Spatial Priorities for Restoring Biodiverse Carbon Forests

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A price on carbon is driving land-use changes globally, including the establishment of biodiverse carbon plantings to sequester carbon. The biodiversity benefits of these plantings depend on many factors, including their spatial locations. We provide an approach for assessing the opportunities and spatial priorities for carbon sequestration and biodiversity restoration through biodiverse carbon plantings. Using Australia as a case study, we show how carbon market conditions affect the potential for achieving biodiversity benefits through restoring heavily cleared vegetation types to 30% of their original extent. Using a midrange carbon price, AU$20 per ton, we discovered that the top 25% of priority areas for biodiverse carbon plantings could sequester 132 megatons of carbon dioxide equivalents annually—more than 5% of Australia’s emissions. Lower carbon prices limit biodiversity outcomes. Spatial priorities for sequestering carbon are different from those for restoring biodiversity; therefore, accounting for both factors maximizes efficiency and opportunities.

Keywords: biodiversity, carbon, carbon sequestration, cobenefits, prioritization, planning, reforestation, restoration, revegetation

Climate change and biodiversity loss are two of the most pressing environmental concerns of the twenty-first century (Lindenmayer et al. 2010, Mantyka-Pringle et al. 2012). Market mechanisms to drive land-use changes, such as payments for the retention and restoration of forests systems, have the potential to address both concerns and are receiving significant media, public, and scientific attention (Pandey 2002, O’Connor 2008, Bradshaw et al. 2009, Grainger et al. 2009, Stickler et al. 2009, Jackson and Baker 2010, Wendland et al. 2010, Busch et al. 2011). Annual global emissions are estimated to be around 36 gigatons of carbon dioxide equivalents (CO₂e) per year (Global Carbon Project 2014). More than 40 nations have put a price on carbon and policies to sequester carbon and reduce emissions are becoming commonplace (Climate Commission 2013). For example, in Australia the government has committed $2.55 billion to an emissions reductions fund, to be rolled out over a number of years, with the potential for further funding (Commonwealth of Australia 2014a). This fund covers a range of emission abatement and sequestration methodologies, including reforestation. Landowners can offer to sell carbon from proposed reforestation projects on their land, with funding allocated through a competitive auction process.

Only a portion of the global potential for terrestrial carbon storage through forests is likely to be realised, because of socioeconomic constraints and competition for land use with expanding human settlements, agriculture, and industries such as mining and renewable energy (Steffand-Dewenter et al. 2007, Smith et al. 2013). For example, recent research shows that only a fraction of Australia’s forests can be restored for carbon sequestration profitably under any likely economic scenario, because of the associated costs and the loss of profitable agricultural production (Polglase et al. 2013). These constraints highlight the importance of considering the cobenefits of carbon farming, both for diversifying funding sources for reforestation and for maximising multiple benefits in the landscape—for example, biodiversity and ecosystem services (Lin et al. 2013).

Carbon plantings have the potential to benefit biodiversity but this is dependent on the planting methodology used (Fensham and Guymmer 2009, Edwards et al. 2010, Hatanaka et al. 2011). Monoculture plantations can have perverse outcomes on biodiversity, such as the introduction of diseases and other threats to neighboring native forests (Huston and Marland 2003). Conversely, biodiverse forests contain a mixture of native plant species and are intended to restore native ecosystems benefiting biodiversity as well as sequestering carbon (Dwyer et al. 2009, Fensham and Guymmer 2009, Lindenmayer et al. 2012, Pichancourt et al. 2014). Biodiverse plantings can also be more resilient to threats such as fire and climate change, store more carbon because of increased vegetation complexity, and be relatively cheap to establish in previously forested regions where seedbanks remain (Schirmer and Field 2000, Dwyer et al. 2009, Fensham and Guymmer 2009, Bradshaw et al. 2013, Evans et al. In Press).
The opportunities and threats that a carbon market through vegetation restoration poses to biodiversity (Stickler et al. 2009) have led to financial initiatives for supporting the associated cobenefits of tree planting (Swingland and The Royal Society 2003, Baker et al. 2010). For example, carbon produced under the Reduced Emissions from Deforestation and forest Degradation’s (REDD+) scheme considers biodiversity and sustainability and has the potential to fetch a premium price in the voluntary carbon market (Angelsen et al. 2012). Furthermore, governments have the potential to establish biodiversity banks to supplement a carbon market that also considers biodiversity (Bekessy and Wintle 2008, Crossman et al. 2011, Bryan and Crossman 2013).

