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Wildlife and water-use trade-offs with biofuel crop production

Running title: Trade-offs: biofuel, biodiversity, and water

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Abstract: Biofuels from agricultural sources are an important part of California's strategy to reduce greenhouse gas emissions and dependence on foreign oil. Land conversion for agricultural and urban uses has already imperiled many animal species in the state. This study investigated the potential impacts on wildlife of shifts in agricultural activity to increase biomass production for transportation fuels. We applied knowledge of the suitability of California's agricultural landscapes for wildlife species to evaluate wildlife effects associated with plausible scenarios of expanded production of three potential biofuel crops (sugar beets, bermudagrass, and canola). We also generated alternative, spatially-explicit scenarios that minimized loss of habitat for the same level of biofuel production. We used trade-off analysis to compare the marginal changes per unit of energy for transportation costs, wildlife, and water-use, and found that all three of these factors were influenced by crop choice. Sugar beet scenarios require the least land area: 3.5 times less land per liter of gasoline equivalent than bermudagrass and five times less than canola. Canola scenarios had the largest impacts on wildlife but the greatest reduction in water use. Bermudagrass scenarios resulted in a slight overall improvement for wildlife over the current situation. Relatively minor redistribution of lands converted to biofuel crops could produce the same energy yield with much less impact on wildlife and very small increases in transportation costs. This framework provides a means to systematically evaluate potential wildlife impacts of alternative production scenarios and could be a useful complement to other frameworks that assess impacts on ecosystem services and greenhouse gas emissions.

Introduction

Biofuels have gained support as environmental, economic, and political concerns about the production and use of fossil fuels have grown. A number of recent studies suggest that the substitution of biofuels for fossil fuels could in many cases reduce anthropogenic greenhouse gas (GHG) emissions (de Oliveira et al. 2005; Kim and Dale 2005; Hill et al. 2006; and Tilman et al. 2006). However, the biomass used to produce biofuels has a lower energy-density than coal and petroleum and requires larger land areas per unit of energy (McDonald et al. 2009). Meeting ambitious policy targets for biofuel production may cause widespread land use change with unintended consequences for biodiversity, water quality and quantity, and ecosystem services (Groom et al. 2008; Robertson et al. 2008; McDonald et al. 2009; Dominguez-Faus et al. 2009; Williams et al. 2009; Dauber et al. 2010; and Dale et al. 2011). The sustainability of biofuels with respect to these environmental indicators will depend on the type of biomass and where it is grown (Robertson et al. 2008).

There has been little quantitative analysis of the potential impacts of biofuel crop production on species habitats (Geyer et al. 2010b). Predicting these impacts is challenging because distributions of both wild species and biofuel crops are environmentally and geographically constrained, so that impact analysis requires spatially explicit models (Barney and DiTomaso 2010; Evans et al. 2010; and Jager et al. 2010). In addition, the starting land use conditions from which effects are calculated vary across the landscape. The likelihood of conversion of land to biofuel crops depends on economic factors such as net profit relative to existing crops or land use and proximity to biofuel conversion facilities. Compounding this complexity is the finding that biodiversity impacts can be non-linear with the level of biofuel production, such that each consecutive marginal increase in production leads to a more rapidly increasing impact (Geyer et al. 2010b).

Before policy makers and business leaders commit to large-scale production of biofuels, they need to be informed about the potential impacts of that production on biodiversity (Hanegraaf et al. 1998; and Chan et al. 2004) and water (Dominguez-Faus et al. 2009; and Wu et al. 2009). Shifting from current land use to biofuel crops could have positive effects on some species. For example, planting perennial crops like switchgrass or mixed grasses on degraded annual cropland is predicted to improve habitat quality for some species (Meehan et al. 2010). On the other hand, scientists have speculated that policies and market forces favorable for biofuel could make some marginal and retired lands attractive for conversion to annual energy crops to the detriment of some wildlife species (Fargione et al. 2009; and Meehan et al 2010). Effects of increased biofuels production on water consumption will also vary geographically depending on supply, cost to growers, and the irrigation requirements of particular crops.

Robertson et al. (2008) called for an integrated framework to assess trade-offs between biofuel production and other environmental objectives beyond the conventional factors of greenhouse gas emissions and fossil energy use. Several spatially-explicit frameworks have explored trade-offs between energy production and a suite of environmental concerns such as GHG emissions, net energy, and ecosystem goods and services with respect to profit (Graham et al. 1996; Bryan et al. 2010; and Zhang et al. 2010). The frameworks of Bryan et al. (2010) and Zhang et al. (2010) used process simulation models to predict yields and other impacts from environmental variables. Bryan et al. (2010) used life cycle assessment to derive greenhouse gas emissions and net energy. They then applied economic modeling to identify economically-viable lands at different levels of subsidy. Other authors have used similar bioeconomic models of competition between biofuel crops to allocate them spatially (Walsh et al. 2003; Scheffran and BenDor 2009; and Hellmann and Verburg 2011). Zhang's framework applied multiobjective optimization modeling for optimal spatial allocation to biofuel crop production to meet different combinations of objectives. Bryan et al. (2010) assumed rationale economic behavior to drive their spatial allocation. So far, biodiversity concerns have generally not been integrated in these frameworks, although recent work has begun to address this shortcoming (Gevers et al. in press).

Here we evaluate potential effects of expanded biofuel crop production on wildlife species and water use in California. Our analysis combines agroeconomic modeling of currently grown crops and potential biofuel crops, spatial analysis of available and suitable land, and species-specific wildlife habitat suitability modeling. We generate spatially-explicit scenarios of crop production based on competing objectives of minimizing costs to transport biomass from farms to biorefineries vs. minimizing habitat loss. We evaluate alternative futures in terms of social, economic, and environmental concerns such as biofuels costs, biodiversity, and water to address the following research questions:

- How might habitat suitability for wildlife species of special concern change in response to plausible scenarios of production of three contrasting types of biofuel crops in California?
- How much flexibility exists to reduce adverse effects on wildlife species while producing the same total yield of biofuel crops? How much would this change increase transportation costs of hauling biomass to biorefineries?

Materials and Methods

Study area

California is a leader in the transition to renewable energy to mitigate the effects of climate change. The Governor's Executive Order S-06-06 sets goals for increasing reliance on in-state production of biofuels, stipulating that California produce 75 percent of the biofuels consumed in the state by 2050. With projected demand for gasoline that contains 5.7 percent ethanol by volume (E5.7) and five percent content of renewable biodiesel (B5), this target translates to roughly 3,300 million liters of ethanol and 1,100 million liters of biodiesel by 2050. Initial estimates suggest that half of the state's irrigated crop land would be needed to fully meet targets with biofuel crops (California Biomass Collaborative 2006).

