# Capitalising on the carbon sequestration potential of agroforestry in Germany's agricultural landscapes: Realigning the climate-change mitigation and landscape conservation agendas[1]

Tobias Plieninger[2]

## Abstract

The potential of agriculture, forestry, and other land uses to sequester carbon offers a powerful tool for controlling the global climate regime, but practices capable of creating "collateral" benefits for landscape conservation have thus far been disregarded. This paper calls for greater integration of scattered trees into agricultural landscapes, hypothesizing that agroforestry practices effectively store carbon and deliver other important ecosystem services as well. Several agroforests from the Upper Lusatia area in Eastern Germany have been selected for analysis. They cover relatively large areas of land (8.2%), even within this intensively used agricultural landscape, and their extent increased from 1964-2008 by 19.4%. Practices of conserving or promoting the six agroforest classes are compared with a catalogue of essential properties for becoming effective "carbon offset projects". Criteria from mandatory and voluntary carbon markets for carbon sequestration are then applied (additionality, baselines, permanence, and carbon leakage). The study concludes that steps towards realization of "carbon sequestration projects" should include collecting empirical evidence regarding the carbon sequestration potential of temperate agroforestry systems, developing localised demonstration projects, and upscaling these projects to participate in established carbon markets.

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[2] Berlin-Brandenburg Academy of Sciences and Humanities, Ecosystem Services Research Group, Jägerstr. 22/23, 10117 Berlin, Germany and Humboldt-Universität zu Berlin, Geography Department, 10099 Berlin, Germany, e-mail: plieninger@bbaw.de

## Introduction

In the global quest to reduce greenhouse gas (GHG) emissions, landscapes are of paramount importance, due to their ability to assimilate and sequester carbon from the atmosphere (Huston & Marland, 2003). From 1989 to 1998, terrestrial ecosystems absorbed around 29% of all anthropogenic GHG emissions (IPCC, 2000). For the European continent, the terrestrial biosphere was a net carbon-sink equivalent of 7 to 12% of the anthropogenic carbon emissions in 1995 (Janssens *et al.*, 2003). Among European countries, there is large variability, with heavily forested countries such as Sweden or Slovenia sequestering more than 50% relative to their fossil fuels emissions standing in contrast to cropland-dominated or peat-extracting countries such as Moldova and Ireland, where terrestrial carbon stocks emit GHG at a rate equivalent to more than 25% of the nation's total fossil fuel emissions (for Germany, this rate is about 7%) (Janssens *et al.*, 2005). Consideration of the potential of landscape elements to act as sources of or as sinks for GHG offers a powerful tool for controlling the global climate regime. Contributions of land-use practices to climate change mitigation have been acknowledged in Articles 3.3 and 3.4 of the Kyoto Protocol; specified in a "Special Report on Land Use, Land-Use Change, and Forestry" (IPCC, 2000); and implemented in the Marrakech Accords in 2001. Two basic avenues for mitigation have been identified:

- Reduction of GHG emissions through, for example, use of biomass for fuel, power, or heat generation, reduction of fertilizer inputs, and conservation of carbon sinks;
- Increase of carbon sinks in above- and below-ground biomass and in soils through, for example, sequestration by farmland afforestation, improved forest management, wetland and peatland restoration, and no-tillage agriculture.

The deliberate management of landscapes for increasing carbon sinks represents a type of commodification where an ecosystem service is transformed into a marketable good. Carbon credits – "Certified Emission Reduction" (CER) credits and "Emission Removal Units" (ERU) in Kyoto jargon (UNFCCC, 2011) – are created and traded on global markets. Other ecosystem services (e.g. soil conservation, landscape aesthetics) do not, however, have such marketability. This leads to shifts in the functional arrangement of cultural landscapes, to trade-offs between different ecosystem services (DeFries *et al.*, 2004), and to questions of who owns the rights to these landscape attributes (Tovey, 2008). Cases such as the creation of large-scale plantations of non-native Sitka spruce (*Picea sitchensis*) in Norway (Austad & Hauge, 2008) or corn monocultures in Germany (Plieninger *et al.*, 2006; Plieninger *et al.*, 2009) illustrate the negative ecological and social side-effects of simplistic large-scale environmental policies that take into account only a single ecosystem service. Frequent calls have been made to address various societal and ecological dimensions simultaneously (e.g. by Koziell & Swingland, 2002) and to search for synergies between the goals of three major multilateral environmental agreements: the Framework Convention on Climate Change, the Convention on Biological Diversity, and the Convention to Combat Desertification (Cowie *et al.*, 2007; Fehse, 2008). These efforts have in some cases resulted in concrete policy measures, such as the integration of selected nature conservation principles into Germany's Renewable Energy Sources Act (Plieninger & Bens, 2007). There have been far fewer attempts to identify synergies between climate policies and landscape agendas; one reason for this is certainly the lack of a global complement to the European Landscape Convention.

One salient approach for addressing interlinkages between climate change, biodiversity loss, and land degradation – in the process leading to potential “win-win opportunities” when implementing countervailing measures – is agroforestry: an ancient practice of integrating trees into farms and rural landscapes (Nair, 2007; Jose, 2009). Including agroforestry practices into international climate regimes could harmonize carbon sequestration with generation of a set of collateral benefits for biodiversity, soil, and water, as well as the sustainable development of rural communities – that is, it promises to generate “charismatic” carbon credits with added environmental and social value (Pandey, 2002; Verchot *et al.*, 2007).

