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LETTER

Analysis of Trade-Offs Between Biodiversity, Carbon Farming and Agricultural Development in Northern Australia Reveals the Benefits of Strategic Planning

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Abstract

Australia's northern savannas are one of the few remaining large and mostly intact natural areas on Earth. However, their biodiversity and ecosystem values could be threatened if proposed agricultural development proceeds. Through land-use change scenarios, we explored trade-offs and synergies among biodiversity conservation, carbon farming and agriculture production in northern Australia. We found that if all suitable soils were converted to agriculture, habitat at unique recorded locations of three species would disappear and 40 species and vegetation communities could lose more than 50% of their current distributions. Yet, strategically considering agriculture and biodiversity outcomes leads to zoning options that could yield >56,000 km^2 of agricultural development with a significantly lower impact on biodiversity values and carbon farming. Our analysis provides a template for policy-makers and planners to identify areas of conflict between competing land-uses, places to protect in advance of impacts, and planning options that balance agricultural and conservation needs.

Introduction

Land-use change is a major driver of habitat degradation and species extinction worldwide (Sala *et al.* 2000; Foley *et al.* 2005; Fischer & Lindenmayer 2007). In Australia, nearly 50% of natural vegetation has been cleared or severely modified since 1788, leading to the extinction of numerous species and critically endangering many others (Bradshaw 2012; Lindenmayer & Possingham 2013).

Land clearing is spatially uneven across Australia. For example, only one third of natural vegetation remains in south-eastern Australia, while the tropical savannas of northern Australia currently occupy 99% of their original extent (Woinarski *et al.* 2011; Bradshaw 2012). While extensive pastoral activity has modified the composition and structure of much of the northern savanna forests and woodlands (e.g., Woinarski *et al.* 2011), most of the landscape remains at least structurally intact (Woinarski *et al.* 2006, 2007, 2011; Andersen *et al.* 2012). However, recent rapid declines in fauna populations across much of northern Australia due to a range of factors (including feral predators and other invasive species, overgrazing, altered fire regimes) indicate the desperate and immediate need for strategic land management approaches in the region (Woinarski *et al.* 2011, 2015).

In September 2014, the Australian Government identified options to promote the economic development of northern Australia over a 20-year period (Joint Select Committee on Northern Australia 2014). Among the proposed initiatives is the staged development of irrigated agriculture schemes "to help double Australia's agricultural output" (Joint Select Committee on Northern Australia 2014, p. 6). Announcement of a $5B Northern Australian Infrastructure Facility indicates that the government is taking northern economic development very seriously (Commonwealth of Australia 2015). To put this proposal in a geographic context, the northern savannas occupy an area approximately the size of France and Germany combined, with about 20% being deemed highly suitable for agricultural intensification based on soil properties (Wilson *et al.* 2009, 2013). This highlights the magnitude of the economic opportunity, but also the scale of the threat to northern Australia's biodiversity.

There has also been substantial uptake of carbon-emission reduction initiatives linked to payments for improved fire management (Cook *et al.* 2012; Russell-Smith *et al.* 2013; Walton & Fitzsimons 2015), known in Australia as "carbon farming." In tropical savannas, carbon emission reductions are achieved by using low-intensity, early-season burns to minimize the amount of fuel burnt in large-scale, high-intensity late-season wildfires (Cook & Meyer 2009; Bradshaw *et al.* 2013). Cooler, early-season burns are generally considered to be commensurate with biodiversity conservation objectives. Carbon farming in northern Australia could promote biodiversity conservation and socio-economic development of local indigenous communities (Woinarski *et al.* 2011; Cook *et al.* 2012; Fitzsimons *et al.* 2012; Russell-Smith *et al.* 2013).

The prospect of a major shift in land-use from relatively low-impact rangeland grazing to relatively high-impact irrigated intensive agriculture presents opportunities and challenges for regulators, industry, carbon-farming investors, conservation organizations and other stakeholders. Regulators need to balance the financial and food security benefits of expanded agriculture against the potential negative impacts on other industries such as fishing, prawning, several types of tourism, biodiversity, carbon-farming options and areas of indigenous cultural significance. Governments, conservation organizations, and broader society need to identify the most irreplaceable areas that may be lost to agricultural development and its offsite impacts, determine how to protect whole of landscape and hydrological functioning (which is so important for the savannas Woinarski *et al.* 2007), and use appropriate conservation and partnership mechanisms to conserve landscapes with significant ecological values. Similarly, carbon-farming investors could secure commitments from current lease-holders to minimize carbon emissions which could have some auxiliary benefits for biodiversity. Balancing these competing objectives and identifying satisfactory solutions requires a strategic approach to land-use planning and management, which could be achieved under a legislated strategic planning process (e.g., Strategic Assessments under the Federal *Environment Protection and Biodiversity Conservation Act 1999* -EPBC Act).