If such a massive conversion of land to dedicated energy crops occurs, substantial effects on other values may follow. The state's agricultural land is highly productive of food and fiber, producing more than half of all US grown fruits, nuts, and vegetables (California Department of Food and Agriculture 2010). Most potentially arable land is already in production. Nearly half of the terrestrial vertebrate species in California use the state's agricultural lands, and many of the native plants and animals associated with these landscapes are threatened or endangered (Brosi et al. 2006). Some remnants of native habitats persist in major agricultural regions such as the San Joaquin Valley, Sacramento Valley, Imperial Valley and Salinas Valley (Figure 1), although these habitats are fragmented and often highly degraded. California's Mediterranean climate of dry summers and rainy winters requires most farmland to be irrigated. There is a perennial conflict over water allocation to satisfy agricultural and urban water demand while meeting desired environmental flows (Hanak et al. 2011).

[insert Figure 1about here]

We limited our analysis to the most important agroecosystem regions in the state: the Central Valley (comprised of the San Joaquin and Sacramento Valleys), the Salinas Valley, and the Imperial Valley (Figure 1). Cultivated land within these regions equals approximately 3.9 million ha. We use “agroecosystem” as a general term that includes crop and pasture habitats plus the remnants of natural or semi-natural habitats within and adjoining those habitats. We delineated agroecosystems by one square-mile “sections” (approximately 260 hectares) based on the Public Land Survey System (PLSS) where crops were grown in 2005 as reported to the California Department of Pesticide Regulation (DPR). For completeness of the agroecosystem landscape, adjacent and interspersed sections of natural or semi-natural habitats were also included in the study area, which encompasses 25,715 sections or approximately 6.7 million ha (~16% of total land area of California).

Candidate biofuel crops

Three crops are analyzed that have potential to become more widespread as biofuel feedstock crops in California—sugar beets (*Beta vulgaris*) for sugar-based ethanol, perennial bermudagrass (*Cynodon dactylon*) for lignocellulosic ethanol, and canola (*Brassica campestris*) for biodiesel (Williams et al. 2007, Kaffka 2009). This set of crops represents three different feedstock types (sugar, cellulose, and oil) and corresponding refining technologies, although cellulosic conversion technology is still not commercially viable. Each grows best in different regions, has different water requirements, and has different wildlife habitat attributes. Determining the effects on native wildlife species of increasing production of any of these crops requires spatially-explicit scenarios of conversion from current crops to specific biofuel crops, and models of how each species might respond to that conversion.

To address this challenge, we developed a four-step integrated framework. Step 1: a farm-scale agroeconomic model predicts the level of biofuel crop production and associated water demand at an assumed level of profit. Farms are stratified by 45 geographic subregions that are relatively homogeneous in terms of climate and agronomic factors. Step 2: habitat suitability modeling estimates current landscape suitability for a set of wildlife species and a revised suitability should the landscape be converted to biofuel crop production. Step 3: a land allocation model generates spatially-explicit scenarios of biofuel crop production that seek to minimize the total cost to transport biomass to the nearest biorefinery. Alternative scenarios are also generated to minimize loss of wildlife habitat. Step 4: trade-off analysis uses a multicriteria decision analysis of scenario effects on cost, wildlife, and water. The following sections describe these steps in more detail.

Biofuel crop production and water modeling

A key but uncertain variable in modeling biofuel production is the future location of infrastructure to produce biofuels from agricultural feedstocks. We adopt the sites from Tittmann et al. (2008), who modeled optimal locations for ethanol and biodiesel refineries based on potential supply of biomass in California. Although that study only considered existing feedstock sources (e.g., forest and agricultural residues, municipal solid waste), the locations of potential biorefineries are a reasonable basis for crop biomass biorefineries in the absence of a focused analysis. Biorefineries in Tittmann et al. tend to be located where transportation and transmission infrastructure reduce costs associated with biofuel production. Tittmann et al. (2008) also calculated average transportation costs to move biomass from county centroids through the road and railway network to their least-cost biorefinery site. We extrapolated those transportation costs from county centroids to individual farms as a function of distance and biomass weight.

The California Bioenergy Crop Adoption Model (Kaffka and Jenner 2011) is an agroeconomic optimization model that identifies the amount of land that might be converted to these potential biofuel crops under advantageous price conditions. The model simulates economic conditions for farms producing annual or short-lived perennial crops on crop land in the state of California. The model's primary purpose is to identify the price and yield at which new bioenergy crops enter cropping systems, area and locations for crop adoption, which crop activities are displaced, and the associated change in water consumption. It was assumed that the agricultural water levels between 1998 and 2007 were available for use, and water could be transferred between crops or reduced on farms, as is common practice by California growers. The model was parameterized for 45 subregions that account for significant regional differences in climate and soils among farms. Kaffka and Jenner (2011) simulated a range of output prices, input costs, and crop yields that resulted in $50 and $100 per hectare ($20 and $40 per acre) profits for biofuel crops. We used the land area in each subregion that was predicted for a $100 per hectare profit to guide the detailed scenarios. Therefore our scenarios assume the maximum potential adoption of biofuel crop production within the range of profits that was investigated. This profit level is extremely optimistic and may only be possible with very high oil prices and/or generous government subsidies. The entry of biofuel crops were modeled individually, rather than allowing them to compete with each other as well as with the current crops. Therefore each spatially-explicit scenario analyzes the effects of a single biofuel crop.

Production of biofuel feedstocks was excluded on public or privately-protected lands, water bodies and wetlands, and lands with high capital investment (e.g., existing urban development, orchards, and vineyards) (Haughton et al. 2009). Land that is not cropland or pasture was also assumed to be physically (and hence economically) unsuitable to produce biofuel crops.

Subregions where the California Bioenergy Crop Adoption Model predicted biofuel crops would not be adopted even at the $100 per hectare profit benchmark were screened from the set of available and suitable land, regardless of their ownership or current land cover. Roughly half of the study area was considered available and suitable for sugar beets and canola, with only one-third for bermudagrass. We describe below in the scenarios section how the land area predicted for each crop by the California Bioenergy Crop Adoption Model were allocated within these available and suitable lands.

Wildlife habitat suitability modeling

We used an existing database to assign species-specific habitat suitability scores to land use/land cover types. The California Wildlife Habitat Relationships (CWHR) database is a state-of-the-art information system about California's wildlife (Airola 1988), developed and maintained by the California Department of Fish and Game. The core feature of CWHR is a set of expert-based habitat suitability ratings summarized in a matrix with 695 species and 59 habitat types, including eight agricultural types (Irrigated Row and Field Crops, Dry Grain Crops, Irrigated Grain Crops, Deciduous Orchard, Evergreen Orchard, Vineyard, Irrigated Hayfield, and Pasture). Each habitat type is scored as high (1), medium (0.66), low (0.33), or unsuitable (0) for reproduction, cover, and feeding for each species. We used the average of the three scores as a measure of overall suitability. The CWHR database also contains a biogeographic range map for every species. We assumed species were confined to suitable habitats within their biogeographic range (Airola 1988).

We compiled a map of habitat types from two sources. Existing natural and semi-natural habitat types were interpreted from a recent, 30m resolution land cover map produced for the U.S. Gap Analysis Program (Lennartz et al. 2009). We re-assigned the Cropland type in the map to specific crop types based on the Department of Pesticide Regulation's database and then re-coded those crop types to the corresponding CWHR habitat. The three biofuel feedstock crops being analyzed belong to four distinct habitat types (Table 1). Canola can be grown with or without irrigation depending on the region of the state. Note that bermudagrass is a model for other salt tolerant perennial grasses that might find use as a biofuel feedstock in California.

