Using Changes in Agricultural Utility to Quantify Future Climate-Induced Risk to Conservation

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Abstract: Much of the biodiversity-related climate change impacts research has focused on the direct effects to species and ecosystems. Far less attention has been paid to the potential ecological consequences of human efforts to address the effects of climate change, which may equal or exceed the direct effects of climate change on biodiversity. One of the most significant human responses is likely to be mediated through changes in the agricultural utility of land. As farmers adapt their practices to changing climates, they may increase pressure on some areas that are important to conserve (conservation lands) whereas lessening it on others. We quantified how the agricultural utility of South African conservation lands may be altered by climate change. We assumed that the probability of an area being farmed is linked to the economic benefits of doing so, using land productivity values to represent production benefit and topographic ruggedness as a proxy for costs associated with mechanical workability. We computed current and future values of maize and wheat production in key conservation lands using the DSSAT4.5 model and 36 crop-climate response scenarios. Most conservation lands had, and were predicted to continue to have, low agricultural utility because of their location in rugged terrain. However, several areas were predicted to maintain or gain high agricultural utility and may therefore be at risk of near-term or future conversion to cropland. Conversely, some areas were predicted to decrease in agricultural utility and may therefore prove easier to protect from conversion. Our study provides an approximate but readily transferable method for incorporating potential human responses to climate change into conservation planning.

Keywords: agricultural utility, climate change, conservation area, crop model, opportunity cost, South Africa, *Triticum aestivum*, *Zea mays*

Uso de Cambios en la Utilidad Agrícola para Cuantificar Riesgos Futuros para la Conservación Inducidos por el Clima

Resumen: Mucha de la investigación de los impactos del cambio climático relacionados con la biodiversidad se ha enfocado en los efectos directos sobre las especies y los ecosistemas. Se le ha prestado muy poca atención a las consecuencias ecológicas potenciales de los esfuerzos humanos para tratar los efectos del cambio climático, lo cual puede igualar o exceder los efectos directos del cambio climático sobre la biodiversidad. Es probable que una de las respuestas humanas más significativas sea mediada por los cambios en la utilidad agrícola del suelo. Mientras los granjeros adapten sus prácticas a los climas cambiantes, pueden incrementar la
presión en algunas áreas que son importantes de conservar (tierras de conservación) y disminuirla en otras. Cuantificamos cómo la utilidad agrícola de las tierras de conservación en Sudáfrica puede alterarse por el cambio climático. Asumimos que la probabilidad de que un área sea cultivada está relacionada con los beneficios económicos de hacerlo, usando los valores de productividad del suelo para representar el beneficio de la producción y la robustez topográfica como un sustituto para los costos asociados con la posibilidad de trabajo mecánico. Computamos valores actuales y futuros de la producción de maíz y trigo en tierras importantes de conservación usando el modelo DSSAT4.5 y 36 escenarios de respuesta de los cultivos al clima. La mayoría de las tierras de conservación tuvieron, y se predijo que seguirían teniendo, una utilidad agrícola baja por su ubicación en terreno escabroso. Sin embargo, se predijo que en varias áreas se mantendría o se ganaría una utilidad agrícola alta y por eso podría estar en riesgo de convertirse en tierras de cultivo en poco tiempo o en el futuro. Inversamente, se predijo que en algunas áreas disminuiría la utilidad agrícola y por eso podría ser más fácil protegerlas de la conversión. Nuestro estudio proporciona un método aproximado pero listo para transferirse para incorporar respuestas humanas potenciales al cambio climático a la planeación de la conservación.

Palabras Clave: Área de conservación, cambio climático, costo de oportunidad, modelo de cultivo, Sudáfrica, utilidad agrícola, Triticum aestivum, Zea mays

Introduction

Climate change will further complicate the task of biodiversity conservation by altering species’ ranges and population sizes and disrupting ecological communities (Thomas et al. 2004; Holec et al. 2009; Huntley & Barnard 2012). Conservationists are increasingly trying to account for these changes by factoring climate change impacts into planning (Heller & Zavaleta 2009), drawing on a growing literature that examines how biodiversity will be directly affected by changing climatic variables (Turner et al. 2010).

Another important concern is the indirect impacts that human adaptation to climate change may have on biodiversity (Paterson et al. 2008; Turner et al. 2010; Oppenheimer 2012). To date, this facet of climate change has received little direct attention by conservationists (see Bradley et al. 2012; Hannah et al. 2013), yet history suggests that human responses to climate disturbances can have larger and more rapid ecological impacts than those resulting directly from climate change (Turner et al. 2010; Oppenheimer 2012).