Here, we analyze trade-offs between biodiversity, carbon, and agricultural intensification in northern Australia using maps of agricultural intensification potential, carbon-farming potential, and geographic distributions for 611 species and 43 vegetation communities. Through systematic spatial prioritization, we identify the strategies available to conservation practitioners, regulators or carbon-farming investors to maximize their respective objectives. Our analysis highlights the importance of considering the threat of land-use change in a spatially explicit way, and the relatively high biodiversity benefits that can be achieved at relatively low economic opportunity cost by a regulator who systematically balances biodiversity and economic development options. Our results are vital for planners and policy-makers considering developing northern Australia, but also hold important lessons for other relatively undeveloped regions that are slated for future land-use change.

Methods

Study area

The study area comprises the tropical savanna of northern Australia, extending between latitudes 10–20°S and covering approximately 960,000 km^2. *Eucalyptus* open forests and woodlands with a grassy understorey dominate the landscape, with *Acacia* and *Melaleuca* woodlands, and hummock and tussock grasslands occurring in some areas. The region contains four nationally threatened ecological communities and 199 threatened species listed under the EPBC Act. Cattle grazing, mining and nature-based tourism are the main industry sectors (Woinarski *et al.* 2007), while protected areas currently cover about 18% of the region.

Mapping biodiversity, carbon, and agricultural opportunity values

To characterize the biodiversity values of the northern savannas, we mapped the distributions of 611 species (tetrapods and plants) and 43 vegetation communities.