[insert Table 1 about here]

For this study, we limited the analysis to fifty-three terrestrial wildlife species of Special Concern identified by the State of California that are associated with agroecosystems (Comrack et al. 2008). These species (see Appendix) are either federally-listed as threatened or endangered, meet the State definition for listing but have not yet been listed, have experienced rapid population declines or range restrictions, or have naturally small populations that are highly susceptible to risk factors. They may be especially vulnerable to a change in habitat area and suitability if biofuel crops were produced in California's agroecosystems.

Information from the habitat map, geographic range maps, and the habitat suitability matrix were used to calculate a suitability score for each PLSS section as an area-weighted suitability rating of the constituent habitat types for reproduction, cover, and feeding separately. An overall suitability score per species was calculated as the average of the three scores. If the section was available and suitable for biofuel crop production, a similar score of area-weighted suitability was calculated for each biofuel crop type.

Generating spatially-explicit biofuel crop production scenarios

An appropriate integrated model is not readily available that can generate spatially-explicit scenarios and assess trade-offs between biofuel crop production and wildlife habitat effects

(Robertson et al. 2008). Crop production modeling integrates agronomic production factors with socioeconomic processes to identify the sites where a crop is highly likely to be grown at a given market price, but such modeling omits wildlife effects (Bryan et al. 2008 and 2010; Scheffran and BenDor 2009; and Hellmann and Verburg 2011). Models for biodiversity come from the area of systematic conservation planning to identify a nominal network of potential conservation areas that efficiently meet representation targets for biodiversity (Margules and Pressey 2000). However, these reserve selection tools do not model resource production such as biofuels. Variations of these models have incorporated resources but have not attempted to meet production targets (Polasky et al. 2008; and Wilson et al. 2010). In the case of biofuels, with many individual decision makers and flexibility in where crops could be grown and refined, we sought a framework that supported proactive, strategic analysis. To this end, we adapted a conservation planning tool (Marxan) to generate spatially-explicit scenarios of land use and crop cultivation based on data on biofuel yield and the cost of transporting crops to hypothetical biorefineries.

Marxan is a freely available and commonly used software tool in conservation planning. It uses a simulated annealing with iterative improvement algorithm to select a set of planning units for a conservation area network at minimum cost (Ball et al. 2009). Selection is guided by the following objective function:

$$\text{Minimize } Z = \sum_{j=1}^{J} c_j * x_j + \sum_{i=1}^{I} SPF_i * p_i \quad (1)$$

$$\text{Subject to } \sum_{j=1}^{J} a_{ij} x_j \geq r_i \quad (2)$$

where a_{ij} is a measure of the amount of feature i in planning unit j (i.e., sections), x_j is a {0,1} variable that has a value of 1 if section j is selected and 0 otherwise. Each section has a cost c_j, and each feature is assigned a desired target r_i. The second term in Eq. 1 is a penalty for failing to achieve the target constraints in Eq. 2 and is comprised of a penalty factor (SPF) for feature i multiplied by difference between the desired and achieved amount of the feature in the final solution (p_i, the "shortfall" for feature i). We included features for biofuel and the wildlife Species of Special Concern. The targets for biofuel were the biofuel yields by subregion in liters of gasoline equivalent (LGe) associated with the land area predicted by the California Bioenergy Crop Adoption Model at the subregional crop yield rates and conversion efficiencies (Table 2). Similarly farm-level LGe was derived from the land area available and suitable in each section. This value served as the amount, a_{ij}, of biofuel that a section could produce. The a_{ij} for Species of Special Concern was the net change of species habitat suitability from current conditions to a biofuel crop future.

[insert Table 2 about here]

We generated basic crop allocation scenarios for the three alternative biofuel conversion technologies. Basic scenarios were designed to achieve subregion-specific production targets for biofuel predicted by the California Bioenergy Crop Adoption Model results at minimum cost (i.e., "Minimize Cost" scenarios). The cost in this case was the transportation cost associated with hauling the biomass yield over the least-cost distance to a potential biorefinery. Alternative scenarios minimized habitat loss while still meeting biofuel production levels (i.e., "Minimize Loss" scenarios) by adding a "cost" of suitability loss to the transportation cost. It was expected that minimizing habitat suitability loss would require greater overall transportation costs. In contrast to conventional conservation planning practice, no conservation targets were set for wildlife species.

Trade-off analysis

The scenarios generate information about total biofuel production, costs, and impacts. That information needs to be evaluated to compare the three biofuel crops and the trade-offs among criteria. Because the crops have different energy content and conversion efficiency, it is necessary to standardize some of the criteria according to social preferences from 100 for most desirable social outcome to 0 for least desirable outcome. Five criteria were standardized for the trade-off analysis: cost-effectiveness as mean transportation cost per LGe (lower cost is desired), total energy (LGe) produced (more energy is desired), mean habitat suitability for the Species of Special Concern (more suitability is desired), water efficiency in savings per LGe relative to current crop patterns (less water used is desired), and land efficiency in m^2 per LGe (less land is desired). The habitat suitability criterion was scaled from 100 for the best outcome to 0 for a 10% net loss, which we assumed is the maximum acceptable loss for sensitive species.

Results

Biofuel crop scenarios

Based on the California Bioenergy Crop Adoption Model using a $100 per hectare profit benchmark, canola scenarios would occupy the most land, approximately 8% of California's agroecosystem lands (Table 3). Sugar beet scenarios used 44% as much land, and bermudagrass scenarios only 19% of the land used in the canola scenario. The Minimize Cost and Minimize Loss scenarios would occupy essentially the same land area and produce the same amount of energy (Table 3). Sugar beets could produce more LGe of biofuel than the other two potential crops studied. The bermudagrass scenarios produced 13% of the energy of the sugar beet scenarios, and canola produced 45% of the energy of the sugar beet scenario despite occupying the most land.

[insert Table 3 about here]

Comparing the land requirement on an energy basis (per LGe), sugar beets scenarios require less than 2 m^2 (0.0002 hectares) per LGe on average (4,896 LGe/hectare, Table 2). Bermudagrass requires 7 m^2 per LGe (1,401 LGe/hectare), and canola takes 10 m^2 (995 LGe/hectare) respectively. Canola and bermudagrass have much lower biomass yields per hectare than sugar beets, although this is partially offset by their higher energy content and conversion efficiencies. Land requirements for any given crop were virtually identical for the Minimize Cost and Minimize Loss scenarios.