The potential role of agroforestry for climate-change mitigation has been detected relatively recently. On the one hand, there is an enormous potential for carbon sequestration, with the IPCC estimating a savings of 586 Mt C $yr^{-1}$ by implementing agroforestry globally on 630 Mha of land by 2040 (compared to 14 Mt C $yr^{-1}$ for wetland restoration or 82 Mt C $yr^{-1}$ for cropland-to-grassland conversion) (IPCC, 2000). On the other hand, carbon sequestration through agroforestry is challenged by enormous uncertainties, especially due to a lack of standard methods and procedures for direct or indirect measurement and modelling. Whereas a larger number of recent studies has eliminated some of these gaps for the tropics (see Nair *et al.*, 2009b for a review), the role of agroforestry in developed countries is still a blind spot, as even the most fundamental figures are unavailable: First, both the existing and potential area of agroforestry systems is unknown and, second, robust data about the *in situ* and *ex situ* carbon storage and dynamics of agroforestry systems are lacking. More specifically, there is an inadequate understanding of the temporal dynamics of soil carbon in agroforestry systems (Nair *et al.*, 2009a; Nair *et al.*, 2009b). As a result, the use of agroforestry systems for carbon sequestration in developed countries has been largely ignored, for example by the IPCC (2000), which is almost exclusively focused on tropical and subtropical agroforestry.

This paper calls for the filling of existing knowledge gaps and aims to contribute towards an assessment of the potential of agroforests in Central European agricultural landscapes to sequester carbon and participate in carbon markets. The hypothesis that I want to explore is that the integration of trees into agricultural landscapes effectively sequesters carbon and, in addition, supports biodiversity and provides other important ecosystem services, such as cultural heritage. It may thus represent a GHG mitigation alternative to often undesirable farmland afforestation. I argue that including climate issues into efforts for protecting, managing, and planning diverse and high-quality landscapes, as postulated in the European Landscape Convention, may guide us towards a more comprehensive sustainability of cultural landscapes.

As to the structure of the paper, first, six classes of historically-grown agroforests are described. Second, the spatial extent, temporal dynamics, species composition, and vertical/horizontal structure of six different classes of agroforest are analysed. Third, the respective contributions of these types of agroforests to climate-change mitigation are assessed qualitatively. Fourth, principles for participation in carbon markets are discussed. These issues are discussed using empirical data from the Upper Lusatia area in Eastern Germany: an intensively used agricultural area that includes various forms of agroforest that are of importance for European conservation.

## Case Study Approach

Upper Lusatia is located in the federal state of Saxony in Eastern Germany, close to the German-Polish-Czech triangle (51°07’-51°13’ N, 14°34’-14°48’ E). The Western section of the special protection area *Feldgebiete in der östlichen Oberlausitz* (“Farmlands of Eastern Upper Lusatia”, extent: 5,172 ha) was selected as the case study area. The area is undulated hill country, dissected by several valleys, and varies in elevation between 170 and 200 m. It is divided among 6 municipalities in 2 rural districts. The landscape is dominated by arable land (70% cover), while grassland (17%) and forests (7%) occur only in fragments. Settlements and traffic infrastructure cover 2%. The prevailing Loess sediments make the area a highly productive agricultural landscape that has been under cultivation for centuries. The climate is subcontinental, with an average annual precipitation of about 650-700 mm and an average annual temperature of 8.3°C (Mannsfeld & Syrbe, 2008)

Within the case study area, 20 quadrats of 50 ha each were randomly selected, and all present agroforest patches were visually digitized in a vector layer using the ArcGIS 9.3 package. The sources for the spatial analysis were digitally georectified aerial photographs from 1964 - 65 (taken by the military topographic service of the former German Democratic Republic) and digital orthophotos of the Saxony land surveying office from 2008. Accuracy was checked through several field visits and through comparison with topographic maps and the Saxony state habitat survey. Data were analyzed with descriptive methods to detect trends of landscape change. The land cover of a 20 m buffer surrounding each agroforest patch was quantitatively determined using the Saxony state habitat survey. The empirical data of the case study area were then examined in the light of existing literature on agroforestry and carbon sequestration.

## Types of Trees and Woodlands in Agricultural Landscapes

Sculpted by land management and land-use history, the Upper Lusatia area exhibits different types of tree-based systems. Frequent classes of such systems include hedgerows, isolated trees / tree groups, riparian woodland, scattered fruit trees, tree rows, and woodlots (Figure 1). Each class provides specific landscape functions and ecosystem services that act at several spatial levels and in different domains (ecological, economic, social) (see Table 1 for some examples). As the focus of this paper is on agricultural land, urban trees were excluded from the analysis.

For each of these classes, there are various understandings and terms. Here, the definitions from the habitat survey of Saxony have been adopted (Freistaat Sachsen, 2009). A minimum threshold for all classes except scattered fruit trees was a patch size of 20 m² (for scattered fruit trees: 500 m² or 10 individual fruit trees). Thus, the survey was more inclusive than the definition of landscape elements in the German regulations on good farming practices (*Direktzahlungen-Verpflichtungenverordnung*). For this study, hedgerows have a minimum length of 20 m, isolated trees are only those that are protected by conservation legislation, tree rows consist of at least five trees with a total maximum length of 50 m, and woodlots are between 100 and 2000 m² in extent.