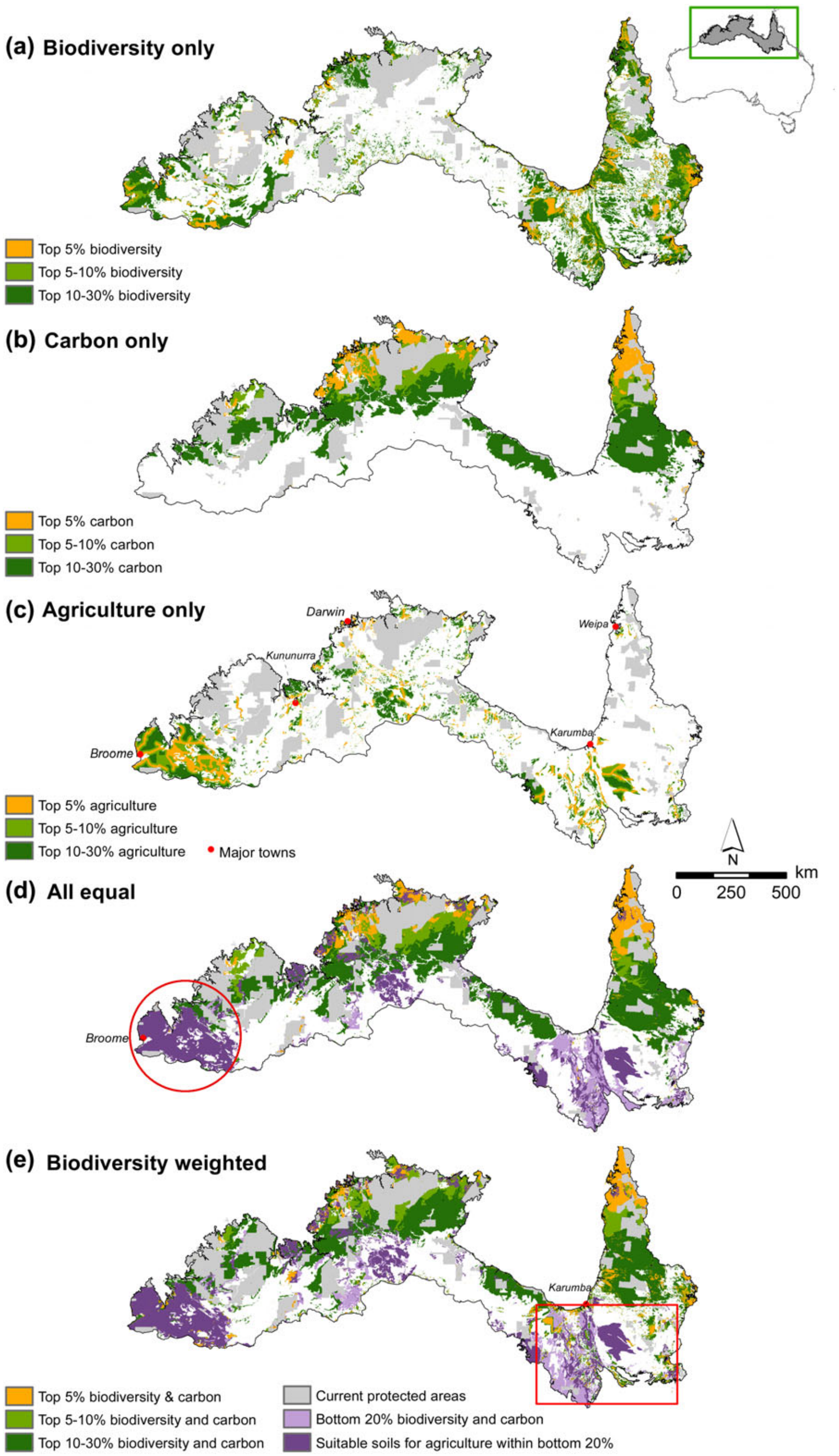


Figure 1 Priority maps for northern Australia based on five different scenarios: (a) a *biodiversity-only* scenario that ranks sites based on their value for 654 biodiversity features, without taking into account carbon storage or agricultural potential; (b) a *carbon-only* scenario that ranks sites based on their value for carbon storage, without accounting for biodiversity or agriculture; (c) an *agriculture-only* scenario that ranks sites based on agricultural potential (i.e., those with the most suitable soils for the development of irrigated agriculture as a function of their accessibility), without accounting for carbon storage potential or biodiversity values; (d) a scenario where all biodiversity features together are weighted the same as agriculture and carbon storage (*all-equal*); and (e) a scenario where all biodiversity features together are weighted 10-fold than agriculture and carbon storage (*biodiversity-weighted*). All scenarios take into consideration the biodiversity values within existing protected areas. See Methods and Supporting Information for further details.

Our aim was to include as many species as possible in order to characterise potential impacts of proposed land-use change on biodiversity as a whole. We developed species distribution models (SDM) for 356 species and also included published distribution maps for an additional 27 threatened species (Maggini *et al.* 2013). We generated presence-absence maps from point occurrence data for another 228 species for which there were insufficient point records to build SDMs. Carbon-security potential was mapped using a spatial layer of above-ground forest carbon stock in tonnes per hectare (Cook *et al.* 2015). Places of high carbon-security potential are primarily places in which there is an opportunity to reduce the loss of carbon stored in the landscape through sympathetic land management practices. We did not account for the carbon-security potential of "future" irrigated agriculture since first, this would be negligible compared with that lost from native woodlands and soils when native vegetation is cleared (Guo & Gifford 2002, Cook *et al.* 2010, Luo *et al.* 2010) and second, little is known about which particular crops are going to be promoted and where exactly they will be located (making impossible their spatially explicit assessment). Agricultural value (also referred to as irrigated agriculture from hereon) was mapped using an agricultural opportunity layer that integrates areas of high suitability of soils for irrigated annuals, irrigated perennials and irrigated improved pastures (Wilson *et al.* 2009, 2013). This layer identifies the areas at potential risk of land cover conversion from natural vegetation (savanna forest/woodland) to agriculture (i.e., to any of these three types of irrigated agricultural practices). The map of agricultural opportunity was further refined to identify areas close to existing roads that may be prioritized for development. See Appendix A1 for full details of data sources and handling, species modelling and mapping methods.

Spatial prioritization analysis

We used Zonation v4.0 (Appendix A2; Moilanen *et al.* 2005, 2012) to conduct a spatial prioritization across northern Australia of the three land-uses: biodiversity conservation, carbon storage and/or irrigated agriculture. We explored five alternative scenarios: *biodiversity-only*, *carbon-only*, *agriculture-only*, *all-equal* and *biodiversity-weighted*. The *biodiversity-only* scenario ranked each 1-km^2 grid cell in the landscape in terms of its biodiversity values on the basis of the distribution maps for all 654 biodiversity features. Zonation uses the relative rarity of species and vegetation communities to identify the most complementary set of cells to conserve at every level of landscape loss from 0% to 100%. The last cells to be lost are considered the most irreplaceable cells (here those with highest biodiversity value). In this scenario all biodiversity features were assigned equal weight, independent of their threat status, under the assumption that any species or vegetation communities could become threatened with the major land-use changes being proposed for the study region. The *carbon-only and agriculture-only* scenarios ranked the landscape using the carbon-storage potential and agricultural opportunity spatial layers to identify the zones of highest vegetative carbon stocks and agricultural potential, respectively (regardless of their biodiversity values).

In each of the above three scenarios we used replacement cost analysis (Cabeza & Moilanen 2006), a feature in Zonation where the removal order of cells can be artificially altered, to account for the existing protected area network in northern Australia. This allowed us to identify high priority locations (best 5%, 10%, and 30% of the landscape) for biodiversity conservation outside the existing reserves (i.e., priority sites for *expanding* the level of protection for biodiversity in the landscape to conserve the features outlined above; Appendix A2). To identify possible areas of synergy or conflict between the three land-uses, we measured and mapped the zones of overlap between high priority locations for biodiversity outside protected areas and the high priority areas for carbon storage and agricultural potential, respectively. We also ran a *biodiversity-only* analysis unconstrained by the current distribution of protected areas, to measure the concordance between irreplaceability and existing reserves.

