



Potential of land use activities to offset road traffic greenhouse gas emissions in Central Spain



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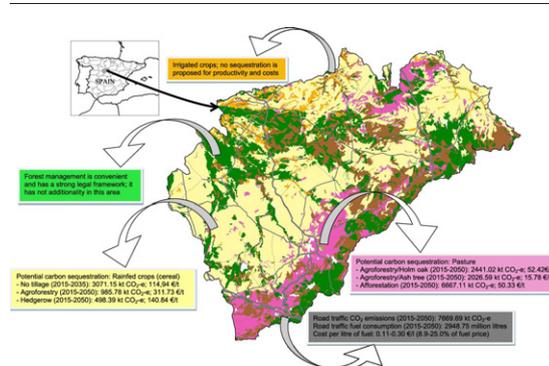
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HIGHLIGHTS

- Offsetting road carbon emissions through land use activities is possible in Spain.
- It is possible to link carbon sequestration, biodiversity and rural development.
- The challenge to offset carbon emissions is funding.
- It is possible to apply a fuel tax, in accordance with the polluter-pays principle.

GRAPHICAL ABSTRACT



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ABSTRACT

The transport sector is one of the main sources of greenhouse gases, adding in Spain near a quarter of the total national emissions, the majority in road transport. Therefore, road contribution to climate change should be mitigated to achieve the proposed goals in the fight against climate change. Policies and strategies suggest several preventive mitigation options, but have paid little attention to compensatory mitigation. We have conducted a theoretical case study in a Spanish province, Segovia, estimating the carbon dioxide emissions in the road network between 2015 and 2050, and analysing different compensation possibilities through conservation agriculture, agroforestry, afforestation and hedgerow plantation. We have calculated carbon sequestration in the reference period and costs per tonne for each option, estimating the budget range of offsetting road carbon emission, and funding possibilities, especially through fuel taxes. The paper demonstrates that offsetting carbon emissions produced by roads in this area is technically possible and highly desirable, unifying carbon sequestration, biodiversity improvement and rural development. The main challenge is funding, which depends largely on the political will and the awareness of the citizens.

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1. Introduction

Climate change is a major global problem, caused by the emission of greenhouse gases (GHG) and, with significant but smaller importance,

by the destruction of sinks; both aspects increase the atmospheric concentration of GHG, exacerbating the natural greenhouse effect.

Numerous activities contribute to GHG emission, and only a few can act as sinks. Transport sector is a key emitter activity, representing almost a quarter of Europe's GHG emissions. Although GHG emissions in the EU-28 were down by 22.9% in 2014 compared with 1990 levels (EUROSTAT, 2016), transport has not seen the same gradual decline as

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other sectors; emissions only started to decrease in 2007 and still remain higher than in 1990 (EC, 2016). Within the transport sector, the contribution to GHG emissions of road transport is especially remarkable; according to the Spanish 2014 GHG inventory, road transport emits 75,652 kt CO₂-e, 23% of the GHG national emissions (MAPAMA, 2016).

The European Strategy for Low-Emission Mobility (EC, 2016) proposes that GHG emissions from transport will be at least 60% lower than in 1990 by midcentury, identifying three priority areas for action: increasing the efficiency of the transport system, speeding up the deployment of low-emission alternative energy for transport, and moving towards zero-emission vehicles. To achieve these objectives, there are already some regulations, such as those aimed at reducing emissions from new passenger cars (EU, 2014). In road transport specifically, climate change mitigation is proposed through: improvement in vehicle efficiency; low carbon fuels; reduction of road traffic; intermodal connections; public transport; non-motorized mobility; modal shift to railway; behavioural changes (avoidance of unnecessary trips, efficient driving); fuel taxes; sustainable mobility in urban planning; greater occupancy of vehicles; or environmental criteria in urban parking management (MMA, 2007; Sims et al., 2014; MAGRAMA, 2015).

