Carbon Storage in Protected Areas – Technical Report

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Contents

Executive Summary

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Our assessment of carbon storage in protected areas integrates information from the best available data sources, with the aim of informing decision-making at global, regional and national levels. Earth's terrestrial ecosystems are estimated to store around 2,050 gigatons (Gt) of carbon in their biomass and soil (to 1 m depth). Protected areas worldwide cover 12.2% of the land surface, and contain over 312 GtC, or 15.2% of the global terrestrial carbon stock.

This estimate is broken down by region and IUCN protected area management category. South America is notable for both its large volume of carbon and for the high proportion of this carbon stored within protected areas; 27% of a total store of 340 GtC. By way of contrast, the Pacific has a low total carbon store but a high carbon density, and only 4% is stored within protected areas. Increasing protected area coverage in this region would provide a higher carbon benefit per unit area than for other regions. Amongst the IUCN categories, only 4% of the carbon stock is contained within protected areas designated under categories I-II, which generally place stringent restrictions on resource use. More research is required into the carbon storage implications of the various types of protected area management. A greater level of carbon loss would be expected from areas allowing sustainable forest management, for example, than those that restrict use of forest resources. A notional estimate of the financial value of the carbon storage services provided by the world's protected area network is also presented. If all of the carbon stored within ecosystems were to be valued according to current carbon market prices, it would have an estimated worth of €5,700 billion

The data presented also allow identification of areas of high carbon value which are not covered by the current protected areas network on a global and regional level. This also provides the opportunity to identify areas that are not just high in carbon, but also have high biodiversity value, increasing the scope for delivering 'multiple benefits' from climate mitigation. By way of demonstration, the global figures presented here were overlain with areas of high biodiversity, based on the spatial overlay of the outcomes of multiple conservation priority setting exercises, for Tanzania and Papua New Guinea.

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The estimates reported here should be viewed in the context of our knowledge of the success of protected areas in reducing or halting land cover change. Evidence suggests that protected areas are effective at reducing land cover change within their boundaries (Clark *et al.* 2008), although one issue rarely taken into account is that of leakage. While protected areas may effectively reduce deforestation within their borders, there is a risk that deforestation pressures are merely displaced elsewhere; either to other areas of forest or to other ecosystems entirely. This highlights the issue that although the total figures for carbon within protected areas appear high; this is still a small proportion of the global terrestrial carbon stock. 85% of the global carbon stock lies outside of the protected area network, and could be considered more vulnerable to release through land use change. Forests are not the only ecosystem that store carbon and this should be taken into account in the development of climate change mitigation policies; in particular there is a large carbon store in northern latitude soils and peatland. It is vital from a climate change perspective that this carbon is managed appropriately.

It is clear that there is no ‘one size fits all’ approach to protecting carbon stocks within terrestrial habitats. Other land use options for the protection of carbon should be incorporated, including through community-conserved areas and the development of best practices for land management and land use planning. The implementation of REDD on a large scale is unlikely to be feasible without the support of indigenous and local communities. The official recognition and encouragement of community-based forest management is becoming more widespread, and could also become a viable component of, or complement to, protected areas in reducing deforestation.

Although it is recognised that extension or strengthening of the protected area network is only one possible element in the management of terrestrial carbon, the large amount of carbon stored within protected areas, particularly in proportion to the land area covered, suggests that protected areas could play a role in climate change mitigation. Investment in a protected area network could be a valuable component of a national strategy for reducing emissions from deforestation and forest degradation, in support of the objectives of the UN Framework Convention on Climate Change.

Introduction

Recent recognition of the importance of land use change in the carbon cycle, and the commitment to include reduced emissions from deforestation and degradation (REDD) in the post-2012 agreements of the UNFCCC, has raised the policy relevance of carbon storage in terrestrial ecosystems. Research has traditionally focused on the role of ecosystems as carbon sinks, rather than as potential sources, but the importance in climate change mitigation of protecting the *existing* carbon stocks is becoming increasingly recognised. Depending on the method of forest clearing and the subsequent use of the felled trees and land, deforestation not only releases carbon stored in the above ground biomass, but leads to decomposition of roots and mobilization of soil carbon. Global greenhouse gas emissions from changes in land use, including tropical deforestation, are estimated to make up around 20% of annual global emissions from all sources (IPCC 2007), though there is a high level of uncertainty attached to the precise figure. Forest degradation, the loss of carbon stocks from land still officially designated as forest, adds another unquantified volume of CO_2-equivalent gases to the atmosphere every year. Forest fragmentation and degradation also increase the risk of forest fires, which release further carbon emissions and increase susceptibility to future fires.

Protected areas are primarily designated for the purpose of biodiversity conservation, but have a substantial additional value in maintaining ecosystem services; including climate regulation through carbon storage. Despite this, there is little knowledge of the carbon storage within the world's protected area network, and no global scale estimate has previously been produced. Such knowledge would quantify one of the multiple benefits provided by protected areas, which could be useful in protected area planning and financing. Discussions at the recent UNFCCC's 13th Conference of the Parties focussed on guidance for demonstration (pilot) REDD projects, potential policy mechanisms and incentives for developing countries. The precise form of any future REDD mechanism as part of a post-2012 emissions reduction agreement is yet to be determined.

In the context of the carbon stocks already under protection, a distinction should be made between the actual process of reducing emissions from land use change, and the proposed REDD mechanism under discussion at the UNFCCC. Whilst the current protected area network undoubtedly plays a role in conserving the carbon stock, it is not clear whether existing protected stocks will be included in a REDD mechanism. Currently, there are a number of options on the table, including the measurement of emissions from deforestation and degradation against past rates of deforestation; with compensation for existing protected stocks not out of the question but appearing less likely. This should be taken into account when reading this report, which has a focus on the potential role of protected areas in the actual achievement of reductions in emissions from land use.

The global protected area network contains many ecosystem types other than forest, each with its own carbon storage capacity. This technical report presents an estimate of the total carbon storage function of protected areas. The report is broken down into four main sections, with background information reported in the Annexes. Section 1 reports the level of carbon storage within the protected area network, broken down by region and according to the IUCN protected area management category. A rough estimate of the financial value of the carbon storage services provided by the global protected area network is presented in Section 2. Section 3 presents the regional analyses used to validate the global data, and the outputs of this study are contextualised in Section 4 through a demonstration of the potential use of the data in identifying areas of high carbon and high biodiversity areas in Papua New Guinea and Tanzania. A review of the available carbon storage datasets used to produce the global carbon map, and a review of carbon market values used in the selection of an estimated value for terrestrial carbon can be found in Annexes 1 and 2 respectively

This work illustrates the potential role of protected areas in climate change mitigation and will be a useful input to current discussions on a mechanism for reducing emissions from deforestation (REDD) under the UN Framework Convention on Climate Change (UNFCCC), or any other mechanism for protecting carbon stored within ecosystems.

Section 1 - Carbon storage within the protected area network

Methodology

Global carbon storage in terrestrial ecosystems

The methods for estimating carbon storage vary widely, and no single method is considered highly accurate. The use of improved technology for biomass estimation and databases for soil carbon estimation is likely to improve the accuracy of carbon estimates in coming years. A global scale dataset on carbon in live biomass (Ruesch & Gibbs, in review), and a dataset on soil carbon produced by the International Geosphere-Biosphere Programme (IGBP-DIS 2000) were selected for use in this analysis following a comprehensive review of the available data (Annex 1).

The biomass carbon stock data were estimated using the Intergovernmental Panel on Climate Change (IPCC) Tier-1 approach (IPCC 2006, Gibbs *et al.* 2007). A combined map of carbon storage in terrestrial ecosystems was produced using globally consistent estimates for above and below ground biomass. These are the most recent estimates available for global vegetation carbon, and the only global estimates to follow IPCC Good Practice Guidance for reporting greenhouse gas emissions (IPCC, 2006).

It is also important to quantify soil carbon storage, as research has suggested that soil carbon accounted for 28% of net loss from land use change in the period 1850-1990 (Houghton 2005). A soil organic carbon dataset (SOC), published by the IGBP in 1998, was selected for use in this study (IGBP-DIS 2000) on the basis of availability, scale and provenance. It estimates organic carbon density to 1 m depth, at 5 minute resolution, which is appropriate for quantifying SOC in most cases, but undoubtedly underestimates SOC storage in deeper peatland systems. No global spatially explicit map of peat extent and depth is yet available, and this is an acknowledged limitation of the current data, particularly given that peatlands have been estimated to contain at least 550Gt of carbon, containing as much carbon as all terrestrial biomass but covering only 3% of the land areas (Parish *et al.* 2008).

A globally consistent map of carbon storage in terrestrial ecosystems (
Figure **1**) was produced by combining a number of datasets

1. Global biomass carbon stock map based on IPCC Tier-1 Methodology. (Ruesch & Gibbs, in review).
2. Global Soil Data Products CD-ROM. (IGBP-DIS 2000).
3. Coastlines and country's boundaries of the world /World Vector shoreline plus, 3rd edition. (the National Geospatial-Intelligence Agency, 2004)
4. Area Correction Global Grid, ACGG. (UNEP-WCMC 2007)

ACGG, the global raster dataset (ArcInfo Grid format) identifying the actual area of a grid cell on the Earth surface in km^2 (with a precision of 0.001 km^2 for cells of 0.0045 degree resolution; about 500 meters on the equator, henceforth referred to as "standard resolution"), was applied as a template for all intermediate maps and the final combined map. All original sources and outputs were maintained and analysed in the common original projection (Geographic, spheroid/datum WGS84). ACGG values were applied to reflect on-the-surface grid cell size change at various latitudes; in particular in calculation of areas and other statistics derived from the combination of area and other parameters (e.g. carbon stock within a particular region derived from carbon density values).

World Vector Shoreline Plus (vector dataset) was applied as a high resolution (1:250,000) basemap. It was converted into the standard resolution raster (ArcInfo Grid format).

Both biomass carbon and soil carbon maps (raster datasets) were converted into the standard resolution grids. As the original resolution of these data was lower than required, minor amendments were applied to ensure that the whole terrestrial area was covered by the combined map. These minor amendments included elimination of the area falling beyond the extent of the basemap over the coastline, and the assignment of the nearest cell value to terrestrial areas close to the coastline that had been omitted in the original sources due to lower raster resolution. The total extent of the area where this extrapolation applied did not exceed 0.5% of the total land surface.

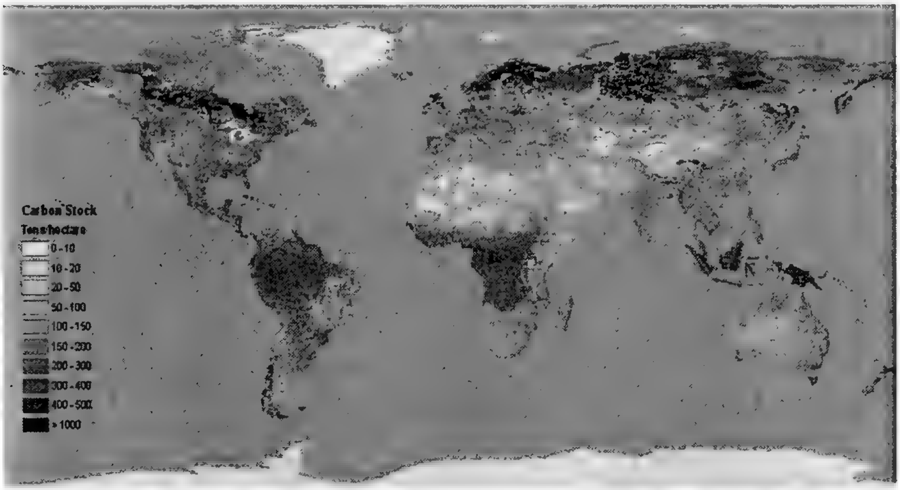

Figure 1: Global carbon stock density in terrestrial ecosystems (above and below ground biomass plus soil carbon) (Gibbs *et al.* 2007; Ruesch & Gibbs in review; IGBP 2000)

A carbon stock estimate for tropical forest is also presented (Figure 2), as an example of how the carbon data can be separated according to ecosystem and region of interest.

On a global scale, the use of biome averages and the increased uncertainty of carbon storage estimates for higher biomass classes tend to lead to a less accurate picture for individual regions than equivalent regional maps (Annex 1). Whilst much variability can be found at a regional scale, these biome-based estimates do provide a consistent indicative picture of the pattern of carbon storage.