Adaptation in the agricultural sector is of particular concern, given its large spatial extent, prominent role in driving habitat loss, and sensitivity to climate (Tilman 1999; Howden et al. 2007; Gibbs et al. 2010). In recent decades agriculture has rapidly transformed high biodiversity regions, such as the Brazilian Cerrado and Southeast Asian tropical forests (Koh & Wilcove 2008; Faleiro et al. 2013), and is expected to heavily impact African savannas in the near future (Morris & Byerlee 2009; Rulli et al. 2013). Climate-related agricultural changes, driven by both policy and altered productivity, are also contributing to habitat losses. For example, farmers in the Peruvian Andes can now cultivate 300 m higher than just a few decades ago, increasing pressure on previously unfarmed high elevation areas (Halloy et al. 2005). High commodity prices driven partly by biofuel mandates are causing farmers in the American Midwest to rapidly convert grasslands to corn and soybean crops (Wilson et al. 2008; Wright & Wimberly 2013).

In the future, human population growth combined with climate change may greatly exacerbate losses of biodiversity if producers respond to changing agricultural productivity by converting natural ecosystems to farmland (Jetz et al. 2007; Bradley et al. 2012). Alternatively, some current farmland is likely to lose productivity and may thus become available for conservation or restoration, revert to natural cover, or lead to more conservation compatible land uses such as ranching (Jones & Thornton 2009; Bradley et al. 2012; Seo 2012; Lorencová et al. 2013).

These findings suggest it is important to anticipate how conservation and agriculture will interact under climate change. One potential approach is based on estimating the agricultural potential of land, which is negatively correlated with protected area presence (Rouget et al. 2003; Joppa & Pfaff 2009) and a strong predictor of the likelihood that natural landscapes will be turned to crop cultivation (Stephens et al. 2008; Rashford et al. 2011). Agricultural potential is therefore indicative of the pressure to convert land to agricultural uses. This pressure stems from opportunity cost, the value that is foregone by choosing not to farm the land (or put it to some other valued use [Dixon & Sherman 1991; Naidoo & Adamowicz 2005]). Agricultural potential is used in existing systematic planning approaches to help schedule conservation acquisitions, based on the idea that areas with the highest potential (i.e. the highest opportunity cost) are likely to be converted most rapidly (Margules & Pressey 2000).

Because agricultural productivity varies with climate (Karkee et al. 2008), climate change can alter the agricultural potential of land. Projecting how agricultural potential changes under future climates may provide a first-order measure of how climate change will affect
agricultural land-use pressure on areas of conservation concern. To assess this possibility, we simulated the current and future agricultural potential of protected areas and areas prioritized for future protection (hereafter priority areas; we refer collectively to both kinds as conservation lands) based on their potential productivity for maize or wheat. We used these values together with terrain characteristics to calculate the agricultural utility (the nonmonetized potential benefit that could be derived from farming) of conservation lands, which formed the basis of a framework for classifying their current and future vulnerability to agricultural conversion. We focused on South Africa, which is useful for studying climate-driven land-use interactions because it has a large agricultural sector, globally significant biodiversity, and high projected vulnerability to climate change (Bradley et al. 2012). Furthermore, there is already evidence of land competition between the agriculture and biodiversity conservation sectors (Wessels et al. 2003; Neke & Du Plessis 2004; Reyers 2004).

The resulting vulnerability framework can help conservation planners anticipate the potential impacts of climate change adaptation in one of humanity’s most extensive and fundamental endeavors.

Methods

Study Area

Maize and wheat are South Africa’s 2 dominant staple crops by production area and consumption (Bradley et al. 2012), and South Africa is a regionally and globally important producer of these 2 crops (Estes et al. 2013a). Despite having a semiarid climate, more than 85% of South African maize and wheat production is rainfed and occurs on commercial farms (Hardy et al. 2011; Bradley et al. 2012). Maize is mostly grown in the summer rainfall zones in the northeastern part of the country (Fig. 1a), with production spanning 3.1 million ha, whereas wheat production is concentrated in the southwest (Fig. 1b) and covers 820 thousand ha (Bradley et al. 2012).

South Africa’s current protected area network comprises 597 statutory reserves covering 8 million ha, and 237 informal conservation lands occupy another 900,000 ha. Many protected areas were established to conserve water catchments, thus mountainous areas are over-represented in the current network (Rouget et al. 2003). The National Department of Environmental Affairs and the South African National Biodiversity Institute recently identified 12 million ha as priorities areas for conservation to correct this trend and meet national biodiversity conservation goals (Government of South Africa 2010). We considered both protected areas and priority areas in assessing future agricultural pressure on conservation lands.