Carbon sequestration potential, biodiversity, and opportunity costs (i.e., the costs of giving up alternative land uses such as agriculture) are unevenly distributed throughout landscapes (Nelson et al. 2008, Crossman and Bryan 2009, Ego et al. 2010, Kessler et al. 2012). Recent research has highlighted scale-dependent spatial trade-offs between the amount of carbon stored and indices of biodiversity in existing forests (Chan et al. 2006, Anderson et al. 2009, Venter et al. 2009, Ego et al. 2010, Strassburg et al. 2010). Importantly, a much larger suite of biodiversity benefits can be captured by strategically protecting certain forests from deforestation, for just a small increase in costs or a slight decrease in carbon storage (Venter et al. 2009, Hirsch et al. 2011, Onaindia et al. 2013, Phelps et al. 2012). Much less attention has been given to the importance of spatial planning for restoring biodiversity and sequestering carbon through biodiverse plantings, despite the fact that carbon planting projects have yielded a greater total profit than REDD in recent years (Peters-Stanley et al. 2012). Bryan and colleagues (2014) show that there is potential for improving biodiversity outcomes from plantings on agricultural land but that this is dependent on economic factors such as the carbon price.

The spatial considerations for establishing carbon forests are likely to differ from those involved with protecting existing forests, because of different opportunity and management costs (Schirmer and Field 2000) and the nonuniform nature of historic land clearing (Maron and Cockfield 2008, Boakes et al. 2010). Greater biodiversity benefits would be expected when restoring forests in areas that might provide increased habitat for threatened species, important refugia, or landscape connectivity and in areas historically covered with vegetation types that have since been heavily cleared (Munro et al. 2009, Thomson et al. 2009, Shoo et al. 2011). However, as the most affected habitats and heavily cleared vegetation types are the most valuable for agriculture (Bradshaw 2012), the opportunity costs of revegetation might also be higher. An improved understanding of where to reestablish forests to sequester carbon and enhance biodiversity across vast regions is critical when planning to achieve both of these benefits efficiently.

Here, we explore the potential for biodiverse carbon plantings to contribute to the biodiversity goal of restoring ecosystems and illustrate an approach for identifying spatial locations for plantings to achieve carbon and biodiversity restoration at continental scales. We define biodiversity as woody vegetation representative of the type that previously existed in each cleared area. We use Australia as a case study, a nation where land clearing over the past 200 years has heavily affected particular vegetation types in productive areas of the continent, leaving many vegetation types severely underrepresented in the landscape (Lindenmayer 2007). We assume that biodiverse carbon plantings restore the vegetation type that previously existed at a site. However, we acknowledge that restored ecosystems almost never exactly resemble the original ecosystem (Gibson et al. 2011, Martin et al. 2013).

Specifically, we use our case study to assess the potential for restoring the most heavily cleared (those with less than 30% of original extent remaining) vegetation types back up to at least 10%, 20%, and 30% of their preclearing extent under a range of carbon market conditions. Although these targets are arbitrary and higher targets could be examined, our aim here is to demonstrate an approach for identifying spatial locations for carbon plantings that also meet a biodiversity objective; therefore, our focus on the most heavily cleared vegetation types. We then focus on a midrange carbon market scenario to demonstrate our approach for identifying priority areas for biodiverse carbon plantings that most cost-effectively restore heavily cleared vegetation types to 30% of original extent while sequestering carbon. Finally, we use our example scenario to compare planning approaches that focus on meeting carbon and biodiversity goals simultaneously and in isolation.

Planning for carbon and biodiversity

We use a case study across the continent of Australia to investigate spatial priorities for carbon reforestation and the impact of carbon price on biodiversity outcomes.