### *Hedgerows*

Hedgerows are linear, narrow, and richly structured tree and shrub populations (usually composed of indigenous woody species). They have often established themselves spontaneously by succession on marginal sites, forming singular, unconnected rows and are situated along the edges of fields and roads, on clearance mounds, and other abandoned sites. Most hedgerows in central Europe are not older than 150 years, as extensive grazing and crop cultivation prevented their establishment before the middle of the 19th century (Müller, 2005). Hedgerow vegetation is managed through coppicing.

### *Isolated Trees / Tree Groups*

Isolated trees and tree groups are arrangements of up to 5 single trees, usually planted and situated within a patch of grassland or arable land. They are appreciated both for their park-like appearance and for the animal diversity they support. In most cases they have evolved from systematic plantation that aimed at timber harvesting, using acorns and beech-nuts as forage, soil conservation, improving grassland productivity or creating a visually pleasing landscape. The protection and regeneration of these trees is often challenging (Manning *et al.*, 2006).

### *Riparian Woodlands*

Riparian woodlands are point or linear landscape elements (maximum width: 15 m), found alongside rivers, creeks, ditches, ponds, lakes, and wetlands. This definition is more comprehensive than that of the German Federal Water Act (*Wasserhaushaltsgesetz*), which considers riparian buffers only up to 5 m in width. Small river courses may have been accompanied by woodland strips throughout history, but riparian buffer strips are assumed to have increased in extent after livestock grazing impacts decreased in consequence of agricultural changes in central Europe in the 19th century (Müller, 2005). Forest management includes thinning, coppicing, and sometimes pollarding.

### *Scattered Fruit Trees*

Scattered fruit trees *(Streuobst)* are extensively used open stands of standard fruit trees within grass or fallow lands. Trees need to have a minimum stem height of 160 cm to allow for sound utilization of the ground below tree canopies. They can cover whole valley slopes, form greenbelts around villages or alleys, or occur as individual trees or tree groups. They were first systematically introduced as a land-use innovation to many German regions in the 18th and 19th centuries, mainly with the aims of improving the profitability of agriculture and providing the population with food. First established on gardens and crop fields, these lands were later converted to meadows. Fruit trees are usually planted, grafted, and pruned (Herzog, 1998).

### *Tree Rows*

A tree row is a set of (usually deciduous) trees planted along a road or a path, on either one or both sides (minimum length: 50 m). They are regularly pruned. Primarily prominent in landscape gardens, in Germany they have become widespread alongside rural roads since the Renaissance, having been established for aesthetic and practical reasons, such as protection from sun, wind, and snow, and delivery of firewood, fodder, and fruit. Today, they are mostly appreciated for their natural beauty and as habitat corridors for migrating species (Lehmann & Mühle, 2006).

### *Woodlots*

Woodlots are islets of trees and shrubs in the agrarian landscape that are not directly connected to a forest. Here, they are defined as having a maximum extent of 7.0 ha and are characterized by a specific microclimate that differs from closed forests in terms of higher exposure to light and larger fluctuations in temperature and humidity. They are affected by matter inputs from surrounding agricultural land uses (e.g. in the form of fertilizers or pesticides). Some woodlots have never been put to agricultural use, due to steep slopes, shallow soils, or stagnant water. But most woodlots are a result of either natural succession or afforestation of former arable or grass lands. Thinning and coppicing are frequent forest management techniques. Recently, the creation of woodlots has been proposed as a low-cost strategy for ecological restoration and ecosystem services provision (Rey Benayas *et al.*, 2008).

## Assessment of Extent, Dynamics, and Structure of Agroforests in Upper Lusatia

### *Woodland Cover in 2008*

Table 2 shows that agroforests cover 8.2% of the case study area: a significant share given that there is hardly any contiguous forest there. Woodlots (63%) and riparian buffers (23%) have the largest share in terms of woodland cover. In contrast, the largest patch numbers are found in tree rows (57%), isolated trees/tree groups (15%), and riparian buffers (14%). According to their average extent, woodlots (8,043 m²), scattered fruit trees (3,363 m²), and riparian buffers (1,887 m²) form the largest contiguous agroforests. Average size for the linear or punctual elements is clearly smaller (tree rows: 134 m², solitary trees/tree groups: 150 m², and hedgerows: 279 m²).

### *Transitions from 1964 to 2008*

Both the cover and patch numbers of the six agroforest classes in the study area changed considerably over the 44 years examined in this study (Table 3). With the exception of scattered fruit trees, all classes showed a remarkable persistence and even expansion. Land cover of tree rows, hedgerows, riparian woodlands, isolated trees/tree groups, and woodlots has increased by 10-104 %, while almost 45% of scattered fruit trees were lost. The increase in land cover of five agroforest classes is also a consequence of 6-70% increases of the respective patch numbers. This indicates that the increase is also an effect of the establishment of new agroforests and not only of the expansion of previously existing ones.