Defining Agricultural Utility

In calculating the agricultural utility of land, we assumed that agricultural land-use patterns are primarily determined by natural features related to potential productivity and production costs. This assumption is based on several factors, including South Africa’s recent agricultural history. Up until the late 1980s, government subsidies promoted maize and wheat farming in marginally productive areas (Hardy et al. 2011). Following the removal of subsidies, cereal farming retreated toward more climatically suitable areas (Hardy et al. 2011), such that most of the high potential arable land is cultivated (Wessels et al. 2003). Given this already extensive distribution and South Africa’s well-developed infrastructure, we assumed that distance to market and transportation infrastructure are minor spatial determinants of South African farmlands. Other studies support this assumption. Their results show that infrastructure is less important in shaping farmland or deforestation patterns than slope and other terrain characteristics, particularly where road networks are dense (Jasinski et al. 2005; Mann et al. 2010; de las Heras et al. 2012; Green et al. 2013). Work from the forestry sector connects terrain to production costs, showing that roughness (e.g., rockiness) and slope synergistically affect operating costs (Haarlaa 1975). We assumed that topography similarly influences crop production costs (Karkee et al. 2008).

We therefore developed a 2-predictor model to calculate the potential profit or loss of farming a given piece of land for maize or wheat. To develop the model, we first
used logistic regressions (McCullagh & Nelder 1989) to find the probability that a given area was being farmed with maize or wheat, based on its potential yield for the crop and its topographic ruggedness, which measures local elevational variation. We then divided ruggedness values into discrete intervals and within each interval averaged the predicted probabilities for areas that were observed to have farms and those that were not. The midpoint between these values was the break-even yield, above which cropping, on average, improved the farmer’s welfare (or utility) and therefore the probability that the land would be farmed (Naidoo & Adamowicz 2005). We fit a linear function through these values to find the predicted probability of farming for all possible values of ruggedness and then solved for the break-even yields by rearranging the logistic regression equation (these steps are explained in detail in Supporting Information).

Subtracting the break-even yield from estimated yields provided utility in cereal productivity units. Converting these remainders into production (tons) and integrating the resulting values from all pixels (we used gridded estimates of yield and ruggedness) falling within a defined area, yielded that area’s net agricultural utility. A negative value (e.g. -1000 tons) means farming the area would return an annual loss equivalent to the value of that crop tonnage, whereas a positive tonnage indicated that farming would be profitable.

The Agricultural Utility of Conservation Areas

We used the decision support system for agrotechnology transfer (DSSAT, version 4.5.0.047) (Jones et al. 2003; Hoogenboom et al. 2012) to model current South African maize and spring wheat yields, as well as the suitable (or potential) growing region for each crop. Our simulations produced average yields for 1979–1999 (period for which historical weather data were available). The input datasets, modeling procedure, and results (for yield and suitability) are described in Estes et al. (2013a, 2013b) and summarized in Supporting Information. The modeled yield maps (in grids of 923 m resolution) for wheat and maize had respective $R^2$ values of 0.37 and 0.4 when compared with remotely sensed yield proxies and were 87% and 96% accurate in delineating suitable growing regions.

To calculate ruggedness, we used the topographic ruggedness index (Riley et al. 1999) and a 92 m resolution shuttle radar terrain mapping (SRTM) digital elevation model (DEM). The resulting map (aggregated to 923 m) provided the mean squared elevation difference between each DEM pixel and its 8 neighbors.

To create the break-even yield model, we used randomly selected subsets ($n = 2000$ for maize; $n = 888$ for wheat) of point observations for each crop (SIQ 2007) to represent farm presence. For farm absence, we randomly placed the same amount of points in the unfarmed areas of each crop’s growing region. We used these points to extract values from the yield and ruggedness maps, estimated the logistic regression models, and then calculated break-even yields. We assessed logistic regression fit with the area under curve (AUC) of the receiver operating characteristic curve (Fielding & Bell 2002) and used binary classification error to assess how effectively break-even yield values distinguished between farm and non-farmed points (see Supporting Information for details). We repeated this process 1000 times and calculated 95% confidence intervals for each parameter from their estimated values over the 1000 iterations. We used the mean break-even yield intercept and slope to calculate each crop’s break-even yield map, which we subtracted from the corresponding yield maps and converted to tons. We integrated all values within each conservation land to calculate its agricultural utility.

