership (Central Valley Joint Venture 2006). In addition to natural wetlands, the area devoted to cultivating rice in the CVC has expanded in recent years and now exceeds 200×10^3 ha (California Department of Food and Agriculture 2006). Flooded rice fields can provide some natural wetland ecosystem services (Elphick and Oring 2003) and influence the distribution of waterfowl (Fleskes et al. 2005).

Future threats to wetlands in the CVC are overwhelmingly related to water and human population growth. Climate change will impact the quantity and timing of water available for domestic, agricultural, and natural resource uses. Wetland management in the CVC relies on the ability of managers to manipulate water,

TABLE 2. Total area enrolled in seven USDA conservation programs within the Central Valley of California (CVC) and the percentage of the total Central Valley the area represents.

USDA conservation program	Area (ha)	Area (% of CVC)
Conservation Reserve Enhancement (CREP)	752	<0.1
Conservation Reserve (CRP)	22 736	0.4
Conservation Technical Assistance (CTA)	283 222	5.3
Conservation Technical Assistance: Grazing (CTA)	12 577	0.2
Environmental Quality Improvement (EQIP)	113 970	2.1
Wetland Reserve Program (WRP)	16 041	0.3
Wildlife Habitat Improvement (WHIP)	2051	<0.1
Total land enrolled in USDA programs	451 348	8.4

TABLE 3. The 15 most common conservation practices employed on Wetland Reserve Program (WRP) easements in California's Central Valley during 2000–2006, percentage of the WRP area on which they have been applied, and definition of the practice.

Conservation practice and code	Area applied (%)	Definition
Wetland Wildlife Habitat Management (644)	27.1	Retaining, developing, or managing wetland habitat for wetland wildlife.
Wetland Restoration (657)	26.3	The rehabilitation of a degraded wetland or the reestablishment of a wetland so that soils, hydrology, vegetative community, and habitat are a close approximation of the original natural condition that existed prior to modification to the extent practicable.
Wetland Enhancement (659)	12.1	The rehabilitation or reestablishment of a degraded wetland, and/or the modification of an existing wetland.
Upland Wildlife Habitat Management (645)	7.0	Provide and manage upland habitats and connectivity within the landscape for wildlife.
Prescribed Burning (338)	6.9	Controlled fire applied to a predetermined area.
Pest Management (595)	5.6	Utilizing environmentally sensitive prevention, avoidance, monitoring, and suppression strategies to manage weeds, insects, diseases, animals, and other organisms (including invasive and noninvasive species) that directly or indirectly cause damage or annoyance.
Land Smoothing (466)†	3.2	Removing irregularities on the land surface, reshaping the surface of land to planned grades, or reshaping the surface of the land to support recreational land use.
Conservation Cover (327)	2.9	Establishing and maintaining permanent vegetative cover to protect soil and water resources.
Tree/Shrub Establishment (612)	2.6	Establishing woody plants by planting seedlings or cuttings, direct seeding, or natural regeneration.
Prescribed Grazing (528)	2.5	Managing the controlled harvest of vegetation with grazing animals.
Use Exclusion (472)	2.2	The temporary or permanent exclusion of animals, people, or vehicles from an area.
Critical Area Planting (342)	0.5	Establishing permanent vegetation on sites that have or are expected to have high erosion rates, and on sites that have physical, chemical, or biological conditions that prevent the establishment of vegetation with normal practices.
Atmospheric Resource Quality Management (370)	0.3	A combination of treatments to manage resources that maintain or improve atmospheric quality.
Wetland Creation (658)	0.3	The creation of a wetland on a site that was historically non-wetland.
Riparian Forest Buffer (391)	0.3	An area predominantly trees and/or shrubs located adjacent to and up-gradient from watercourses or water bodies.