### *Woody Species Composition*

Examples for the composition of woody species in the study area are shown in Table 4. As a consequence of frequent coppicing, hedgerows mainly consist of shrubs and light-demanding forest species. Isolated trees and tree groups are composed of long-living deciduous trees, such as *Quercus robur* and *Tilia cordata*. Riparian woodland is dominated by moisture-tolerant species, with species composition depending on local site factors, such as oscillation of groundwater tables and nutrient availability. Scattered fruit trees are by definition dominated by standard fruit trees, mainly *Malus silvestris*, *Pyrus comunis*, and *Prunus avium*. Tree rows contain a wide range of tree species from landscape gardening and orcharding. Next to linden and oaks, fruit tree species are among the most common tree row species in the study area. Sometimes, tree rows are composed of a single tree species. Woodlots are generally composed of forest species that demand light and tolerate coppicing, the most common being *Corylus avellana*. Though every class has its own specific species composition, all agroforests in the area seem to be clearly impacted by nutrient inputs from surrounding agriculture, as indicated by the abundance of nitrophilous plants, such as *Rubus* sp., *Sambucus nigra*, and *Urtica dioica*.

### *Land-Cover Characteristics*

The composition of the field layer is an important factor for assessment of the carbon-sequestration potential of agroforests. Due to the scattered and rather informal nature of the six agroforest classes looked at here, field layers are mainly determined by surrounding land cover. Table 5 summarises the respective shares of land cover types within a 20 m buffer around the habitats. Given the large share of arable land (70%) in the study area, all six classes are underrepresented near arable land. Nevertheless, tree rows (58%), hedgerows (49%), and woodlots (39%) are often found near arable land, while riparian buffers (21%) and isolated trees/tree groups (27%) are rather rarely located there. Grasslands occur rather frequently around riparian woodland (56%), isolated trees/tree groups (56%), woodlots (40%), and hedgerows (30%). Given the small land cover of traffic and settlement infrastructure (2%), all agroforest classes do frequently occur nearby (11%–35%), with the exception of riparian buffers (7%). Agroforests are, however, rarely connected to forests.

### *Spatial Arrangement*

The six classes under study vary in terms of their spatial arrangement, which can either be mixed (dense or sparse) or zoned (lines in the centre of fields or boundary planting). Figure 2 represents examples of the horizontal structure of the six classes. Hedgerows are contiguous linear features, usually located along field margins. Tree rows are also linear, but single trees are often disconnected from the next trees in line and are usually situated along roads. Riparian woodlands form linear buffers along water courses. Fruit trees are scattered across grasslands, while woodlands are compact units within the agricultural landscape.

## Carbon Mitigation through Tree-Based Systems

The "carbon-sequestration potential" (defined as the amount of $CO_2$ in tons that a project can realistically sequester over its lifetime, CSP) of an agroforestry system (Jindal *et al.*, 2008) is assessed as the overall difference between carbon accumulated by photosynthesis and carbon released by respiration resulting from a specific management practice (e.g. the plantation of scattered trees on arable land) over a certain period of time. In contrast, "carbon storage" refers to the total of carbon stocks in an agroforestry system – stocks in standing biomass, soil (in situ stocks), and wood products (ex situ stocks) – at a given point in time. A CSP expresses the difference between carbon storage at time n+1 and carbon storage at time n within a particular agroforestry system. Effective carbon offsets can be achieved only through carbon sequestration (i.e. through improvements in carbon storage). As carbon sequestration depends on baseline carbon stocks, the land-use systems that are replaced by agroforestry are of paramount importance: Replacing forests by agroforestry systems will in most cases reduce carbon stocks, while establishing agroforests on treeless lands increases carbon storage. Therefore, tree-based agriculture on currently degraded and non-productive land as well as on permanent agricultural or pasture land (with generally depleted above-ground carbon pools) offers the prospect of creating a carbon-negative land-use system (Schroeder, 1994).

Two types of land-management options are available to sequester carbon in an agroforestry context: a) to increase the amount of carbon stored in trees and wood fibres and b) to increase the amount of carbon stored in soils (Montagnini & Nair, 2004). Management practices to increase carbon storage in biomass include: 1) the establishment of new trees, 2) the increase of the age of existing tree stands, 3) the increase of carbon in wood products and wood waste, and 4) a decrease of the loss of carbon stored in trees. Techniques for carbon sequestration in soils comprise a) decreasing soil disturbance from tillage, 2) increasing carbon inputs from plant residue, and 3) increasing the proportion of plant biomass retained (Wiley & Chameides, 2007). Globally, the total soil carbon pool of 2,300 Pg is around 3.8 times larger than the vegetation pool of 610 Pg. Thus, any change in soil carbon pool would have a significant effect on the global carbon budget. The biomass-based carbon-sequestration potential for agroforestry strongly depends on site characteristics, land-use types, species involved, stand age, management practices, and other factors. The soil carbon-sequestration potential of agroforestry systems differs strongly depending on the biophysical and socio-economic characteristics of system parameters. However, a general trend of increasing soil carbon storage in agroforestry compared to other land-use practices (with the exception of forests) is discernible, and the soil organic content of agroforests is definitively larger than that of tree plantations, grassland, or arable crops (Nair *et al.*, 2009a). The potential to create offsets has been considered “high” for establishing new trees and decreasing carbon lost from forests, “moderate” for increasing carbon stored in existing woodlands, and “low” for increasing soil carbon (Wiley & Chameides, 2007). Costs per ton of carbon sequestered are “low” for tree establishment, “low to moderate” for increasing soil carbon, “moderate” for decreasing carbon lost from forests, and “high” for increasing carbon stored in existing forests. Altogether the supply of offsets at moderate costs for temperate areas has been considered “high” for tree establishment, but “low” for all other management options discussed.