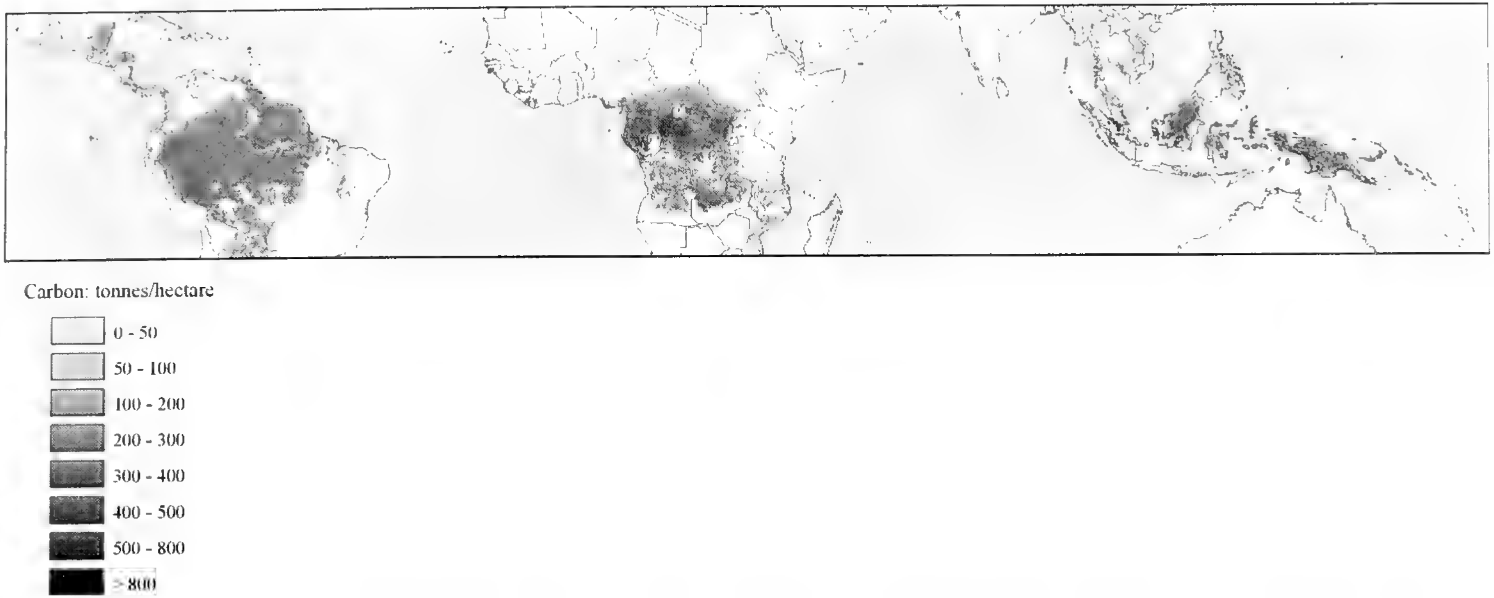

Figure 2: Carbon stock density in tropical forest (above and below ground biomass plus soil carbon) (Gibbs *et al.* 2007; Ruesch & Gibbs in review; IGBP-DIS 2000

Selection of regional data

There are a large number of national and regional estimates of carbon storage in terrestrial ecosystems (Annex 1, Table 6). Such estimates tend to be more accurate because they are extrapolated over smaller scales, rely on better inventory data, and can account for spatial variation in more detail. Comparisons of the global datasets used in this analysis with regional data were carried out for the purposes of data validation.

Datasets for biomass in the Amazon Basin (Saatchi *et al.* 2007) and SOC in Canada (Tarncoi & Lacelle 1996) were selected to assess the accuracy of the global data for both biomass and soil in two areas of high carbon storage. Following review of available estimates (Annex 1), both datasets were considered to be the most accurate available both for the regions and carbon pools that they provide estimates for. Although other datasets for the Amazon could be considered equally accurate, they do not provide estimates for all vegetation classes.

Selection of protected area data

Broadly speaking, protected areas can be defined as areas of land or sea "dedicated to the protection and maintenance of biological diversity and of natural and associated cultural resources, managed through legal or other effective means" (IUCN 1994). Protected area data were obtained from the World Database on Protected Areas (WDPA), which holds spatial and attribute information on over 120,000 nationally and internationally protected sites.

The International Union for the Conservation of Nature (IUCN) describes six management categories for protected areas, according to the objectives for management. Any protected area must have biodiversity conservation as a major aim, but the degree of permitted use varies. Amongst the categories, I and II are more restrictive; III and IV are variable, whereas V and VI explicitly recognise sustainable use as an appropriate land use. The WDPA also holds information on a large number of protected areas that have no formal designation or for which the designation is not known, and for areas that may not meet the protected area definitions such as forest reserves or community conservation areas. Difficulties with data validation are an acknowledged limitation of the WDPA, as the data is received from a number of different sources. Whilst this is true for all of the data contained within the WDPA, data for which an IUCN category has been provided is considered to be more robust than that for which designation is unknown. The WDPA is currently undergoing redevelopment to improve data validation processes.

For the purposes of this analysis, all WDPA sites were incorporated to allow inclusion of those areas that meet the protected area definition, but may not have an IUCN management category recorded. In addition, it was considered that any area of land with some degree of protection conferred upon it should be included in the analysis. For reporting purposes, all sites stored within the WDPA will be referred to as 'protected areas' in full recognition that these areas may not have official protection status.

The results are presented initially for carbon stored in all WDPA sites (including those with no IUCN category). In view of the fact that not all protected areas are managed for the same purpose, as defined above, the results are also broken down into protected area categories I-II, I-IV, I-VI. This allows for some degree of separation of:

a) The areas of land that have been given management categories (and are therefore more likely to be officially recognised protected areas) from those that may be forest reserves
b) Protected areas that allow different degrees of resource use and land use change, as defined by the IUCN protected area management category (outlined above).

This separation is made for the purposes of comment on the potential level of protection afforded to the carbon. For example, substantial land cover change would not be expected in any protected area, but increases in sustainable use of land within categories V and VI might be expected, with implications for the carbon stored in that area. It should be noted that this analysis does not incorporate any actual measure of the likelihood that the carbon will be conserved within protected sites.

Production of the global carbon storage within protected areas map

The globally consistent map of carbon storage in terrestrial ecosystems was overlaid with data from the WDPA.

To enable overlay of the protected areas with the combined carbon density maps, the vector data from the WDPA (UNEP-WCMC & IUCN, version 2007) were converted to the standard resolution raster. This process was straightforward for polygonal data. Additional data represented only by approximate location of the protected area (latitude/longitude) and its total area were transformed into proportional circles, centred at the given location and equal in area to the size recorded in the WDPA. These new polygons were also converted into the raster and incorporated, as they provided additional data for the analysis. Although this method assumes considerable distortion for particular protected areas boundaries, it is widely applied for protected coverage estimates over large territories, and at the continental or global level potential distortion in coverage assessment does not exceed 3-4 %, according to our calculations. Polygonal layers of protected areas, in particular IUCN category I-VI and protected areas with no IUCN category assigned, were converted to separate raster datasets.

All of the maps represented in this report were produced using the combined raster map of a carbon class and relevant protected areas class (one or more categories brought into a single raster). It should be noted that, due to overlap between various categories of protected area, statistics on total extent or carbon content within categories and groups of categories of protected areas cannot be calculated as a simple sum of relevant totals. All calculations were based on spatial analysis, through identification of the actual total extent of protected areas, and overlay of this intermediate dataset with the rasters identifying the carbon content distribution. Analyses were conducted using ESRI ArcGIS 9.2 with the Spatial Analyst extension.

How much carbon is stored within the protected area network?

Global protection

The combined map of global carbon storage (Figure 1) shows that earth's terrestrial ecosystems store an estimated 2,052 gigatons (Gt) of carbon in their biomass and soil. Two distinct bands of high carbon density can be noted in the northern latitudes and the tropics.

According to our estimates, 15.2% of the global carbon stock is contained within the protected area network, highlighting the relevance of protected areas to climate change mitigation. As protected areas cover 12.2% of the land area (according to the criteria used in this analysis) (Table 1), they capture a proportionately high amount of carbon given that they were not designated for this purpose. There are a number of potential reasons for the high carbon benefit of protected areas; it could be that high carbon areas such as tropical forest are more likely to be protected, or it could be the case that much of the carbon in non-protected areas has been lost already. Clearly, land that has already been cleared for agriculture or urban growth will have lower carbon content than land that has been protected; this factor was not incorporated into our analysis. Conversely, some protected areas cover rock and ice deserts that would not be expected to have high carbon content. Regardless, it appears that protected areas could have a role to play in future ecosystem based climate change policies.

A total of 312 Gt carbon is currently under some degree of protection (taking into account all sites within the WDPA) which would be equivalent to 1142 Gt CO_2 if lost to the atmosphere; or more than 43 times the total annual global emissions from fossil fuel (26.4Gt; IPCC, 2007). This comparison is made for perspective only; even if all protected areas were converted to a different land use not all of this carbon would be released to the atmosphere. A large amount of carbon will likely be emitted from conversion of forest to agriculture, for example, but this will also depend on the type of agriculture and the management of the agricultural land. The loss of 2.5% of carbon within protected areas would result in higher carbon dioxide emissions than an entire year of fossil fuel combustion.

Table 1: Global terrestrial carbon storage in protected areas

Protected area category	% land cover protected	Total carbon stored (Gt)	% terrestrial carbon stock in protected areas
IUCN category I-II	3.8	87	4.2
IUCN category I-IV	5.7	139	6.8
IUCN category I-VI	9.7	233	11
All WDPA sites	**12.2**	**312**	**15.2**

The extent to which protected areas are effective at conserving their carbon stores is another question. This depends on a number of factors such as whether areas are actively managed, the level of enforcement, the level of resource use permitted, land use change pressures, and governance. Much of the study on this topic has focused upon forested protected areas, and a review of the evidence suggests that protected areas are an effective tool for reducing deforestation within their boundaries; that is, there is usually less deforestation within formally protected areas than in their immediate surroundings (Clark *et al.* 2008).

Clark *et al.* (2008) also identified that protected areas designated under categories I-II seem to be more effective at reducing deforestation than those which include a focus on sustainable use (V-VI); although there are comparatively few studies on deforestation rates within category V-VI protected areas. This is an important point to consider, as protected area categories I-II, which are the most restrictive in terms of land use, store only 4.2% of the carbon stock (
Table 1), whereas double the percentage of total carbon stock is protected when considering categories I-VI. It could be expected that some carbon may be lost from the less restrictive protected areas through, for example, the sustainable use permitted in category V-VI areas; but conversely this may avoid leakage of deforestation to other areas. More research would be required into the impact of such management practices on carbon stocks, and the type of land use permitted in each protected area, before even qualitative statements as to the carbon storage value of the different protected area management categories could be made. Analysis of the potential carbon protection benefit of protected areas in terms of the emissions that would likely be prevented through protection of carbon 'on the ground' is beyond the scope of this present study

Carbon outside the protected area network

Although protected areas clearly have a large carbon storage benefit, there is still a total of 1,740 Gt of carbon lying outside of the protected area network. This carbon could be considered more vulnerable to release into the atmosphere if fewer restrictions are placed on land use change. There have been very few studies able to quantify, for example, the extent to which land-use change is displaced from protected areas to surrounding land, although there is some evidence that this does occur (Ewers & Rodrigues 2008). Although the reduction of carbon emissions is undoubtedly the first priority of policies such as REDD, from a conservation perspective the potential for land use change to be displaced into lower carbon areas with high biodiversity value needs to be considered. Even purely from a carbon perspective there is a risk of displacement into high carbon non-forest areas. Efforts to reduce emissions from land based carbon should not focus on forests alone (Miles & Kapos 2008).

Protected areas are not the only tool that should be utilised in protecting the carbon stored in terrestrial ecosystems. Community conserved areas (CCAs) and Indigenous lands have been shown to be effective tools for reducing deforestation, even more so than many protected areas (Clark *et al.* 2008). The potential for reducing carbon emissions through improved forest management is another avenue for exploration, and is particularly important if we are to reduce emissions from forest degradation. A recent study has reported that reduced impact logging can reduce carbon emissions by approximately 30% over conventional logging, and estimated that improving logging practices in managed forests globally could retain at least 1.6Gt carbon per year (Putz *et al.* 2008); more carbon than is currently protected in the Pacific (Figure 3). In addition, participatory forest management in Tanzania has been shown to lead to improved forest condition (Blomley *et al.* 2008). From a climate change mitigation perspective, the high amount of carbon outside of the protected area network suggests a need to both ensure the protection of carbon within protected areas, and to improve land use planning and management in areas identified as high in carbon content, for which the designation of new protected areas would only be one available option.

Regional protection
There are regional variations in both the total carbon store and the amount that is protected (Figure 3). Although the data reported here gives an overview, ideally more accurate regional source data would be used to determine carbon protection priorities.

For the purposes of this study, the global map was divided into major continuous geographical regions. The largest carbon stores can be found in North Eurasia, North America, South America and Africa (Figure 3). Protected areas in South America store the most carbon, both in absolute terms (91Gt) and as a proportion of total stock (27%; Table 2). Comparatively high levels of protection can also be seen in Central America & Caribbean and Greenland (although these regions have a low total stock and the carbon is arguably less vulnerable to disturbance as fewer pressures are acting upon the land).

Low levels of protection are evident in North Eurasia, with only 8.8% of carbon protected out of the largest regional carbon stock. This is likely due to the large amounts of carbon stored in the biomass, and particularly the soils, of the large tracts of mostly unprotected boreal forest in this region (Schmitt *et al.* 2008). Again, this is not to say that the carbon stored in these areas is necessarily more vulnerable to release, as the land is arguably subject to less land-use pressure than carbon outside protected areas in tropical regions. Indonesia, for example, has high deforestation rates (Hansen *et al.* 2008) due to factors such as oil palm expansion (Nellemann *et al.* 2007) which can involve emissions from the burning of high carbon peatland as well as that from deforestation. It could be considered that the estimate of only 15% of carbon protected in this region is of more concern than the lower levels of protection in North Eurasia. Indeed, although South America has the highest amount of carbon protected, a recent study has estimated that over three-fifths of forest clearing occurs in this region (mostly in Brazil; Hansen *et al.* 2008), suggesting a need for increased conservation and protection measures.