We calculated future agricultural utility for conservation lands using DSSAT-simulated maize and wheat yield projections for 2046–2065, run under 36 different climate-crop response scenarios (Estes et al. 2013a) (summarized in Supporting Information). The crop models were run with 18 downscaled climate scenarios twice, once with crop growth simulated under projected future CO$_2$ concentration levels and once under 1979–1999 CO$_2$ concentrations. These 2 treatments were used to assess uncertainties in crop responses to elevated CO$_2$. We extracted the 10th, 50th, and 90th percentile yield projections from each CO$_2$ treatment, which resulted in 6 simulated yield surfaces. We subtracted the break-even yield map from each of the 6 yield projections, converted the remainders to tons, and integrated the values within conservation lands.

We confined our analysis to conservation lands that contained at least 86 ha (i.e. 1 pixel) of land suitable for growing one of the 2 crops, either currently or in the future (as projected by Estes et al. 2013a). We segregated the selected conservation lands by crop type because potential maize and spring wheat production areas have little overlap. To further simplify the analysis, we excluded protected areas smaller than 700 ha (median size, which is roughly equivalent to a small provincial nature reserve) and priority areas smaller than 168 ha (75th percentile size). Using these criteria, we assessed 32% of South African protected areas and 15% of priority areas falling in the potential maize production region and a further 23% of protected areas and 7% of priority areas within the potential wheat region.

To examine how agricultural utility under present climate has affected the spatial distributions of conservation lands and farmland in South Africa, we compared the summary statistics (Fig. 4) of conservation lands’ utility values with those of maize and wheat farms (see note on comparison scale in Supporting Information).
Incorporating Agricultural Utility Changes into Vulnerability Assessments

To indicate the relative vulnerability of conservation lands to current and future agricultural conversion pressure, we adapted Margules and Pressey’s (2000) 4 quadrant framework (their fig. 8) for prioritizing conservation action (Fig. 2). We modified their framework by dropping the irreplaceability dimension (their y-axis) and replacing it with projected agricultural utility, which describes future vulnerability to agricultural conversion (areas with positive values are more vulnerable). We used the utility resulting from the crop model’s median yield simulation under the high CO$_2$ treatment to define each conservation land’s y-axis position, whereas utilities derived from the other 5 projected yield surfaces (see previous section) indicated model uncertainties. We retained Margules and Pressey’s (2000) existing vulnerability dimension (x-axis) to describe present-day conversion risk based on current agricultural utility.

Results

Break-Even Yield Model

The mean logistic regression AUC after 1000 iterations was 0.79 for wheat and 0.80 for maize (Supporting Information); thus, yield and ruggedness (expressed in meters) were reasonable predictors of the likelihood that an area was being farmed. The coefficients confirmed that yield and ruggedness were respectively positively and negatively correlated with farm presence (Supporting Information).

The break-even yield models indicated that farms in flat terrain (ruggedness = 0) must yield more than 1038 kg/ha.
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for maize or 1351 kg/ha for wheat to be farmed profitably (Fig. 3 & Supporting Information). For every unit increase in ruggedness, an additional 284 kg/ha of maize and 112 kg/ha of wheat is required to compensate for the added costs of ruggedness. The break-even yield lines correctly classified farmed and nonfarmed locations with an average accuracy of 72% for maize and 71% for wheat.

Current Agricultural Utility of Conservation Lands

The median utility of conservation lands is strongly negative under current climate conditions, ranging between −92 (wheat region priority areas) and −166 (maize region protected areas) tons, and less than 25% of these areas have positive agricultural utility (Fig. 4). In contrast, the majority of currently farmed maize or wheat fields have positive agricultural utility, with median values of 27 (maize) and 28 (wheat) tons.