Methodologically, determination of the carbon-sequestration potential of agroforests includes the design of a forest sampling system, the performance of initial field measurements, the conversion of field measurements into carbon mass through application of allometric equations, and the carrying out of subsequent field measurements to determine changes in carbon stocks over time (Wiley & Chameides, 2007). Unfortunately, European agroforestry is heavily understudied, and – as it remains unconsidered in forestry inventories – statistical information on carbon stocks and carbon sequestration potential is not available. A seminal study (Dixon et al., 1994) found a carbon sequestration potential through agroforestry ranging from 15 to 198 t C $ha^{-1}$ in temperate areas, with a modal value of 34 t C $ha^{-1}$. An assessment in three experimental agroforestry sites in France, Spain, and the Netherlands predicted that mean carbon sequestration ranged from 0.1 to 3.0 t C $ha^{-1}$ $a^{-1}$ over a 60 year-period (Palma *et al.*, 2007). Estimates for agroforestry systems in the US were in a similar magnitude (Nair & Nair, 2003). To refine these general figures, system-specific measurements of carbon stocks are needed. But despite the general lack of empirical evidence, at least some preliminary guidelines for the design and management of agroforestry systems can be derived. In the literature on agroforestry, the following practices have been identified as offering the greatest mitigation potential (Dixon, 1995; Montagnini & Nair, 2004; Nair *et al.*, 2009a):

- Establishment of high-density rather than low-density stands;

- Establishment of mixed-species stands (especially of fast- and slow-growing trees) rather than single-species stands;
- Practices that maintain a stable field layer, avoiding tillage, burning, manuring, chemical fertilization, and frequent soil disturbance;
- Practices that increase net primary productivity and/or return a greater portion of plant materials to the soil;
- Practices minimizing wind and water erosion;
- Practices reclaiming degraded lands;
- Practices establishing nitrogen-fixing plants, such as legumes, and reducing chemical N-fertilization; and
- Use of harvested wood products, if the use of these products involves long-term carbon storage or substitution of petrol-based products.

One critical trade-off is the length of the cutting cycle: Standing biomass and carbon stocks are obviously greater in systems with longer cycles, but young trees can have higher carbon sequestration rates due to their faster growth (Schroeder, 1994). More complex agroforestry systems (for example the Spanish holm oak dehesas, Plieninger, 2007, or the Norwegian wooded hay meadows, Austad & Hauge, 2008) are able to capitalise on both long-term carbon sequestration and energetic use of biomass: Regular pollarding or pruning every 5-10 years will provide biomass, while for a typical lifetime of 200-400 years ensures long term carbon storage. This results also in a durable and active root system, and a stable field layer, which can be beneficial in regard to carbon storage. In addition, the resulting ancient trees are important habitats for epiphytic vegetation, insects, mites, and other species groups. (Bergmeier *et al.*, 2010). Another critical question concerns the use of fast-growing species that may exhibit traits of invasive weeds (e.g. ability to outcompete weeds, long canopy duration, high water-use efficiency) (Raghu *et al.*, 2006). Such agroforestry species may have negative allelopathic effects on food and fodder crops and their use may involve unfortunate consequences on biological diversity in the field layer. Therefore, tree species with no or positive effects on companion crops should be especially considered for agroforestry programs. As tree species remain a part of an agroecosystem for a long period, and most of them produce large amounts of leaves and litter, their allelochemicals may play an important role in developing an eco-friendly pest management strategy (Rizvi *et al.*, 1999; Batish *et al.*, 2009).

## Principles for Participation in Carbon Markets

The principle policy approach towards reducing global GHG emissions has been assigning value to emission reductions or carbon sequestration by creating tradable carbon credits. Due to the rather restrictive regulations imposed, the current number of land use-related projects in regulatory carbon markets is low. However, a strongly rising volume of offsets generated by land-use projects is currently being traded in the so-called voluntary market, where the rules are typically more flexible and accommodating. Companies invest in voluntary offsets for marketing purposes, to meet voluntary corporate social responsibility objectives, or to keep ahead of emerging regulations. Also rising is the number of individuals intending to offset their carbon footprints by projects in agriculture and forestry (Streck *et al.*, 2008). Both for regulatory and voluntary markets, the important issues of additionality and baselines, permanence, and leakage need to be considered (Ebeling, 2008).

### *Additionality and Baselines*

The first crucial question of any offset project is whether the specific land management regime being employed effectively produces carbon storage benefits beyond those that would have been created under business as usual, meaning in the absence of the project. The business as usual scenario is called the baseline, and the premise to achieve additional effects against this baseline is called additionality. Baseline scenarios can be derived either from land use in an area prior to implementation of a project activity or from nearby lands comparable to project lands and representative of land management practices in the region. The common "proportional additionality method" considers the proportion of a project that will be additional. Basically, the difference between the emissions and sinks on project lands and those on comparable non-project lands represents the GHG benefits that count as offsets. If tree hedges are established on 10% of the farmland in a project region, developers would discount the total amount of GHG benefits the project achieves by 10%. Determination of baseline emissions can be made at various intensities. In the simplest case, baseline net GHG removals by sinks are assumed to be insignificant and are accounted for as zero. In more complex cases (in which e.g. carbon stocks are expected to increase in the absence of a project), carbon stocks in the living biomass pool of woody perennials and below-ground biomass of grasslands need to be calculated; then baseline emissions must be subtracted from project emissions. According to this, baseline emissions can be considered zero in intensively used cultural landscapes where no increase in carbon stocks can be reasonably expected. In landscapes experiencing extensification or land abandonment, however, calculation of baseline carbon stocks is indispensible.

