

Trade-offs in water and carbon ecosystem services with land-use changes in grasslands

JOHN H. KIM,^{1,4} ESTEBAN G. JOBBÁGY,² AND ROBERT B. JACKSON^{1,3}

¹Nicholas School of the Environment, Duke University, Durham, North Carolina 27708 USA

²Grupo de Estudios Ambientales, IMASL, Universidad Nacional de San Luis/CONICET, Ejército de los Andes 950, D5700HHW San Luis, Argentina

³Department of Earth System Science, Woods Institute for the Environment, Precourt Institute for Energy, Stanford University, Stanford, California 94305 USA

Abstract. Increasing pressures for food, fiber, and fuel continue to drive global land-use changes. Efforts to optimize ecosystem services under alternative land uses are often hampered by the complex interactions and trade-offs among them. We examined the effects of land-use changes on ecosystem carbon storage and groundwater recharge in grasslands of Argentina and the United States to (1) understand the relationships between both services, (2) predict their responses to vegetation shifts across environmental gradients, and (3) explore how market or policy incentives for ecosystem services could affect land-use changes. A trade-off of ecosystem services was evident in most cases, with woody encroachment increasing carbon storage (+29 Mg C/ha) but decreasing groundwater recharge (−7.3 mm/yr) and conversions to rain-fed cultivation driving opposite changes (−32 Mg C/ha vs. +13 mm/yr). In contrast, crops irrigated with ground water tended to reduce both services compared to the natural grasslands they replaced. Combining economic values of the agricultural products together with the services, we highlight potentials for relatively modest financial incentives for ecosystem services to abate land-use changes and for incentives for carbon to drive land-use decisions over those of water. Our findings also identify key opportunities and caveats for some win–win and lose–lose land-use changes for more integrative and sustainable strategies for land management.

Key words: agriculture; carbon sequestration; ecosystem service; land-use change; water provisioning; woody plant invasion.

INTRODUCTION

Land-use changes for producing food, fiber, and fuel are the dominant landscape conversions on Earth and affect many ecosystem processes (DeFries et al. 2004, Kareiva et al. 2007, Searchinger et al. 2008, Lambin and Meyfroidt 2011). Their effects on ecosystem services are increasingly important for long-term human well-being (MEA 2000, Foley et al. 2005), as rapid population growth, increasing drought from climate change, and other factors pose challenges to food and water security (Rosegrant and Cline 2003, Courtney and Zencey 2012, Morgan 2013). Land-use changes often increase one ecosystem service for economic gain but can decrease the benefits from other services (e.g., food production vs. carbon sequestration, Matson et al. 1997; or commercial forestry vs. water provisioning, Farley et al. 2005), often creating trade-offs between multiple products and services (Christensen et al. 1996, Jackson et al. 2005, Andersson et al. 2007, Fisher et al. 2008).

The quantitative relationships among different ecosystem services and their biotic and abiotic drivers are often unclear (Chan et al. 2006, Bennett et al. 2009, De Groot et al. 2010). Recent advances in mapping and spatial analyses have allowed researchers to quantify ecosystem services for different land-use categories (Schröter et al. 2005, Naidoo and Ricketts 2006, Troy and Wilson 2006). These ecosystem service and land-use relationships nevertheless remain qualitative for most ecosystem services (ICS 2008, Koch et al. 2009, Plummer 2009). We address these gaps in the potential trade-off between two important ecosystem services, carbon sequestration and water yield, that accompany land-use changes across diverse environmental gradients.

Vegetation type and cover affect many ecosystem services, particularly carbon sequestration and water provisioning, because vegetation drives most terrestrial carbon and water fluxes (Jackson et al. 2001, Schlesinger and Bernhardt 2013). Land-use changes are sometimes used to manipulate carbon and water cycling, for instance to mitigate climate change and freshwater scarcity, two important global issues (Vorosmarty et al. 2000, IPCC 2007, UNEP 2007). However, because plants fix atmospheric carbon into biomass and release soil water to the atmosphere, higher primary production typically

Manuscript received 12 May 2015; revised 17 January 2016; accepted 28 January 2016. Corresponding Editor: E. Huber-Sannwald.

⁴Current address: Max Planck Institute for Biogeochemistry, Hans Knoell Strasse 10, Jena, 07745, Germany. E-mail: jhk11@duke.edu

accompanies greater transpiration, reducing flows to surface and ground waters. Vegetation shifts may thus result in trade-offs between carbon sequestration and water provisioning, where land uses that store more carbon result in smaller water yield and vice versa (Guo and Gifford 2002, Jackson et al. 2002, Farley et al. 2005, Knapp et al. 2008, Kim and Jackson 2012). However, few studies have examined both services concurrently, and there is ongoing debate on the generality of these trends (Huxman et al. 2005, Wilcox and Huang 2010).

Ground water supplies a quarter of the world's population and provides 40% of global irrigation and 20% of global crop output (Molden 2007, Gleeson et al. 2012). Groundwater replenishment can be highly sensitive to land-use change and is often outpaced by extraction for human use (Shiklomanov 2000, Kim and Jackson 2012). In fact, groundwater use is rapidly depleting aquifers in many locations around the world, driven in part by rising population growth and increasing droughts, and posing challenges for balancing present and future water needs (Vorosmarty et al. 2000, Foley et al. 2005).