As specified previously, the figures reported above in Figure 3 and Table 2 are for all sites within the WDPA, including those designated under the less restrictive land use categories V-VI and those that have not been assigned an IUCN management category. Estimates for the total carbon storage for each region under protected area categories I-II, I-IV, I-VI, and all protected areas are shown in Figure 4, ranked according to land area.

Two thirds of the large amounts of carbon protected in South America are in the less restrictive protected areas, and the majority of the 20Gt total is protected in categories V-VI in East Asia. Generally, between a third and a half of the protected area carbon is stored in the more restrictive categories I-IV across the regions, with the exceptions of Australia/New Zealand, North Eurasia and Greenland

Table 2: Estimated carbon storage within protected areas (Gt), by region. Percentages calculated from carbon figures in tonnes, rather than the Gigatonnes presented here.

Region number	Region	Terrestrial carbon stock, Gt		Carbon in protected areas, %
		Total	In protected areas	
1	North America	388	59	15.1
2	Greenland	5	2	51.2
3	Central America & Caribbean	16	4	25.2
4	South America	341	91	26.8
5	Europe	100	14	13.6
6	North Eurasia	404	36	8.8
7	Africa	356	49	13.7
8	Middle East	44	3	7.8
9	South Asia	54	4	7.2
10	East Asia	124	20	16.3
11	South East Asia	132	20	15.0
12	Australia/New Zealand	85	10	12.0
13	Pacific	3	0.1	4.3
14	Antarctic & peripheral islands	1	<0.1	0.3

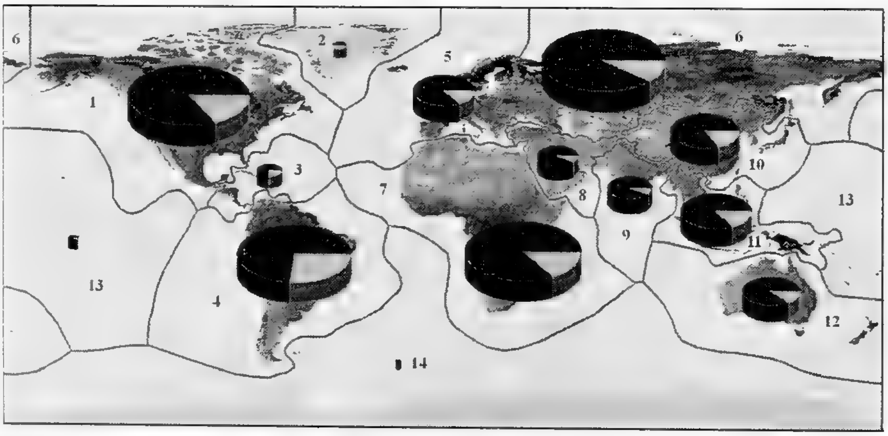

Figure 3: Terrestrial carbon stock in the protected area network by region. Total (proportional pie-charts), and stored within the protected areas network (green segments); red numbers are region numbers from Table 2.

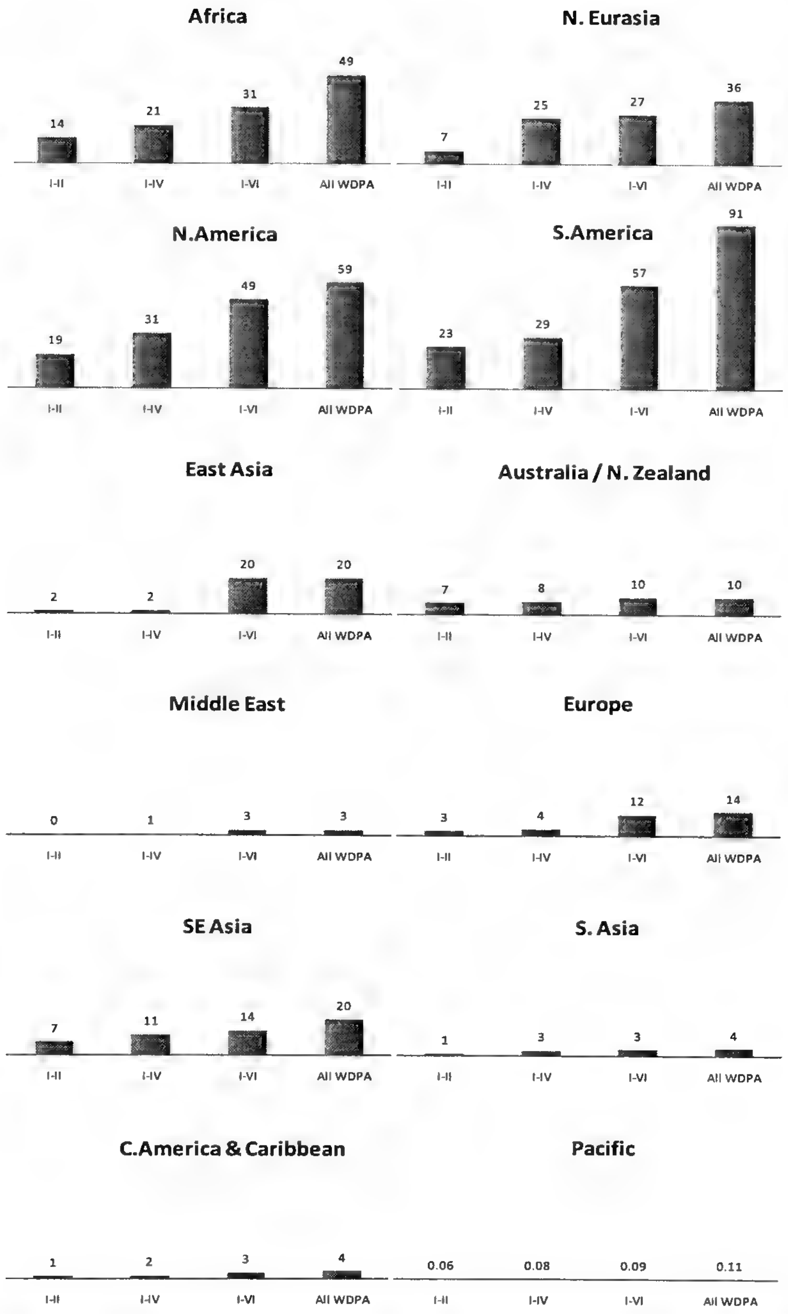

Figure 4: Regional variation in total carbon stores (Gt) across protected area categories. Regions are ordered according to land area (Greenland and Antarctic not shown).

A large proportion of carbon protected in Africa and South America is in areas which do not have an IUCN management category. Again, it is not clear what implication this has for the vulnerability of the carbon store within protected areas, although as discussed earlier categories I-II are more successful in reducing deforestation (Clark *et al.* 2008) and by definition are more restrictive of land use change.

Total figures of carbon storage in each region are clearly important for carbon accounting, and quantifying the current carbon storage benefits of the protected area network. However, as suggested in Figure 4, regional totals are in general indicative of the land area of the region, rather than 'carbon richness' *per se*. It is perhaps more appropriate to consider the carbon density of an area when, for example, identifying priority areas for REDD. Such patterns can be more readily seen when regions are ranked by land area, and the amount of carbon per hectare of land is displayed (Table 3).

Table 3: Regional variation in carbon density

Region	Land area (million km2)	Total carbon stock (Gt)	Carbon density t/ha
Africa	30	388	119
North Eurasia	22	5	185
North America	21	16	182
South America	18	341	192
Antarctic	14	100	0.4
East Asia	12	404	108
Australia/New Zealand	8	356	107
Middle East	7	44	66
Europe	5	54	195
South East Asia	**5**	124	**267**
South Asia	4	132	120
Greenland	2	85	21
Mesoamerica & Caribbean	**0.8**	3	**214**
Pacific	**0.1**	1	**239**

Although comparatively low in total carbon stocks, it is clear that the South East Asia, Central America & Caribbean, and Pacific regions could be considered 'high carbon density' areas. In addition to this, the Pacific has the lowest proportion of total carbon stock within protected areas at 4% (not inclusive of Antarctica), despite the fact that more carbon would be protected per hectare of land protected than in any of the other region outside of South East Asia. Purely from a carbon storage perspective, increasing protection in these regions would provide more 'value for money' than anywhere else on the globe. In addition, a low total land area but high carbon density would suggest that carbon could be vulnerable to land use pressures in these areas. It appears appropriate therefore, that Papua New Guinea is a potential pilot country to receive assistance in developing and implementing REDD strategies. Further information of high carbon density and high biodiversity area mapping in Papua New Guinea can be found in Section 4.

It is clear that protected areas have the potential to make a useful contribution to protecting carbon stored in ecosystems. However, evidence shows that they need proper investment if they are to be effective at avoiding land use change (or carbon loss through land degradation), and therefore act as effective tools for the protection of carbon stores. A lack of sustainable financing for the protected area network has clearly been a barrier to effective protected area management in the past. The following section of this report considers the notional value of the protected area network, if the carbon stored within protected areas was to be valued according to current market prices.

Section 2 - The value of carbon stored within protected areas

Carbon emissions from deforestation account for an estimated 20% of global carbon emissions (IPCC 2007); second only to that produced by fossil fuel combustion. Despite this, projects relating to Land Use, Land Use Change, and Forestry (LULUCF) in 2006 accounted for only 1% of an international carbon market that has risen to US$64 billion (€47 billion) in 2007 (Capoor & Ambrosi 2008). Given the contribution of deforestation and land degradation to carbon emissions, it is likely that the value of carbon storage in ecosystems will increase, particularly as the overall carbon market is projected to increase in value (Annex 2).

For the first time, one of the non-provisioning ecosystem services provided by protected areas has a financial market associated with it in which the international community is engaged. In addition, the data presented here has gone some way towards quantifying the carbon storage service provided by protected areas; providing an opportunity to illustrate the value of carbon stored within protected areas if it was to be traded on the current carbon market.

A notional value of the carbon stored within the protected area network is presented here, based on a review of carbon markets, and the current levels of finance attached to land-use based carbon (Annex 2). From the values reviewed, it would appear that a reasonable range for the valuation of carbon stored in terrestrial ecosystems is €1-10 for the retail price. Within this, a conservative estimate of €3 – €7 at the higher end would appear acceptable for carbon stored in ecosystems across the board, based upon the range of current market prices and considering that forestry based projects command higher prices within the voluntary market, whereas carbon stored within other ecosystems will undoubtedly command a lower price (Annex 2).

The price of stored carbon will be variable, and any single value placed on carbon stored in ecosystems should therefore be considered very speculative, particularly given that the scale of the market is yet to be determined through, for example, REDD implementation. In addition, the access that carbon already stored within the protected area network would have to carbon finance is not clear. The values reported below should be viewed only as an indication of the worth of carbon stored in protected areas according to current market prices, rather than an estimation of their value. The notional estimates are reported with full recognition that not all carbon stored in ecosystems will have a financial value, and that the value will differ for carbon from different sources and regions.

Estimates of the financial value of carbon stored within protected areas by region (Table 4) are based on the application of values of €3, €5, and 7€ /tCO_2e to all carbon stored in the protected area network. The mid-range value of €5 /tCO2e gives an estimate of €5,700 billion for the carbon within protected areas, if it were valued at current market prices. Even taking the lower range estimates of €3 and €1, the value is more than €1,100 billion. Again, this should not be taken as an estimate of protected area value; such comparisons are problematic as it is not possible to equate stored carbon to carbon 'not emitted'.

Table 4: Estimated value of carbon storage within protected areas by region

Region	Carbon stock (Gt)	Co2e (Gt) (~notional value at €1)	Notional value (€billion) Priced at €3	**Notional value (€billion) Priced at €5**	Notional value (€billion) Priced at €7
North America	59	215	644	**1,074**	1,504
Greenland	2	9	26	**43**	60
Central America & Caribbean	4	15	45	**75**	105
South America	91	334	1,003	**1,671**	2,339
Europe	14	49	148	**247**	346
North Eurasia	36	130	390	**650**	910
Africa	49	179	537	**895**	1,253
Middle East	3	12	37	**62**	87
South Asia	4	14	43	**71**	99
East Asia	20	74	222	**371**	519
South East Asia	20	73	218	**363**	508
Australia/New Zealand	10	37	112	**186**	261
Pacific	0.1	0.4	1	**2**	3
Antarctic & peripheral islands	0.002	0.007	0.02	**0.04**	0.05
TOTAL	312	1,142	3,425	**5,709**	7,992

To put these figures in context, it has been estimated that $6 billion per year is spent on protected area management, less than 12% of which is spent in developing countries (Balmford *et al.* 2003). Balmford *et al.* (2003) also estimated the costs of effective protected areas in densely settled regions of Latin and Central America, Africa, and Asia; and found that costs ranged from $130/km2/year, to $5,000/km2/yr, with typical costs falling in the region of $1,000/km2/yr. Moore *et al.* (2004) estimated that the entire budget for ecoregion conservation in Africa would be $630 million. However, the calculation above based on total stock is different from the value calculated on the basis of emissions avoided, and such carbon finance will mostly be made available through REDD. As noted previously, the position of protected areas within a REDD mechanism is unclear, and it is most likely that the current protected area network would only receive a portion of REDD finance if they were demonstrably at risk of deforestation. The identification of such areas would be a useful topic for further analysis.