### *Permanence*

One risk that separates projects in the land-use sector from emission-reduction projects in the industrial and energy sectors is that carbon uptake is not necessarily permanent, meaning that it may be reversed by natural causes or through intermediate land-use decisions (Schlamadinger *et al.*, 2007). If a sink burns, then the sequestered carbon will be released back into the atmosphere and there will be no net emission reduction in the end. In contrast, measures in the field of reducing fossil-fuel consumption will have a permanent effect: "If an installation producing electricity from solar energy goes out of service after several years and the old oil-fired power station comes back online, the emission reductions that have been achieved will not become undone and there will be – permanently – less $CO_2$ in the atmosphere" (Ebeling, 2008, p. 47). In the intricate negotiations of the Kyoto Protocol, the issue of non-permanence was effectively resolved such that carbon sinks cannot be granted *permanent* certified emission reductions, but instead may receive *temporary* credits whose validity is limited to a certain time span. This replacement liability can be fulfilled either by demonstrating that the underlying sequestered carbon stock still exists by reverification of carbon stocks in planned intervals or by replacing a forestry through a non-forestry carbon credit.

### *Carbon Leakage*

Another issue that needs to be addressed during the development of a carbon sink is leakage: changes in GHG emissions or carbon stocks that occur outside a project's boundaries but are attributable to the project's activities. Leakage can diminish the overall benefit of a project; therefore, projects designed to produce marketable offsets should subtract these elements from their net GHG benefit. Carbon leakage takes place when a project reduces the supply of a good, displacing production – and thus GHG emissions – to another location. Leakage between locations may occur when a new land use is established that shifts pre-existing uses elsewhere (so-called activity shifting, e.g. when a forestation project is created on formerly agricultural land and previous land users are displaced) or when either agricultural or forestry production is reduced to curtail GHG emissions ("market leakage"). Market leakage is rather indirect and works through the law of supply and demand: for example, if crop prices rise through a reduction of arable land in consequence of carbon forestry activities and if rising prices trigger forest clearance for agriculture elsewhere. Market leakage is common in all kinds of climate mitigation activities. For example, an additional wind-energy plant may increase energy supply and, thereby, decrease electricity prices, which may again increase electricity use (Ebeling, 2008). Leakage can be calculated by considering the relative sensitivities of the quantities of goods supplied to a market when the prices of those goods change. In the case of agroforestry activities in Germany, leakage through activity shifting seems unlikely. Long-term land tenure and use rights of land users are clearly defined, and conversion of forests into farmland is effectively controlled. In particular, the great advantage of carbon agroforestry is that it does not displace, but rather integrates previous pastoral or agricultural uses. Unless an agroforestry carbon project seriously inhibits agricultural production, market leakage is likely to be of marginal relevance.

## Perspectives

Each of the six agroforest classes examined within this study shows specific properties that determine their potential contributions towards climate change mitigation (Table 6). Some systems, for example woodlots, are suitable for emissions reduction, as they can be used to produce woodfuels. Other systems, such as alleys or scattered fruit trees, store large amounts of carbon in their standing biomass. Some systems especially build up or conserve soil organic carbon through minimizing wind and water erosion (e.g. hedgerows).

The analysis showed that agroforests cover relatively large areas of land in the study area, even though it is situated in an intensively used agricultural landscape. They have also demonstrated a remarkable continuity over 45 years in the landscape, even throughout periods of comprehensive land-use change such as the industrialization of Eastern German agriculture in the 1970s and the political ruptures of German reunification in 1990. Therefore the challenge of safeguarding the permanence of carbon sequestration seems a much smaller one here than in other forestry-based projects. With the largest areas of land covered and the largest mean patch sizes, woodlots and riparian woodlands can be expected to have the largest carbon-sequestration potentials of the agroforest classes studied. Tree densities and diameters of the different classes were not measured here. But vegetation structures indicate that these figures – indicative of their carbon-sequestration potential – are high for woodlots, riparian buffers, and scattered fruit trees. Tree diameters are high, but tree densities low, for tree rows, isolated trees, and tree groups. In contrast, densities are high, but diameters low, for hedgerows. None of the agroforests described involve severe soil disturbances, which is a very decisive factor for carbon sequestration.

One idea behind this paper has been to develop carbon sequestration projects that promote the establishment and management of agroforestry systems in Central Europe's agricultural landscapes. Formal *and* informal as well as historical *and* modern agroforestry systems are capable of generating a broad range of societal benefits, but have widely been neglected in current land-use practice. Consequently, the additionality of any project creating new agroforestry systems would be easy to verify. While industrial-scale carbon forest plantations composed of exotic trees have been criticized for locking up agricultural soils – inhibiting rural development and endangering both landscape amenity and biodiversity (Koziell & Swingland, 2002) – agroforestry projects may produce plausible and compelling win-win scenarios, generating benefits far beyond carbon sequestration (Ferrari & Rambonilaza, 2008). Although the six agroforestry classes examined here differ in focus, they are all able to integrate multiple ecosystem services and, taken altogether, strengthen the multifunctionality and value of cultural landscapes. They can thus serve as good models for creating future land-use systems in the agricultural landscape. Therefore, it will be necessary to determine the key elements of these historically-grown systems that provide ecosystem services and to integrate these into novel agroforestry systems, for example high-value timber plantation or alley cropping systems for biomass production.