The potential trade-off between ecosystem services following land-use changes can be better understood through economic valuation (Kreuter et al. 2001, Zhao et al. 2004). Ecosystem services are often outside of market economies and undervalued, which can lead to their degradation and unsustainable use (MEA 2000, NRC 2005, Claassen et al. 2008). Economic valuations combined with biophysical measurements help determine the benefits or costs of land-use changes and are needed to incentivize and optimize multiple ecosystem services through policy and market mechanisms, including taxes, subsidies, government regulations, and cap-and-trade markets. With such mechanisms being considered by more than 60 national and regional governments, the potential for ecosystem services to shape future policy and regulations is increasingly likely (Kossoy et al. 2014). Water and carbon ecosystem services are especially recognized for their value and marketability (Wilson and Carpenter 1999, Kossoy et al. 2014), leading us to construct a socioecological framework for analysis in our study regions in Argentina and the USA. However, carbon and water markets can sometimes have high transaction costs, volatile prices, and logistical challenges for quantifying ecosystem services (Robertson 2004, Norgaard 2010); we therefore ask how efficient market or policy mechanisms for these ecosystem services would affect land-use decisions.

Our results also address how adaptation of payments for carbon and water ecosystem services would affect land-use decisions under current market-based economies, which may not represent the values of the services in the future. In general, methods such as cost-benefit analysis focus on a single criterion or monetary value, which can create a short-term solution for internalizing these services into economic and policy decisions. However, these methods inadequately incorporate social or existence values, often failing to address issues such as intergenerational equity,

fair distribution, and ecological sustainability (Martinez-Alier 2003, Spash 2008). A different model of human behavior, such as multi-criteria analyses with participatory process, is sometimes used to incorporate a range of different goals and values (including non-monetary ones) through surveys to enable comparison of goals or goods across preference measurement scale (O'Neill 2001, Curtis 2004, Bryan and Kandulu 2011, Larsen et al. 2011, Koschke et al. 2012, Schwenk et al. 2012).

To examine potential trade-offs with land-use changes, we compared carbon storage and groundwater recharge in natural grasslands plots paired with rain-fed cultivation, irrigated cultivation, or woody-plant-invaded plots in both the USA and Argentina. Our sites spanned broad climate and soil gradients, as predictive understanding of the trade-offs depends on both biotic and abiotic factors (Kim and Jackson 2012, Schlesinger and Bernhardt 2013). We combined our biophysical assessment of ecosystem services with available estimates of their economic values from the literature to quantify their associated costs/benefits for the land-use changes that we studied. We compared the ecosystem service costs and benefits to the expected income from the land-use changes (e.g., crop production) to estimate the net economic value of the land-use changes for the U.S. study region.

METHODS

We evaluated the potential for land-use changes to alter carbon and water resources in arid and semi-arid grasslands of Argentina (the Pampas) and the USA (shortgrass steppe, southern mixed prairie, and tallgrass prairie). Grassland soils contain roughly half as much carbon as is contained in the atmosphere, with large sink and source potentials (Jobbágy and Jackson 2000, Schlesinger and Bernhardt 2013). Plains grasslands are also relatively dry, making groundwater an essential resource for human and natural communities and leading to an overdraft of aquifers in many systems (Vorosmarty et al. 2000, Kim and Jackson 2012). Cultivation and woody encroachment are prevalent land-use changes in grassland biomes, with an estimated 80% of the world's natural grasslands replaced by annual crops and an estimated one-third of U.S. rangelands undergoing woody encroachment (Houghton et al. 2000, Ramankutty et al. 2008). Production pressures such as emerging biofuel markets and higher and more continuous grazing intensities, which can trigger woody encroachment, are likely to extend land-use conversions in the remaining grasslands (Archer 1994, Fargione et al. 2008). Although we examined vegetation shifts to woodlands and annual croplands from natural grasslands, transitions among forest, pasture, and crops are common globally, and our work should provide insight for trade-offs in other systems as well.

In Argentina, we studied natural grasslands at five locations that had adjacent or nearby (<1 km) rain-fed cultivated or woody-plant-invaded plots. The five locations

encompassed relatively flat (<5% slope) landscapes along a precipitation gradient from 382 to 1215 mm/yr in the Pampas (Appendix S1: Table S1). Additionally, a native woodland, a regenerating woodland, and a rain-fed cultivation plot were paired to a maintained pasture at a site in the ecotone between natural grasslands and dry forests (*Prosopis caldenia* woodlands). In the southern Great Plains of the USA, we selected five more study sites with natural grasslands paired to rain-fed and/or irrigated croplands along a precipitation gradient (407–890 mm/yr). In addition to our new field data, we also analyzed soil samples from four additional paired grassland and woodland sites sampled previously in the southwestern Great Plains across a precipitation gradient (220–1070 mm/yr; Jackson et al. 2002).

Most plots had >30 yr of constant land use. Farm managers were surveyed for land-use history at each site, such as species grown, rotations, and inputs, including fertilizer and irrigation (Appendix S1: Table S2). The ages of tree stands were verified with aerial photos or tree ring cores (Mast et al. 1997). Precipitation data were obtained from >30 yr records maintained by weather stations within 30 km from the National Climatic Data Center or maintained onsite *available online*⁵ (Appendix S1: Table S1). Economic data on ecosystem service values and productive income for alternative land uses (e.g., pasturing for livestock, rain-fed cropland, and irrigated cropland) were available at county or larger geographical units (Appendix S1: *Methods*). With this level of aggregation, we opted to focus on the most common land uses in each region, targeting those land uses and woody plant invasion in our field sampling.