The effects of climate change are tangible and demand actions; climate change mitigation is necessary, and urgent, to achieve the goals of the climate agenda. According to the mitigation hierarchy, negative environmental impacts should be avoided, if this is not possible then corrected and, as a last option, compensated. The current approach on climate change mitigation in the transport sector places emphasis on preventive mitigation, undoubtedly the best strategy to avoid GHG emission. In addition, the regulatory framework for GHG emissions pays particular attention to regulated sectors such as industry and energy, subject to carbon trading according to the Kyoto Protocol (UN, 1998) and the EU Directive 2003/87/EC (EU, 2003), but these schemes leave out diffuse sectors such as transport. However, in order to support the path towards reducing emissions, compensatory mitigation should not be undervalued as a complementary strategy, which would allow a reduction in the short or medium term of atmospheric concentrations of GHG while achieving the main mitigation objectives.

Offsetting GHG emissions is not attracting much attention. Some papers have related urban green areas with offsetting carbon emissions (Jo, 2002; Zhao et al., 2010). Martin and Point (2012) analyse the budget for financing GHG emissions offsetting projects in roads based on the opportunity costs. There are not case studies on direct offsetting of road GHG emissions, probably due to the dissociation between the impact, GHG emission, and the possible compensation.

Compensatory mitigation for climate change may be done through a reduction in atmospheric GHG concentration, with natural sinks or artificial capture and storage. Land Use, Land Use Changes and Forestry (LULUCF) activities have an enormous potential for carbon sequestration, with associated advantages as landscape and biodiversity improvement, especially forest-based measures, which merits consideration as cost-effective actions in the climate change policies (Galik and Jackson, 2009; Lubowski et al., 2006). LULUCF is the only net sink sector, and although traditionally excluded from GHG accounting, the 2030 EU Climate and Energy Framework (EC, 2015) will include it, which would imply a boost to these activities as a means to contribute to the achievement of the countries' climate goals.

In biodiversity compensation it is usually preferable using on-site measures (Cuperus et al., 1999; Rajvanshi, 2008), but in GHG compensation there is no such need, and can be off-site. This has led to numerous carbon offset projects being shifted to developing countries, where their implementation is cheaper and it is possible to use avoided deforestation schemes not applicable to developed countries. This has advantages, such as mobilizing capital from developed to developing countries, but also disadvantages, such as not to assume locally the impacts associated with development and minimizing the costs offshoring the compensation. Although it is possible, and probably necessary, to

compensate in third countries, it would be also desirable to implement local GHG offsetting projects, so that compensation is assumed where the emissions are produced. This may have several advantages. On the one hand, the concepts of impact and compensation, which are otherwise dissociated, are linked. On the other hand, the cost of compensation is more real; if the impact occurs in a developed country and compensation in a developing country, the economic measurement scale is different. The benefits of climate change mitigation are global, but usually not tangible at the local level (Wilbanks et al., 2007; Klein, 2011), which can reduce social acceptance; in local compensation the investments are locally tangible. Finally, emission targets are set at the country level, so local actions through LULUCF activities have a positive influence in the nations' GHG balance, aiding to achieve emission targets.

Compensatory mitigation through LULUCF activities is effective to reduce atmospheric CO₂ concentration only in a short span of time on geologic scale, but no permanently, because the carbon is fixed in lignocellulosic products, with a variable but limited duration before decomposing and releasing back into the atmosphere. Consequently, sequestration is not an alternative to reducing GHG emissions. However, although technological advances are progressively faster, the urgency to reduce atmospheric concentrations of GHGs is even greater, so it is highly advisable to adopt all kinds of complementary strategies, including compensatory mitigation, which, moreover, have other induced benefits, ecological, social and landscape, if they are well designed.

The aim of this paper is to analyse the feasibility of offsetting locally the GHG emissions generated by a road network through LULUCF activities under a Mediterranean climate, without environmental or social impacts, determining the costs and funding possibilities.

2. Methods

2.1. Research questions

There are two research questions: (i) Is it technically possible to offset locally the GHG emissions of a road network through LULUCF activities under a Mediterranean climate, without environmental or social impacts? (ii) If possible, what are the costs, how they are compared to the current carbon markets, and how could be funded?

To answer these questions, first we made a forecast of the CO₂ emissions in a spatial and temporal scope, to determine the amount of compensation that must be provided. Then, we have proposed compensation possibilities based on LULUCF activities, following a triple objective: carbon sequestration, biodiversity and landscape improvement and rural development. For each measure, we have analysed the technical feasibility and costs, discussing their potential and funding possibilities. The future trends discussed on this paper are based on existing

Table 1
Land uses in Segovia province in 2013.