The collective effects on the 53 Species of Special Concern, expressed as net species' habitat gain or loss, vary between crops and scenarios (Table 4, effects on individual species is provided in the Appendix). Canola scenarios negatively impacted the greatest number, whereas sugar beets and bermudagrass scenarios resulted in only small effects for most species. For example, the bermudagrass scenario produced no more than 2% habitat suitability loss for any of the species and resulted in habitat suitability increases for 22 species, but also converted much less land and produced less energy than the other biofuel crops in the modeling. Effects on most amphibians, reptiles, and mammals were slightly negative or neutral. Only the Western spadefoot (sugar beets or canola scenarios) and Kit fox (bermudagrass scenarios) had positive effects in these taxa. Most of the large effects (i.e., >5% loss or >2.5% gain) occurred for birds. Long-Billed Curlew had gains of 6-20% in bermudagrass and canola scenarios. Vermillion Flycatcher had large losses for sugar beets and canola but large gains for bermudagrass. Several other birds had large gains with canola (Northern Harrier, Loggerhead Shrike, Vesper Sparrow, and Savannah Sparrow), whereas as many as 13 had large losses. Round-tailed ground squirrel in the canola scenarios was the only mammal with large losses.

[insert Table 4 about here]

Canola, being a winter crop that can be largely rain-fed, resulted in the largest overall reduction in water use at nearly 6% of current statewide irrigation. Moreover the water reduction would occur in a majority of crop subregions throughout the state. For bermudagrass, reductions were only predicted in a few crop subregions, so the average reduction per LGe was quite small. Sugar beets required the same amount of irrigation water as the crops they would replace so there would be no net change.

Trade-offs

As expected, scenarios that attempt to reduce the impact of biofuel crop production on habitat suitability for the Species of Special Concern increase the cost of transporting the biomass to the least-cost biorefinery (Figure 2). For sugar beets, the cost would increase about 2% from $0.149 to $0.153 per LGe whereas the loss of habitat suitability could be reduced 22%. The transportation cost in bermudagrass scenarios is one-half of that for sugar beets. This lower cost is primarily due to the higher energy content of bermudagrass so that less biomass needs to be transported to produce each LGe of fuel. The second major difference is that the effect of bermudagrass scenarios on habitat suitability overall is equally positive in the Minimize Cost and Minimize Loss scenarios. Cost also is virtually the same in both bermudagrass scenarios. Canola would cost approximately 4% more per LGe to reduce habitat suitability loss by 63%. Canola, despite very low biomass yields relative to sugar beets, has a higher energy density, making the transportation costs very low (only $0.03 per LGe). Because the biomass yields are lower, producing one LGe occupies more land than sugar beets, so the net impact of canola is much greater.

[insert Figure 2 about here]

One way to visually compare trade-offs is with a spidergram that portrays the relative performance between the alternatives (three biofuel crops) on the criteria (Figure 3). The results shown here are for the Minimize Loss scenarios, but the Minimize Cost results are very similar. No crop is superior in all criteria. All three crops retain at least 97% of current habitat suitability. The canola scenario scores best for transportation costs and water reductions. It scored lowest of the crops for land area per LGe and habitat impacts. Less energy was produced with canola relative to sugar beets. Sugar beets were the most expensive crop for transporting on an LGe basis and had no benefits for water consumption. This crop showed the greatest potential to produce ethanol assuming the $100 per hectare benchmark, and it used the least land area per LGe. At the assumed price, bermudagrass could only supply 16% of the energy as sugar beets. It scored moderately high in land area and cost. It scored low on water savings but highest on habitat suitability.

[insert Figure 3 about here]

Discussion and Conclusions

Response of wildlife species to biofuel crop scenarios

Agricultural lands in California have relatively low suitability for wildlife Species of Special Concern that utilize agroecosystems compared to the suitability of natural habitats for those same species. Nevertheless, our findings show that the choice of biofuel crop matters for these species.

In general, suitability rankings are lower for reproduction than for foraging or cover, which indicates that most wildlife species tend to rely on adjacent patches of natural habitat for reproductive habitat. If these remnant patches were converted to biofuel crops, the ability of the entire landscape to support wildlife would diminish further. Based on the agroeconomic modeling, the scenarios varied from converting as little as 100,000 hectares to bermudagrass to more than 500,000 hectares for canola. The aggregate change for all 53 Species of Special Concern ranged from a 2.2% loss of total suitability in the agroecosystems statewide with canola's Minimize Cost scenario to a slight increase of 0.8% for bermudagrass if it was grown like alfalfa hay in the Minimize Loss scenario. Fletcher et al. (2011) reported similar wildlife benefits of cropland being converted to grass. Bermudagrass is rated as moderate risk for invasion in California, particularly in disturbed riparian areas (Cal-IPC 2006) and thus may have additional consequences not captured by the habitat suitability modeling. Given that bermudagrass is already common grown in pastures, hayfields, parks, golf courses, and lawns and in widely dispersed irrigation ditches throughout the state, the marginal risk associated with growing bermudagrass for biofuel may be modest. Comparing net habitat effects on a per LGe basis, canola would have the highest negative impact, sugar beets a medium impact, and bermudagrass a small positive net gain in suitability. These averages, however, mask wide variation in individual species' responses.

Trade-offs between wildlife and transportation costs

Despite the large area of land conversion from food crops to biofuel crops in the scenarios, there is sufficient available and suitable cropland to provide flexibility in where conversion might occur. A relatively slight relocation of farms producing biomass in the Minimize Cost scenarios could dramatically reduce wildlife impacts. We found this result for all three biofuel crops, but especially for canola. It is encouraging that in these scenarios the increase in transportation cost would be relatively small compared to large gains (reduced losses) in habitat suitability. The California Bioenergy Crop Adoption Model predicted low production levels for bermudagrass, relative to sugar beets and canola. Thus there is more flexibility to redistribute bermudagrass to satisfy other social objectives such as wildlife conservation and yet be almost as cost-effective as when minimizing cost alone.

Agroecosystems also provide many ecosystem services that are affected by land use decisions such as changing to biofuel crops (Dale et al. 2011). These potential impacts were not assessed in our study. As an example, bermudagrass can also be used for reclamation of salt affected lands and for other aspects of salinity management (Kaffka 2009). Perennial crops such as bermudagrass sequester more carbon in soil and roots than annual crops (Tilman et al. 2006). Potential biofuel crops and the food crops they may replace also have specific requirements for nitrogen fertilization. Crops requiring greater fertilization may emit higher levels of nitrogen into surface waters causing eutrophication and nitrous oxide, a potent greenhouse gas, to the atmosphere (Kaffka 2009). These flows and their impact on ecosystem services should be considered in a more comprehensive trade-off analysis.

Model uncertainties and limitations

The key inputs to our framework are:

- Location of hypothetical biorefineries, biomass yields and water use.
- Conversion efficiencies of biomass to energy.
- Rules about which lands are suitable and available for biofuel crop production.
- A map of current wildlife habitats.

- A matrix of species-habitat suitability ratings.

The wildlife analysis depended on the availability of the CWHR database. Similar habitat suitability models have been developed by the U.S. Gap Analysis Program, which is currently completing geographic range maps and distribution models for vertebrate species across the entire country (Aycrigg 2010). To the extent that these models include habitat information, especially information that distinguishes different crop types in a way that allows comparison of alternative biofuels, they will allow analyses similar to ours in other regions and with other potential biofuel crops.