Uncharted territories have to be entered when trying to harness central European agroforestry practices for carbon sequestration. To the author's knowledge, so far no efforts have been undertaken to create carbon credits from agroforestry systems in Europe. Therefore, considerable preparatory work needs to be done for full participation in global carbon markets to be achieved. Of course, chances for success here strongly depend on the outcomes of future climate negotiations, especially with regard to more comprehensive integration of the "agricultural, forestry, and other land use" (AFOLU) sector.

A first step in this direction would be to substantiate the scientific basis of carbon sequestration through agroforestry. The carbon-stock and carbon-sequestration potential of the dominant European agroforestry systems need to be analysed, potential target areas identified, and ecological and economic implications assessed. At the same time, awareness concerning the manifold benefits of agroforestry systems for meeting societal needs should be raised. As a second step, localised projects of need be developed to test and demonstrate the feasibility of carbon sequestration through agroforestry in practice. For many cultural landscapes in Germany, a range of regional marketing activities for agricultural and forestry products, such as specialty cheeses, apple cider, or organic lamb, has been developed. Both consumers and local businesses might be willing to acquire voluntary carbon credits from a regionalized source providing multiple ecosystem services. Moreover, carbon sequestration might be integrated into the goals of agri-environmental programs as a contribution towards the often-postulated synergies between nature conservation and climate change mitigation through land use. The third and most demanding step would be to upscale these local experiences and organise participation in international voluntary or regulatory carbon markets. This step involves considerable transaction costs, as the verification and registration of carbon offsets is substantial. Still, a window of opportunity for tapping into the mitigation potential of agroforestry in particular may open up in the post-Kyoto climate regime, where agriculture and forestry are more and more being recognized as an indispensable component in the mix of future mitigation efforts. It may, therefore, be timely to include carbon sequestration both as an ecosystem service and a potential income source in any future strategies for cultural landscape development.

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## Tables

**Table 1:** Examples for functions and services at landscape-level of six agroforest classes.

**Hedgerows (Baudry *et al.*, 2000):**
- Regulation of water fluxes, soil conservation
- Provision of habitats, corridors, refuges, barriers
- Cultural and amenity functions

**Isolated trees / tree groups (Manning *et al.*, 2006):**
- Provision of wood products like firewood, fence posts and charcoal
- Provision of shade and sheltered grazing for livestock, fodder for livestock
- Recreational value for walkers and hunters

**Riparian woodlands (Ruhl *et al.*, 2007):**
- Maintenance and enhancement of water quality through reduced movement of associated nutrients, sediments, organic matter, pesticides, and other pollutants into surface waters and groundwater recharge areas

**Scattered fruit trees (Herzog, 1998):**
- Provision of edible fruits
- Reservoir of manifold genetic varieties and habitat for specialized flora and fauna
- Cultural services in terms of recreation, scenic values, and regional identity
- Improvement of local climate

**Tree rows (Müller, 2005):**
- Enhancement of natural beauty
- Provision of habitat corridors for migrating species

**Woodlots (Rey Benayas *et al.*, 2008):**
- Maintenance of conservation values of extensive agricultural landscapes
- Increased heterogeneity of uniform landscapes and connectivity among forest remnants
- Addition to farm income by increasing game and crop production

**Table 2:** Land cover and number of patches of the six agroforest classes in the study area in 1964 and 2008 (mean ± standard error, n = 20 samples).

| **Agroforest class** | **Land cover 1964 ($m^2\ km^{-2}$)** | **Land cover 2008 ($m^2\ km^{-2}$)** | **Number of patches 1964 (n $km^{-2}$)** | **Number of patches 2008 (n $km^{-2}$)** |
|---|---|---|---|---|
| Hedgerows | 452 ± 181 | 921 ± 301 | 2.0 ± 0.7 | 3.3 ± 0.8 |
| Isolated trees, tree groups | 1,018 ± 263 | 1,591 ± 346 | 6.8 ± 1.2 | 10.6 ± 2.3 |
| Riparian woodlands | 17,210 ± 4,596 | 19,058 ± 5,304 | 9.4 ± 1.7 | 10.1 ± 1.9 |
| Scattered fruit trees | 5,764 ± 2,694 | 3,027 ± 1,963 | 1.3 ± 0.6 | 0.9 ± 0.4 |
| Tree rows | 3,978 ± 836 | 5,593 ± 885 | 39.4 ± 4.8 | 41.7 ± 6.2 |
| Woodlots | 39,978 ± 10,153 | 51,472 ± 12,544 | 4.8 ± 0.9 | 6.4 ± 1.4 |
| Sum | 68,400 ± 12,244 | 81,662 ± 14,286 | 63.8 ± 6.4 | 73.0 ± 9.2 |

**Table 3:** Relative changes of land cover and patch number of the six agroforest classes in the study area between 1964 and 2008.