Consideration of the value of carbon storage within protected areas also provides no indication of the mechanisms through which this money could be made available, nor the stakeholders to whom the finance would be available to. Whilst such a discussion is beyond the scope of this report, it is worth noting that this is a major issue for REDD. There are no guarantees that even for new protected areas included in a REDD mechanism carbon finance from national level systems will come back to the site level, let alone the local people and forest users. In addition, the financial value of carbon is likely to be lower for non-forest ecosystems; with the potential to result in the conservation of forest at the expense of other ecosystems. Inequitable distribution of benefits and unresolved issues of land tenure would appear to be the major stumbling blocks to ensuring that finance from the conservation of carbon reaches the appropriate stakeholders (Coad *et al.* 2008), and need consideration in the development of REDD policies.

The potential role of protected areas in REDD policy

As has been indicated throughout this report, the relationship between REDD policy and protected areas is complex. This has been highlighted through the difficulty in attaching carbon finance to protected areas. As in theory carbon stored within protected areas is not at risk of release to the atmosphere, it would not be explicitly included in a REDD mechanism that was focused on *reducing* national emissions, rather than rewarding countries for protecting their carbon stocks. Whilst there is still the potential for countries to be compensated on the basis of existing carbon stocks through mechanisms such as that suggested by the Terrestrial Carbon Group (TCG 2008), it appears more likely that REDD will take the format of measuring reduced emissions from deforestation and degradation against past baselines

Clearly, where protected areas are at risk from deforestation, there could be a role of strengthening the protected area network, and further study would be required into emissions from protected areas through deforestation. In addition, expansion of the protected network would be one option for reducing emissions.

Regardless of the role of protected areas within REDD, it is clear that they have a large role to play in the actual process of reducing emissions from land use change, as they store a large amount of carbon; the protection of which could play a large role in the mitigation of climate change. This clearly makes protected areas relevant to all decisions related to carbon in ecosystems, including those relating directly to REDD; especially if we are concerned with delivering biodiversity and livelihood co-benefits from climate mitigation measures.

Section 3 - Comparison of regional and global results

An initial analysis of the uncertainty in global estimation of carbon stocks is reported here, based on a comparison of selected regional datasets with the global data. As there was no suitable regional dataset available to simultaneously analyse carbon storage in biomass and in soil, regional datasets were cross-checked against relevant layers of the global map. For this purpose, the original Global Biomass Carbon Stock Map (Ruesch & Gibbs, in review) was compared with data for the Amazon (Saatchi *et al.* 2007); and Global Soil Data (IGBP-DIS 2000) was compared with soil and peatland data for Canada (Tarnocai & Lacelle 1996; Tarnocai 2005).

Above ground biomass – Brazilian Amazon

Saatchi *et al.* (2007) estimated carbon stocks in Amazon Basin vegetation by combining data from biomass plots and remote sensing data (incorporating forest characteristics and environmental variables). This approach combines biomass estimates (limited in spatial coverage) with remote sensing for the entire region (limited in capacity for biomass estimation), improving the capacity of the predictive model (Houghton *et al.* 2007). A decision tree approach was used to develop the spatial distribution of Above Ground Biomass (AGB) in 7 distinct biomass classes in lowland old-growth forests with more than 80% accuracy. AGB for other vegetation types such as the woody and herbaceous savannah and secondary forests were directly estimated from the regression analysis of satellite data.

The legend in Figure 5 shows the class ranges applied by regional study authors. Some areas outside of the Amazon basin, that were present in the original dataset are not shown on this map and were not encountered in cross-checking with global data.

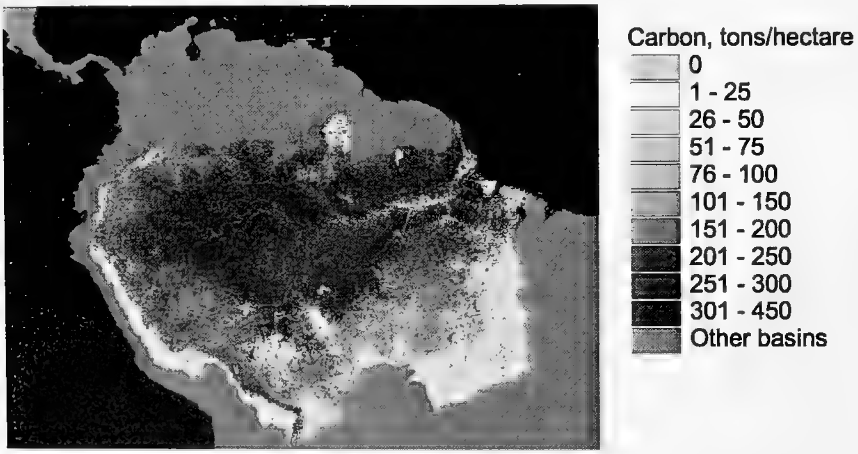

Figure 5: Carbon density in Amazon Basin (based on Saatchi *et al.* 2007; extent and colour scheme are amended).

The equivalent estimate from the global vegetation carbon map is presented in Figure 6.

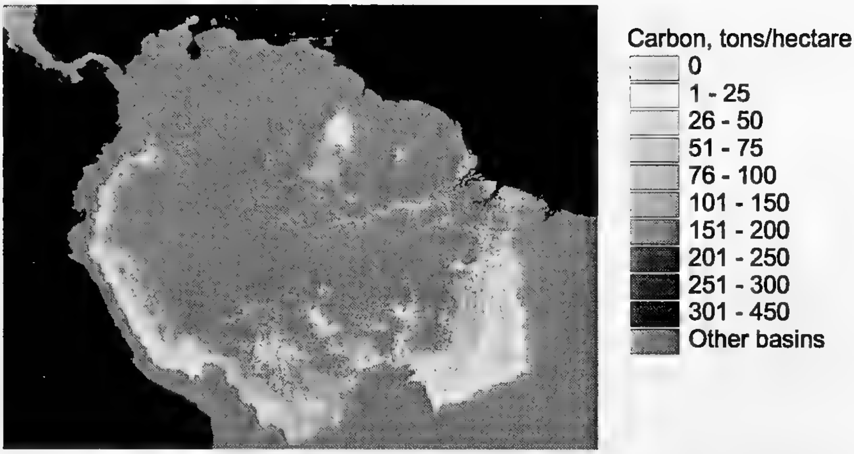

Figure 6: Carbon density in Carbon density in Amazon Basin (based on Ruesch & Gibbs, in review).

It is apparent that the global data did not identify areas with carbon density above 200 tonnes per hectare; in fact approximately 80% of this territory was assigned with a single value (193 t/ha). This corresponds with the conclusion of Saatchi *et al.* (2007) that biome averages are likely to underestimate carbon density due to the lack of dependency between vegetation type and biomes, and could account for a large proportion of the disagreement between the two datasets

Due to the relatively broad range of values (50 t/ha steps) included in separate classes for the regional data sources, there was no straightforward way to calculate the potential carbon stock in the region with any precision. As a simplified assumption, the mid-point value was taken as a basis for calculation of the carbon stock. An estimate of the carbon stock based on regional data for above ground biomass is 125.2 Gigatons against 101.9 Gt from the global dataset. Although the result of this simplified comparison (23% difference) cannot be applied as a precise measurement, it is likely that the global map underestimates the carbon content across the Amazon region.

Considering that the global data is obviously more coarse scale, this is an expected level of variation between the two datasets. The Saatchi *et al.* (2007) data was obtained from both sampling of biomass plots and remote sensing data, and included old growth forest, floodplains, and small coastal patches, using a more recent land cover map at 1km resolution. The Amazon regional estimate also included differentiation of disturbed and non-disturbed forest, whereas the global data necessarily utilised biome averages. Further efforts are required for bringing together outputs of extensive regional studies and for making their results more easily comparable and compatible in respect of methodology and data formats, as it appears that the global data underestimates carbon stocks in high biomass areas.

Soil carbon – Canada

The Soil Organic Carbon Digital Database of Canada (Tarnocai & Lacelle 1996) is based on the Soil Landscapes of Canada (SLC version 2), part of the National Soils Database, and maintained by the Eastern Cereal and Oilseed Research Centre of Agriculture and Agri-Food Canada. The Canadian SOC Database provides estimates for carbon density and total stock for over 10,000 landscape units representing the whole territory of Canada (Figure 7). The equivalent estimate from the global SOC map is presented in Figure 8.

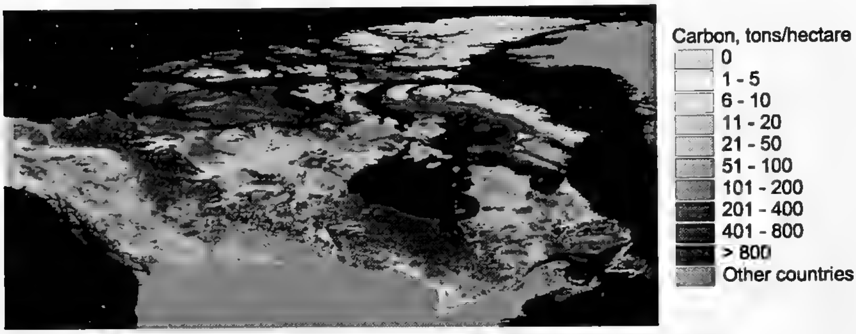

Figure 7: Soil carbon density in Canada (based on Tarnocai, Lacelle, 1996).

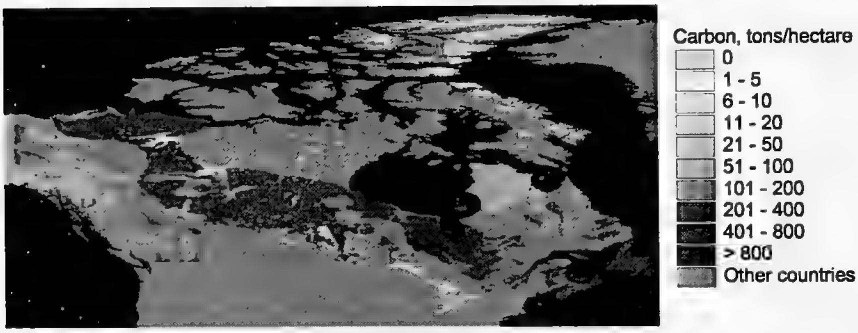

Figure 7: Soil carbon density in Canada (based on IGBP-DIS, 2000).

Comparison of the maps derived from these two datasets reveals substantial differences both in relative abundance of carbon across geographical regions and in absolute values of carbon stock in high density areas. In particular, the national dataset depicts vast territories in the Canadian north and across sub-arctic islands as areas in which soil carbon density exceeds 300 tons/ha, whereas no density above 200 t/ha is identified for these territories from a global dataset. The high carbon "belt" expanding from north-west Canada through its central part towards south-east part seems to be depicted similarly by both datasets, but soil carbon density differs considerably. The maximum density identified by a global dataset is 822 t/ha and only 53,000 km^2 is identified with density above 800 t/ha. In contrast, the regional dataset shows the extent of the territory with carbon density above 800 t/ha to exceed 839,000 km^2 and within this, 115,000 km^2 has an estimated density in excess of 1,600 t/ha.

The estimate of total carbon stock in Canada derived by authors of the regional study (Tarnocai & Lacelle, 1996) is 262.3 Gigatons. This number is 40.6% higher than the relevant number derived from a global dataset (186.6 Gt). This higher level of uncertainty is expected for soil data, which has not been accurately estimated at a global scale (Annex 1), and it is clear that the underestimation of carbon in soil in high density areas is a limitation of this study.

Peat land carbon – Canada

The Peatlands of Canada Digital Database (Tarnocai *et al.* 2005) provides an estimate of the peatland extent of Canada. The map presented in Figure 9 is derived from this regional source and estimates the average density of peat carbon within all landscape units containing peatlands. It should be noted that, due to variations in the ratio of peatland area within landscape units, the densities depicted on the map may represent the total density of soil carbon within a particular unit only when peatland completely covers that particular landscape unit. For units with a lower ratio of peatland area, an additional amount of carbon is expected to be found in non-peatland habitats. An example of continuous territory in which peatlands cover reaches 100% is highlighted on the map (Figure 9).

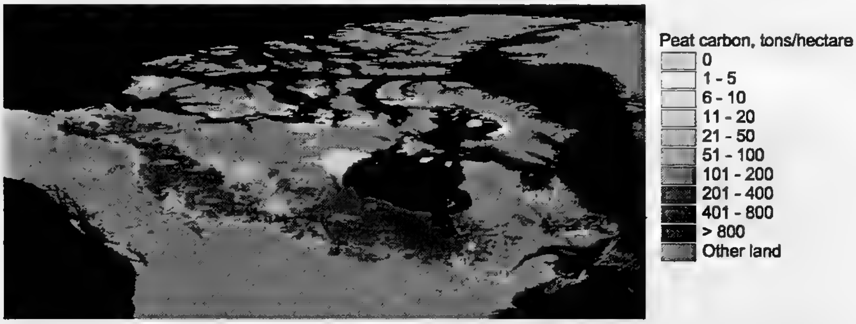

Figure 8: Peat carbon component density in selected Canadian landscapes (based on Tarnocai *et al.* 2005). Red outline indicates the territory with 100% peatland coverage.