Land use		Area (ha)	Percentage (%)	
Arable land	Herbaceous crops	Rainfed Cereal	167,365	24.18
		Other	35,823	5.17
	Irrigated		17,416	2.52
		Fallows	2756	0.40
Meadows and pastures	Woody crops	43,645	6.30	
	Natural meadows	6139	0.89	
	Pastures	129,511	18.71	
Forest land	Timber woods	119,302	17.23	
	Open wood	33,913	4.90	
	Shrub wood	35,236	5.09	
	Other areas	Wasteland pasture	54,783	7.91
	Unproductive land	4832	0.70	
	No agricultural area	34,602	5.00	
	Rivers and lakes	6929	1.00	
		692,252	100.00	

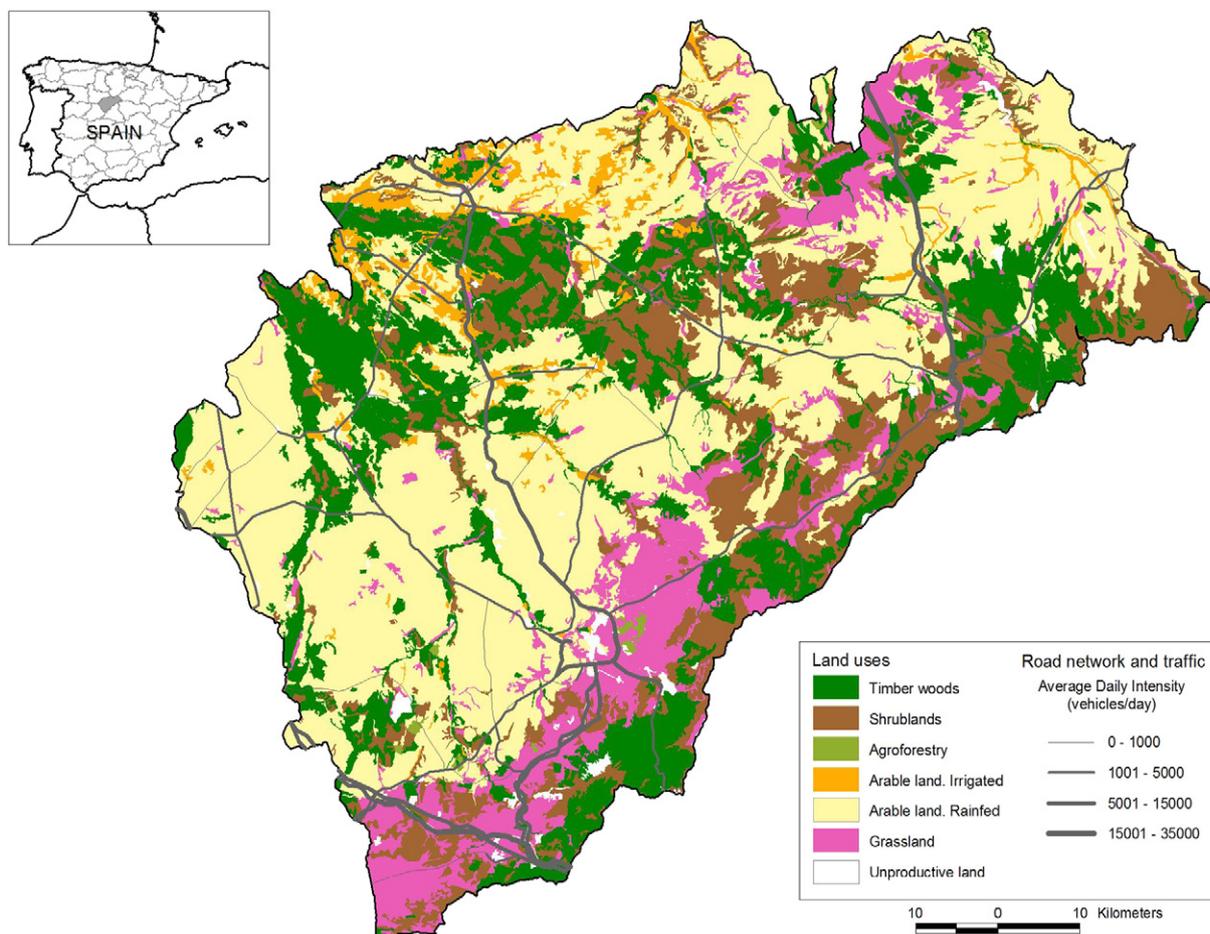


Fig. 1. Land use and road network of Segovia province.

models, policies and targets, so may or may not offer an accurate account of what might happen in the future.