The *all-equal* and *biodiversity-weighted* Zonation scenarios combined maps of biodiversity, carbon-storage and agricultural potential to explore options for balancing or trading-off between competing land-uses. In these analyses, the value of each 1-km^2 cell for agriculture is introduced to Zonation as a cost, which, when all else is equal, favours the conservation of cells with lower agricultural value. In the *all-equal* scenario, biodiversity features were all weighted equally (1/654 each) and carbon storage and agricultural suitability were weighted 1.0 and –1.0, respectively. This implies that that the net value of all biodiversity features is equal to the net value of carbon storage, which is equal to the net value of agriculture in the region. It also assumes that biodiversity conservation and carbon storage are compatible land-uses, while intensive irrigated agriculture is incompatible with both. We acknowledge this is a simplified view of the system since our assumptions are not universally true (e.g., carbon farming may not necessarily be compatible with biodiversity conservation and agriculture can provide habitat and resources for biodiversity; Thomas *et al.* 2013; Luck *et al.* 2015); however, with this analysis we sought to find a solution that maximizes both biodiversity and carbon objectives simultaneously (Venter *et al.* 2009; Thomas *et al.* 2013), while avoiding areas that are potentially good for agriculture (Moilanen *et al.* 2011). The *biodiversity-weighted* scenario was built under assumptions similar to the *all-equal* scenario except it prioritizes biodiversity values more than carbon outcomes and agriculture suitability (i.e., it weighted biodiversity features ten times more with a weight of 10/654 for each feature than carbon storage and agricultural suitability). For all scenarios it was assumed that, outside of the current protected area system, any land-use could be possible, regardless of underlying tenure.

Results

High-priority areas for biodiversity conservation outside current protected areas are mostly concentrated in the north, east and south-western regions of northern Australia (Figure 1a). Carbon storage increased from south to north, corresponding with the rainfall gradient from semi-arid to subtropical and tropical regions in the study area (Figure 1b). The best areas for developing irrigated agriculture based on soil conditions are scattered across the landscape, although there are three highly ranked areas that stand out for their large and continuous extent in the southwest, center, and southeastern parts of the study area (Figure 1c). The map outputs from the *all-equal* and *biodiversity-weighted* analyses (Figures 1d–e) show how prioritizing biodiversity and carbon-storage tends to push agriculture further south in the region, leaving relatively irreplaceable sites for biodiversity conservation less impacted in the north, where carbon stocks are highest. The similarity between Figures 1(b) and (d)–(e) arises because many of the important sites for biodiversity in the north of the region are correlated with high carbon-security opportunity in those areas, and the high biodiversity areas in the south of the region are somewhat exchangeable in terms of species composition with areas further north (red circle Figure 1d). Interestingly, the ranking map output of the *biodiversity-weighted* scenario (Figure 1e) resembled more the *all-equal scenario* (with most biodiversity and carbon valuable sites in the north) than the *biodiversity-only* scenario (Figure 1a). The key difference between the *biodiversity-weighted* scenario and the *all-equal* scenario is that the former identifies some irreplaceable sites for biodiversity in the south-eastern part of the study region (red rectangle Figure 1e).

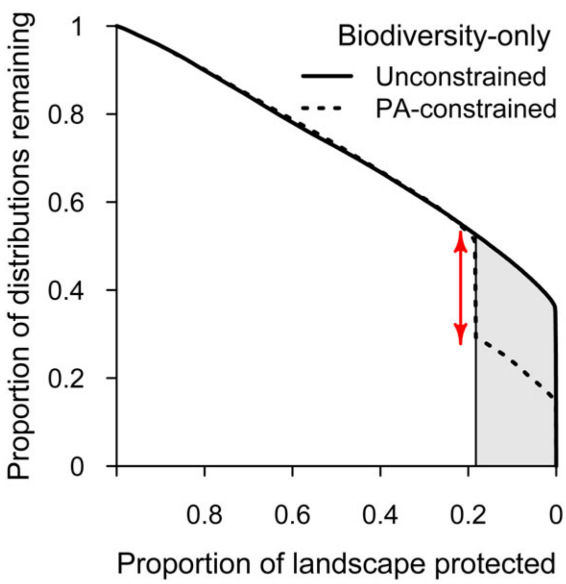


Figure 2 Representation of the distribution ranges of the 654 biodiversity features within current network of protected areas in northern Australia. The *Y*-axis represents the extent of suitable geographic range available for the biodiversity features, ranging from 0 – no suitable conditions available for the features – to 1 all suitable range available to the features. The *X*-axis represents the proportion of total landscape protected. The solid and dotted black lines represent the average performance of the 654 biodiversity features (read from the *Y*-axis) under the unconstrained and constrained solutions of the *biodiversity-only* scenario, respectively. The constrained solution artificially alters the order of cell removal in Zonation, forcing the existing protected area network into the top fraction of the landscape. The unconstrained solution identifies the areas that are most important to capture biodiversity values, irrespective of their current protection status. The grey shaded area delimits the extent of the current network of protected areas in northern Australia (read from *X*-axis). The difference between the solid and dotted lines read from the *Y*-axis (red arrow), indicates the opportunity for conservation under the unconstrained solution compared to what it is currently protected by the reserve system (i.e., average gain in distribution ranges of the 654 biodiversity features).

