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 km2 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-intensity rangeland grazing to relatively high-intensity 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 km². 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-km² 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-km² 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 sub-tropical 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).

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 communities), 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

![Figure 2](image-url)
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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 km² 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 km² 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 km², 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 km² (~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–
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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.

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 km² 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 proposals 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

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

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Appendix 2. Description of the spatial prioritization methodology

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