Soil samples were taken from three to eight deep boreholes (either to 9 m depth or, instead, to the groundwater table) at each land-use plot and were used to measure soil carbon storage and to estimate recharge (Appendix S1). Aboveground herbaceous biomass and litter were harvested in three to eight randomly placed 0.5 × 0.5 m quadrats (USA) or 0.3 m diameter rings (Argentina) in grassland and woodland plots. Basal diameters or diameters at breast height and the height of individual woody stems were measured in one to three 20 × 20 m quadrats in woodland plots. We applied species- and region-specific allometric equations to these measurements to estimate tree volume and biomass (Appendix S1: Table S2). Aboveground crop biomass was not considered as carbon storage due to its annual turnover with crop harvest. Logistical difficulties prevented multiple sampling for estimating temporally averaged crop biomass. Detailed information on the recharge estimation techniques is found in Appendix S1 and in Kim and Jackson (2012).

Our goals for the economic analyses were to (1) assess the net cost or benefit of changes in carbon storage and groundwater recharge after land-use changes, (2) compare these net costs or benefits with the benefits derived from traditional economic activities at each site, such as

commodity production, (3) evaluate which ecosystem service is more likely to drive land-use decisions under hypothetical market or policy incentives, and (4) determine under which environmental conditions such incentives would encourage grassland conversions to other land uses.

We determined the economic values of carbon sequestration and groundwater recharge using reported literature values from near our sites with similar social and geophysical settings (e.g., Brouwer 2000, Barbier 2011). Net environmental costs and benefits incurred by the land-use change over time were estimated by multiplying our biophysical measurements of ecosystem services with their shadow prices (value of an additional increment in a given service), discounted annually at inflation-adjusted rate of 4% using modeled temporal changes in the services. Our simulations were designed to reflect relatively short-term (e.g., ≤30 yr) time frames of current policies or market incentives. We also include a sensitivity analysis of the land-use-induced costs and benefits in ecosystem carbon and water against a range of temporal dynamics.

To address uncertainties in using prices from carbon markets and water valuations as proxies for the ecosystem services we measured, and to address market volatilities, we conducted an additional sensitivity analyses with different sets of carbon and water prices. For the unit value of carbon sequestration, we used estimates based on social costs of US\$15 for 1-ton CO₂ emissions, as well as US\$3 and \$30 based on market prices (IPCC 2007). For groundwater recharge valuation, we used location-specific values of irrigation water (higher end prices) from the literature, as well as marginal pumping costs (lower end prices) based on aquifer depth and specific yield (Fig. 1). The lower values for carbon and water represent business as usual or scenarios where policies with only modest incentives for ecosystem service provisioning exist. Higher values represent scenarios with stronger policy of market incentives.

We used grasslands as the baseline land use in our analysis, capturing the costs or benefits of woody encroachment and rain-fed or irrigated cultivation that hypothetical incentives for carbon and water pricing could confer. To place the ecosystem-service values into context, we compared their net present values to those of average net income of different land-uses by county (e.g., livestock grazing, rain-fed and irrigated cropping) from the United States Department of Agriculture Cash Rents Survey. We focused our economic analysis for sites in the USA due to the lack of water valuation data in our Argentine study region, but we discuss the results in context of the carbon and water trade-offs and associated policy implications for both regions.

We also compared the trade-offs between carbon and water from biophysical and economic perspectives to illustrate the different conclusions one would draw from trade-off analyses depending on the valuation approach and assumptions. Because economic values of water were

⁵<http://www.ncdc.noaa.gov/oa/ncdc.html>

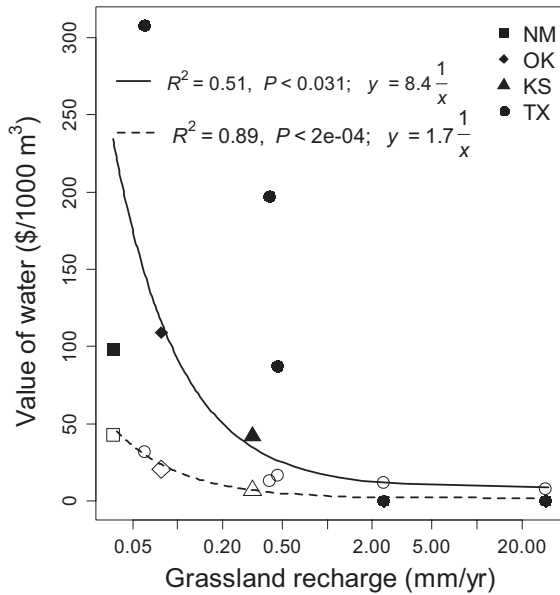


FIG. 1. Water values in our study region from our literature review. Water values decline with increasing groundwater recharge or water supply, shown here in log-scale. Water values based on crop production from irrigation are shown as solid symbols, while those with marginal pumping costs are shown as open symbols (Appendix S1). Water values may be sensitive to precipitation and temperature; our recharge estimates are affected by both variables (Kim and Jackson 2012). All values were adjusted for inflation and presented in 2015 US\$. Regression statistics for multiplicative inverse (i.e. reciprocal)-transformed data with fixed intercept at 0 are shown. Abbreviations are NM, New Mexico; OK, Oklahoma; KS, Kansas; and TX, Texas.

not available for our Argentina sites, we looked for a good predictor of water values from our literature review among site variables such as climate, soil, recharge rates, crop type, and population. Grassland recharge rates, which can be seen as the sustainable supply of ground water, was the best predictor of the water values from our U.S. study region (Fig. 1). We applied this relationship between recharge and water value to our biophysical measurements to estimate the relative value of changes to groundwater recharge across all our sites. In contrast, because establishment of regional or national emissions trading market or tax would set a uniform price across the area, the economic value for carbon was assumed to remain fixed across sites. Details of the net present value calculations, statistical analyses, sensitivity analyses, cash rents, and shadow prices of carbon and water are described in Appendix S1.