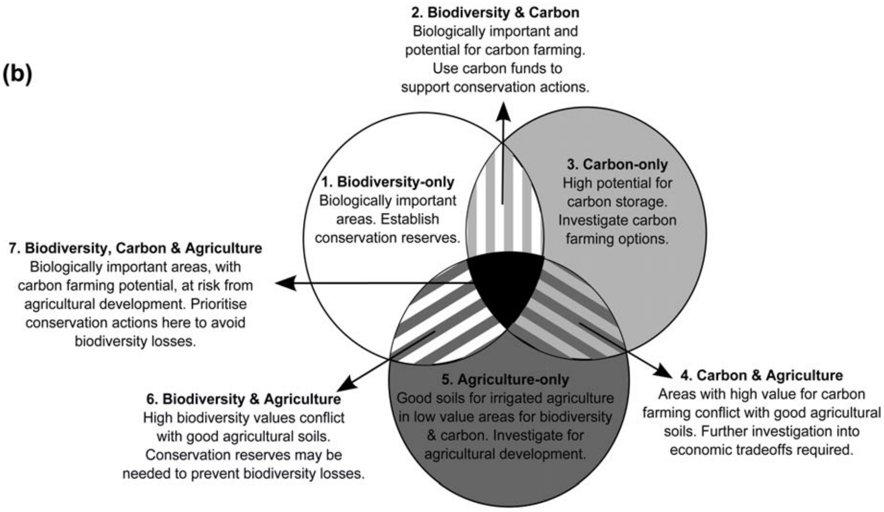
Opportunities for conservation gains

Comparing the prioritization analysis for biodiversity that ignores the current distribution of conservation reserves with the analysis that constrains the solution to include existing conservation reserves, shows that the current protected area network captures on average (across all species and vegetation communitites), 29% of the distributions of all 654 biodiversity features (Figure 2). If arranged to optimize representation, the same area of land (around 18.3% of the study area) could have represented up to 50% of the distributions of the same biodiversity features (based on an unconstrained prioritization of biodiversity values). Our analysis highlights a significant opportunity to dramatically increase representativeness with a minor expansion of the reserve system or other forms of protection by being more strategic about where new conservation areas are placed. For example, by expanding the protected area network to capture an additional 5% of northern Australia, we could

(a)

Scenario	5%	10%	30%
1. Biodiversity-only	30,406	62,630	124,883
2. Biodiversity & Carbon	4,520	11,291	93,416
3. Carbon-only	33,496	69,163	149,034
4. Carbon & Agriculture	9,490	14,066	36,153
5. Agriculture-only	162,789	147,464	78,788
6. Biodiversity & Agriculture	10,580	20,599	60,304
7. Biodiversity, Carbon & Agriculture	238	968	7862

(b)



(c)