Note: The total area enrolled in the WRP was 16 041 ha.
† The conservation practices 462 (Precision Land Forming) and 566 (Recreation Land Grading and Shaping) are included in practice 466 (Land Smoothing).

and water management is carried out on >83 000 ha of private and public seasonal and semipermanent wetlands (Central Valley Joint Venture 2006). Under the CVC Project Improvement Act (CVPIA), 521×10^6 m^3 of water are now supplied for wetlands annually. However, total water needed to meet the needs of birds in existing wetlands in the CVC has been estimated to be 1.4×10^9 m^3, or about three times the amount now supplied (Central Valley Joint Venture 2006). Annual water shortages in California, during years of normal precipitation, are currently $\sim 2.0 \times 10^9$ m^3 and are expected to increase to 3.0×10^9 m^3 by 2020 (Hutson et al. 2001). Population growth will likely further exacerbate this water deficit, as well as contribute to land use conversion. The population of the CVC is projected to increase 120% from the current 6.3×10^6 in 2006 to 13.9 $\times 10^6$ by 2050 (California Department of Finance 2007). This trend in human population growth is forecasted to occur in both urban centers and in agricultural lands, where as many as two-thirds of managed wetlands exist (American Farmland Trust 2006). Continued population growth will further challenge water availability, water quality, and alter land use patterns.

ECOSYSTEM SERVICES

Wetlands provide a variety of ecosystem services that benefit human societies (Millennium Ecosystem Assessment 2005). Primary ecosystem services provided by wetlands in the CVC are groundwater recharge, flood storage, improving water quality, and support for biodiversity. Although CVC wetlands contribute to groundwater recharge, little information exists for this benefit in the CVC. Our review and assessment of wetland ecosystem services addresses flood storage, nitrogen removal as one element of water quality improvement, and biodiversity support as evidenced from bird and invertebrate communities. The geographic scope or our review is limited to the CVC. A comparative assessment of ecosystem services provided by wetlands in seven regions of the United States is provided by Brinson and Eckles (2011).

Flood storage

Flood storage of wetlands in the CVC has not been widely documented. However, surface area of wetlands has been estimated at several periods. We used surface area of palustrine and riparian wetlands reported in 1998 to estimate potential flood storage, assuming a peak flood depth of 0.5 m. We estimated flood storage capacity of WRP wetlands from 1998 and 2008 data provided by the USDA (J. Groves, USDA, Davis, California, USA, *unpublished data*). Total area in the WRP in the CV in 1998 was 14 344 ha, and by 2008 it had increased to 39 351 ha. Most, although not all, of this area is in seasonal wetlands. Levees surrounding these wetlands are typically 1.0–1.5 m tall; we assumed a peak flood depth for WRP wetlands of 1.0 m. For vernal pool wetlands, we estimated flood storage capacity by calculating the average depth of 24 vernal pools in the Sacramento River basin from published data (Wilcox and Huertos 2005) and multiplied the average depth (20 cm) by the total area of vernal pools wetlands reported for the CVC (Holland 1998).

Flood storage capacity of WRP wetlands has increased in the past decade (Table 4). Flood storage capacity of WRP wetlands in 2008 was comparable to the service provided by other types of wetlands a decade earlier (Table 4). Although our analysis of flood storage potential provided by CVC wetlands is simplistic, we believe it represents a first-order estimate of this ecosystem service. The potential for flood storage by wetlands in the CVC is substantial and perhaps illustrated the fact that, in the 1870s, Tulare Lake was the largest lake west of the Rocky Mountains.

Nitrogen removal

In surface waters, excess nitrogen and phosphorus has long been recognized as contributing to eutrophication, leading to increased growth of algae and rooted aquatic plants, lower and more variable oxygen concentration in water, altered biological community structure, reduced biological diversity, and habitat loss (Carpenter et al. 1998). The impact of excess nitrogen on terrestrial ecosystems is less well documented than on aquatic ecosystems. However, many negative responses to excess nitrogen in terrestrial ecosystems have been reported, including elevated emission of N gases from soils, increased atmospheric haze, alteration of alpine plant communities, alteration of lichen communities, enhanced growth of exotic species, altered C cycling in forests, and expansion of forests into grassland ecosystems (Fenn et al. 2003*a*).

The ability of wetlands established and managed through a variety of conservation practices on WRP lands to reduce excess nitrogen and other pollutants in surface waters could be a substantial benefit. Demand for water in California is already high, with agricultural demands in the CVC about double the amount received as precipitation (Newbold 2005). Anticipated population growth combined with climate change (Hayhoe et al. 2004) will place even greater demands on water resources and foreshadow conflicts between agricultural water users and urban centers for clean water. Preventing degradation of water is among the most effective means of increasing water supplies. Furthermore, wetland restoration is one of the most cost-effective means of reducing water quality degradation from excessive nitrogen loading (Gren 1995).

Table 4. Potential flood storage capacity of palustrine, riparian, vernal pool, and Wetland Reserve Program (WRP) wetlands in the Central Valley of California.