RESULTS

Changes in carbon storage with grassland conversions to rain-fed croplands or encroached woodlands in the USA and Argentina were negatively correlated with changes in groundwater recharge, with larger gains in one ecosystem service offset by larger losses in the other ($P < 0.0003$; Fig. 2a). Rain-fed croplands had 32 Mg/ha

lower total carbon storage on average than native grasslands, driven primarily by losses in soil organic carbon (paired t test, $P < 0.0005$; Table 1). However, the same croplands gained 13 mm/yr of groundwater recharge compared to their native grassland pairs, a six-fold increase in the magnitude of this service (signed-rank test, $P < 0.001$). Although a few cases of woody encroachment resulted in losses of both carbon and water, woodlands overall had 29 Mg/ha more total carbon storage than native grasslands (paired t test, $P < 0.02$) but only half the groundwater recharge (-7.3 mm/yr; signed rank test, $P < 0.002$). These results indicate a trade-off between two ecosystem services for both land-use changes.

In contrast to rain-fed crops and woody encroachment, irrigated crops tended to reduce both carbon storage and groundwater recharge, by 14 Mg/ha and 330 mm/yr, respectively, compared to their grassland pairs and, in fact, resulted in net discharge of ground water (Table 1). The discharge was attributable to the greater extraction of groundwater for irrigation compared to drainage. No cases of land-use changes that we examined resulted in gains of both ecosystem services, suggesting that the elimination of grasslands results in loss of at least one of the services, and reciprocally, the reestablishment of grasslands may increase one or both services.

Changes in ecosystem services depended on climate and soil attributes, indicating that environmental variables can be used to help predict the trade-offs described previously. For example, carbon losses for sites with rain-fed cultivation were larger at locations with higher clay content (multiple regression, $P < 0.0015$), whereas water gains were smaller ($P < 0.05$), suggesting that in coarser textured, sandier soils, this land-use change may have a less negative environmental impact (i.e., lose less carbon and gain more water). If changes were immediate and constant for 30 yr after rain-fed cultivation, a loss of 1 Mg of carbon would produce 150 Mg of recharge gain in sandy soils, but only 23 Mg of water gain in clayey soils (Appendix S1: Fig. S1).

Land-use effects have a stronger interaction with climate in the case of groundwater recharge (larger impact under humid climates, multiple regression with $P < 0.0003$) than in the case of carbon sequestration. The lack of interaction in the case of carbon resulted from shifts in biomass and soil stocks showing opposite trends and cancelling each other along gradients of increasing humidity (Appendix S1: Fig. S2). These patterns suggest that rain-fed cultivation may be more attractive in humid climates (i.e., large water gains with average carbon losses), whereas woody encroachment may provide greater benefits in arid climates (i.e., smaller water losses with average carbon gains). However, the fact that ground water may have lower values in humid areas (Fig. 1) necessitated better accounting of the ecosystem service values.

Using medium (US\$15/Mg CO_2) and high (irrigation values) prices for carbon and water, respectively, grassland conversions to woody encroachment and