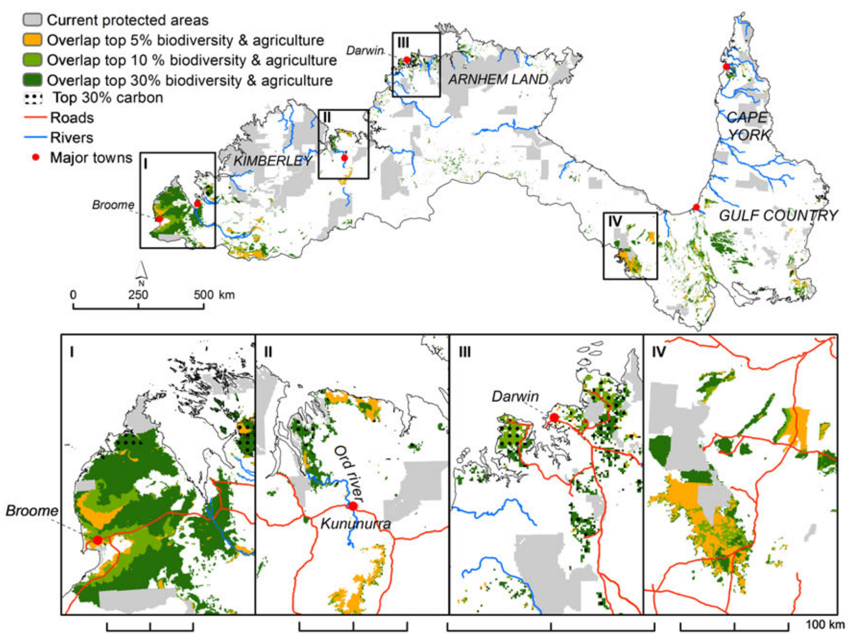


Figure 3 (a) Degree of overlap between any area suitable for agriculture and high priority areas (best 5%, 10%, and 30%) for biodiversity conservation only and carbon storage only (area in squared km). For example, whereas 30,406 km^2 of northern Australia has been identified as high priority for biodiversity (within the top 5 % of the *biodiversity-only* scenario landscape ranking), only 4,520 km^2 overlaps with high priority areas for carbon storage (within the top 5% of the *carbon-only* scenario). (b) Venn diagram showing the areas of potential conflict (trade-offs) or synergies between the three land-uses as well as their implications for policy making. (c) Location of sites where there is spatial overlap between the high priority areas (best 5%, 10%, and 30%) for biodiversity conservation only and any area suitable for agriculture in northern Australia (i.e., areas of potential conflict between biodiversity and agriculture). The map also shows the sites where these areas of potential conflict between biodiversity and agriculture overlap with high values for carbon storage (top 30% of the *carbon-only* scenario). Panels I, II, III, and IV show these overlaps in detail for four different areas of the study region.

increase the representation of biodiversity features under some form of protection from 29% to 57%.

Trade-offs and synergies between land-uses

Eighty-eight percent of the best soils for agriculture occur outside the current protected area network. However, there is considerable overlap between priority areas for biodiversity conservation outside current protected areas and locations most suitable for agriculture (60,304 km^2, Figure 3a, scenario 6). If agricultural development is expanded in northern Australia, there is likely to be future conflict between these two land-uses (Figure 3b, scenario 6). The largest areas of overlap between biodiversity and agriculture occur in the southern parts of the study area (Figure 3c, panels I and IV). Conversely, 56,441 km^2 (~30%) of the best agricultural soils occur within areas of relatively low conservation priority based on our criteria (the bottom 30% of the *biodiversity-only* scenario). Areas that are most important for all three land-uses represent a small fraction of the overall landscape (<0.025 %; Figures 3a–b, scenario 7) and are mainly located in the north of the study area (Figure 3c, panels II and III).

Prioritizing land-use based only on opportunities for high intensity irrigated agriculture or carbon storage is predicted to lead to total habitat loss for at least one species, even when only a small proportion of the landscape is converted (Figures 4b–c). By explicitly including species distributions in prioritizations of agricultural area development, even the most heavily impacted species retain a small proportion of their current distribution with relatively high rates of land-use conversion toward agriculture (Figures 4d–e). The performance of the worst-off 10% of species and communities (average performance of biodiversity features within the bottom 10th percentile of data) was markedly higher under the *all-equal* and (especially) the *biodiversity-weighted* analysis compared with both *carbon*-only and *agriculture-only* scenarios (Figure 5a). The *agriculture-only* and *carbon-only* analyses predict much larger losses in the distributions of biodiversity features than the *all-equal* and *biodiversity-weighted* analyses (Figure 5b; Table 1). For example, when approximately 20% of the landscape is converted to agriculture, all known records of three biodiversity features and the total extent of one vegetation community would likely be totally lost under the *agriculture-only* scenario. A further 36 species and vegetation communities would have more than 50% of their current distribution impacted. In contrast, converting the same area of land under the *all-equal* or *biodiversity-weighted* scenarios would lead to no species losing their last remaining suitable habitat, and only seven or five biodiversity features having 50–