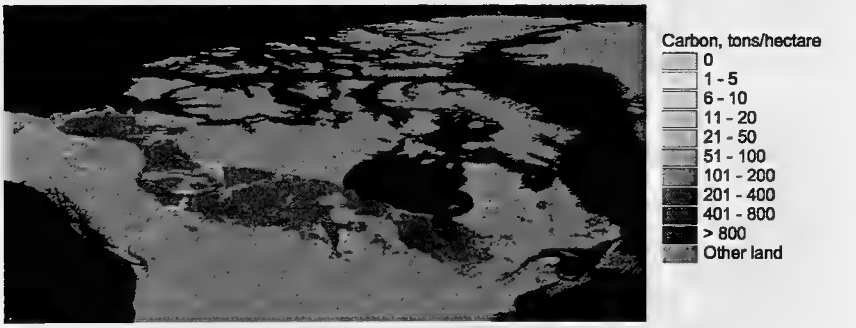

Figure 9: Soil carbon density in Canada (based on IGBP-DIS, 2000).

Comparison of these two datasets reveals substantial differences in SOC estimates for peatland. For the regional dataset, the maximum density of peatland carbon in separate landscape units reaches 3,500 tons/ha, while there are no values higher than

822 tons/ha identified by the global dataset. Within the area represented by continuous peatlands (highlighted on figure 9), estimates available from the regional dataset exceeded ones derived from the global data by 500-1000 tons/ha for almost the entire sample area. An estimate of total soil carbon within all landscape units represented on the map is 110.5 Gt (based on global data) whilst the carbon stock of the peatlands alone is estimated as 144.5 Gt (based on Tarnocai *et al.* 2005) or 30.7% higher. Considering that additional carbon is stored by non-peat soils, and their extent within the study area, its total stock here may be higher by 31 Gt (a modest estimate based on the assumption that 100 tons/ha is the average carbon content for all remaining territory) or up to 56 Gt (based on an extract from a global dataset, where the lowest carbon content area equivalent in size to the "non-peatland" extent of the study area was accounted for).

These preliminary comparisons indicate that there is a high probability that the global map of carbon content under-estimates soil carbon stocks, and further efforts are required to increase reliability of global data. This is particularly true for peatland, as a global estimate for carbon storage in peatland was not available at the time of study. The estimates presented in this report should therefore be considered conservative, and this emphasises need for the development of a more accurate global carbon map, particularly for high carbon soils such as peatland. The spatial distribution of carbon does appear to be estimated with more accuracy on a global scale than total values.

Section 4 - Carbon and conservation priority areas

The concept of identifying 'win-win' areas where ecosystem services and biodiversity overlap is growing in prominence, but is difficult to put into practice due to a lack of quantitative data (Naidoo *et al.* 2008). The data presented here allow identification of areas of high carbon value which are not covered by the current protected areas network on a global level. This provides the opportunity to identify areas for protection or management in selected regions that are not just high in carbon, but also have high biodiversity value; i.e. managing for 'multiple benefits'. This data in particular should provide useful input into the development of climate mitigation policies, such as REDD, although localised pressures such as deforestation pressure and the costs of protection should also be taken into account (Miles & Kapos 2008).

For these analyses, areas of high biodiversity value were identified based on the spatial overlay of the outcomes of multiple conservation priority setting exercises. These layers were: WWF Global 200 terrestrial priority ecoregions (Olson *et al.* 2001), WWF Global 200 freshwater priority ecoregions (Olson *et al.* 2001), amphibian diversity areas (Duellman 1999), Endemic Bird Areas datasets (Stattersfield *et al.* 1998) and Conservation International hotspots (Myers *et al.* 2000). Areas were assigned a value according to the number of 'priority' layers they represented (e.g. areas that were included under all of the conservation priority areas were assigned a 5).

The utility of such mapping is demonstrated here through case studies in Tanzania and Papua New Guinea, which have been chosen as they are the first two countries selected for assistance in developing and implementing REDD strategies by the Norwegian *Fund for Prevention of Deforestation in Developing Countries*, launched at the UN Framework Convention on Climate Change Conference of Parties in Bali, December 2007. They also host very different ecosystems, cultures and political contexts.

The maps for protected area coverage and carbon storage (Figure 10) combined with conservation priorities in Tanzania (Figure 11) suggest that there is a large area of unprotected land that is both high in carbon value and a priority for conservation. This is also the case in Papua New Guinea (Figure 12, Figure 13). It should be noted that priority setting schemes often use the lack of protected areas as an indicator of threat, so high priority areas may appear to be situated outside of the protected area network as an artefact of this. Regardless, such mapping allows for identification of areas that should be focused on in future conservation strategies if the aim is to prevent carbon emissions whilst conserving biodiversity.

These maps serve to demonstrate the relatively simple nature of combining carbon and biodiversity data to set conservation priorities, and should be viewed more as a tool for demonstration in priority setting workshops rather than as a tool for priority-setting at a national level *per se*. Ideally, more accurate and context specific national data should be used for the setting of national priorities, as these might differ from those that would be determined on a global scale, and could correspond to the land use pressures acting in that area.

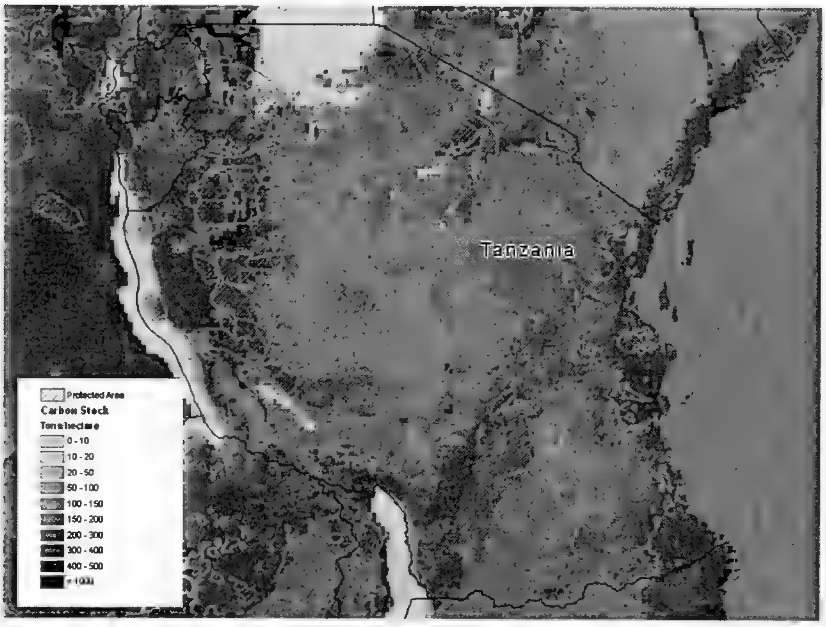

Figure 10: Protected areas and carbon storage, Tanzania. Protected area data includes all sites stored within the WDPA, including forest reserves.

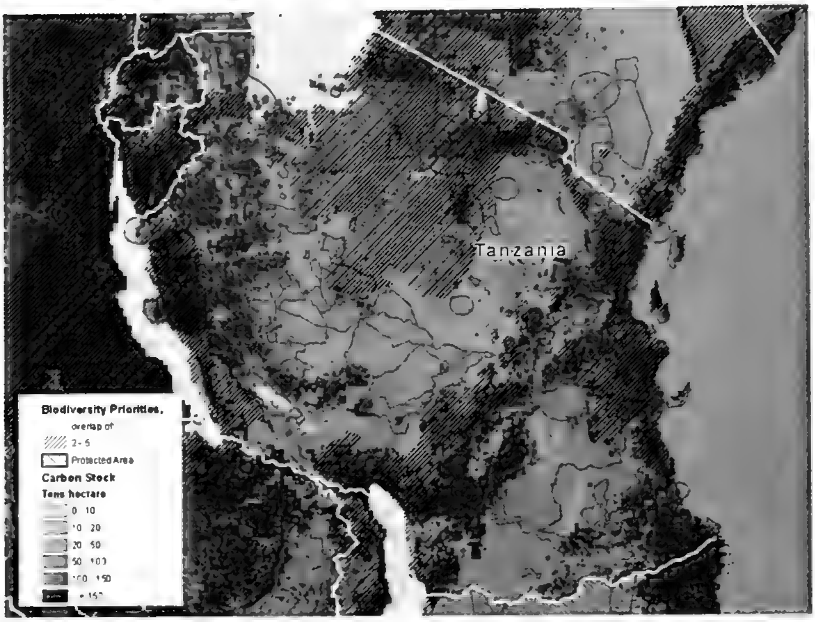

Figure 11: Carbon and biodiversity values, Tanzania.

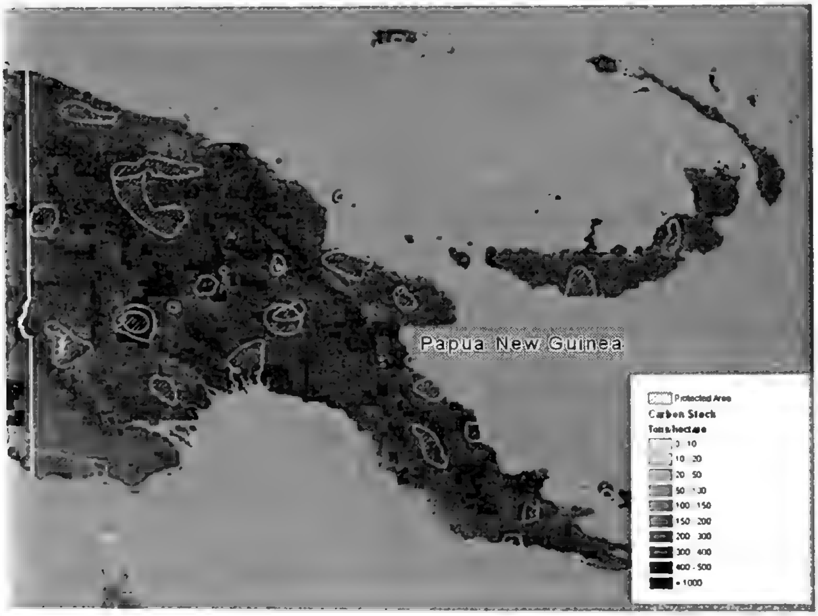

Figure 12: Protected areas and carbon storage, Papua New Guinea

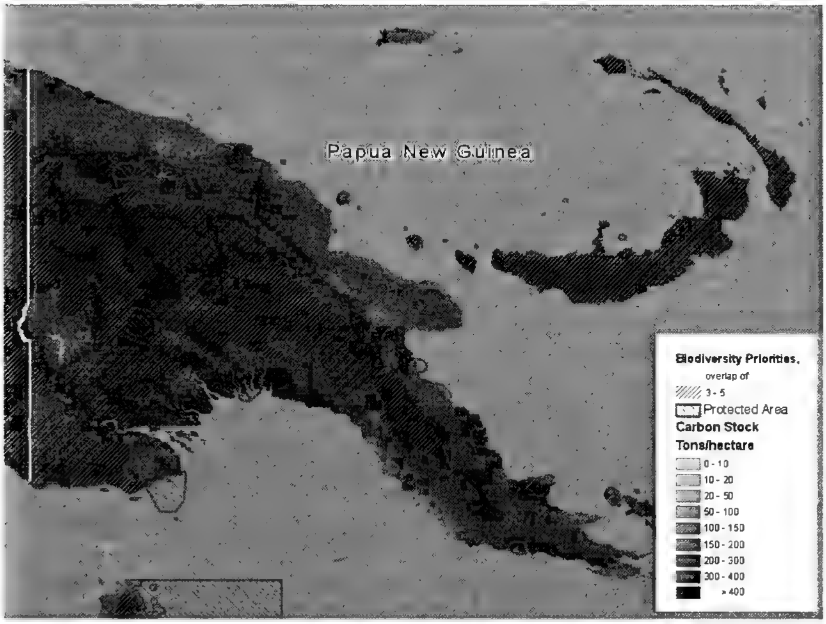

Figure 13: Carbon and biodiversity values, Papua New Guinea. Note that the scale differs from that presented for Tanzania; highlighted areas have a higher carbon content and conservation priority.

Summary

This analysis has brought together global data on carbon storage in vegetation and soil to estimate the amount of carbon stored within the protected area network. The carbon data used was considered to be the best available at the time of study, but is less accurate than regional data and likely underestimates carbon storage in high biomass areas; particularly in soil.

From the information presented in this report, it is clear that protected areas store a large amount of carbon; 312 Gt or 15.2% of the total terrestrial carbon stock. Strengthening of existing protected area networks and the creation of new protected areas could therefore form part of a climate change mitigation strategy. Based on current market prices, the carbon stored in ecosystems would be worth between €1,142 and €7,992 billion, if each tonne was valued in the market. This is the first attempt to quantify one of the benefits of the protected area network that had until recently been largely overlooked. Less than half of the carbon within the protected area network is stored in the more restrictive IUCN protected area management categories I-IV, but more research is required as to the impacts of different management categories on stored carbon

Regions differ in carbon storage totals, densities, and levels of protection. South America has the largest total carbon stores and the highest levels of protection at 25% (not including Greenland). The Pacific has the lowest level of protection with 96% of the carbon unprotected, and is also one of the regions with the highest carbon density, second only to South East Asia. A significant carbon store in the boreal soils and northern latitude forests of Eurasia also has low levels of protection, but is likely subject to less land use pressure than that of the tropics.