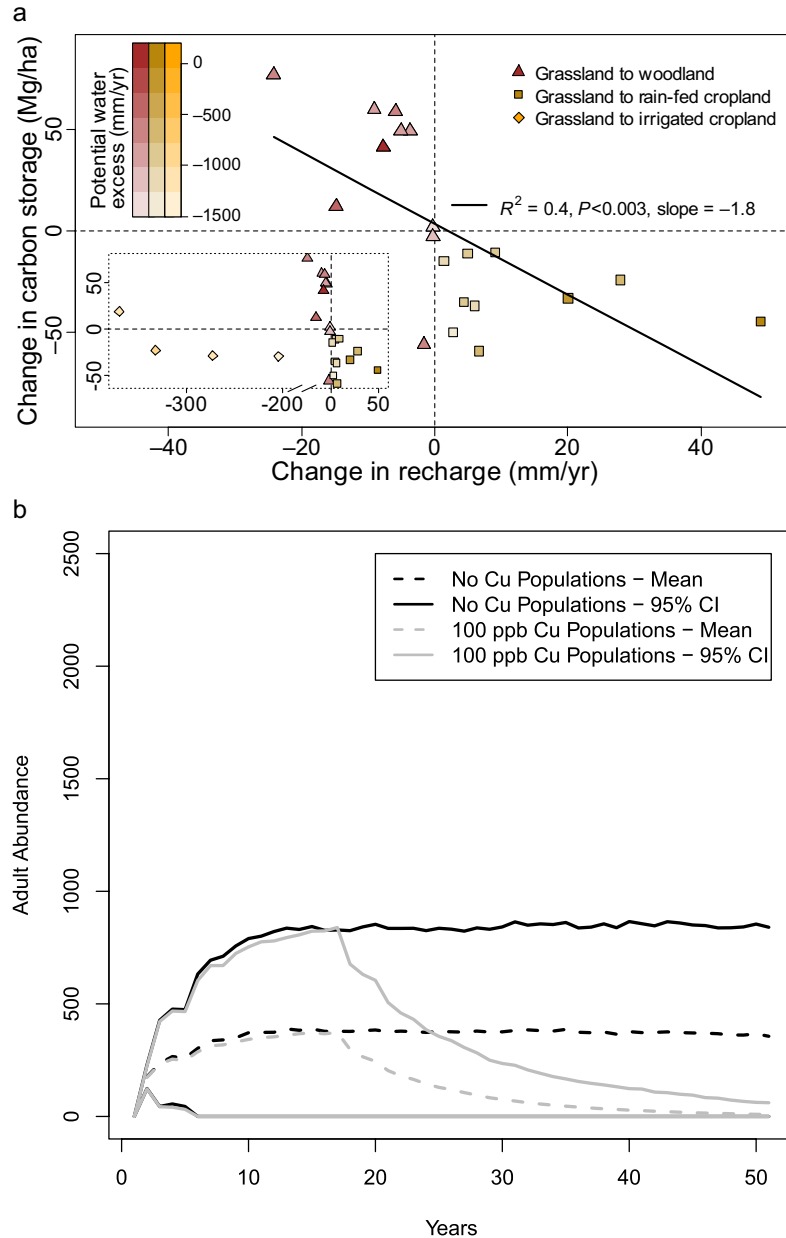


FIG. 2. The trade-off between carbon storage and groundwater recharge with land-use changes in U.S. and Argentinean grasslands displayed with (a) absolute changes in carbon and water and (b) estimated relative values of the changes assuming a global carbon price and water price as a function of groundwater recharge from Fig. 1. Darker shades represent data from sites with more humid climates. Insets show the full range of the data, including values for irrigated cultivation. – and + of the inset axes in panel (b) indicate costs and benefits, respectively. The lack of data points in the upper right quadrants suggests that land-use changes do not typically increase both carbon storage and groundwater recharge (the win-win scenario). Regression shown for data excluding the four conversions to irrigated croplands.

rain-fed cultivation in the southwestern USA resulted in negative net present values (NPV), indicating that environmental costs exceeded benefits (Table 2; –2 to –2500 in 2015 US\$/ha). NPV for grassland conversions to irrigated cultivation varied from US\$740 to –14100/ha. Under the market scenario of medium and high prices for carbon and water, respectively, seven (five rain-fed and two irrigated) out of nine cultivated plots would fail

to offset the net environmental costs of the carbon and water changes through land-use income (Table 2). Using the highest market value of carbon, all cultivated plots would result in complete loss of productive income, indicating that agricultural conversion would cease under the high carbon value and the current commodity prices (Appendix S1: Table S3). Rain-fed cultivation would remain profitable only under the low carbon price, while

TABLE 1. Changes in organic carbon stocks (to 3 m-depth for soil) and groundwater recharge rates with grassland land-use changes.

Site	Biomass carbon (Mg/ha)		Soil carbon (Mg/ha)		Recharge (mm/yr)	
	Crop cultivation†	Woody encroachment†	Crop cultivation†	Woody encroachment†	Crop cultivation†	Woody encroachment†
Nahuel Mapa	...	25.3	...	24‡	...	-3.6‡
Dixonville	-4.9	47.2	-5.5	13.2	8.3	-9.1
Caldenadas	-9.5	32.0	-1.6	17.6‡	4.9‡	-5.1‡
Parera	-2.3	60.2 (46.8)	-21.9	5.8 (2.5)	27.9‡	-25.2‡ (-5.9)
San Antonio	-3.7	72.6	-41.1‡	-31.3‡	48.9‡	-7.7‡
San Claudio	-11.4	...	-21.9‡	...	20‡	...
Sevilleta	...	0.4	...	1.4	...	-0.025‡
San Angelo	-3.6 (-3.6)	...	-46.6‡ (-26.0)	...	2.7‡ (-194‡)	...
Goodwell	-1.8 (-1.8)	...	-12.3 (21.5)	...	1.4 (-372‡)	...
Vernon	...	4.7	...	-7.6	...	-0.03
Quanah	-2.5 (-2.5)	...	-34.0‡ (-25.8‡)	...	6.0‡ (-331)	...
Tribune	-1.5 (-1.5)	...	-33.5‡ (-21.8‡)	...	4.4‡ (-438‡)	...
Riesel	-4.0	5.3	-55.4‡	-61.4‡	4.8‡	-1.64‡
Engeling	...	44.4	...	-32.2‡	...	-14.8‡

†Values in parentheses indicate irrigated cultivation for crop cultivation and regenerating woodland for woody encroachment.

‡Indicates statistically significant differences ($P < 0.05$) between grassland and other land uses at each site.

TABLE 2. Net present values (NPV) of changes in ecosystem services and land-use income forecasted for a 30-yr timeframe.

Site	Land-use change	Carbon (\$/ha)†	Water (\$/ha)†	ES value (\$/ha)‡	Net income (\$/ha)§	Net LUC value (\$/ha)¶
San Angelo	rain-fed	-2600 (-510)	9.8 (1.8)	-2600 (-510)	1300	-1300 (780)
Goodwell	rain-fed	-640 (-130)	3.4 (0.89)	-640 (-130)	600	-38 (470)
Quanah	rain-fed	-1900 (-370)	120 (5)	-1700 (-370)	300	-1400 (-69)
Tribune	rain-fed	-1600 (-310)	5.9 (0.97)	-1600 (-310)	840	-730 (520)
Riesel	rain-fed	-3000 (-610)	0 (2.4)	-3000 (-610)	600	-2400 (-9)
San Angelo	irrigated	-1500 (-300)	-2800 (-530)	-1500 (-830)	2400	920 (1600)
Goodwell	irrigated	560 (110)	-4900 (-1300)	-4300 (-1100)	2300	-2100 (1100)
Quanah	irrigated	-1400 (-290)	-17 000 (-690)	-18 000 (-980)	4400	-14 000 (3400)
Tribune	irrigated	-950 (-190)	-3000 (-500)	-4000 (-690)	4400	430 (3700)
Sevilleta	WPI	47 (9.4)	-0.05 (-0.02)	47 (9.4)	-53	-6.4 (-44)
Vernon	WPI	-40 (-8.0)	-1.5 (-0.16)	-41 (-8.1)	-210	-250 (-210)
Riesel	WPI	-1700 (-340)	0 (-2.7)	-1700 (-340)	-350	-2000 (-680)
Engeling	WPI	170 (35)	0 (-16)	170 (35)	-280	-110 (-250)

Notes: Land-use changes are as follows: rain-fed, rain-fed cropping; irrigated, irrigated cropping; WPI, woody plant invasion. Abbreviations are ES, Ecosystem service; LUC, Land-use change. †NPV of changes in ecosystem services for 30 yr following the land-use change based on modeled temporal dynamics (e.g., Appendix S1: Fig. S3) using price of US\$15/ton CO₂ and irrigation water values. To represent business-as-usual scenario, NPV using low shadow prices of US\$3/ton CO₂ and marginal pumping costs are given in parentheses.