Our results and any conclusions about impacts, trade-offs, or sustainability of biofuel crops are all contingent upon many assumptions (detailed in Stoms et al. 2011) made at each of the four steps in the framework. A sensitivity analysis with the California Bioenergy Crop Adoption Model found a wide range in area of biofuel crop adoption in response to changes in key assumptions about crop price and crop biomass yield (Kaffka and Jenner 2011). Those results have not yet been extended to the wildlife effects assessment. For reference, the \$50 per hectare profit benchmark predicted much less land relative to the \$100 per hectare benchmark (55% for sugar beets, 23% for bermudagrass, and 38% for canola; Kaffka and Jenner 2011). The reduction in crop adoption was not uniform across the state, however, as biofuel crops would not be adopted in some subregions at the lower profit level. It is also worth noting that at the height of the state's sugar beet industry in the early 1970s, a maximum of around 120,000 ha was planted, compared to the 218,000 ha modeled here. Because of these variations in amount and location in crop adoption at different potential profit levels, total wildlife impacts would not scale proportionally with area or profit level. The common assumption in California is that for all practical purposes, it is unlikely to expect an expansion of irrigated lands in California in the

440 future and that the land that currently can be profitably cultivated and irrigated is likely an upper limit (Kaffka and Jenner 2011). Therefore the California Biofuel Crop Adoption Model was run exclusively on existing irrigated cropland. A small amount of land is farmed in California without irrigation in foothill regions in the central coast and surrounding California's Central Valley. There may be modest opportunities to increase cropped areas in these regions, which are highly suitable for a range of wildlife species. These lands were not included in the irrigated land model. When that assumption is relaxed, net habitat suitability would be 0.7-3.0% lower for Minimize Cost scenarios and 0.1-1.8% lower for Minimize Loss (Stoms et al. 2011).

We modeled scenarios for each biofuel crop separately because the analysis with the California Bioenergy Crop Adoption Model did not consider introductions of multiple crops. More likely, they would be produced as a mixture of feedstocks along with other sources of biomass (e.g., forest residues, agricultural residues, and municipal solid wastes). This modeling remains to be done. We did not take into account any global increases in crop prices in response to reduction of crop land in California. These price increases might induce landowners abroad to clear native habitats to fill the void, with consequent effects on biodiversity (e.g., Searchinger et al. 2008). Most of the crops displaced in the California Bioenergy Crop Adoption Model, however, are not traded internationally from California or only in small amounts unlikely to affect large price signals. The actual response is a complex set of crop shifts within the state in response to largely local price signals, resulting in within-state crop production. In the absence of a price signal, there might be no indirect effect on land change abroad. We allocated all impacts to the production of biofuel crops. As there are often co-products generated in association with biofuels, such as animal feed (e.g., oilseed meals, sugar beet pulp) or chemicals (e.g., glycerin), the full impacts should not be allocated solely to biofuel (Halleux et al. 2008). The positive effects of bermudagrass on most species in this assessment are based on the assumption that bermudagrass grown for biofuel would have the same habitat suitability as irrigated hayfields, which in California are mostly alfalfa. There is evidence that bermudagrass will have slightly lower suitability than alfalfa hayfields for some wildlife species (Nogeire et al. in preparation). Therefore the beneficial effects of bermudagrass reported here may be overestimated.

Future research directions

Assessing biodiversity impacts from renewable energy production poses a number of methodological challenges. Researchers in life cycle assessment (LCA) have endeavored to develop methods for incorporating biodiversity as an indicator in their impact assessment methods. Biofuel crops in particular have been a promising product system to test because of the large-scale changes in land use and habitats involved in commercial scale production. Geyer et al. (2010a and 2010b) proposed a methodology based on the type of wildlife habitat suitability modeling used in this study, and results such as reported here can be readily incorporated to provide biodiversity indicators for LCA s of bioenergy development.

Some studies have excluded prime farmland from consideration for growing biofuel crops to avoid conflicts with food production (Lovett et al. 2009; Fiorese and Guariso 2010). We did not evaluate this policy option in this study because of the assumption that only irrigated cropland would be converted to biofuel crops. The framework could readily accommodate this variation, however, either by masking prime farmland as “unsuitable” for biofuel crops or by excluding sections with prime farmland in the scenario runs. Prime farmland is quite widespread in the study area. Very little land in California is considered marginal or underutilized that could supply biofuel crop feedstock compared to other agricultural regions (Hill et al. 2006; and Meehan et al. 2010). We expect that policy options that retained all prime farmland for food production might either increase the transportation costs dramatically or fail to achieve the biofuel output levels. Consequently preserving food production would have to be balanced against energy production or cost.

Complementing an integrated framework for trade-off analysis

Robertson et al. (2008) called for an integrated framework to assess trade-offs between biofuel production and environmental objectives. Our framework and Zhang's both apply forms of multiobjective optimization modeling for spatial allocation to biofuel crop production to meet different combinations of objectives. We did not model many of the impacts in the other frameworks such as greenhouse gas emissions or nutrient loss. On the other hand, our analysis is unique in identifying impacts on and the potential for trade-offs with wildlife species. We anticipate that our habitat suitability modeling or something similar could be adapted to function within the other frameworks. Our framework has a further advantage in that it can be used to assess full or partial scenarios generated externally. For instance, biodiversity conservation stakeholders might design a scenario of sites they wish to preserve, which could be excluded from any biofuel scenario (i.e., declare the land unavailable for biofuel crops) to determine the effect of conservation. The framework can also assess the relative marginal effects of individual biorefineries or energy production levels (Stoms et al. 2011). The most noteworthy contribution presented here is that the approach is more spatially-explicit than many others (McDonald et al. 2009), which are top-down and aggregated in ways that cannot represent the finer-scale characteristics of landscapes that are all-important in determining wildlife effects. Without this level of spatial detail, the trade-offs between renewable energy and biodiversity cannot be adequately portrayed to stakeholders.

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678 # Tables and Figures

679 **Table 1. Habitat types associated with biofuel feedstock crops.**

Crop	Habitat name
Sugar beets	Irrigated Row and Field Crops
Bermudagrass	Irrigated Hayfield[a]
Canola (rain-fed)	Dry Grain Crops[b]
Canola (irrigated)	Irrigated Grain Crops[b]

680

681 [a] Bermudagrass is classified as Pasture in CWHR when it is grazed, but we assumed that for biofuel it would be grown tall and
682 harvested, more like an alfalfa habitat type. We therefore classified it as Irrigated Hayfield.
683 [b] Canola is grown in the winter rainy season. We assumed it (and other small grains) would be cultivated as Dry Grain Crops in
684 northern California and as Irrigated Grain Crops in the south where rainfall is less.
685

686

Table 2. Conversion coefficients from tons of crop biomass to liters gasoline equivalent (LGe) and LGe per hectare.

Crop	Biofuel type	Biofuel yield (liters biofuel / ton feedstock)	Gasoline equivalent (liters-gasoline/ l-biofuel)	Energy yield (LGe / ton feedstock)	Biomass yield (tons feedstock / hectare) [e]	Biofuel yield (LGe / hectare) [e]
Sugar beets	Ethanol	103.7 [a]	0.67 [d]	69.5	70.7	4,896
Bermudagrass	Ethanol	216.1 [b]	0.67 [d]	144.8	10.1	1,459
Canola	Biodiesel	431.5 [c]	1.03 [d]	444.4	2.2	995

[a] Williams et al. 2007; Shapouri et al. 2006; [b] Anderson et al. 2008; [c] Tyson et al. 2004;
[d] Tittmann et al. 2008. Note that the yield for bermudagrass is still largely theoretical.
[e] Derived from results of California Bioenergy Crop Adoption Model and energy conversion coefficients, averaged over the State of California. Conversion rates of cellulosic biomass sources like bermudagrass or other perennial grasses to ethanol are theoretical values at this time. Converting vegetable oils to biodiesel and sugar to ethanol is currently done on a commercial scale, so empirical conversion factors can be used.