Wetland type	Storage capacity (10^6 m^3)	
	1998	2008
Palustrine	4159	...
Riparian	2182	...
Vernal pool	2140	...
WRP	1434	3935

Note: Ellipses indicate that data were not available.

Nitrogen is introduced to surface waters in the CVC primarily from nonpoint source runoff from agriculture and atmospheric deposition. In the United States, >80% of nitrogen discharged to surface waters is from nonpoint sources, with agricultural activities representing ~65% of all nonpoint nitrogen discharged (Carpenter et al. 1998). In the CVC, nonpoint source discharge of nitrogen from agriculture likely represents a greater proportion than the national pattern. Annual agricultural application of nitrogen to the CVC was recently estimated to be 352×10^6 kg N/yr (Newbold 2005). Of this total, an estimated 4.7×10^6 kg N/yr (1.3%) was delivered to surface waters in runoff, while 30.0×10^6 kg N/yr (8.5%) leached to groundwater and could later move to surface waters. Newbold (2005) modeled nitrogen attenuation in CVC wetlands as a function of load, water retention time, water depth, and a removal rate constant. Newbold (2005) assumed the mechanisms for nitrogen removal were mainly conversion by microorganisms into gaseous forms or plant uptake and estimated that wetlands in the CVC could attenuate 0.4×10^6 kg N/yr or 9.1% of the nitrogen runoff to surface waters.

Atmospheric deposition is an important nonpoint source of nitrogen loading to surface waters and terrestrial ecosystems. Sources of atmospheric-N deposition in the western United States are primarily from transportation, power generation, and industry as NO_x-N and agriculture as NH_x-N (Fenn et al. 2003*b*). In this region, emissions of nitrogen oxide, nitrogen dioxide, nitric acid and nitrate (NO_x-N) are roughly double emissions of ammonia and ammonium (NH_x-N) (Fenn

TABLE 5. Potential NO_3-N loss from a WRP wetland in Kern County, California.

Measure	Amount
NO_3 concentration in water	4.67 mg/L
Surface area	246 ha
Flooding depth	30 cm
Wetland volume	
Initial filling	738 000 m^3
Precipitation	282 900 m^3
Evapotransipiration loss	728 160 m^3
Total volume	1 183 260 m^3
NO_3 loading	
Load from initial filling	3446 kg
Load from evapotransipiration replacement	2079 kg
Load from areal deposition	723 kg
Total NO_3 load	6248 kg
Daily NO_3 loss rate	349 kg/d
Time to denitrify total NO_3 load	17.9 d

et al. 2003*b*). In the atmosphere, NO_x-N can be transformed to nitric acid (HNO_3), nitrate (NO_3), and organic compounds, while NH_x-N is transformed to ammonium (NH_4). Atmospheric deposition of NO_x-N in California is widespread, but rates are greatest downwind of urban centers. Deposition of NH_x-N tends to be more localized, with greatest rates occurring around areas of livestock production. In the CVC, rates of nitrogen deposition from both NO_x-N and as NH_x-N are roughly 6 kg $N \cdot ha^{-1} \cdot yr^{-1}$, with localized areas in the San Joaquin Valley receiving up to 9 kg $N \cdot ha^{-1} \cdot yr^{-1}$ (Fenn et al. 2003*b*). Using the atmospheric deposition rate reported by Weiss (1999) and Fenn et al. (2003*b*), we estimated atmospheric loading of nitrogen to the CVC to be 44.3×10^6 kg N/yr in wet and dry deposition. The delivery of atmospheric nitrogen to surface waters varies with precipitation and the form delivered varies with human activity in the region. After deposition, atmospheric NO_x-N and NH_x-N are presumably available, through ammonification and nitrification, to be transformed to ammonium (NH_4) and nitrate (NO_3). Much deposited nitrogen is stored in grassland soils during dry summer months when vegetative growth stops. Grassland soils can also retain nitrogen during winters with little precipitation before being mobilized during periods of normal precipitation (Ahearn et al. 2005). Our analyses indicate that atmospheric-N loading in the CVC is equal to 12.6% of the N applied by agriculture, accentuating the potential importance of restored wetlands in nutrient removal.