‡Combined NPV of changes in the carbon and water services. NPV based on the low shadow prices of the services in parentheses. §NPV of average net income change from land-use change calculated as NPV of the new land-use subtracted by that of pasturing livestock in grasslands (Appendix S1: Table S7). WPI values shown assuming 50% loss of grazing income from woody encroachment. Numbers are rounded to two significant digits, and any deviations between the columns are from rounding errors.

¶NPV of the land-use changes considering the incomes and environmental costs incurred by the land-use changes. NPV in parentheses are based on the low shadow prices of carbon and water. All currency in 2015 US\$.

woody plant invasion could be profitable only under the high carbon price. In the same sensitivity analysis, the main change introduced by lower water values was to make all the irrigated plots profitable. These results suggest that land-use changes could be slowed if values of carbon and water ecosystem services were directly priced into land-use decisions.

The value of changes in carbon storage tended to overshadow those of groundwater recharge shifts, suggesting that carbon rather than water considerations would have larger impacts on land-use decisions if these two ecosystem services were priced through market or policy mechanisms. The factor by which carbon benefits overwhelmed costs of recharge (and vice versa) varied between

three- and 200-fold and by US\$250/ha on average using the low carbon and high water values, which represent the existence of strong market or policy incentives for water provision only. Using the low ecosystem service values (low incentives for both carbon and water, or business as usual), the value of the carbon changes were greater than those of water by 75- to 470-fold and by US\$230/ha for rain-fed cultivation and woody encroachment. Using the high carbon and low water values (incentives for carbon only), the value of carbon changes were greater than those of water by 510- to 4700-fold and by US\$2240/ha (Table 2; Appendix S1: Table S4). Even the high water valuations for residential uses reflected in the prices found in the regional sale of water rights to municipalities may be unable to offset the value of changes in carbon stocks we observed (Appendix S1: Table S6). Carbon also consistently outweighed water in value across the temporal dynamics simulated, indicating that the carbon dominance likely holds for a wide range of environmental conditions across agricultural landscapes (Appendix S1: Table S4 and Fig. S4).

DISCUSSION

Our results showed a clear trade-off between land-use-induced shifts in carbon storage and groundwater recharge in grasslands of the USA and Argentina. This key result suggests that economic or policy incentives emphasizing one ecosystem service will likely have negative impacts on the other service (Fig. 2a). For example, agricultural conversion of natural vegetation typically results in the loss of ecosystem carbon storage, which may offset the benefits derived from additional recharge and crop production. Building on models and previous studies of ecosystem-service trade-offs (Jackson et al. 2005, Viglizzo and Frank 2006, Seidl et al. 2007, Power 2010), our work provides, to our knowledge, the first empirical evidence of the trade-off between carbon sequestration and groundwater recharge, two important and marketable ecosystem services (Bennett et al. 2009, De Groot et al. 2010). In addition, enhancing both carbon storage and water supply appears to be difficult within our climatic gradient, although the loss of both services with irrigated cultivation and woody encroachment presents opportunities for restoring both ecosystem services through the restoration of grasslands.

Examining relationships of carbon and water resources along environmental gradients also illustrates how abiotic factors such as soil and climate mediate ecosystem responses to land-use change. For example, rain-fed cultivation in fine- vs. coarse-textured soils introduced greater carbon losses (4.3 vs. 0.67 Mg/ha, respectively) per 100 Mg/ha of water gains, indicating that the net balance of these two ecological services would be more disadvantageous in clayey soils (Appendix S1: Fig. S1). The contrasting influence of the abiotic context on ground water recharge (high) vs. carbon sequestration (low) suggests such relationships need to be considered in order to

identify the arrangements of climate, soil types, and land uses that maximize multiple ecosystem services. Such relationships can be especially useful in data-scarce regions (Aylward and Barbier 1992, Pattanayak et al. 2010).

Our results suggest that integrating carbon and water ecosystem services into markets could in some cases help slow or even reverse land-use changes. Most of the land-use changes that we examined would impose environmental costs for carbon and water services and potentially increase commodity prices. Taking grassland conversions to croplands as an example, the net environmental costs of changes in the services were higher compared to the expected income from the land uses, indicating that agricultural conversions from grasslands might not be profitable, and could potentially be abated, at most of our sites if all services were priced fully (Table 2). If the carbon and water footprints of other on- and off-site activities associated with the land-use changes were considered (e.g., fertilizer production, processing, pollution, etc.; West and Marland 2002, Hoekstra and Mekonnen 2012), the net costs would likely be even greater.

Woody encroached plots had overall the most positive ecosystem-service values but the values were only marginally positive. Considering the likely loss of grazing habitat for livestock with woody encroachment (Grover and Musick 1990), the small positive ecosystem-service values (US\$47–170/ha) would be offset if ~30–50% of the potential grazing income were lost with woody encroachment (Table 2). Studies in forested biomes also found higher provisioning and values of services by the natural ecosystems (in our case, grasslands) than other land uses, and highest ecosystem-service values are often attributed to forests and woodlands (Costanza et al. 1997, Balmford et al. 2002, Turner et al. 2003, Kumar 2010). However, the environmental costs that we found with woody encroachment indicate greater value of natural grasslands relative to woodlands in some cases.