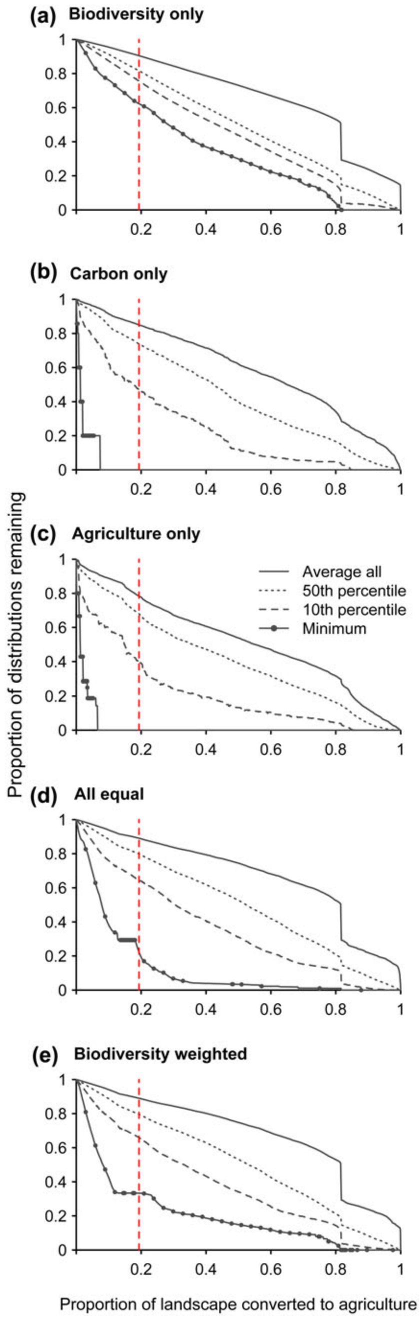


Figure 4 Relationship between the proportion of the landscape converted to agriculture and the performance of the biodiversity features under five prioritization scenarios: (a) *biodiversity-only*, (b) *carbon-only*, (c) *agriculture-only*, (d) and (e) all land-uses (*all-equal* and *biodiversity-weighted*). The grey lines show the average proportion of distributions remaining for all 654 biodiversity features (solid line "average all"), the worst-off 50% and 10% of biodiversity features (dotted -50th percentile- and dashed lines – 10th percentile, respectively), and the feature with the absolute lowest distribution remaining (dotted-solid line, "minimum"). The dashed red line marks the threshold corresponding to the total area covered by the most suitable soils for irrigated agriculture across northern Australia (approximately 20% of the landscape).

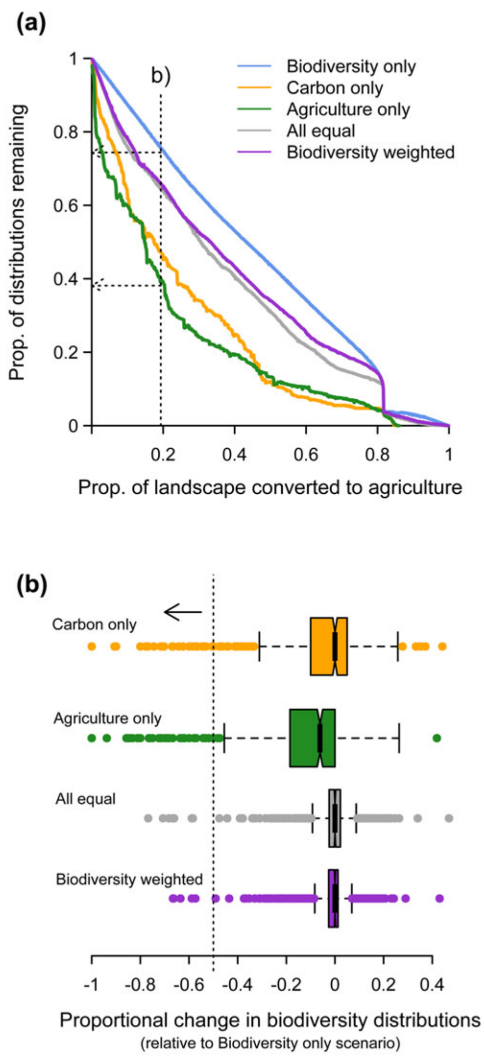


Figure 5 Performance of biodiversity features under five prioritization scenarios. (a) Proportion of the biodiversity features' distributions remaining at different levels of landscape lost due to conversion to agriculture. Lines represent the average performance of the worst-off 10% of the biodiversity features for each scenario (*biodiversity-only*, *carbon-only*, *agriculture-only*, *all-equal*, and *biodiversity-weighted*). Comparison between scenarios can be made at any threshold of landscape conversion along the *X*-axis. For example, a conversion of all suitable soils for agriculture into irrigated crops or pasturelands would imply approximately 20% of landscape loss for other land-uses (dotted black vertical line linking with plot b). At this proportion of landscape loss, the *agriculture-only* scenario predicts that the average distributions remaining for the worst 10% of the biodiversity features is 0.38 versus the 0.75 predicted by the biodiversity only scenario (i.e., a reduction of approximately 50% in predicted distributions between the two scenarios). (b) Relative change in the distributions of each of the 654 biodiversity features predicted under the *carbon-only*, *agriculture-only*, *all-equal* and *biodiversity-weighted* scenarios compared to the *biodiversity-only* scenario when approximately 20% of the landscape is converted into agricultural lands (i.e., when all suitable soils for agriculture are developed). Biodiversity features to the left of the dotted line (following arrow direction) under any of these four scenarios are predicted to lose more than 50% of their distributions.

75% of their current distribution impacted, respectively (Table 1).

Discussion

The policy document *Our North, Our Future: White Paper on Developing Northern Australia* (Australian Government 2015) pays little attention to the potential impact that agricultural development options may have on biodiversity and associated industries (e.g., tourism). Nor does it mention how such impacts would be assessed, risks to biodiversity managed, and appropriately balanced trade-offs between biodiversity, agriculture and other sectors will be achieved. The substantial overlap between agricultural potential and biodiversity value suggests that agricultural development, based solely on considerations about production potential, could have significant negative impacts on biodiversity. Some trade-offs will be necessary if the loss of significant biodiversity values due to agricultural intensification is to be avoided.