The data presented here have also demonstrated the capacity to identify areas that have both high carbon content and high biodiversity value, which could assist in conservation priority setting and the identification of 'multiple benefit' areas for protection or management of carbon for climate mitigation strategies, such as through REDD implementation.

Climate change mitigation policy related to terrestrial carbon storage (namely REDD), has thus far concentrated mostly on forest ecosystems. It should be emphasised that forests are not the only ecosystems that can make a valuable contribution to climate change mitigation; a considerable amount of carbon is also protected in the soil and in the biomass and of other ecosystems. The carbon storage of peatland is a major area that has not been addressed in this report.

In addition, the large majority of global terrestrial carbon stocks are stored outside of the protected area network. Whilst protected areas clearly have a carbon storage benefit and can clearly play a role in reducing emissions from land use change, protected areas are only one option for conserving terrestrial ecosystems. Most carbon is stored outside of the protected area network, and protecting the carbon in one area will be of little consequence if carbon is lost from other land areas. In order to successfully included carbon storage in terrestrial ecosystems as a climate mitigation strategy, other land use options for the protection of carbon should be incorporated, including through CCAs and the development of best practices for land management and land use planning. The implementation of climate policy such as REDD on a large scale is unlikely to be feasible without the support of indigenous and local communities. The official recognition and encouragement of community-based forest management is becoming more widespread, and could become a viable component of, or complement to, protected areas in reducing deforestation

Scope for further research

Data improvements

There are a large number of challenges to estimating carbon storage, and it is likely that improved data for carbon storage in vegetation and soils will become available at global, regional, and national scales. The European Space Agency has recently made available a new global land cover dataset (GlobCover) from 2005 that is considered to be more accurate than the GLC2000. In addition, the FAO has released the Harmonised World Soil Database which provides estimates for soil carbon (FAO/IIASA/ISRIC/ISS-CAS/JRC 2008). Utilising this data, new estimates of calculated carbon stocks using the Intergovernmental Panel on Climate Change (IPCC) Tier-1 approach (IPCC 2006, Gibbs *et al.* 2007) could be generated.

In addition, it is clear that the carbon storage estimates in soils likely underestimate carbon stocks in high density areas. This is particularly the case for peatland, as there is currently no dataset available for peat distribution and depth globally, but it is a significant carbon store. Quantifying this peatland carbon store, and the level of emissions from peatland loss and degradation, would be a valuable contribution to climate policy development

We have also identified that maps of carbon storage within marine and coastal ecosystems are not readily available. This is a potential important area for further research and collaboration building, including with respect to valuation of marine protected areas, but also for the wider issues of carbon storage within marine ecosystems, and the potential impact of human activities with the aim of climate mitigation.

Next steps

Following estimates of the amount of carbon stored in protected areas, the next logical step is to provide some estimate of the efficacy of protected areas in reducing carbon emissions. UNEP-WCMC, in collaboration with The Nature Conservancy and University of South Dakota has provided an estimate of emissions from deforestation within protected areas. The data presented here also provide the basis for mapping high carbon and high biodiversity areas at the scale of the entire tropical biome. This could also include identification of areas under deforestation and degradation pressures, and provide guidance on new methods for doing gap analysis for protected areas with carbon as an input.

Although this report is mainly focused on protected areas, this is only a small area for research in the broader view of carbon storage and biodiversity. A holistic view of the carbon storage implications of improved forest management, and sustainable use of forest resources is an important area for future research; taking into account issues such as certification schemes, leakage and local livelihoods. Information on how IUCN management categories relate to levels of degradation, and the implications for carbon storage, is also required. The impacts of governance on carbon storage in particular would be a useful input to this discussion.

Further research is also required into the carbon storage of non-forest ecosystems and soils. The introduction of REDD could have significant implications for the conservation of these areas, which can have high carbon and biodiversity benefit. This could be explored through the removal of the forest carbon layer from the carbon map, identifying high carbon areas with low forest cover and high biodiversity benefit; analyses which would also be useful for the biofuel debate. The issue of the potential for REDD to conserve forest at the expense of other ecosystems, and how non-forest ecosystems can be incorporated into REDD mechanisms is one requiring further attention.

Indeed, REDD will have implications for biodiversity conservation on all scale, and an analysis of the potential biodiversity impacts of the various proposals for REDD would be useful input to current discussions, which could include discussion of the potential place for protected areas within REDD.

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Annex 1 – Carbon storage in ecosystems data review

A comprehensive literature review of the available data sources for terrestrial carbon storage was undertaken in order to source the most accurate data for global and regional carbon stocks. This section identifies the available carbon storage maps, and provides a summary of the data chosen to produce the global carbon map.

Carbon in terrestrial ecosystems

The IPCC guidelines for national level estimation of carbon stocks identify three broad carbon pools: biomass (above and below ground living vegetation), dead organic matter (DOM), and soil organic carbon (SOC) (IPCC 2006). Carbon stocks are generally measured using inventories over small spatial scales, with allometric or statistical relationships used to determine biomass and carbon stocks over a given area. These can be extrapolated to larger scales with average carbon densities applied according to ecosystem type. Other approaches involve ecosystem modelling, and either of these mapping approaches can be used in combination with remote sensing techniques. Soil stock estimates require knowledge of the organic carbon content of soil profiles and the spatial distribution of the various soil or vegetation types; and can be estimated to varying depths.

Carbon stock estimates differ according to the methodology selected, the comprehensiveness of the inventories, ecosystem model parameters selected, allometric and statistical equations used, and the land cover maps used for spatial representation. One of the major issues with global carbon stock estimation is the existence of a wide range of national and regional estimates that vary in these methodological factors. On the other hand, global datasets may lack accuracy because they do not capture variations in vegetation cover over relatively small scales (Potter 1999).

Global estimates

There are currently a small number of readily available global carbon storage datasets, each providing different estimates and accounting for different carbon pools. Due to differences in national accounting, coarse scale but globally consistent carbon maps necessarily use the 'Tier 1' (broad-brush) IPCC approach, extrapolating carbon densities for vegetation types to global averages on a biome scale. Most estimates are based upon biome carbon averages that are modified in ways not often transparent (Gibbs *et al.* 2007); again indicative of the methodological problems of standardising carbon accounting over a large scale. Until recently, the most widely used reference data for carbon storage in vegetation was from Olson *et al.* (1983), which was based on over 20 years of field investigations and an analysis of published literature (Olson *et al.* 1985). Similarly, soil carbon profiles have often involved the use of carbon density averages from original studies (Zinke *et al.* 1984; Batjes 1996; Post *et al.* 1982) to allocate values to soil types in the FAO soil map of the world.

Data for carbon storage in vegetation

The estimates available to date (Table 5) are derived from either biome averages based on site measurement data, or the use of satellite observations in combination with ecosystem models. A more in-depth look at the three datasets is reported below.

Table 5: Global datasets considered– carbon stored in vegetation

Carbon pools	Methods	Source
Above and below ground biomass,	NASA-CASA ecosystem model driven by AVHRR. Average carbon (g/m2) multiplied by area for each vegetation type to estimate total carbon	Potter (1999)
Above and below ground biomass,	Update of Olson *et al.* (1983) vegetation data onto the Global Land Cover Characteristics Database of 1998	PAGE (WRI 2000)
Above and below ground biomass	IPCC Tier 1 approach. Above ground biomass carbon stock estimates obtained through the application of biome averages to a recent land cover map (GLC2000).	SAGE (Ruesch & Gibbs, in review)

Potter (1999) dataset

A global dataset for above-ground biomass has been compiled by Potter (1999), using an ecosystem model driven by satellite observations, which estimates parameters such as carbon fixation, plant biomass, litter fall, and nutrient exchange on a daily or seasonal basis. Satellite ‘greenness’ data from the Advanced Very High Resolution Radiometer (AVHRR) fed into the NASA-CASA ecosystem model.

One advantage of the ecosystem modelling technique is that it can simulate regional variability in carbon stores (Potter 1999, Cao & Woodward 1998, Ni 2001), long recognised as an issue in biomass estimation across large forested areas (IGBP 1998). Similarly, it can separately model the biomass in wood, leaves, and roots. However, the complexities of ecosystem models mean that they are often more accurate over regional than global scales (Le Toan *et al.* 2004). Indeed, whilst modelling does avoid limitations in forest biomass inventories; incomplete understanding of ecosystem processes, combined with uncertainties in key parameter estimates, severely limit the accuracy of the approach (Tian *et al.* 2000; Malhi *et al.* 2006). Additionally, it has been suggested that current optical satellite sensors, such as AVHRR, cannot be used to estimate carbon stocks with any degree of certainty (Thenkabail *et al.* 2004 in Gibbs *et al.* 2007; GCP; Houghton, 2005) and cannot accurately estimate biomass in closed canopy forests (Houghton *et al.* 2001) or other high biomass areas (Lefsky 2002; Le Toan *et al.* 2004). The output in this case was also based on a now-outdated 1990 land use map.

PAGE (2000) estimate

The Olson *et al.* (1983) map of carbon storage in vegetation, widely considered to be the most consistent on a global scale, was the basis for the global carbon estimate incorporated into the Pilot Analysis of Global Ecosystems (PAGE; WRI 2000). The data were reapplied to the Global Land Cover Characteristics Database of 1998, and the low and high estimates used in modelling (WRI 2000). The spatial data for vegetation from the high range Olson *et al.* (1983) estimates gave a 10 km resolution map of carbon storage in terrestrial ecosystems.

There are a number of issues with this study. The spatial estimation of carbon stocks used a very broad classification of ecosystem types (forest, grassland, etc) by mid, high and low latitudinal bands, instead of more specific vegetation types. The Olson *et al.* (1983) data also relies on direct measurement of biomass, and it had been suggested that this methodology can be biased towards high biomass areas unless statistically consistent inventory methods are used (Fang & Wang 2001, Fang *et al.* 2006).

SAGE (2008) estimate

This estimate calculated carbon stocks using the Intergovernmental Panel on Climate Change (IPCC) Tier-1 approach (IPCC 2006, Gibbs *et al.* 2007). Above-ground biomass carbon stock estimates for each country were obtained through the application of biome averages to a recent land cover map (Bartholome & Belward 2005). Below-ground biomass was similarly estimated using the IPCC root-to-shoot ratios by vegetation type (IPCC 2006). Biomass values reported by IPCC (2006) were converted to carbon stocks through application of the IPCC standard 0.47 carbon fraction. Time-averaged carbon stocks for cropping systems were estimated by assuming linear growth rates, and using half the peak carbon stock (van Noordwijk *et al.* 1997). This data splits carbon estimates into more vegetation classes than the Olson data, allowing for more realistic variation than in the PAGE estimate. For example, Olson *et al.* (1983) used a single value for all tropical forest (Gibbs *et al.* 2007). The data used in this estimate varies by continent, ecoregion, and vegetation type, for both above and below-ground biomass (H. Gibbs pers comm.).

There are some drawbacks to his approach. As with all studies using biome averages, there is no variation within vegetation classes, and therefore the abrupt changes between e.g. grassland and shrubland at the boundaries are not realistic. More detailed regional studies have demonstrated significant variation in biomass on much smaller spatial scales (Saatchi *et al.* 2007, Malhi *et al.* 2006). Regardless, these data are the most recent available for global vegetation carbon, and as the only global estimates to follow IPCC guidelines they appear to be the most accurate and the most relevant to REDD negotiations. The data was also readily available for use following communication with the author, and was therefore selected for use in this study

Other global data sources (Luyssaert *et al.* 2007, Bolin & Sukumar 2000, Kauppi 2003, Dixon *et al.* 1994, Cao & Woodward 1998) exist, but are either outdated or focused only on forest ecosystems. The Global Carbon Project aims to provide detailed data sources for accurate accounting of carbon storage, but these data are not yet available. Long wavelength SAR and Vegetation Canopy Lidar (VCL) have been identified as potential tools for the production of a global estimate (Drake *et al.* 2002) VCL shows potential for obtaining biomass estimates from space and has the ability to measure forest height, and SAR should have the capacity to produce global biomass maps up to values of 100 t/ha. Global biomass estimations may also be improved using imagery from the Advanced Land Observing Satellite (ALOS), a Japanese satellite featuring PALSAR (an L- band frequency high performance SAR satellite) and ideal for biomass estimation (JAXA EORC 2008). The satellite covers each of the earth's land masses three times a year, and has the capacity to produce the first systematic global observations for biomass map generation (Kellendorfer *et al.* 2008)

Data for carbon storage in soil

The importance of carbon storage in soil is becoming increasingly recognised following observations that the soil carbon store contains three times as much as that of vegetation (Smith 2007, IPCC 2000); with storage in peat soil contributing a significant amount towards this total (Mitra *et al.* 2005, Hoojier *et al.* 2006, Botch *et al.* 1995).