Our sensitivity analyses also point to how changes in commodity prices and ecosystem-service values could affect land-use changes. The relatively small differences between net income of the land uses and ecosystem-service values highlight the influence that volatile prices for carbon, water, or agricultural commodities could have on market dynamics and land-use decisions (Table 2). Using a carbon price of US\$15 per ton of CO₂, seven out of nine cultivation cases would become unprofitable with hypothetical carbon and water markets, compared to all cases and six cases with US\$30 and US\$3 per ton of CO₂, respectively. Whereas rain-fed cultivation was more sensitive to carbon prices, varying water prices affected the economic feasibility of irrigated croplands. Such uncertainties are important to acknowledge in designing market-based mechanisms to achieve sustainability goals (Engel et al. 2008).

The potential for growth in regional and global carbon markets suggests that carbon sequestration may become a more important driver of land-use decisions than water supply, at least in the short term. For example, at the

carbon price of US\$15, ecosystem carbon changes alone would negate the net income of rain-fed cultivation across our relatively dry study region in the USA. Even at low carbon prices, water prices or yields necessary to offset changes in carbon values would need to be three to >200 times greater than those in our literature review, indicating that value of changes in water provision is unlikely to offset those of carbon in the land-use changes and regions examined here, even considering higher prices from recent market transactions of water rights (Adams et al. 2004, Brookshire et al. 2004; Appendix S1: Tables S4 and S6). Because water markets tend to be comparatively informal and local in extent, emergence of a national carbon market may create local losses of

water provisioning (e.g., Carey and Sunding 2001). When satisfying a demand for global ecosystem services such as carbon sequestration, local needs for other services should be carefully considered, the combined value of which could sometimes exceed that of carbon sequestration (Plantinga and Wu 2003). Just as importantly, a suite of other ecosystem services needs to be valued for a more complete accounting of nature's services; our results should be regarded as a starting point for more comprehensive analyses.

Shadow prices of water varied across our sites, highlighting the importance of weighting the services by their values. Water is expensive to transfer over large distances, and its value shows high spatial variability driven

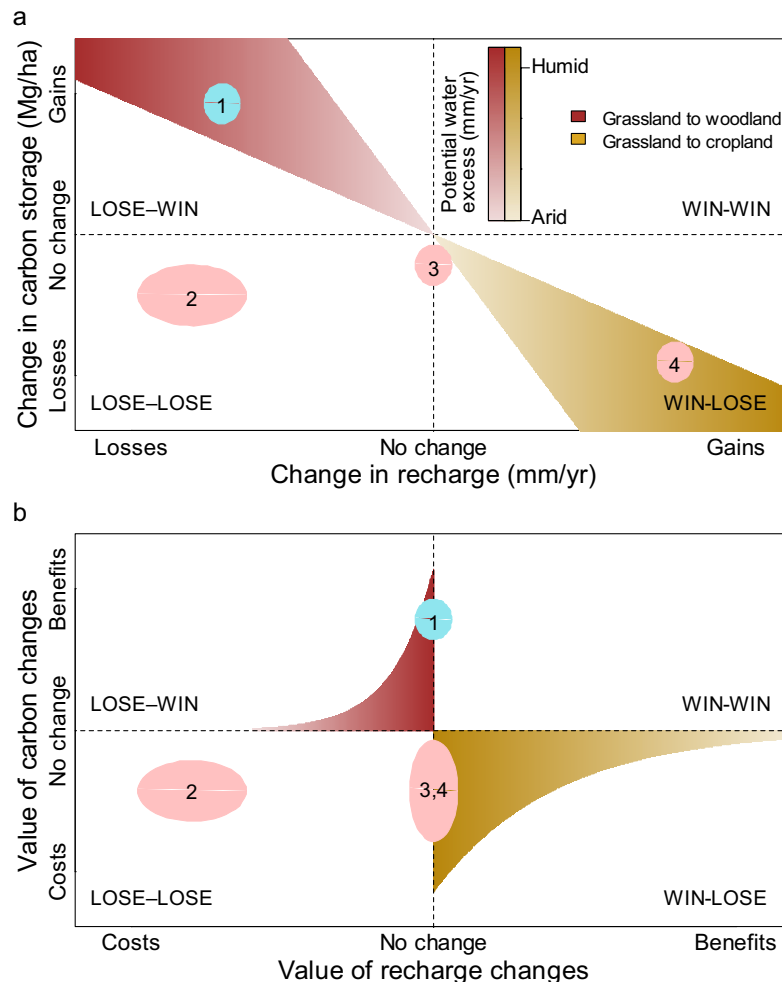


FIG. 3. Conceptual diagram of trade-off between carbon sequestration and groundwater recharge with land-use changes based on our data in Fig. 2: (a) costs and benefits of changes in carbon and water assuming global prices for the two services, and (b) costs and benefits of the carbon and water changes incorporating the context-dependent nature of the water provisioning. Panel (b) highlights the importance of recharge in arid climates where water is inherently limited (Fig. 1). The following lose-lose or win-win exceptions to the trade-off are represented in red or blue ellipses, respectively, and are more intuitive when overlaid on panel (b) than on (a): (1) Forest protection in cloud forest or afforestation in humid flood-prone areas results in win-win due to increased water provisioning from flood protection (Jobbágy and Jackson 2004); (2) Irrigated cultivation results in lose-lose from net discharge of groundwater (Scanlon et al. 2007, Kim and Jackson 2012); (3) woody encroachment in clay soils leads to lose-lose from loss of soil organic carbon (this study); and (4) rain-fed cultivation in humid flood-prone areas leads to lose-lose from increased flooding risks (Aragón et al. 2011).

by local availability (seven-fold in our U.S. study region; Fig. 1). In contrast, carbon sequestration can be traded globally and priced uniformly as a public good (Balmford and Whitten 2003, Bateman et al. 2011). The context-dependent nature of water provisioning is better illustrated by accounting for the scarcity of the resource. Representing values for groundwater as a function of recharge accentuates the smaller changes in arid climates where the renewal of the resource is inherently low and the unit value of the service is high (Fig. 2b).