Table 3. Statewide totals of "Minimize Cost" (MC) and "Minimize Loss" (ML) biofuel crop scenarios.

	Sugar beets (MC)	Sugar beets (ML)	Bermuda grass (MC)	Bermuda grass (ML)	Canola (MC)	Canola (ML)
Land area converted to biofuel crop in thousand hectares (% of agroecosystem lands)	218.2 (3.5%)	218.2 (3.5%)	120.2 (1.5%)	120.2 (1.5%)	512.2 (7.8%)	512.3 (7.8%)
Biofuel production in million LGe per year [a]	1068.5	1068.4	168.5	168.4	509.6	509.7
Net change in habitat suitability	-1.0%	-0.8%	+0.8%	+0.8%	-2.2%	-0.8%
Net reduction in water demand in million cubic meters (% of all irrigation)—from CBCAM model results	0 (0%)	0 (0%)	14.8 (0.1%)	14.8 (0.1%)	1283.1 (6.7%)	1283.1 (6.7%)

LGe = liters of gasoline equivalent; CBCAM = California Bioenergy Crop Adoption Model

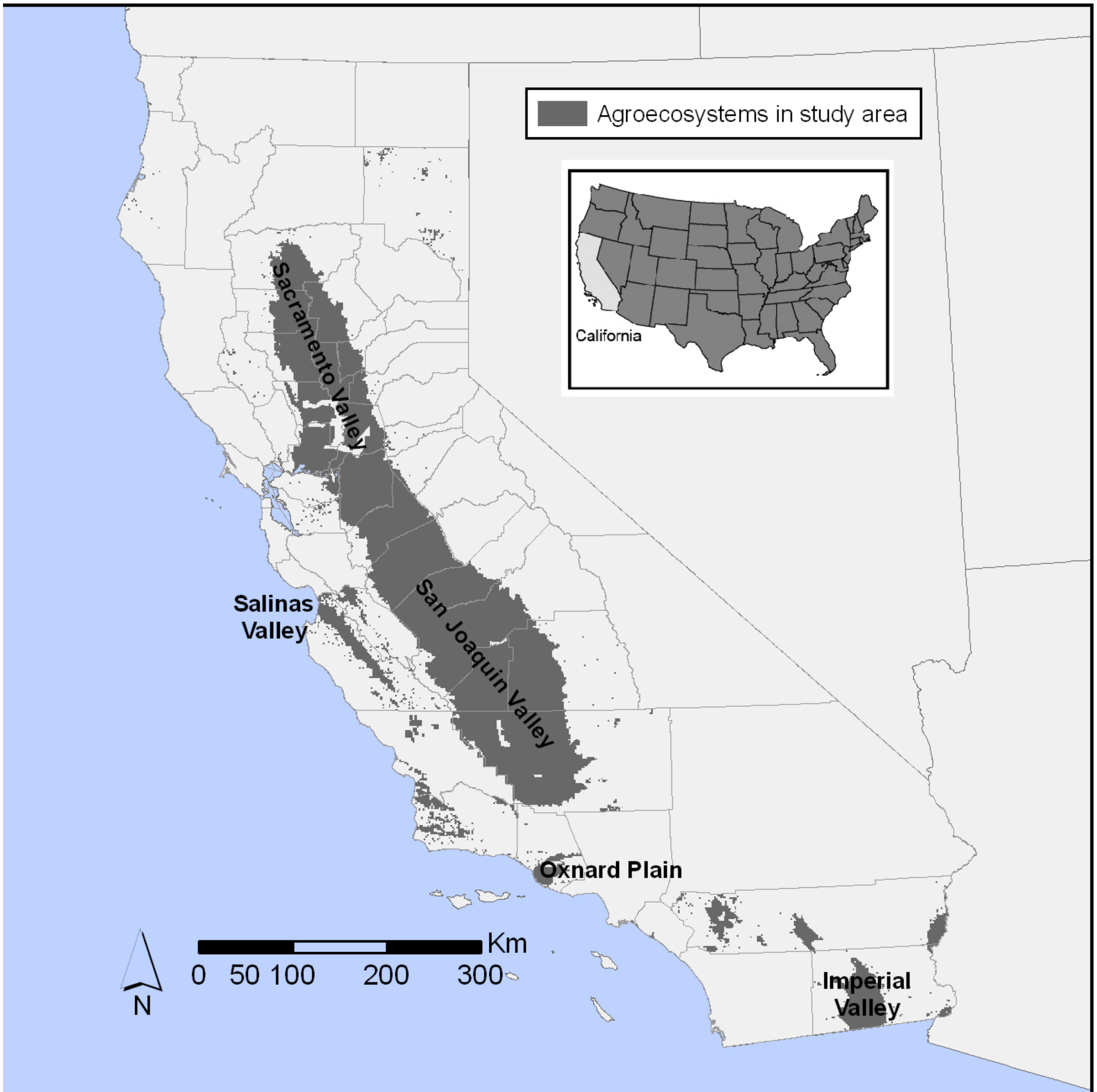
Table 4. Number of Species of Special Concern by level of change in habitat suitability for Minimize Cost (MC) and Minimize Loss (ML) biofuel crop scenarios.

Percent change	Sugar beets (MC)	Sugar beets (ML)	Bermuda grass (MC)	Bermuda grass (ML)	Canola (MC)	Canola (ML)
> 10% loss	0	0	0	0	8	6
7.5 – 10% loss	0	0	0	0	2	1
5 – 7.5% loss	1	2	0	0	4	3
2.5 – 5% loss	5	3	0	0	7	1
0 – 2.5% loss	22	23	19	20	13	21
0% - no change	17	17	12	12	12	13
0 – 10.7% gain	8	8	22	21	7	8
Total number of species	53	53	53	53	53	53

Figure 1. California agroecosystems considered for biofuel crop conversion in this study.

Figure 2. Trade-offs between cost and net impact on habitat suitability per liter of gasoline equivalent (LGe) for the three biofuel crops. The axes are drawn so that social benefit is highest at the origin (i.e., lowest cost and positive impact on wildlife). MC = Minimize Cost scenarios, ML = Minimize Loss scenarios.

Figure 3. Spidergram of trade-offs between criteria for the three biofuel crops in the Minimize Loss scenarios. Axes drawn with best societal outcome at 100, poorest at zero.