Current global estimates are based upon the small number of available estimates of carbon in various soil profiles (Eswarran *et al.* 1993, Batjes 1996, Zinke *et al.* 1984) or vegetation units/climatic zones (Post *et al.* 1982). Large scale estimates of soil carbon are still limited by a lack of knowledge of different soils in terms of spatial distribution and land use (Batjes 1996). There is also some debate over the depth to which carbon storage in soils should be measured for carbon accounting. The default value specified in the IPCC guidelines is 0-30cm (IPCC 2006), but the vertical distribution of SOC is poorly understood (Jobbagy & Jackson 2000), as is its vulnerability to disturbance at different depths and by different processes. It could be considered that the IPCC guidelines are conservative, and consequently most global estimates of SOC are to a depth of 1m (Mikhailova & Post 2006).

Potter & Klooster (1997) and WRI (2000) have produced global carbon maps based on data from Post *et al.* (1982) and Batjes (1996) respectively. Jobbagy & Jackson (2000), Puzachenko *et al.* (2006), and The United States Department of Agriculture - Natural Resources Conservation Service (USDA-NRCS) have similarly produced global SOC maps (1m depth). Various other studies have modelled the potential impact of climate change on soil carbon pools (Jones *et al.* 2005), but do not include data on soil profiles and are aimed at more theoretical projections of future carbon stores than quantification of current carbon stock. Work is currently in progress to create improved an improved soil map through the SOTER project. Whilst SOTER maps are already available for Eurasia, parts of Africa, and South America, a global dataset has not yet been developed (Dobos *et al.* 2005). The Global Environment Facility Soil Organic Carbon Modelling System (GEFSOC) project (Easter *et al.* 2007) has produced some regional SOC estimates but is not currently available for global estimates.

A SOC dataset published by the International Geosphere-Biosphere Programme in 1998 (IGBP-DIS 2000) estimates organic carbon density to 1 m depth, at 5 minute resolution. This dataset is based on the FAO Soil Map of the World and ISRIC pedon data and was selected for use in this study as a readily available data source that is considered reliable on a global scale (downloaded from http://daac.ornl.gov/). The 1m depth is appropriate for this analysis, but likely underestimates carbon emissions from deeper peatland systems. No global dataset of peat depth is yet available.

Regional estimates

There are a large number of national and regional estimates of carbon storage in terrestrial ecosystems (Table 6). Such estimates tend to be more accurate because they are extrapolated over smaller scales, rely on better inventory data, and can account for spatial variation in more detail.

Table 6: Selected regional studies considered for use due to quality or availability of data.

Region	Ecosystem	Carbon pool	Availability	Reference
Amazon Basin	All	Vegetation biomass	Readily available	Saatchi *et al.* (2007)
Amazon Basin	Old growth forest	Vegetation biomass DOM	Unknown	Malhi *et al.* (2006)
Brazilian Amazon	All	SOC	Readily downloadable	Cerri *et al.* (2007)
Tropical Africa	Forest	Woody Biomass	Available	Gibbs *et al.* (2007)
Southern Africa	Forest	SOC	Available	Zinke *et al.* (2002)
Tropical South East Asia	Forest	Vegetation biomass	Available	Brown *et al.* (2001) Gibbs *et al.* (2007a)
Tropical SE Asia	Forest	Vegetation biomass & SOC	Unknown	Brown *et al.* (1993)
Northern Latitude	Forest	All	Do not appear to be spatially explicit	Goodale *et al.* (2002)
Northern Latitude	Forest	Above ground biomass	Unknown	Myeni *et al.* (2001)
USA	All	All	Unknown	Potter (2006)
USA	All	SOC (2m depth)	Unknown	Guo *et al.* (2006)
Canada	All	SOC	Available	Tanocai & Lacelle (1996)
Canada	Peatland	SOC	Available	Tarnocai & Lacelle
Russia	All	All	Unknown. Does not appear spatially explicit	Nilsson *et al.* (2000)
Russia	All	SOC	Unknown	Rohzkov *et al.* (1996)
Russia	Forest	Forest stand	(http://daac.ornl.gov/RLC/guides/RLC_forest_carbon_73.html)	Stone *et* al (2003)
Europe	Forest	Vegetation biomass	Map produced would require author contact	Nabuurs & Schelhaas (2003)
Europe	All	SOC	Available	Jones *et al.* 2005

Tropical estimates

Given the importance of tropical forest deforestation in carbon fluxes, much of the national and regional analysis has focused upon the tropical forest ecosystems (Achard 2004, DeFries *et al.* 2002, Houghton 2003). Many studies have focused specifically on tropical forest within Latin America (Brown & Lugo 1992, Chave *et al.* 2003, Baker *et al.* 2004, Malhi *et al.* 2006, Saatchi *et al.* 2007) with wide ranging results in carbon storage and distribution estimates (Houghton *et al.* 2003). Interestingly, the Olson *et al.* (1983) data and Potter (1999) were shown to underestimate biomass in the Amazon, and lack accurate spatial representation of biomass densities respectively. Other studies have focused upon tropical Asia (Brown *et al.* 1993; Chabra *et al.* 2002) including one comprehensive study by Gibbs & Brown (2007a), updating estimates based on GIS processing of FAO georeferenced data onto the GLC 2000 land cover map. Relatively few carbon stock estimates have been carried out in Africa, the most comprehensive of which was provided by Gaston *et al.* (1998) and updated by Gibbs & Brown (2007b).

Saatchi *et al.* (2007) estimated carbon stocks in Amazon Basin vegetation by combining data from biomass plots and remote sensing data (incorporating forest characteristics and environmental variables). This approach combines biomass estimates (limited in spatial coverage) with remote sensing for the entire region (limited in capacity for biomass estimation), improving the capacity of the predictive model (Houghton *et al.* 2007). In contrast with other studies of the Amazon, biomass values were calculated according to all vegetation types present, such as old growth forest, floodplains, and small coastal patches. The Saatchi *et al.* (2007) estimate improved the model by combining optical data with radar data (Houghton *et al.* 2007). This dataset was considered to be one of the most reliable for the tropical region, accounting for all vegetation types in a region for which the need to protect forest from deforestation has been highlighted. The dataset was also readily available, and was therefore appropriate for use in this study.

Despite the fact that there is a substantial carbon store in the soils of tropical forest (41% of the total tropical carbon store according to Brown & Lugo (1982)), very few studies have estimated SOC for tropical regions. A number of estimates do exist for parts of Africa (Zinke *et al.* 2002, Batjes 2004, Milne *et al.* 2006) and Brazil (Batjes & Dijkshoorn 1999, Batjes 2005, Bernoux 2002, Moraes *et al.* 1995, Cerri *et al.* 2007) but do not correspond to the geographical area covered by Saatchi *et al.* (2007) and were therefore not selected for use in this study.

Northern Latitude estimates

Although a large amount of detailed inventory data is available for northern latitude forests (Dong *et al.* 2003), there are many areas in which inventory data is patchy and not adequately georeferenced (Houghton *et al.* 2001). Biomass of ecosystems other than forest is also less well known, and accurate soil carbon data for boreal ecosystems is lacking.

There are a number of estimates of the total carbon storage in northern latitude forest (Goodale *et al.* 2002, Myeni *et al.* 2001, Liski *et al.* 2003), with other studies focusing on Russia (Shivdenko & Nilsson 2003, Alexeyev *et al.* 1995, Houghton *et al.* 2007, Stone *et al.* 2003), China (Wang *et al.* 2007, Piao *et al.* 2005), North America (Birdsey 1992, Zhang & Kondragunta 2006) and Europe (Kauppi *et al.* 1992, Nabuurs, &. Schelhaas 2003). There are in addition some estimates of the entire carbon store for USA (Potter 2006) and Russia (Nilsson *et al.* 2000). A recent study into the North American carbon budget (CCSP 2007) has estimated the terrestrial carbon stocks (biomass, litter and soil) across ecosystems, biomes, and countries (USA, Canada and Mexico) in North America but does not provide spatially explicit data. Many of these studies are based on old inventory data, and do not appear to have produced readily available spatially explicit estimates. In addition, the carbon storage in northern latitude soils is receiving increased attention due to estimates that they account for approximately 45% of the entire terrestrial carbon store (Post *et al.* 1982, Gower *et al.* 2001). The decision was therefore taken to identify a SOC dataset for northern latitudes, as there were few accurate biomass datasets obviously available.

Datasets for SOC were identified in China (Xie *et al.* 2007, Yu *et al.* 2007), Russia (Orlov *et al.* 1996, Rozhkov *et al.* 1996, Stolbovi & Vladimir 2004) and Europe (Jones *et al.* 2005, Dobos *et al.* 2005). In selecting a SOC dataset, however, it seemed appropriate to choose an area of high carbon storage, incorporating peatlands, such as the boreal area of Russia and North America. The Soil Organic Database of Canada is considered to be one of the most accurate data sets available for soil carbon content (Kuhry *et al.* 2002) and a map of soil organic carbon in Canada (Tarnocai & Lacelle, 1996), was therefore selected for use in this study. Peatland soils store a large amount of carbon (Mistra *et al.* 2005, Hoojier *et al.* 2006), and Canada has the largest area of peatland soil in the world. In addition, a recent map of carbon in peat soils in Canada has been produced (Tarnocai 2005), providing a comprehensive spatially explicit and detailed carbon storage estimate. This appears to be the most comprehensive SOC data available across a large and high carbon content region to date. The CARBO-North Project, due for completion in 2010, is likely to be a useful information source in the future.

Summary of global and regional estimates

It is clear that there are a large number of datasets available, providing carbon estimates for a variety of ecosystems, regions, and carbon pools. The majority of studies focus upon forest biomass and soil carbon, and carbon storage in other ecosystem types is less well known. The methods for estimating carbon storage vary widely, and no single method is considered highly accurate. The use of improved technology for biomass estimation and databases for soil carbon estimation is likely to improve the accuracy of carbon estimates in coming years.

On a global scale, the use of biome averages and the increased uncertainty of carbon storage estimates for higher biomass classes tend to lead to a less accurate picture for individual regions than equivalent regional maps. Whilst much variability can be found at a regional scale, these biome-based estimates do provide a consistent indicative picture of the pattern of carbon storage. From the global datasets assessed here, the SAGE estimates using IPCC methodologies (Reusch & Gibbs, in review, Gibbs *et al.* 2007) have been selected for use. The data are globally consistent and split carbon density averages more finely into more vegetation classes than the data provided by Olson *et al.* (1983).

It is also important to quantify soil carbon storage, as research has suggested that soil carbon accounted for 28% of net loss from land use change in the period 1850-1990

(Houghton 2005), and failure to include soil carbon would underestimate carbon storage at northern latitudes, which is estimated to contribute 53% of the total carbon store (WRI 2000). The IGBP-DIS (2000) soil data was selected for use as a readily available source to 1m depth. The only global litter carbon estimate was produced through ecosystem modelling as part of the Potter (1999) study, and was not considered appropriate for this study.

At a regional scale, there is a much wider range of data available for carbon storage. Datasets for biomass in the Amazon Basin (Saatchi *et al.* 2007) and SOC in Canada (Tarncoi & Lacelle 1996) were selected to provide context of the accuracy of the global data for both biomass and soil in two areas of high carbon storage. Both datasets are considered to be the most accurate available both for the regions and carbon pools that they provide estimates for, as although other datasets for the Amazon could be considered equally accurate, they do not provide estimates for all vegetation classes.

Carbon in marine ecosystems

From the review above it is clear that many studies have focused on the estimation of carbon storage within terrestrial ecosystems. Comparatively, knowledge of carbon storage within marine environments is limited, and no equivalent literature exists. For this reason, we were not able to include marine ecosystems in this analysis. This would appear to be a significant knowledge gap, considering that the total amount of carbon stored in the ocean is 50 times that of the atmosphere (IPCC 2001). Despite this, there is some information available relating to carbon storage in specific marine ecosystems, such as mangroves and coral reefs; and marine organisms.

Mangroves

Mangrove forests are highly productive (Bouillon *et al.* 2008), and their ability to store organic carbon is extremely significant, despite accounting for less than 1% of total forest cover on earth (Ayukai 1998). The total global storage of carbon in mangroves has been estimated at 4 PgC (Twilley *et al.* 1992). Various techniques can be used to estimate the standing biomass of mangrove forests, most commonly satellite imagery combined with field data (Mann 2000); a methodology used for biomass estimation in Florida (Simard *et al.* 2006) and South Africa (Steinke *et al.* 1995). Other studies have estimated carbon storage in mangrove forests of Australia (Ayukai 1998, Matsui 1998), Brazil (Soares and Schaeffer-Novelli 2005), and the Dominican Republic (Sherman *et al.* 2003) through inventories, aerial photography and statistical relationships; producing varying results. Of these, only the estimate by Steinke et al (1995) considered below ground biomass. Also important is the carbon stored in the soils of mangrove swamps and sand marshes, which has been estimated on a global scale (Chmuera *et al.* 2003). As with terrestrial forest biomass, remote sensing appears to lack accuracy in estimation of carbon stored in high biomass areas (Lucas *et al.* 2007, Mougin *et al.* 1999, Simard *et al.* 2006; cited in Proisy *et al.* 2007).