Changing Agricultural Utility and Vulnerability of Conservation Lands

The majority of conservation lands in both cropping regions (89% of area) have negative agricultural utility now and in the future, placing them in the low pressure quadrant of the agricultural vulnerability framework (Figs. 2, 5 & 6, Supporting Information) (see Supporting Information for projected agricultural utility values for individual conservation lands). In the maize production region, 8% of the assessed protected areas and 3% of priority areas were classified as urgent because of their positive current utility, whereas only 3% of the assessed protected areas and 0% of priority areas were classified as urgent in the wheat region.
Figure 5. Changes in agricultural utility, from current to future projected values, for protected areas (top) and priority conservation areas (bottom) in the maize production region of South Africa. Graphs illustrate the range in projected agricultural utility and the boundaries delineating the 4 related agricultural conversion risk categories. Maps illustrate each conservation land’s risk classification, as projected under the median result of simulations conducted under the assumption that maize will respond positively to elevated CO\(_2\). A further 3% of protected areas and 3% of priority areas were classified in the increasing pressure quadrant. Conservation lands in these 2 categories are primarily located between the borders of Lesotho and Swaziland. One percent or less of conservation lands, mostly located in the west of the maize growing region (Fig. 5), were projected to transition from positive to negative utility (decreasing pressure). In the wheat production region, conservation lands in the urgent (5% of protected areas; 7% of priority areas) and increasing pressure (4% of protected areas; 3% of priority areas) quadrants lie mostly in the coastal areas of the Cape region (Figs. 5 & 6). None were placed in the decreasing pressure quadrant in this region.

There was substantial variation within crop yield projections (Estes et al. 2013a), which translated to large differences in the agricultural utility estimates for individual conservation lands. This variation exceeded 30% (relative to the median of all 6 projected utility estimates) for 49% of protected areas and 55% of priority areas (Figs. 5 & 6, Supporting Information). However, the assigned vulnerability category was fairly insensitive to this large variation in projected agricultural utility. Each conservation land could have 2 vulnerability classifications on the basis of this framework (low or increasing pressure when current utility is negative; urgent or decreasing when current utility is positive), provided at least one agricultural utility projection fell in the quadrant opposite to that of the primary classification (based on the median high CO\(_2\) treatment). However, only 14% of protected areas and
15% of priority areas received dual vulnerability classifications (Supporting Information).

Discussion

Implications for South African Conservation Lands

Our results show that South Africa’s conservation lands generally have low agricultural utility and thus reduced vulnerability to agricultural conversion. This finding expands on an earlier study of the Cape Floristic Region (roughly coinciding with the wheat production region; Fig. 1) that found mountainous areas are over-represented in existing protected areas (Rouget et al. 2003), a distributional bias that is also globally evident (Joppa & Pfaff 2009). This low vulnerability is likely to persist under future climates because the agricultural utility of most conservation lands was projected to remain negative (Figs. 5 & 6; Supporting Information).

There are several exceptions to this pattern, however. Several conservation lands were classified as urgent (Figs. 5 & 6) because of their high current and projected future vulnerability. Of greatest concern are the cluster of priority areas northeast and east of Lesotho in the maize growing region (Fig. 5) and those lying along the coast in the wheat production region (Fig. 6). The latter comprise some of the last remnants of high altitude grasslands, which are rich in endemic bird and plant species that may be particularly exposed to direct climate change effects (Reyers et al. 2001; Huntley & Barnard 2012). The latter areas fall within the fynbos biome, a global biodiversity hotspot that is also directly threatened by climate change (Midgley et al. 2003). These particular priority areas overlap substantially with conservation planning units designated as irreplaceable by a previous study (Cowling et al. 2003). Following Margules and Pressey’s (2000) prioritization framework, these areas should be placed at the top of the acquisition schedule.

At potential future risk of agricultural transformation are the few conservation lands projected to change from negative to positive agricultural utility (Figs. 5 & 6). Several priority areas in the aforementioned grassland region fall into this class. Planners could opt to assign these lower near-term priority than the surrounding urgent areas but should increase their priority as (and if) these areas become more agriculturally valuable in the future. Conversely, if these areas have comparable biodiversity values, acquiring them now before their utility increases may be more cost-effective than purchasing the adjacent urgent areas, whose higher current utility should make them more expensive.

Several priority areas in the western maize production region currently have positive agricultural utility values (Fig. 5) that are projected to become negative (decreasing pressure category). This suggests they might be currently vulnerable to cropland conversion, but this risk and their acquisition cost may decrease over time. Provided these are not highly irreplaceable areas, postponing their acquisition would allow resources to be channeled to more urgent areas.

The implications of changing agricultural utility are somewhat different for protected areas, which have legal status that makes their conversion less likely. However, high agricultural utility could influence decisions to degazette protected areas under certain circumstances. For example, protected areas that are already under social or political pressure for conversion could be more likely to lose protected status if their agricultural utility is high or increases with climate change. This possibility should be assessed for protected areas that are currently classified as urgent, particularly those in the high altitude grassland region.