2.2. Spatial scope

The compensation through LULUCF activities, both in terms of effectiveness and costs, depends on the local conditions, which determine the possibilities of action, usable species and execution and compensation costs. Therefore, a study of this type needs to refer to a concrete area. Spain is divided into 50 provinces, a good unit of study because they present enough extension for this type of analysis, being quite homogenous from the climatic, ecological and economic points of view. The differences among provinces in extension, population, traffic or land uses are high.

For this study we have considered the province of Segovia, in Central Spain, with an area of 6923 km², close to the national average, and a low population, 159,127 inhabitants (INE, 2015), although a more important traffic because it borders with the province of Madrid, the largest population in Spain, and it is crossed by two of the country's main

motorways, A-1 and A-6. In addition, it is a typically Mediterranean continental province, representative of the large cereal plateaus of Central Spain. The altitude ranges between 850 and 1000 m, and the average precipitation between 400 and 500 mm, except in a narrow mountainous band in the East, with a maximum altitude of 2430 m and precipitation of 1200 mm. The main land uses (JCYL, 2015a, Table 1, Fig. 1) are rainfed crops, mainly cereal, pastures and timber woods.

The provincial road network has three jurisdictions (Table 2), Central State (main roads), Autonomous Community (regional roads) and Provincial Council (local roads). We have considered the first two, accounting for 47.5% in length but 94.6% in traffic (Fig. 1).

2.3. Temporal scope

Carbon sequestration by vegetation depends on plant growth, so its estimate should span over a period of time, affordable for planning and large enough to compensate differences in growth intensity due to age. The horizon year is conditioned by the availability of data to make

Table 2
Road network of Segovia province in 2014, according to jurisdiction and road type.

Road jurisdiction	Road type	Road length			Traffic		
		Partial (km)	Total (km)	%	Average (veh/day)	Total (Million veh/day)	%
Central State	Toll motorway	67	368	15.79	7787	2866.99	63.67
	Motorway	48					
	Conventional	253					
Autonomous community	Motorway	64	739	31.72	1881	1391.28	30.90
	Conventional	675					
Provincial council	Conventional	1223	1223	52.49	200	244.60	5.43
		2330	2330	100.00	1932	4502.87	100.00

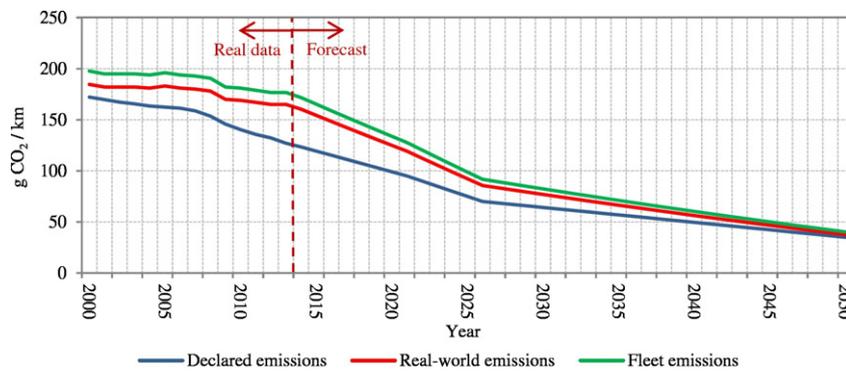


Fig. 2. Vehicle CO₂ emission rate (2000–2050).

reliable forecasts, especially for vehicle emissions; the longer-term estimates of average GHG emissions of vehicles are for 2050, as indicated below. Consequently, we have considered a temporal scope of 35 years, spanning from 2015 to 2050.

2.4. Calculation of CO₂ emissions

Traffic forecast is based on 2014 data (MFOM, 2015; JCYL, 2015b), and relies on the traffic growth percentages established by a 2010 Ministry Order (BOE, 2010), 1.12% from 2013 to 2016 and 1.44% from 2017 onwards.