Carbon sequestration and market scenarios. Our study spans areas across Australia that have been cleared of native vegetation, with the exception of built areas and areas that were not previously covered by vegetation types containing trees of at least 1.3 meters (m) tall. The remaining cleared areas are considered to be suitable for biodiverse carbon plantings (figure 1). We use the term biodiverse carbon plantings to mean the restoration of woody vegetation representative of the vegetation types preexisting in each location. The potential area for biodiverse plantings is based on cleared areas identified in the Integrated Vegetation Cover for Australia and data from the Statewide Landcover and Trees Study for Queensland. We use data from (Polglase et al. 2013) who predicted rates of carbon sequestration per year averaged over a 40-year period at a resolution of 1 square kilometers (km²) for mixed environmental plantings on the basis of the 3-PG model. The 3-PG model (Landsberg and Waring 1997, Sands and Landsberg 2002, Sands 2004) predicts growth of tree stands according to climatic and soil conditions, as they affect availability of water and nutrients, light interception.
and therefore the accumulation and partitioning of biomass. Polglase and colleagues (2013) developed and applied an improved version of the model (3-PG2), which provided more robust methods for calculating plant available water, stand water use, biomass partitioning and inclusion of understory as opposed to modelling only a single stratum of trees and therefore is more suitable for modelling structurally complex, native vegetation. The model was calibrated against an extensive data set of aboveground biomass from 53 sites and validated against 16 sites for environmental plantings in southeastern Australia, details of which can be found in Polglase and colleagues (2013). We assume that these same sequestration rates could be generated by planting a range of native species reflecting preexisting vegetation types in each cleared location that was planted.

Polglase and colleagues (2013) estimated the potential profitability over a 40-year period for tree plantings for 105 scenarios covering a range of carbon prices, establishment costs, discount rates and rates of carbon sequestration (supplemental table S1). The opportunity cost was taken as the value of the agricultural land, which accounts for both existing land use and loss of option value. The carbon-selling price is assumed to be net of transaction costs. A 40-year period for economic analysis was chosen to be consistent with medium-term, international policy targets. As future revenues are discounted in the economic model, carbon sequestration beyond this period has a negligible impact on profitability.

Scenarios 1–84 covered the factorial of combinations of seven different carbon prices ($5, $10, $15, $20, $30, $35, $40), and therefore the accumulation and partitioning of biomass. Polglase and colleagues (2013) developed and applied an improved version of the model (3-PG2), which provided more robust methods for calculating plant available water, stand water use, biomass partitioning and inclusion of understory as opposed to modelling only a single stratum of trees and therefore is more suitable for modelling structurally complex, native vegetation. The model was calibrated against an extensive data set of aboveground biomass from 53 sites and validated against 16 sites for environmental plantings in southeastern Australia, details of which can be found in Polglase and colleagues (2013). We assume that these same sequestration rates could be generated by planting a range of native species reflecting preexisting vegetation types in each cleared location that was planted.

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$40, and $50 per ton of CO$_2$e), two establishment costs ($1000 and $3000 per hectare [ha]), three discount rates (1.5%, 5.0%, and 10%) and two rates of carbon sequestration (baseline condition and a 30% decrease in the baseline condition). Scenarios 85–105 added the cost of a water license, which might be required for some types of new forest plantings, to scenarios with establishment costs of $1000 per ha and the baseline condition of carbon sequestration. The 30% reduction in carbon sequestration is an arbitrary, conservative measure to account for negative potential impacts of climatic variability and change such as tree mortality from droughts and fire. Under any particular scenario there are some areas that are not profitable for carbon plantings, indicating that the current land use is more profitable than carbon plantings. As economic conditions become more favorable for carbon plantings, more areas become potentially profitable. The potentially profitable area in any scenario is not intended as a prediction of actual carbon plantings but shows where in the landscape carbon-market driven reforestation is most likely, allowing us to consider how this might be best combined with biodiversity objectives.

**Vegetation types as biodiversity surrogates.** We use woody vegetation types as surrogates for measuring the potential of carbon plantings to contribute to the restoration of the full range of biodiversity that was present at each site. We intersect the 63 major vegetation subgroups covering Australia from the National Vegetation Information System (NVIS v3.1) with 85 bioregions based on the Interim Bioregionalisation of Australia (IBRA 6.1) to create 1886 unique vegetation types, as used in previous Australia-wide conservation planning exercises (Carwardine et al. 2008, Klein et al. 2009). Of these, 1185 vegetation types qualified for carbon forestry, containing trees of at least 1.3 m tall. We determine the proportion cleared of each of these vegetation types by overlaying the pre-1750 extent with the current extent of all vegetation types using the NVIS data set. A total of 139 vegetation types (covering 32 major vegetation subgroups) have been cleared to below 30% of original extent (figure 1). Of these, 42 vegetation types have been cleared to below 10% of original extent. We determine the area requiring restoration for each vegetation type to reach at least 10%, 20%, and 30% of its pre-1750 extent. A total of 96 vegetation types are already present at 10% or more of their pre-1750 extent, and 43 of these are present at above 20% of this extent.