| **Agroforest class** | **Changes in land cover** | **Changes in patch number** |
|---|---|---|
| Hedgerows | 103.5% | 70.0% |
| Isolated trees, tree groups | 64.4% | 55.9% |
| Riparian woodlands | 10.7% | 8.5% |
| Scattered fruit trees | -44.8% | -28.6% |
| Tree rows | 40.6% | 6.1% |
| Woodlots | 28.8% | 28.0% |
| Sum | 19.4% | 14.4% |

**Table 4:** Cover/abundance of woody plant species of agroforests at six exemplary sites in the study area (Braun-Blanquet scale, Kent & Coker, 1992).

| **Species** | **Hedgerows** | **Isolated trees / tree groups** | **Riparian woodlands** | **Scattered fruit trees** | **Tree rows** | **Woodlots** |
|---|---|---|---|---|---|---|
| *Acer platanoides* | | | + | | | |
| *Acer pseudoplatanus* | + | 3 | | | | |
| *Alnus glutinosa* | | | 3 | | 2 | 1 |
| *Alnus incana* | | | | | | |
| *Betula pendula* | | | | | 1 | 1 |
| *Buddleja davidii* | | | | + | | |
| *Cornus sanguinea* | 3 | | | | | |
| *Corylus avellana* | 2 | | | | 2 | 3 |
| *Fraxinus excelsior* | | | 3 | | 2 | 2 |
| *Juglans regia* | | | | + | | |
| *Malus silvestris* | | | | 3 | 1 | |
| *Picea abies* | | | | + | | |
| *Populus nigra* | | | | | 2 | |
| *Populus tremula* | | | 3 | | | |
| *Prunus avium* | | 3 | | 2 | 1 | 2 |
| *Prunus domestica* | | | | + | | |
| *Prunus padus* | | | | | | 1 |
| *Prunus persica* | | | | 1 | | |
| *Prunus spinosa* | | | | | | 1 |
| *Pyrus comunis* | | | | 2 | 1 | |
| *Quercus robur* | | 3 | | | 3 | 2 |
| *Rhamnus carthagicus* | 1 | | | | | |
| *Rosa* sp. | 2 | | | | 2 | |
| *Rubus* sp. | | | 1 | | 2 | 1 |
| *Salix* sp. | | | 1 | | | 1 |
| *Sambuca nigra* | 3 | | 1 | | 1 | 1 |
| *Sorbus aucuparia* | | | | | 2 | 1 |
| *Tilia cordata* | | 3 | | | 2 | 1 |
| *Ulmus glabra* | | | + | | | |
| *Viburnum opulus* | 2 | | | | | |
| *Viscum album* | | | | + | | |

**Table 5:** Land cover in a 20 m buffer surrounding the six agroforest classes in the study area.

| Agroforest class | Arable land | Grassland | Forest | Settlement, traffic | Water-bodies | Other agroforest |
|---|---|---|---|---|---|---|
| Hedgerows | 48.5% | 30.1% | 3.9% | 16.5% | 0.0% | 0.9% |
| Isolated trees, tree groups | 26.7% | 55.6% | 2.8% | 12.4% | 0.5% | 1.9% |
| Riparian woodlands | 20.6% | 55.9% | 3.7% | 7.0% | 10.8% | 1.9% |
| Scattered fruit trees | 24.7% | 13.7% | 0.0% | 35.2% | 0.2% | 26.2% |
| Tree rows | 57.5% | 27.1% | 1.7% | 11.5% | 0.7% | 1.5% |
| Woodlots | 38.7% | 39.7% | 4.1% | 11.1% | 2.8% | 3.4% |
| Total | 41.0% | 38.2% | 3.1% | 11.2% | 3.7% | 2.6% |

**Table 6:** Summary of the properties of six agroforest classes found in the study area that may contribute to carbon sequestration / conservation and emissions reduction. Characteristics refer to the ability to sequester carbon in woody biomass and to additional mitigation-related benefits.

| Agroforest class | Hedgerows | Isolated trees / tree groups | Riparian woodlands | Scattered fruit trees | Tree rows | Woodlots |
|---|---|---|---|---|---|---|
| *Structure and composition of trees as relevant for carbon sequestration* | | | | | | |
| Large contiguous vegetation patches | | | + | + | | + |
| High-density tree stands | | | | + | | + |
| Large, long-lived trees | | + | + | + | + | + |
| Land-use continuity | + | + | + | | + | + |
| Mixed-species stands | + | + | + | + | + | + |
| *Additional mitigation-related benefits* | | | | | | |
| Low inputs of chemicals / machinery | + | + | + | + | + | + |
| Minimization of soil erosion | + | | + | | | |
| Carbon storage in wood products | | | | | | + |
| Woodfuel use | + | | + | | + | + |
| Nitrogen-fixing species | | | + | | | |

## Figures

**Figure 1:** Agroforests in the case study area (from upper left crosswise to lower right): a) hedgerow, b) isolated tree, c) riparian woodland, d) scattered fruit trees, e) tree row, f) woodlot.

**Figure 2:** Horizontal structure of the tree layers of a) a hedgerow, b) isolated trees and tree groups, c) riparian woodland, d) a scattered fruit tree meadow, e) tree rows, and f) woodlots in six exemplary sites in the study area.