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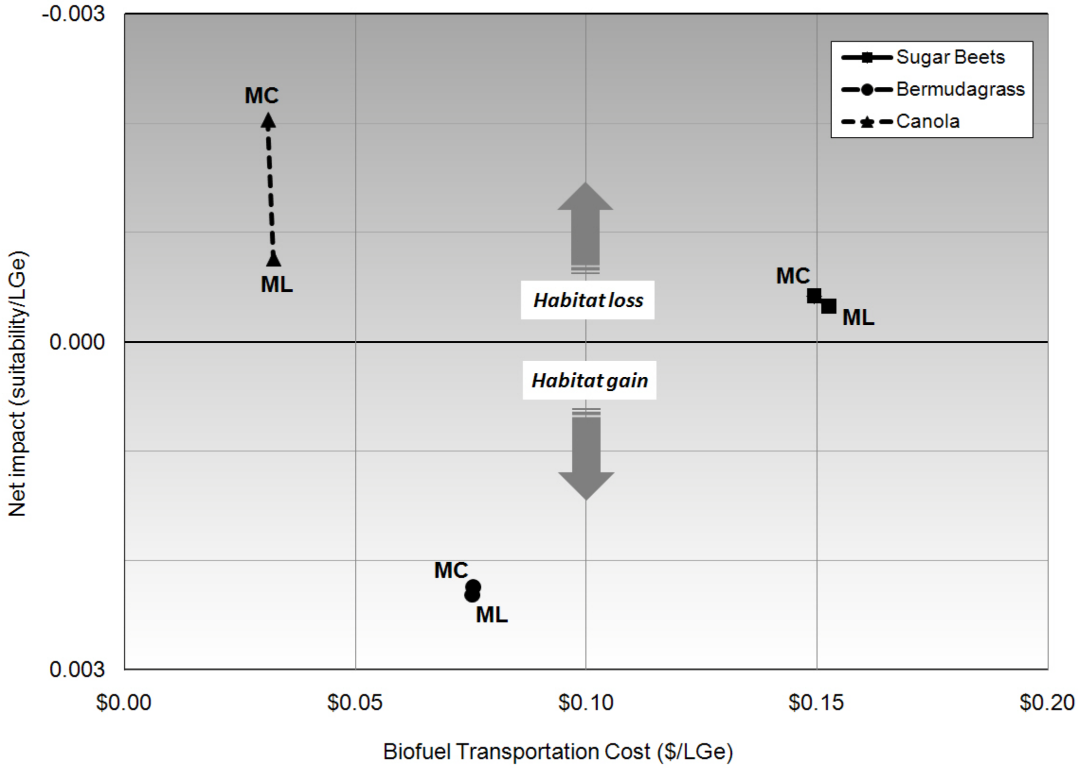

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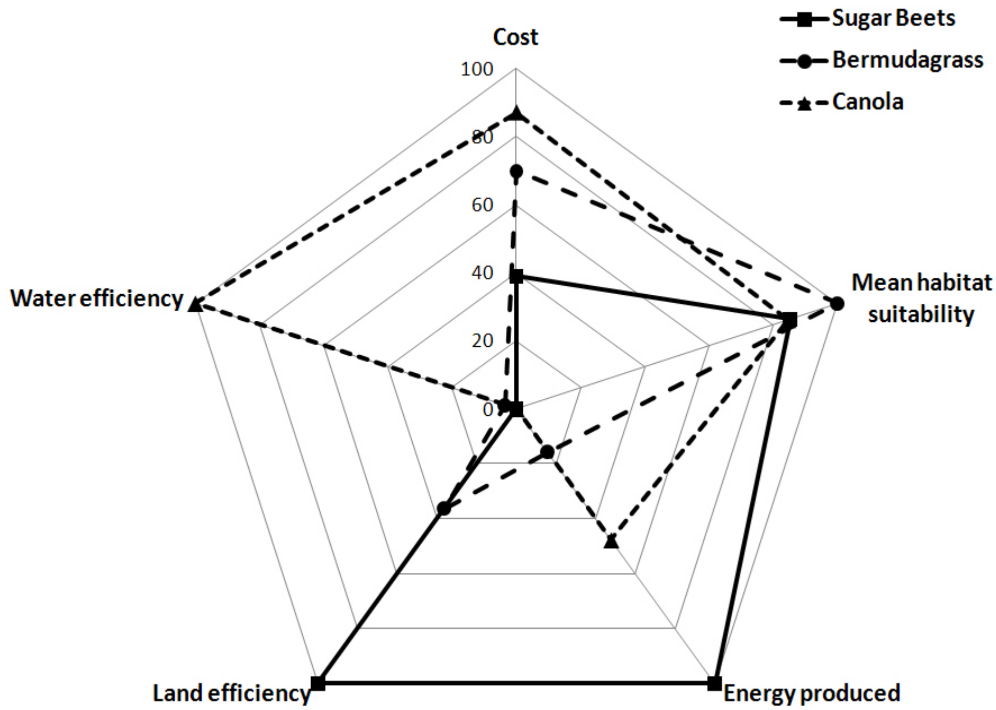

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Appendix. Species of Special Concern and suitability-weighted area under biofuel crop scenarios as a percent of current.

Scenario with lowest percent value shown in **bold** font; highest value in ***bold italics***. Shaded rows indicate species that were not affected by any change of crops.

WHR Code	Scientific Name	Common Name	Current suitability-weighted area	Sugar Beets MC	Sugar Beets ML	Bermuda grass MC	Bermuda grass ML	Canola MC	Canola ML
A001	*Ambystoma californiense*	CALIFORNIA TIGER SALAMANDER	873,587	***100.0***	***100.0***	99.6	99.6	**99.3**	99.8
A028	*Spea hammondii*	WESTERN SPADEFOOT	2,389,987	101.5	101.3	**99.3**	**99.3**	***103.1***	102.3
A030	*Bufo alvarius*	COLORADO RIVER TOAD	9,278	100.0	100.0	100.0	100.0	100.0	100.0
B042	*Pelecanus erythrorhynchos*	AMERICAN WHITE PELICAN	70,976	97.1	97.8	***99.4***	99.3	**93.9**	98.7
B050	*Ixobrychus exilis*	LEAST BITTERN	104,963	98.6	99.1	***99.6***	99.5	**96.6**	99.4
B062	*Plegadis chihi*	WHITE-FACED IBIS	153,750	100.1	100.2	***100.7***	***100.7***	**89.1**	89.9
B065	*Dendrocygna bicolor*	FULVOUS WHISTLING-DUCK	174,114	100.0	***100.1***	***100.1***	100.0	**79.3**	84.1
B070	*Anser albifrons*	GREATER WHITE-FRONTED GOOSE	1,813,954	99.0	99.2	***100.8***	100.7	**86.5**	87.9
B090	*Aythya americana*	REDHEAD	162,928	98.2	98.6	***99.7***	99.6	**96.2**	99.3
B113	*Haliaeetus leucocephalus*	BALD EAGLE	386,616	99.7	***99.8***	98.9	99.0	**98.0**	99.3
B114	*Circus cyaneus*	NORTHERN HARRIER	3,582,494	**96.8**	97.2	101.3	101.3	106.7	***108.6***
B121	*Buteo swainsoni*	SWAINSON'S HAWK	1,433,143	98.4	98.8	101.3	***101.4***	**96.5**	98.5
B124	*Buteo regalis*	FERRUGINOUS HAWK	1,182,864	98.0	98.5	101.9	***102.0***	**94.7**	97.7
B125	*Buteo lagopus*	ROUGH-LEGGED HAWK	1,202,194	98.4	98.8	101.1	***101.2***	**95.8**	98.1
B150	*Grus canadensis*	SANDHILL CRANE	1,873,265	**98.7**	99.0	***101.7***	101.6	100.0	101.5
B154	*Charadrius alexandrinus*	SNOWY PLOVER	9,551	100.0	100.0	100.0	100.0	100.0	100.0
B159	*Charadrius montanus*	MOUNTAIN PLOVER	996,437	***100.3***	100.2	100.1	100.1	**84.6**	85.8
B173	*Numenius americanus*	LONG-BILLED CURLEW	1,160,369	**96.0**	97.2	105.8	105.6	113.9	***119.7***