We calculated potential nitrogen loss from a wetland established on lands enrolled in WRP to illustrate the potential water quality ecosystem service provided by wetland restoration and associated conservation practices. The selected site is located in the Tulare Basin, near the southern end of the CVC, and was restored by the USDA in 2000. The size of this wetland (246 ha) is representative of wetlands restored under WRP in the CVC that average 143 ha, but vary in size. We assumed the wetland would be flooded during November through February since managed wetlands in this area are typically flooded to provide waterfowl habitat during late fall through late winter. Assuming a flooding depth of 30 cm, we calculated volume as $v = a \times d$, where v is volume (m^3), a is area (m^2), and d is depth (m) (Table 5). We then calculated the volume of water needed to maintain water depth during this period by subtracting average precipitation (11.5 cm) from evapotranspiration (29.6 cm) (Table 5) reported during November through February 2000–2004 at Kettleman City, within 30 km of the WRP (California Department of Water Resources 2007*a*). Potential denitrification of NO_3-N from the drain water available to fill and maintain the WRP wetland was calculated using data from Sheibley et al. (2006), who reported denitrification rates were strongly correlated with initial NO_3-N concentrations in a restored riparian wetland along the Consumnes River. In this study, the authors collected wetland soil samples from 12 locations and estimated denitrification of Consumnes River water in the laboratory using the acetylene (C_2H_2) inhibition technique. We derived potential denitrification rates for this WRP wetland by regressing NO_3-N loss rates against beginning NO_3-N concentration reported by Sheibley et al. (2006) to estimate potential denitrification rates from drain water that could flow into the wetland (Fig. 3). Denitrification in wetlands is influenced by initial NO_3-N concentration, as well carbon sources and water temperature (Sirivedhin and Gray 2006, Burchell et al. 2007). We reviewed water quality data from four agricultural drains in the vicinity of this WRP wetland (California Department of Water Resources 2007*b*). Ranges in monthly values of NO_3-N (0.6–195.0 mg/L), total dissolved solids (1240–11 600 mg/L), and water temperature (16°–20°C) suggest substrate and water temperature were favorable for denitrification. In this example, we selected one drain in which the concentration of

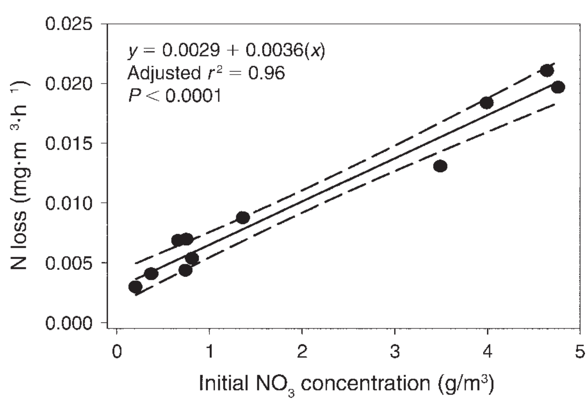

FIG. 3. Relationship between NO_3 concentration and the rate of denitrification derived from data presented in Shiebly et al. (2006). Dashed lines are 95% confidence intervals.

NO_3-N fit within the limits of our regression model (<5 mg/L).

Our analysis suggests that restored wetlands on WRP lands could remove substantial amounts of NO_3-N from inflowing floodwater. Loss of the total NO_3-N load to this WRP wetland was theoretically completed within 18 days (Table 5). We did not estimate the fate of lost nitrogen, including nitrification and ammonification. However, nitrous oxide (N_2O), a greenhouse gas, is formed during an intermediate step in denitrification. Nitrogen loss from these wetlands could contribute to greenhouse gas emissions, but we have no information on the extent of any emissions. Furthermore, only NO_3-N concentrations were reported for these drains and total nitrogen concentration was undoubtedly higher, but we cannot say how much. Still, NO_3-N from agricultural drains in this area is substantial and contributes as much as 50% of the NO_3-N load to the San Joaquin River (Dubrovsky et al. 1998). When wetland source water has very high concentrations of nitrogen, it may be necessary to establish treatment wetlands upstream of wetlands restored to achieve other ecosystem services.

Bird use of restored wetlands may transfer nitrogen from terrestrial to aquatic habitats. Nitrogen loading from birds using a southern California treatment wetland was estimated to be 25 kg $N \cdot ha^{-1} \cdot yr^{-1}$ (Andersen et al. 2003), and loading rates of similar magnitude have been reported from other areas (Hayes and Caslick 1984, Manny et al. 1994). Nitrogen loading from birds, if of similar magnitude, could double the loading in our example restored wetland that was receiving source water with 5 mg NO_3/L, but would represent only ~4% of the total load if nitrate concentration in the source water was 122 mg NO_3/L.