We propose a conceptual model of carbon and water trade-offs with land-use conversions based on variations in the services and their values (Fig. 3). Assuming fixed prices for water and carbon, Fig. 3a illustrates a negative linear relationship between carbon and water as suggested by our biophysical measurements in Fig. 2a, where larger gains in one are offset by larger losses in the other service. However, a different picture of the trade-off emerged when applying the recharge vs. water value relationship from Fig. 1 to all our sites (Figs. 2b and 3b), indicating that any linearity of the trade-off needs to be applied with caution when assessing specific environmental costs and benefits in some cases. On the one hand, some situations may escape the trade-off relationship, such as the lose–lose cases of irrigated cultivation. On the other hand, the magnitude or even the sign of the value of the water service may vary with the socioecological setting. Incorporating the different values of water services, Fig. 3b shows that while land-use changes occupy the same win–lose and lose–win space, the linear relationship of the trade-off from Fig. 2a disappeared, with greater carbon gains offsetting smaller water losses and vice versa (i.e., increasing benefit from a service leads to decreasing cost of the other). The win–win or lose–lose exceptions to the trade-off also fall closer to the respective trade-off space quadrants.

One exception in our system is the potential for win–win transitions associated with flooding. Specifically, high recharge rates in the humid Pampas of Argentina can induce groundwater flooding due to shallow water tables and a lack of surface drainage features (Aragón et al. 2011). At the wettest end of our study gradient (>1000 mm rainfall), land-use changes that gain carbon but lose water, such as woody encroachment, might represent win–win situations by contributing to flood mitigation (Fig. 3b). In contrast, the Argentinean agro-pastoral system may currently be experiencing a lose–lose scenario under market pressures to cultivate rain-fed crops in the productive humid Pampas (Viglizzo et al. 2009), increasing flooding risks while driving livestock production to the marginal drier grasslands and potentially increasing woody plant dominance in the drier grasslands (Archer 1994).

In the southwestern USA, degradation of water quality from enhanced agricultural recharge could sometimes negate the benefit of the additional recharge and result in lose–lose situations (Jobbágy and Jackson 2004, Jayawickreme et al. 2011). Accumulated salts in grassland soils are vulnerable to dissolution and leaching

with the higher recharge rates under rain-fed cultivation, potentially leading to soil and water salinization (Scanlon et al. 2007). In some places the agricultural conversion of natural grasslands as a means to enhance water provisioning could be inappropriate, where water uses are restricted by water quality thresholds. Conversions to croplands more often may represent lose–lose situations for carbon and water services compared with vegetation shifts to forests or woodlands (Fig. 3b). Such interactions between social and ecological thresholds described here for the USA and Argentina should be key considerations in adaptive management of ecosystems (Kremen 2005, Bennett et al. 2009, Fisher et al. 2009, Koch et al. 2009).

Finally, we acknowledge how different economic methods may affect results. In addition to cost–benefit analyses (CBA), which are widely used in the field of economics and in policy decisions of many national governments, other methods are also utilized. For example, multi-criteria analysis (MCA) can sometimes accommodate a wider range of goals, values, and uncertainties, but studies comparing different methods show no consensus on the better methodology (see Kompas and Liu 2013 and citations within). Despite a few qualitative comparisons (i.e., Joubert et al. 1997), there has also been little empirical comparison of CBA and MCA specifically for ecosystem services. With MCA, greater values may be observed for both the ecosystem services and land-use products that we examined; avoiding irreversible changes like drawdown of non-renewable fossil water in arid regions or uncertainties associated with climate change and independence from foreign agricultural imports are some of additional preferences that could theoretically become evident with MCA.

In conclusion, we quantified carbon–water trade-offs and interacting abiotic drivers for carbon sequestration and groundwater recharge. Our results highlight the importance of, and challenges in, increasing the provisioning of multiple ecosystem services. They also illustrate the importance of considering holistically the effects of land-use changes by policy or market mechanisms that usually promote ecosystem services individually. Market incorporation of these two services should encourage more selective grassland conservation, abating future land-use changes and could also lead to more effective decision-making that optimizes economic and environmental benefits.

ACKNOWLEDGMENTS

This work was supported by the U.S. National Science Foundation (DEB#0717191, IOS#0920355, GRFP#2006044266, and DDIG #0910294) and USDA/NIFA (2012-68002-19795). We thank M. Beget for providing weather data, and R. Andres, M. Cleary, and L. Konopinski for their assistance in the field. We also thank the landowners and staff who provided logistical support and access to sites: Grupo Estudios Ambientales in San Luis, Institute for Agricultural Plant Physiology and Ecology at Universidad de Buenos Aires (UBA), and Estancia San Claudio of UBA in Argentina; Western Kansas Agricultural Research

Center in Tribune, Oklahoma Panhandle research and extension center in Goodwell, Texas AgriLife Research and Extension Centers at Vernon and San Angelo, and USDA-ARS Grassland Soil and Water Research Laboratory in Temple, Texas, USA. We thank B. Murray for helpful comments on the paper.

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