**Investigating vegetation restoration targets under different carbon market conditions.** We map potentially plantable areas at 1 km$^2$ across Australia and overlay areas that have been cleared to below 30% of their original vegetation extent. We determine the total proportion of plantable area made up of these heavily cleared vegetation types and their total carbon sequestration potential. Using the extent of potentially profitable area for each of the 105 scenarios, we determine how many vegetation types could be restored up to target levels of 10%, 20%, and 30% of pre-1750 extent under each scenario. It is not expected that all profitable areas would be restored under any given scenario, because of socioeconomic constraints. However, this analysis gives an indication of the relative potential for biodiversity conservation as a cobenefit to planting for carbon sequestration under different market conditions.

**Spatial priorities for plantings to meet carbon and biodiversity goals simultaneously and independently.** We demonstrate an approach for prioritizing locations that have the potential for meeting both carbon and biodiversity goals at a minimum cost, and we compare this integrated approach to approaches that plan for carbon and biodiversity independently. This necessitates focusing on one particular set of carbon market conditions and biodiversity targets. The 105 carbon market scenarios cover a wide range of input assumptions. Some are more plausible than others given current and future expected markets. We choose one scenario, scenario 11, that was midrange in the set of assumptions, that is considered plausible and which also identifies a sufficiently large area of economic opportunity that allows demonstration of how biodiversity targets intersect with carbon markets. Scenario 11 has an establishment cost of AU$1000 per ha, no water cost, baseline growth rate, discount rate 5%, and a carbon price of $20 per ton of CO$_2$. We focus on 30% targets for restoring vegetation types, although we acknowledge that some vegetation types might require more than 30% of original extent to ensure their persistence and also that in many cases 30% targets are not readily achievable because of competing objectives and constraints.

We compare three alternative sets of priority areas: Priority set 1 is carbon focused: All areas that are potentially profitable for biodiverse plantings under a midrange carbon market scenario (scenario 11), including a carbon price of AU$20 per ton which has the potential to sequester 294 megatons (Mt) CO$_2$e (table S1). Priority set 2 is biodiversity focused: The priority areas for meeting 30% vegetation restoration targets at a minimal opportunity cost, without targeting carbon. Priority set 3 involves carbon and biodiversity combined: The priority areas for meeting 30% vegetation restoration targets at a minimal opportunity cost, without compromising carbon sequestration (sequestering 294 Mt CO$_2$ per year). In all three priority sets, we assume that landholders receive payment for restoring native vegetation on their land equal to its profitability for carbon plantings.

In order to conduct and compare planning approaches, we use a planning unit layer containing 99,190 grid-based units of 4 km$^2$ (the smallest resolution computationally feasible for the optimization software) over the cleared areas of Australia with potential for biodiverse carbon plantings. We determine the extent of each vegetation type in each planning unit using the tabulate area command in Spatial Analyst (ArcMap v10). One vegetation type (melaleuca open forests on Victorian volcanic plains) is unable to be restored to 30% because a majority of its preexisting extent is covered by built areas and therefore was set the maximum possible restorable area, which is 11% of original extent. We assign average sequestration rates and
profitability per ha under scenario 11 to each planning unit and multiply each by the plantable area in each planning unit to give the total potential carbon sequestered per year and the potential profitability for biodiverse plantings in each planning unit under scenario 11. Planning units in our data set that are identified as profitable for biodiverse plantings have the potential to generate a net financial benefit to landowners over and above the cost of restoring vegetation. The opportunity cost of restoring areas not profitable for carbon is the amount of supplemental funds required to make these areas profitable to landholders. Therefore, the relative cost of restoring native vegetation in each planning unit is the amount of supplemental funds required to lift the net present value to break even (see the supplemental material for more details on the opportunity cost layer).