Few investigations of potential nitrogen loss from California wetlands have been published. Sheibley et al. (2006) studied the benefits of riparian–river connectivity by estimating nitrogen loss from a restored 36-ha riparian wetland along the Consumnes River. They found that the percentage of organic matter was the best predictor of soil denitrification potential and that denitrification potential was also strongly correlated with the percentage of total nitrogen and the percentage of total carbon in soils. Sheibley et al. (2006) estimated that, in 2001, a dry year, nitrate loss from the riparian could account for 118 kg/yr or 23.7% of the river's N load. In 2000, a wet year, they estimated that the nitrate loss from the restored riparian area could account for 850–6150 kg N/yr or 0.6–4.4% of the river's annual nitrogen load. Newbold (2002) used landscape modeling to assess the potential nutrient loss from wetlands throughout the CVC. He used data from water quality monitoring stations on rivers on the up- and downstream sides of watersheds to develop estimates of nutrient loading, then estimated nutrient loss or gain from wetland, agricultural, upland, and urban areas. Newbold (2002) estimated that wetlands in the CVC could attenuate 9.1% of the nitrogen in runoff, but data available to calculate nitrogen loading were limited.

Biological diversity

Bird surveys in the CVC indicate spatial and seasonal variations in diversity and abundance, depending on a species' life history requirements and resource availability. Although most restoration projects are assumed to have benefitted wildlife, species-specific management practices may further exacerbate losses by depriving breeding birds and other fauna of wetland habitat when they need them the most (Engilis 1995, Shuford et al. 1998). Furthermore, effects of WRP conservation practices and seasonal water management on non-avian wetland-dependent species are poorly understood. Historically, overbank flooding of rivers and streams in winter and spring inundated large areas of the CVC and filled large shallow wetlands in the Tulare Basin. A slow drawdown would have ensued over the summer months, followed by dry conditions in the fall. Today, summers in the CVC are characterized by a lack of seasonal wetlands, with artificial flooding in the fall and winter. Prior to conversion, the Tulare subbasin would have provided much of the late-summer/early-fall habitat as other areas of the CVC dried out. Diversion of water for agricultural and municipal purposes has largely drained the lakebeds that covered the southern portion of the Valley, leaving behind the driest region of the CVC (Central Valley Joint Venture 2006).

Despite heavy losses, CVC wetlands continue to support more shorebirds during winter and spring than any other inland site in North America and are reported to be the most important habitats for wintering populations of Sandhill Cranes (Pogson and Lindstedt 1991, Hickey et al. 2005, Central Valley Joint Venture 2006). Recent studies indicate that the Tulare subbasin is a high-priority region for breeding shorebirds and waterfowl, particularly over summer and early fall (Hickey et al. 2008). Chronic water shortages coupled with dry climate have reduced available habitat in the southern CVC, resulting in relatively higher densities of waterfowl and shorebirds. Overcrowding and poor water quality put them at risk for disease. In winter, shorebirds move from the Tulare Basin to the San Joaquin Valley, where their use of wetlands is supplemented by flooded rice fields (Manolis and Tangren 1975, Shuford et al. 1998). More than half (52%) of the WRP easement areas in the CVC lie in the northern portion of the valley in the Sacramento subbasin. If WRP is to provide support for shorebirds and breeding waterfowl, there needs to be a greater focus on wetland conservation and provision of clean water to the southern CVC.

Approximately 10% of WRP land is enrolled in the San Joaquin subbasin in the central CVC, where the Grasslands, an area of extensive marshes dominated by

PLATE 1. Trumpeter swan, a rare visitor to California (USA). Photo credit: Jill K. Duffy.

annual grasses and forbs, divided by the San Joaquin River are located. The Grasslands support at least 15 species of waterbirds other than shorebirds and waterfowl (see Plate1), as well as raptors and songbirds (U.S. FWS 2002). Historically, these Grasslands were flooded by winter rains and snowmelt from rivers draining the Sierra Nevada and supported a diverse number of perennial-bunchgrass ecosystems including prairies, oak–grass savannahs, and desert grasslands. Currently only 36% of the historic 3.2×10^6 ha of grassland remain in California, most of which falls in the CVC (de Szalay et al. 2003). Although by some estimates the Grasslands receive relatively better protection, high shorebird use, particularly over winter, warrant further assessment of current management practices and their effects on diversity and abundance.