Key Uncertainties and Limitations

Although our model agrees with earlier findings showing that agricultural potential is positively correlated with land conversion risk and inversely related to conservation success (e.g., Joppa & Pfaff 2009), anticipating land-use change is difficult, and the threat it poses may differ substantially from our vulnerability assessment (Bradley et al. 2012). For instance, higher production on existing farmland in areas of increasing agricultural utility may limit pressure to convert adjacent conservation lands. Where productivity declines, technological improvements (e.g., improved cultivars) and management practices (e.g., improved soil moisture management) may help prevent loss of agricultural utility and therefore maintain existing land uses; alternatively, farmers could expand their fields to compensate for production losses (Jones & Thornton 2009; Bradley et al. 2012). Our crop modeling framework did not simulate potential agricultural management adaptations, beyond altering planting density and sowing date (Estes et al. 2013a).

We also did not account for other factors that can be important drivers of agricultural land-use patterns, such as changing commodity prices, market accessibility, land ownership, and transportation costs (e.g., Serneels & Lambin 2001; Mann et al. 2010; Wright & Wimberly 2013). We also did not consider alternative land uses, such as livestock ranching (Jones & Thornton 2009; Seo 2012) or tree plantations, which disproportionately affect rugged areas in South Africa and may be increasingly viable under future climates (Schulze & Kunz 1995). These are important limitations that may bias our estimates of agricultural utility and thereby misrepresent threats to conservation lands. However, previous studies suggest that some of these land-use determinants are less influential in circumstances similar to South Africa’s (e.g., roads and access to local markets [de las Heras et al. 2012; Müller et al. 2012]). Furthermore, our 2 predictor
model is accurate in distinguishing between farmed and unfarmed areas, and its lower complexity makes it more generalizable.

Our estimated future agricultural utility was affected by large variations in crop yield projections, resulting in 2 different classifications for several of the most vulnerable conservation lands we highlighted (see previous section). This uncertainty directly impacts prioritization decisions. For example, a classification of increasing pressure suggests a different acquisition timeline than a low pressure classification, the alternative possibility. In many cases, the classification uncertainty was related to yield projections that assumed no positive crop response to elevated CO2, which likely overstated climate-induced yield losses (Estes et al. 2013a). However, soil fertility overestimates and the inability to simulate pest damage may also have caused negative impacts to be underestimated in certain areas (Estes et al. 2013b), thereby leading to overestimates of future vulnerability. A better understanding of agricultural utility shifts under climate change could be obtained by developing estimates based on the outputs of multiple crop models (Estes et al. 2013a, 2013b).

Integration with Existing Conservation Planning Frameworks

Although we altered Margules and Pressey’s (2000) approach for assessing irreplaceability and vulnerability, our approach could be readily incorporated into their original framework. The most direct method would be to replace Margules and Pressey’s (2000) vulnerability axis with our framework collapsed to a single dimension that illustrates the temporal change in agricultural utility as a vector along the x-axis. This would allow for climate-change impacts on conservation value (a factor we did not examine) to be incorporated into the irreplaceability axis (y-axis) as a vector (in which case the classification could shift diagonally to account for changes in both future vulnerability and irreplaceability).

In South Africa, our approach could be added to existing vulnerability frameworks that use suitability-based approaches to examine a wider array of threats, including cultivation, afforestation, mining, and urban expansion (Wessels et al. 2003; Neke & Du Plessis 2004; Reyers 2004). The cultivation components of these studies could be replaced by our method, which may also be adapted to quantify changes in afforestation-based utility.

Our utility modeling method could also be extended by building more detailed land-use models that factor in crop prices, subsidies, market growth, and alternative land uses (e.g., Nelson et al. 2008; Müller et al. 2012).

Broader Implications

Given the continued expansion of agriculture to meet growing food demands (Tilman 1999) and its sensitivity to climate change, conservation planners will increas-ingly need to understand how these 2 major forces interact in order to effectively prioritize conservation actions. Climate-driven agricultural changes will present new risks as well as new opportunities for conservation (Turner et al. 2010; Bradley et al. 2012). Our approach accounts for both current and future agricultural conversion risk due to climate change. Our focus on South Africa provides a useful case study for other regions where significant biodiversity, extensive agricultural development, and substantial climate exposure overlap (e.g., the cerrado [Falcão et al. 2013]). It also provides a basis for developing more sophisticated methods for teasing apart the socioeconomic and climatic factors controlling land-use pressure on natural habitats.

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Supporting Information

Details of the development of the break-even yield model and crop modeling methods (Appendix S1) and the model fit statistics and the baseline and projected agricultural utility values for individual conservation lands (Appendix S2) are available online. The authors are solely responsible for the content of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Literature Cited