We use the conservation planning tool Marxan to explore optimal locations for meeting the objectives under priority sets 2 and 3. Marxan uses a simulated annealing algorithm to identify multiple alternative sets of planning units all of which meet prespecified targets for biodiversity and carbon at a near-minimal cost (Ball et al. 2009). We set Marxan to generate 500 alternative area sets for each of priority sets 2 and 3, and we use the selection frequency of each planning unit as a measure of its relative priority. Planning units selected in all 500 area sets of a particular scenario are essential for meeting its objective. We use the ten best solutions (those which achieved targets for the lowest cost) to compare the area and costs of each scenario, translating the costs back to reflect the actual funds needed to supplement a carbon market to implement each scenario. Because it is not expected that the entire priority area of any of the priority sets would be planted, we investigate a more modest goal and measure how much carbon could potentially be sequestered in the top 10% and the top 25% of areas under priority set 3.

Results

We discover that the carbon price had a significant impact on the potential for achieving biodiversity restoration targets through carbon plantings, and that priority areas for carbon and biodiversity restoration are most efficiently identified through planning simultaneously.

Carbon sequestration and restoration of vegetation types under different scenarios. Planting all of the 92.4 million ha of potentially plantable areas across Australia could sequester an average of 711 Mt CO2 each year (over a 40-year period)—more than Australia’s current emissions which were estimated to be 559 Mt CO2 for 2012 (Commonwealth of Australia 2014b). Only a fraction of these could ever be established because the feasibility of plantings is dependent on a range of socioeconomic factors, such as landholder preferences, the ability to acquire land, the availability of seed, practical limitations, and policy regulation. These factors limit the area of agricultural land converted to forest as a result of food security and water supply concerns. The sequestration figures reported here are lower than the figures reported by Polglase and colleagues (2013) because we excluded areas that were not previously covered by vegetation types containing trees of at least 1.3 m tall. Approximately 46% of Australia’s potentially plantable area contains vegetation types that have been cleared to less than 30% of their pre-1750 extent, and half of this area contains vegetation types cleared to below 10% (figure 1). Collectively, the restoration of all heavily cleared vegetation types (those cleared to below 30% of pre-1750 extent) across Australia could sequester 358 Mt CO2 per year, or 45% of the total potential carbon in all the plantable areas.

Our analysis of the 105 carbon market scenarios shows that the level of restoration that can potentially be reached for heavily cleared vegetation types depends on the total area that is profitable for carbon (figure 2), which in turn is dependent on economic conditions of the carbon market. In the most favorable carbon market scenario (carbon price = AU$50 per ton, discount rate = 1.5%, growth rate = baseline, water cost = 0; scenario 7, table S1), potentially profitable area covers land that could restore 123 of the 139 heavily cleared vegetation types to at least 30% of original extent. This area would meet 131 and 132 of the 20% and 10% targets, respectively. In the less favorable scenarios, no land is projected to be profitable, meaning that no vegetation types can be profitably restored in a market designed for carbon alone (19 scenarios have an estimated profitable area of zero because of combinations of low carbon price and higher establishment cost and discount rates). Under a midway scenario (carbon price $20 per ton, discount rate = 5%, establishment cost = $1000 per ha, water cost = 0, baseline growth rate; scenario 11, table S1), 12 megahectares (Mha) has the potential to be restored with vegetation types that have been heavily cleared. If this entire 12 Mha was restored, 66 vegetation types have the potential to be restored to 30% of original extent or more, with a further 30 types meeting 20% targets, and another 24 meeting 10% targets, whereas the remaining 22 types receive small amounts or no benefits without being targeted more directly.

Among the 105 scenarios, some vegetation types were more likely to benefit from carbon plantings than others. The 139 vegetation types that have been cleared to below 30% of original extent are made up of 32 NVIS major vegetation subgroups. The vegetation subgroups most likely to benefit from reforestation are eucalypt woodlands and brigalow, because of their relative cost effectiveness for carbon sequestration. Mallee, acacia forests and shrubs, and some rainforests are also likely to be profitable. Vegetation types less likely to benefit are arid acacia woodlands, some eucalypt and Callitris forests, including tropical forests and melaleuca. Opportunity costs for restoring these vegetation types are high because of their value for agricultural activities, despite many of these forests having a high carbon sequestration potential.