To forecast CO₂ emission factor (Fig. 2) we used the following data and assumptions:

- Average emissions for new cars sold in the European Union (EU) declared by manufacturers (EEA, 2014, 2015).
- EU emission targets: 130 g/km by 2015, 95 g/km by 2021, 70 g/km by 2025 (recommended) and probably 35 g/km by 2050 (Stiller et al., 2009; Garbe et al., 2011).
- Average emissions measured on real-world driving conditions. There is a gap between laboratory and real-world results, which is getting wider, from 7.25% by 2001 to 29.93% by 2013 (Mock et al., 2014). We assume that 2013 gap is unacceptable, and that by 2050 it will returned to a residual rate of 7.25%.
- Average emissions of the vehicle fleet. The circulating fleet have different ages. Using 2012 data on the number of vehicles by registration date (DGT, 2015), we calculate the average emission rate of the fleet, 176.68 g/km; the difference with new vehicles is considered constant, 7.1% more.
- Average emissions of heavy vehicles, which depend on the type and weight. Using 2014 data on number of buses and lorries classified according to allowed load (DGT, 2015) and the CO₂ emissions according to weight (Hill et al., 2015) we obtain an average emission factor of 505 g/km, equivalent to 3.16 light vehicles.

These estimates are based on the current political trend in Europe and the world, and are considered reliable as long as this trend remains the same.

Using the length and traffic of each road section, the equivalence between heavy and light vehicles and the CO₂ emission factor we obtain the total emissions for each year, and the sum during the reference period.

2.5. Compensation of CO₂ emissions

Our objective is to analyse the feasibility of offsetting CO₂ emissions through LULUCF activities, according to three principles, which influence the selection of alternatives:

- Additionality, providing new carbon sequestration. Forests have a solid legal framework and adequate management in Spain, so

there is no additionality for avoiding deforestation or changes in management; this use has been excluded.

- Improve biodiversity and landscape. This condition implies the use of native species on plantations, avoiding exotic species, even having a greater carbon sequestration.
- Avoid social impacts and competition with productive uses. First we excluded the most productive lands, such as irrigated crops. It is intended to avoid land use changes in productive lands, making compatible the management measures or plantations. Afforestation will be carried out only on marginal agricultural land.

As a consequence, we have selected four compensation measures: agroforestry, afforestation, hedgerow planting and conservation agriculture.

2.6. Compensation costs

These measures are voluntary, so it is necessary to avoid any loss of productivity and income, and at the same time to establish incentives. Consequently, the cost per CO₂ tonne fixed depends on: (i) the effectiveness of the measures (the potential for carbon sequestration); (ii) the implementation costs, especially in plantations; (iii) the compensation for loss of productivity or income from sale of products or leases; (iv) the incentives for the adoption of these measures; it has been considered that at least there should be a 10% increase in the current land revenue to incentivize the owners to accept the changes in their plots. Once the price per tonne of CO₂ was calculated, it has been compared with the values proposed by other authors, and with the prices of the voluntary carbon markets in Spain.

2.7. Funding possibilities

To define funding possibilities we have applied the polluter pays principle (EFTEC and IEEP, 2010). Road traffic CO₂ emissions are produced by vehicles, so the pollutants are their owners, whose should

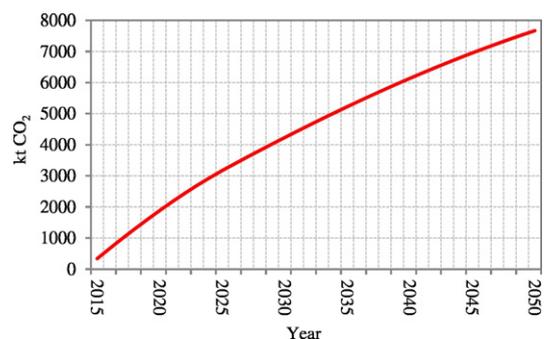


Fig. 3. Accumulated CO₂ emissions of the road network (2015–2050).

Table 3
Carbon fixation in agroforestry measures (2015–2050).