WHR Code	Scientific Name	Common Name	Current suitability-weighted area	Sugar Beets MC	Sugar Beets ML	Bermuda grass MC	Bermuda grass ML	Canola MC	Canola ML
B215	*Larus californicus*	CALIFORNIA GULL	2,278,729	***100.4***	***100.4***	100.2	100.2	**86.9**	87.0
B226	*Gelochelidon nilotica*	GULL-BILLED TERN	570	***100.0***	***100.0***	***100.0***	***100.0***	**91.3**	***100.0***
B235	*Chlidonias niger*	BLACK TERN	334,237	92.7	93.6	101.1	***101.2***	**84.4**	90.4
B259	*Coccyzus americanus*	YELLOW-BILLED CUCKOO	49,466	***100.0***	***100.0***	99.7	**99.3**	***100.0***	***100.0***
B269	*Athene cunicularia*	BURROWING OWL	3,229,015	98.1	98.7	***102.5***	***102.5***	**95.3**	98.2
B273	*Asio flammeus*	SHORT-EARED OWL	3,200,176	***100.3***	***100.3***	100.1	100.1	**89.7**	89.9
B297	*Melanerpes uropygialis*	GILA WOODPECKER	44,819	100.0	100.0	100.0	100.0	100.0	100.0
B324	*Pyrocephalus rubinus*	VERMILION FLYCATCHER	19,217	95.3	95.0	101.5	***104.8***	**89.2**	95.7
B342	*Riparia riparia*	BANK SWALLOW	239,940	***100.8***	100.7	100.6	100.2	**92.6**	93.5
B365	*Campylorhynchus brunneicapillus*	CACTUS WREN	136,256	100.0	100.0	100.0	100.0	100.0	100.0
B399	*Toxostoma crissale*	CRISSAL THRASHER	35,338	100.0	100.0	100.0	100.0	100.0	100.0
B410	*Lanius ludovicianus*	LOGGERHEAD SHRIKE	2,512,099	**98.8**	99.1	101.3	101.3	***105.9***	***107.7***
B461	*Geothlypis trichas*	COMMON YELLOWTHROAT	1,496,061	***100.0***	***100.0***	99.4	99.5	**99.2**	99.6
B494	*Pooecetes gramineus*	VESPER SPARROW	610,932	**98.8**	99.0	101.1	101.1	104.5	***107.0***
B499	*Passerculus sandwichensis*	SAVANNAH SPARROW	2,609,165	**98.4**	98.8	102.0	102.1	100.3	***102.5***
B501	*Ammodramus savannarum*	GRASSHOPPER SPARROW	1,339,773	99.2	99.4	***101.2***	***101.2***	**98.6**	99.5
B520	*Agelaius tricolor*	TRICOLORED BLACKBIRD	1,645,387	***100.1***	100.0	**99.6**	99.7	99.8	***100.1***
B522	*Xanthocephalus xanthocephalus*	YELLOW-HEADED BLACKBIRD	608,921	95.5	96.2	***101.7***	***101.7***	**90.0**	93.7
M006	*Sorex ornatus*	ORNATE SHREW	964,556	99.8	***99.9***	99.2	99.4	**98.6**	99.5
M019	*Macrotus californicus*	CALIFORNIA LEAF-NOSED BAT	29,431	100.0	100.0	100.0	100.0	100.0	100.0
M040	*Nyctinomops femorosaccus*	POCKETED FREE-TAILED BAT	33,804	100.0	100.0	100.0	100.0	100.0	100.0
M068	*Ammospermophilus nelsoni*	NELSON'S ANTELOPE SQUIRREL	286,288	***100.0***	***100.0***	99.9	99.9	**99.7**	99.9
M074	*Spermophilus tereticaudus*	ROUND-TAILED GROUND SQUIRREL	67,531	99.5	***99.7***	99.1	99.5	94.4	**93.3**
M086	*Perognathus longimembris*	LITTLE POCKET MOUSE	94,534	100.0	100.0	100.0	100.0	100.0	100.0
M087	*Perognathus inornatus*	SAN JOAQUIN POCKET	1,274,922	99.5	99.6	***99.8***	***99.8***	**99.2**	99.5

WHR Code	Scientific Name	Common Name	Current suitability-weighted area	Sugar Beets MC	Sugar Beets ML	Bermuda grass MC	Bermuda grass ML	Canola MC	Canola ML
		MOUSE							
M106	*Dipodomys ingens*	GIANT KANGAROO RAT	381,353	100.0	100.0	100.0	100.0	100.0	100.0
M108	*Dipodomys stephensi*	STEPHENS' KANGAROO RAT	17,843	100.0	100.0	100.0	100.0	100.0	100.0
M111	*Dipodomys nitratoides*	FRESNO KANGAROO RAT	333,761	***99.9***	***99.9***	***99.9***	***99.9***	**99.7**	***99.9***
M122	*Onychomys torridus*	SOUTHERN GRASSHOPPER MOUSE	572,573	***100.0***	***100.0***	**99.9**	***100.0***	***100.0***	***100.0***
M148	*Vulpes macrotis*	KIT FOX	1,144,848	98.7	99.1	101.9	***102.0***	**96.1**	98.8
R004	*Actinemys marmorata*	WESTERN POND TURTLE	1,675,450	***99.8***	***99.8***	99.4	99.5	**98.8**	99.5
R014	*Uma inornata*	COACHELLA VALLEY FRINGE-TOED LIZARD	12,805	100.0	100.0	100.0	100.0	100.0	100.0
R019	*Gambelia sila*	BLUNT-NOSED LEOPARD LIZARD	494,020	***100.0***	***100.0***	**99.9**	**99.9**	**99.9**	**99.9**
R052	*Masticophis flagellum*	COACHWHIP	342,817	***100.0***	***100.0***	99.8	99.9	**99.1**	99.3
R079	*Thamnophis gigas*	GIANT GARTER SNAKE	411,319	98.7	***99.1***	98.8	98.6	**96.9**	98.9
	Total or Average		46,108,425	99.0	99.2	***100.8***	***100.8***	**97.8**	99.2
	Minimum			92.7	93.6	***98.8***	98.6	**79.3**	84.1
	Maximum			101.5	**101.3**	105.8	105.6	113.9	***119.7***