Spatial priorities for plantings to meet carbon and biodiversity goals simultaneously and independently. In our carbon-focused analysis (Priority set 1), using the midway economic scenario, approximately 31 Mha has economic potential for planting
native vegetation and sequestering a total of 294 Mt CO₂ per year (priority set 1, figure 3). Although biodiversity is not explicitly targeted in this priority set, the profitable area under this scenario includes areas that if planted could meet 30% targets for 66 vegetation types.

Under the biodiversity focussed analysis (Priority set 2), the minimum area required to meet all of the 30% restoration targets for the 139 vegetation types is approximately 10.3 Mha. There is flexibility in the locations for planting to meet 30% restoration targets, with the highest priority areas occurring around the most heavily cleared vegetation types on the south east and south west coast (figure 4a). Although carbon is not explicitly targeted in this priority set, the area has the potential to sequester 7.23 Mt CO₂. The average carbon sequestration rate over these optimal biodiversity areas is 7.01 tonnes per ha per year. The net cost of reforesting these areas (total opportunity cost minus any profits gained from a carbon market) is estimated to be in the order of AU$45 million, under the $20 per ton scenario. This result assumes that all landowners were able to offset their costs to some extent by accessing financial benefits from a carbon market, although these benefits were small in some locations.

Assuming all of Australia’s plantable area was available for reforestation, our combined carbon and biodiversity goal requires 31 Mha (Priority set 3), approximately the same area as the total profitable area in scenario 11 which met only 66 biodiversity targets. However a supplemental cost of AU$138 million per year would be required to shift the carbon landscape to one that meets our biodiversity targets as well. These supplemental costs make up a relatively small proportion (approximately 2.3%) of the total carbon investment of $5.9 billion under this market scenario.

The spatial priorities for meeting the combined 30% vegetation restoration targets and the 294 Mt carbon sequestration targets together are different than the priorities for meeting either carbon or biodiversity goals alone (figure 4b). There are areas in Queensland, New South Wales, Victoria, South Australia, Western Australia, and Tasmania that are essential for meeting the combined carbon and biodiversity goal cost effectively. The top 10% of priority areas for meeting this goal sequesters 50 Mt per CO₂e per year. The top 25% of priority areas sequesters 132 Mt per CO₂e per year, which is equivalent to 5% of Australia’s emissions and 0.4% of global emissions. Importantly, many of these areas would be missed if planning was carried out for carbon and biodiversity independently, as many are not essential for meeting either goal independently.

Discussion

The economic conditions of a carbon market drive the viability of sequestering carbon and meeting biodiversity goals through reforestation. Factors such as the carbon price dictate which areas across Australia might be profitable for reforestation for carbon sequestration (Bryan et al. 2014, Crossman et al. 2011, Polglase et al. 2013, Evans et al. In Press) and we show that these economic factors have similarly dramatic effects on the nature and extent of the biodiversity benefits that have the potential to be generated. Our analysis suggests that a carbon price of AU$5 per ton (which is close to the 2013 prices on international carbon markets) will not enable the 30% restoration targets to be met for any vegetation types in Australia without additional biodiversity funding. A price of AU$20 per ton (reflecting Australia’s 2011–2013 carbon price) theoretically allows up to half of these restoration targets to be met, without additional funding.

We found that the average sequestration rates among high-priority areas for biodiversity were almost as high as the average sequestration rates across all the cleared areas. However, as discovered in previous studies, the opportunity costs of restoring some heavily cleared vegetation types with biodiverse plantings are prohibitively high unless supplemental funding can be sourced (Crossman et al. 2011, Evans et al. In Press). Under less favorable carbon market conditions, a greater amount of such supplemental funds will be required to make biodiverse plantings viable across areas of cleared land in Australia. The consideration of biodiversity cobenefits diversifies the value of tree planting for carbon...
sequestration, making it effectively more robust to the carbon price (Bekessy and Wintle 2008, Crossman et al. 2011).