The financial benefits of enrolling in the WRP are an important incentive to many landowners. In late fall and winter, conservation practices aimed at attracting wintering waterfowl for sport (e.g., moist-soil management) are common throughout the CVC. Moist-soil management involves techniques designed to encourage germination of seed-producing grasses for wintering waterfowl through intensive hydrological manipulation and weed control. To achieve this, wetlands typically undergo a spring drawdown, followed by irrigation over the summer months to promote the germination of waterfowl food plants. Wetlands are then flooded throughout the fall and winter months. Spring drawdowns may create inhospitable conditions for migratory birds, whose diversity peaks mid-April, and repeated flooding and draining of wetlands reduces aquatic invertebrate species composition and diversity (Ebert and Balko 1987, Engilis 1995). Managing for shallower depths and slow drawdowns during this period would greatly enhance shorebird diversity and abundance in the San Joaquin area over winter (Taft et al. 2002).

Maintenance of permanent water through the summer and early fall is rare due to unreliable and expensive water supplies; however, financial support is available through initiatives such as the California Department of Fish and Game Landowner Incentive Program. Deepwater habitats are not only important to breeding species, they also provide refuges for invertebrates that would otherwise not survive (Euliss and Grodhaus 1987). Aquatic invertebrates become increasingly important in duck diets in late winter, and numerous studies have noted their importance during brood rearing. Aquatic invertebrate densities in semipermanent wetlands were reported to peak in the summer; hence, maintenance of some deepwater habitats may increase invertebrate diversity (de Szalay et al. 1999). Wetland designs that mimic wetland complexes with varying hydrologic regimes may not only benefit species that require some water present over the summer, but reduce management costs (King et al. 2006).

Reverse-cycle wetlands, i.e., those flooded during the spring and summer rather than fall and winter, may be an important strategy to benefit breeding birds and other species adapted to historic wetland hydrology. Studies suggest higher invertebrate abundance in reverse-cycle wetlands than in permanent ponds (de Szalay et al. 2003). Peak invertebrate populations occurred in May in reverse-cycle and permanent wetlands, while in semipermanent borrow areas, densities peaked in March–April. Earlier peaks may benefit prebreeding and breeding waterfowl, while later peaks may benefit brood rearing by waterfowl.

Although much of the focus of WRP has been the creation of seasonal and semipermanent wetlands, the unique hydrology, size, and depth of vernal pools provide habitat to a diverse assortment of endemic plants, invertebrates and amphibians (Powell and Hogue 1980, Silveira 1998, de Szalay et al. 1999). It is estimated that that between 50% and 85% of vernal pool wetlands have been lost since the 1800s. Vernal pools also provide food resources to terrestrial invertebrates, including pollinators, through the germination of flowering plants and provision of nesting sites (Thorp and Leong 1998). The elaborate floral displays of vernal pools attract both generalist and specialist insect pollinators. Bees of the family Andrenidae include specialist species that typically only visit a narrow range of flowering plants found in vernal pools (Thorp and Leong 1998).

Currently, vernal pool area in the CVC varies from $\sim$107 to 286×10^3 ha, depending on the boundary used to define the CVC (Frayer et al. 1989, Engilis 1995, Newbold 2002). In 1995, the USDA suggested that entire vernal pool landscapes be considered for conservation under the Farm Bill, including terrestrial mounds between pools that generally did not meet wetland criteria. By the year 2000, WRP enrollments included 1701 ha of vernal pool habitat. Upland and transitional zones on WRP may benefit species adapted to brief hydroperiods and dry periods. Crustaceans such as tadpole shrimp (*Lepidurus packardi*), vernal pool fairy shrimp (*Branchinecta lynchi*), conservancy fairy shrimp (*B. conservation*), and longhorn fairy shrimp (*B. longiantenna*) are adapted to survive repeated drying and inundation by producing dormant eggs (e.g., Ahl 1991). Vernal pools vary greatly in size, and crustacean diversity is positively correlated with their size and depth (Ebert and Balko 1984, King et al. 1996). Conservation practices such as cattle grazing and burning may enhance aquatic invertebrate diversity by eliminating noxious weeds. Selective foraging on exotic annual grasses by cattle may help maintain a more open canopy, resulting in a more diverse aquatic invertebrate assemblage (Platenkamp 1998, Marty 2004). However, intense physical manipulation (disking, chopping, chiseling, and rolling) may result in the loss of egg banks and resting stages in vernal pools, lowering invertebrate diversity.