In addition to the potential impacts of non-strategic or poorly-regulated agricultural development, our results also highlight the fact that there are up to 56,000 km^2 of high agriculture potential soils within the bottom 30% of the biodiversity values analyzed. That is, there are potentially many opportunities to develop irrigated agriculture in areas that are not high priority for biodiversity (measured as the representativeness of a defined set of features). Our broad-scale prioritization should help guide future finer-scale examination of factors that can further threaten biodiversity conservation including accessibility, existing and likely future irrigation infrastructure, and factors likely to reduce threat from agricultural development, such as flood and cyclone risk or soil erosion (Wilson *et al.* 2013). If specific proposals for agricultural development emerge that identify particular annual or perennial crops or pastures as economically viable in particular places, then the specific impacts of these options on biodiversity, carbon (or other values such as water) can be evaluated using the analytical approach we demonstrate here. However, until specific proposal emerge, the resolution of our analysis seems appropriate for identifying broad areas of potential land-use conflict.

Results of the *all-equal* analysis indicate that the biodiversity features considered in this work could maintain their representation across the study area even with fairly high levels of agricultural development (Figure 5b). However, the actual long-term persistence of those biodiversity features will also depend on ecological processes such as connectivity, dispersal, changing climate and fire regimes, or predation and/or competition from invasive species. The demographic and environmental data

Table 1 Total number of biodiversity features (species and vegetation communities) that would lose >50%, >75% or 100% of their current distribution ranges in northern Australia under the different land-use scenarios and at two different fractions of the landscape converted into agriculture. The number of nationally threatened biodiversity features is indicated in brackets. The development of 50% or 100% of best suitable soils for agriculture corresponds respectively to the conversion of approximately 10% and 20% of the total landscape of northern Australia into irrigated agricultural and pasturelands

	Development of 50% of suitable soils for agriculture			Development of 100% of suitable soils for agriculture		
Scenarios	>50%	>75%	100%	>50%	>75%	>100%
Agriculture-only	15 [1]	3 [0]	1 [0]	40 [1]	15 [1]	4 [0]
Carbon-only	11 [0]	2 [0]	1 [0]	31 [0]	9 [0]	3 [0]
All-equal	4 [1]	0 [0]	0 [0]	7 [1]	1 [0]	0 [0]
Biodiversity-weighted	2 [1]	0 [0]	0 [0]	5 [1]	0 [0]	0 [0]

required to model persistence under threat and land-use change scenarios are typically only available for a small subset of well-studied species. Development of such models for these species can provide further insights into the sustainability of competing land-use, management and impact mitigation options (Sebastián-González *et al.* 2011). Coupled with the need to include information on key breeding areas, refugia and sites of endemicity for species, this could be an appropriate next step in northern Australia to help decision-makers understand the potential implications of development options and the additional conservation investments needed to secure biodiversity persistence.

Future extensions of our study should account for the trade-offs involving other economic development opportunities such as nature-based tourism or shale gas expansion, or for indigenous cultural values that are important from a social and legal perspective. Moreover, the *indirect* impacts of agricultural development on biodiversity (e.g., the construction of transport networks, dams and pipelines) could outweigh the direct impacts of the land-use changes we have analyzed (Kingsford 2000; Letnic *et al.* 2014). On the flipside, the cost and practical impediments to infrastructure development needed to support agricultural intensification are likely to change agricultural priority areas in more complex ways than we have analyzed here. Similarly, we assume that any land-use could occur anywhere outside the existing reserve system, though this is clearly not the case in some areas, due to a range of cultural and regulatory constraints. Refining the biodiversity (i.e., accounting for more species) agriculture and carbon potential mapping, and combining those with other land-use options and constraints currently not included in our analyses constitute obvious extensions to the work presented here. For example, innovation in the agricultural sector could lead to new ways of conducting intensified agriculture in the region that secures more carbon and biodiversity at the site level, making the three land-uses more compatible. We have included the best current information about impacts of proposed agricultural activities on carbon and biodiversity, though our method of analysis easily accommodates new information.

Land-use change remains, arguably, the most potent threat to biodiversity conservation globally. We have demonstrated an approach to quantifying impacts of development options across multiple species and ecological communities, and exploring trade-offs and synergies to minimize impacts through judicious positioning of impacts and conservation measures. Such analyses can provide support to complex land-use planning problems because they can encapsulate relatively complex conservation ideas such as irreplaceability, complementarity, connectivity, and cost-effectiveness in relatively simple map outputs. This has immediate relevance for policy-makers and planners considering the development of northern Australia for agriculture, but the approach presented here can conceivably be adapted to any spatial, multi-objective land-use planning challenge.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Appendix 1. Description of source data used in the spatial prioritization

Appendix 2. Description of the spatial prioritization methodology

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