Our approach can be used to help plan for a landscape that meets combined carbon and biodiversity goals efficiently and to identify the funding gap required for achieving these goals simultaneously. The carbon market and biodiversity targets we use to demonstrate this approach are arbitrary and do not attempt to predict any particular future for Australia’s carbon planting future. However, we show that Australia could theoretically restore all but one of these heavily cleared vegetation types up to 30% of original extent under the 2011–2013 AU$20 per ton carbon price, without compromising the amount of carbon sequestered (294 Mt per year), for only an additional AU$138 million per year. This is less than 20% of the 2013 AU$733 million Biodiversity Fund, a recent Australian Government program intended to combine carbon and biodiversity outcomes (DSEWPAC 2013b). The supplemental funds required to make biodiverse plantings profitable in important biodiversity areas had an average value

Figure 3. The profitability of cleared areas for biodiverse carbon plantings across Australia, assuming a carbon market under scenario 11 (priority set 1)
Effectively, high-priority areas for meeting the combined carbon biodiversity goal across Australia differed from the priorities for meeting each goal independently. Therefore, failing to consider these goals simultaneously when planning for forest restoration will result in missed opportunities across the country. This concurs with previous studies focused on protecting existing carbon stocks which show that regardless of positive correlations between carbon and biodiversity, there are opportunities which will not be identified when pursuing these goals in isolation (Chan et al. 2006, Venter et al. 2009, Egoh et al. 2010, Strassburg et al. 2010, Crossman et al. 2011).

Figure 4. (a) Relative priority for reforestation to meet 30% vegetation restoration targets across Australia, assuming a carbon market as per scenario 11 (priority set 2).
Onaindia et al. 2013, Bryan et al. 2014). There is great heterogeneity in the relative priority of cleared areas across Australia for meeting a combined carbon and biodiversity goal through biodiverse plantings. We identified spatial locations in every state that are a high priority for meeting carbon and biodiversity reforestation goals efficiently, driven by a combination of biodiversity values for redressing past vegetation clearing, carbon sequestration potential, and relative profitability. The priorities for other carbon sequestration and storage approaches such as conserving existing forests, savanna burning and improved agricultural practices are outside the scope of this study. The lack of high-priority areas in northern Australia in our study reflects relatively low past land clearing rates; however, these areas are likely to rank higher for initiatives such as existing vegetation protection and savanna burning (Douglass et al. 2011, Robinson et al. 2012).

We do not attempt to predict any particular outcomes for Australia’s carbon planting future. We acknowledge that priorities might differ with more comprehensive information,
particularly because detailed data on cleared land was not available at a national scale. We measure biodiversity and carbon sequestration coarsely, which was necessary at a continental scale. Our approach could also be applied at finer scales to support regional and local planning. We were unable to consider the preferences and livelihoods of landowners and managers (who might be unwilling to implement reforestation even if it is potentially profitable for them), water availability, food production requirements, and other aspects of biodiversity such as threatened species habitat and increasing connectivity. Estimates of carbon sequestration and profitability were modelled using sequestration rates of mixed environmental plantings, current unimproved land values, and a uniform establishment cost (sensitivity to the model assumptions is discussed in Polglase et al. 2013). Establishment costs for biodiverse plantings will in reality vary across Australia (Strassburg et al. 2010, Crossman et al. 2011, Bryan et al. 2014) and unimproved land values are unlikely to capture the true value of land in many situations, such as on indigenous land (Robinson et al. 2012). If a carbon market were to drive significant land-use change, it is likely there would be flow-on impacts on both establishment costs and land values, something that is not addressed in our model.

We provide an approach and an indication of opportunities for achieving a combined carbon and biodiversity goal through reforestation across Australia, showing that factors such as carbon price have a dramatic impact on the viability of this goal. Through diversifying funding sources and applying an integrated planning approach, we demonstrate the potential efficiencies of planning for carbon and biodiversity simultaneously. As the Australian Government embarks on a major carbon offset purchasing program, our results offer insights into how this scheme could be adapted to have a very significant impact on biodiversity at the same time. Although the amount of the carbon sequestration investigated in our study is modest on a global scale, our approach applied at a global scale could identify opportunities for considerable carbon sequestration and biodiversity benefits. Even with much lower carbon incentives, a rational and integrated approach for planning for carbon landscapes that benefit biodiversity will ensure the greatest outcomes are achieved with limited funds in an increasingly space limited world.

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Supplemental material

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