Coral Reefs

Corals store carbon in their calcium carbonate skeletons. However, due to the production of CO_2 in the calcification process, it has been suggested that coral reefs generally act as alkalinity sinks and CO_2 releasing sites (Suzuki 2003). Unfortunately there is little data involving carbon biomass storage in coral reefs and this is a significant gap in our knowledge. Of the few studies that do exist, they are focused on the calcification and productivity of the coral (Andréfouët & Payri 2001, Field *et al.* 1998)

Plankton

Estimation of carbon storage in the oceans is constrained by the difficulties of measuring biomass of marine organisms such as phytoplankton and zooplankton, which varies on termporal, horizontal, and vertical scales. A number of studies (Kopczyńska & Fiala 2003, Batten *et al.* 1999, Behrenfeld & Boss 2006) have attempted to measure biomass across small scales using plankton recorders, biochemical analyses, and optical indices. In addition, several studies (Goes *et al.* 2004, Smith *et al.* 1998, Fiala *et al.* 1998; Brock & McClain 1992) have used satellite ocean colour remote sensing analysis in order to determine the level of interannual variability of plankton biomass, which is strongly influenced by meteorological and oceanographic conditions (Goes *et al.* 2004). However, there is little data relating to the amount of carbon biomass of marine plankton for a specific area, largely due to the aforementioned spatial and temporal variability. Strong blooms may develop during certain periods during the year, determined by both global and local factors (Twilley *et al.* 1992).

Macrophytes / Microphytes

Seagrasses and seaweeds have high rates of primary production (Alongi, 1997). Remote sensing has been used to estimate seagrass biomass in a number of areas (Armstrong 1993, Mumby *et al.* 1997), and similar remote sensing technology has been used for estimating biomass in submerged Kelp (large seaweeds; Simms 2003). Seagrass meadows have been estimated to account for 15% of the total carbon storage in marine ecosystems (Duarte *et al.* 2004). In addition, the potential contribution of microscopic algae to marine carbon storage should not be overlooked, and their biomass has been measured thorough spectrophotometry in the South West Pacific (Garrigue 1998). The organic metabolism in coastal regions is greatly impacted (particularly in estuaries) by climate variability and anthropogenic activity (Smith & Hollibaugh, 1993).

Duarte *et al* (2004) have constructed a carbon budget model for the coastal ocean in order to examine the organic export from vegetated habitats to the open ocean together with the possible impact of their destruction. Their results estimated an organic carbon burial in the coastal ocean at 210-244 Tg Cy^{-1}, which was found to be almost double the value of the previous assessment of global carbon budget (IPCC 2001; cited in Duarte *et al.* 2004). For example, the Hinchinbrook Channel is known to be net autotrophic, meaning that the respired and buried organic carbon is less than the fixed organic carbon present (Ayukai 1998). In general, marine vegetation is shown to export a significant amount of organic carbon to adjacent ecosystems and also store a vast amount in the sediments (Jennerjahn & Ittekkot 2002, Chmura *et al.* 2003, Brevik & Homburg, 2004; cited in Duarte *et al.* 2004).

Carbon Capture and Storage

Carbon sequestration in marine environments has been suggested as a climate change mitigation option (Preuss 2001). However, there remains a serious question towards the health of marine ecosystems if the sea is continually used to sequester carbon. The

Department of Energy (DOE 1999) claim that there is too little information to estimate the amount of carbon that can be sequestered without harming marine ecosystems, both on a short-term and long-term basis. It is vital therefore to gain further information on the amount of carbon biomass present in marine ecosystems, in order to demonstrate their vulnerability and their essential role in carbon storage.

Summary

There is a current lack of data for carbon storage within marine and coastal ecosystems beyond the site level, and it is therefore difficult to gain a general picture of the carbon storage capacity. For example, comparisons between biomass data from different mangrove areas are difficult as the biomass is a function of the history and structural variability (Soares & Schaeffer-Novelli, 2005). As with the terrestrial carbon data, there are questions over the accuracy of comparing biomass measurements estimated through different methods, yet there is no data for and regional estimates, even on a coarse scale. The difficulty of quantitative biomass measurements in the coastal ocean (Smith & Hollibaugh 1993) has resulted in the marine environment being a significant gap in the carbon budget (Bouillon *et al.* 2008), in particular for seagrasses and coral reefs. This is of particular importance when considering the high carbon storage estimated in the coastal ocean (Duarte *et al.* 2004), which is highly vulnerable to climate change through increasing temperatures and sea level rise.

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Annex 2 – Valuing carbon storage within ecosystems

The value of carbon stored in terrestrial ecosystems

Carbon emissions from deforestation account for an estimated 20% of emissions (IPCC 2007); second only to that produced by fossil fuel combustion. Despite this, projects relating to land use and forestry (LULUCF) accounted for only 1% of an international carbon market worth $30 billion (€23 billion) in 2006 (Capoor & Ambrosi 2007). The value of the market has risen to US$64 billion (€47 billion) in 2007 (Capoor & Ambrosi 2008). Given the contribution of deforestation and land degradation to carbon emissions, it is likely that the value of carbon storage in ecosystems will increase, particularly as the overall carbon market is projected to increase in value (Hasselknippe & Roine 2007, Ebeling & Yasue 2008). Indeed, there have been estimates from some reviewers that over $43 billion could be made available to developing countries if REDD projects are formalized (Roe *et al.* 2007), and that forested areas could be worth $200-10,000 per hectare depending upon a number of factors such as carbon content and project type (Peskett 2007).

The range of forest carbon values reported above (Peskett 2007) highlights the uncertainty in predicting a market value for stored carbon in a relatively volatile market. The top end value corresponds to carbon trading for EUAs (European emission allowances) on the biggest market, the EU Emissions Trading Scheme (EU ETS), and would undoubtedly be an overestimate (Smith *et al.* 2000). There are also a number of issues surrounding the permanence of carbon stored in ecosystems, which lead to further uncertainties in the market value and place its value at a lower level to the broader market e.g. for renewable energy schemes. In addition, carbon related to land use is mostly traded though Verified Emission Reductions (VERs) on the lower value Voluntary Market rather than through Certified Emission Reductions (CERs) under the higher value Clean Development Mechanism (CDM); and the lack of Land use, land use change and forestry (LULUCF) projects under the CDM makes the value of a formalized market for carbon stored in ecosystems difficult to predict. However, a large portion of the offsets in the growing voluntary sector retail market are currently sourced through LULUCF mechanisms (Hamilton *et al.* 2008), and whilst carbon offsetting through afforestation is often criticised, it is likely that an avoided emissions project such as avoided deforestation would be competitive in the market due to the perceived added benefits for biodiversity conservation (Chomitz *et al.* 2006, Stern 2007).

The price of stored carbon will clearly be variable, and determined by a number of factors. Any single value placed on carbon stored in ecosystems should therefore be considered very speculative, particularly given that the scale of the market is yet to be determined through, for example, REDD implementation. Despite this, it is possible to gain some perspective of the potential value of carbon stored in ecosystems through by assigning an indicative value based of the range of values observed in current carbon markets and forestry projects.

Carbon markets

Markets in which carbon is traded can be broadly split into regulated markets and voluntary markets. They are reported here to provide context for this assessment of where carbon stored in ecosystems would likely sit in the overall carbon market. The volume and value of carbon trading is clearly highest in regulatory markets (Table 7), although the voluntary market is increasing rapidly and is indicative of demand for projects not included in the UNFCCC. The regulatory market consists of the EU ETS, the CDM and Joint Implementation (JI) markets, and the New South Wales market. The voluntary market can be split into the Chicago Climate Exchange (CCX) and 'over the counter trading' (OTC). The CCX differs from the OTC market in that it is a formal exchange, a legally binding 'cap and trade' system that members sign up to voluntarily; whereas OTC is not driven by an emissions cap and mostly involves project-based transactions generating VERs.

Table 7. Carbon market Transactions and Values, 2006 and 2007. Source: Ecosystem Marketplace, New Carbon Finance, World Bank. Reported in Hamilton *et al.* 2008

Markets	Volume (MtCO2e)		Value (US$million)	
	2006	2007	2006	2007
Voluntary OTC Market	14.3	42.1	58.5	258.4
CCX	10.3	22.9	38.3	72.4
Total Voluntary Markets	**24.6**	**65.0**	**96.7**	**330.8**
EU ETS	1,1044	2,061	24,436	50,097
Primary CDM	537	551	6,887	6,887
Secondary CDM	25	240	8,384	8,384
Joint Implementation	16	41	141	495
New South Wales	20	25	225	224
Total Regulated Markets	**1,702**	**2,918**	**40,072**	**66,087**
Total Global Market	**1,727**	**2,983**	**40,169**	**66,417**

EU ETS

The largest carbon market is the EU ETS, both in terms of volume traded and value of transactions. Forestry credits are not currently eligible for trading on the EU ETS, and its value is therefore not representative of carbon stored in ecosystems (Tollefson 2008). However, it should still be considered because it sends price signals to the rest of the market. The average price for carbon traded on the EU ETS in 2006 was $20 per tCO2e (Capoor & Ambrosi 2007), a price that has risen to €20-25 for EUAs in 2007 (Capoor & Ambrosi 2008). Values for EUAs on the ECX were reported at carbonfinanceonline.com to be €24.66 (from 10th April – 15th May 2008 for Dec08 delivery), with €24.91 reported at carbonpositive.net in the first week of May. The value has been increasing throughout May, closing at €26.11 on Reuters (23rd May 2008), and €26.10 on Point Carbon (closing on 26th May 2008).

Table 9. Market values for carbon in forest sector. Price of land based offsets. Adapted from Kollmuss *et al.* (2008), Taiyab (2006), Hamilton *et al.* (2008)

Offset	Project type	Price (t/CO_2e)
Voluntary carbon standard (carbon market actors)	All minus new HFC	€5-15
VER+	CDM minus large hydro	€5-15
CCX*	All (mostly soil carbon)	€1-2
Climate, Community and Biodiversity standards (NGOs and large corporations)	LULUCF	€5-10
Plan Vivo (NGOs)	LULUCF	€2.5-9.5
Climate Care (UK)	Community based energy, some forestry	£6.50
Conservation International	Forestry	$5 Avoided deforestation $8-12 restoration
Face Foundation	Forestry	€10-13
Future Forests	Forestry (and some energy)	£13-16
Green Fleet	Australia	AUS$ 9.30
Primaklima	Forestry	€1.50

***Values on CCX have risen in early 2008 so this range is likely an underestimate for May 2008**

From the values presented above, it would appear that a reasonable range for the valuation of carbon stored in terrestrial ecosystems falls at €1-10 for retail price, considering that some would be attached to 'standards' and higher value, and assuming that avoided deforestation is tested on the voluntary market for formalization in the UNFCCC. Within this, a conservative estimate of €3 – €7 at the higher end would appear acceptable for carbon stored in ecosystems across the board, considering that forestry based projects command higher prices within the current averages traded in the voluntary market and the values for forest carbon projects, and that carbon stored within other ecosystems will undoubtedly command a lower price. It is recognized that the value is highly speculative, and is being used only as an indication of the potential worth of carbon stored in protected areas, rather than as a prediction or thorough estimation of their value.

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Table 8. Percentage share of land use project types in the voluntary market (OTC & CCX). Hamilton *et al.* 2008

Project type	Percentage of land use market
Afforestation/Reforestation Plantation/Monoculture	13%
Afforestation/Reforestation Native Restoration	42%
Avoided deforestation	28%
Agricultural soil	16%
Other biological sequestration (such as wetlands preservation)	0.1%

It is difficult to forecast what the discussions at the UNFCCC conference in Bali will do to the market, with Merril Lynch recently announcing a $9 million investment in a REDD project in Aceh and the likelihood of further REDD testing in the voluntary market. Recent commentary on carbonpositive.net suggested that the inclusion of REDD in the UNFCCC will likely change the market for forest carbon. New Forests, one example of a carbon company interested in investing in REDD in Papua New Guinea, propose to protect various tracts of land to create VERs that they estimate will be in the $3-$11 price range

Forestry carbon projects

A recent evaluation of the potential carbon finance that could be generated through REDD (Ebeling & Yasue, 2008) based calculations on a range of €5-30/tCO2; obtained through analysis of international markets. The lower range estimates appear more accurate in the current market, especially when considering the value of carbon traded through various carbon sequestration and storage projects. The Scolel de Te project in Mexico generated carbon emission reduction units (ERUs) worth $10-12/tc (de Jong *et al.* 2000, Brown *et al.* 2004) under the Joint Implementation (JI) mechanism. The lower price applied to existing carbon stock conservation because of their lack of inclusion in the CDM (Brown *et al.* 2004). Future Forests also purchases carbon from reforestation projects at $12/tc (Smith & Scherr 2002).

Analysing predicted 'forest carbon' prices from a number of sources (Grubb *et al.* 2001, Point Carbon 2001, den Elzen & De Moor 2002), Smith & Scherr (2002) concluded that market price estimates fall within an $8-40t/c range, most likely to command a price of $15-20 if the US ratifies Kyoto and credits are banked for the second commitment period. However, Neef *et al.* (2007) maintain that with few market signals available for forest carbon under the CDM, the most reliable price remains that established by the BioCarbon Fund of US$4 per carbon credit. Others report that a price for stored carbon of $10 per ton is more realistic, and could likely increase over the coming decades (Laurance 2007).

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