Freshwater marsh wetlands, on the other hand, may benefit from such practices, as studies on rice fields show. Perturbation of rice straw enhances decomposition after harvest and may stimulate plant diversity and benefit small shorebirds. Aquatic invertebrates in freshwater marshes exhibit mixed responses to these practices, with abundance either increasing or decreasing among different taxa due to complex interspecific interactions (de Szalay et al. 1999). Responses may also vary due to differences in plant recolonization. Mowing was found to result in dense recolonization by a single plant species (e.g., saltgrass), while disking and burning resulted in more diverse plant communities.

Riparian wetlands provide habitat for 62 resident, migrant, and nonmigrant wintering species of songbird and at least 18 special-status vertebrates (Hunter et al. 1999, Humple and Geupel 2002). Nongame bird species richness in refuges of the Sacramento subbasin peak in the spring, and density of spring migrants is highest in areas of extensive riparian woodlands adjacent to other habitats (Gilmer et al. 1998). It is estimated that 98% of the original 900 000 ha of riparian wetlands have been lost, with much of the remaining riparian forests fragmented in small patches surrounded by agricultural fields (Hunter et al. 1999). There are currently 2311 ha of WRP floodplain easements emphasizing stream corridor stabilization and floodplain expansion.

Riparian forest stand age, spatial heterogeneity, distance to remnant riparian forest, and plant diversity all influence bird density and diversity (Gaines 1974, Golet et al. 2003, Hickey et al. 2005). At sites revegetated with native plants in the Sacramento River that were greater than five years old, bird diversity approached that of remnant woodland (Golet et al. 2003). In Iowa, VanRees-Siewert and Dinsmore (1996) observed that the mean number of breeding birds was significantly higher in older restored wetlands and that species richness increased with percent cover of emergent vegetation. Although most conservation actions favor the preservation of mature riparian forest, maintaining a mosaic of early, mid- and late-successional habitat is critical for faunal diversity, as several bird species were reported to be negatively associated with mature riparian habitat characteristics such as high canopy cover (Wood et al. 2006). Riparian wetlands restored under WRP are typically $<$10 years old, (ranging from 0 to 12 years), thereby potentially providing a variety of successional stages. A survey conducted by Hickey et al. (2008) reported that restored riparian sites in the San Joaquin subbasin exhibited higher bird diversity than the Sacramento subbasin. The condition and age of riparian buffers included in the survey was unclear.

The quality of water sources for wetlands will continue to pose a threat to wetland-dependent species in the CVC. Wetlands established through WRP and other wetlands offer the potential for reducing nutrient loads that threaten wildlife, but will not remove salts in agricultural drain water. In the San Joaquin Valley, salt accumulation in the upper soils due to traditional irrigation practices in the arid environment resulted in high selenium (Se) cycling and mobility (Wu 2004). Agricultural return water from the San Joaquin Valley has been implicated in multiple threats to water-dependent birds, including: salt toxicosis and reduced body condition (Gordus et al. 2002); contaminant accumulation in diets, tissues, and eggs (Hothem and Ohlendorf 1989, Saiki et al. 1993, Hothem and Welsh 1994); and reproductive impairment (Paveglio et al. 1992).

Future directions

Wetlands restored under WRP and other USDA-funded programs have great potential to restore ecosystem services to the highly modified landscape of the CVC. Anecdotal evidence indicates that WRP has enhanced biodiversity and flood storage, and has contributed to ameliorating nitrogen loss in agricultural landscapes. Increasing effectiveness of WRP will depend on developing an understanding of how USDA conservation practices affect delivery of these services. However, documenting WRP's contribution to these conservation goals can only be determined through effective monitoring and evaluation. With increasing population growth, urbanization, and climate change, water deficiencies are expected to increase. The effects of shortages on water delivery to WRP wetlands and management of WRP easements, particularly in the drier southern CVC, are yet to be seen. As WRP easements continue to grow in the CVC, continued provision of the services described here hinges upon a reliable water delivery system.

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