Species	Tree characteristics				CO ₂ fixed in 35 years					
	DBH37 (cm) ^(a)	Biomass (kg/tree)	Carbon		Per tree (kg/tree)	Per compensation measure				
			(%)	(kg/tree)		Land use	Area (ha) ^(e)	Density (tree/ha)	Per area (t ha ⁻¹)	Total (kt CO ₂)
<i>Quercus ilex</i>	14 ^(b)	135.14 ^(d)	47.5 ^(d)	64.19	235.58	Cereal	167,365	25	5.89	985.78
						Pasture	103,609	100	23.56	2441.02
<i>Fraxinus ang.</i>	23 ^(c)	446.02 ^(d)	47.8 ^(d)	213.20	782.44	Pasture	25,902	100	78.24	2026.59
										5453.39

^a Diameter at breast height with 37 years.

^b Ximénez de Embún (1963).

^c Modrego and Cisneros (2008).

^d Montero et al. (2005).

^e Table 1.

bear the costs of compensation. The emission of CO₂ occur as a result of fuel consumption, which depends on the vehicle type, efficiency and driving behaviour. Consequently, a possible funding source, although probably not the only one, is a fuel tax.

3. Results

3.1. Emissions

Traffic is expected to grow 64.42% between 2015 and 2050, but the emission factor in vehicles will decrease 76.67%. Consequently, the estimation of annual emissions decreases by 60%, from 336.52 kt CO₂ by 2015 to 134.60 kt CO₂ by 2050. The expected total emission of the road network in the reference period (2015–2050) is 7669.69 kt CO₂ (Fig. 3).

3.2. Compensation of CO₂ emissions

3.2.1. Tree planting: agroforestry, afforestation and hedgerows

Agroforestry systems combine farming with the presence of trees, allowing agricultural production and carbon sequestration simultaneously, not requiring a full land use conversion (Flugge and Abadi, 2006; Balderas et al., 2010; Bryan et al., 2014). It has a great potential as a carbon sequestration strategy, not adequately exploited (Montagnini and Nair, 2004; Jose and Bardhan, 2012). The advantage of agroforestry is to link ecological, social and scenic objectives in a win-win strategy, increasing the diversity of products, producing carbon sequestration, reducing land clearing, maintaining carbon stocks and changing the rural landscapes (Schroeder, 1994; Holderieath et al., 2012). In Spain there is a traditional agroforestry system called *dehesa* (Joffre et al., 1988, 1999), which consists on cereal crops or pasture with a sparse cover of 20–100 trees/ha (Olea and San Miguel, 2006), generally *Quercus ilex* or *Q. suber*, but also *Fraxinus angustifolia* in moist soils. Although *dehesas* occupied large areas in the past, crop intensification has largely reduce them.

FAO (2001) notes that agroforestry, by social and cultural reasons, is difficult to promote. In crop areas the presence of trees obstructs tilling and harvesting, while in grazing areas it requires the protection of trees until maturity to avoid livestock damages. These drawbacks are bearable by landowners when the presence of trees increases their income, which is not currently the case in Spain. To encourage agroforestry expansion it would be necessary to establish financial incentives (Holderieath et al., 2012) to compensate for the operational difficulties, and to generate some profit. We studied two possible measures:

- Agroforestry in rainfed cereal crops, with 25 trees/ha of *Quercus ilex*. A guard frame of 2 m² per tree to prevent damages during tilling and harvesting, would produce a loss of farmland of 100 m²/ha (1% of the area).
- Agroforestry in pastures, with 100 trees/ha of *Quercus ilex* in dry soils (80% of the province) and *Fraxinus angustifolia* in moist soils (20%). A shelter of 1 m² per tree to avoid livestock damages implies a loss of pasture of 100 m²/ha (1% of the area).

An interesting possibility for carbon sequestration is afforestation of unproductive farmland. We designed a plantation of *Quercus ilex* (50%), the main potential tree in the area, and *Pinus pinaster* (50%), currently the main forest species (JCYL, 2007). The density is 1111 tree/ha of 2 year plants, considering that 40% of them would survive up to 35 years (final density of 444 tree/ha). We assume that all the wasteland pasture could be afforested.

The traditional landscape of this region was a mosaic of farm plots with hedgerows, especially of *Quercus pyrenaica*, *Q. ilex* and *Fraxinus angustifolia*, mixed with spinal shrubs of *Rubus ulmifolius*, *Rosa canina*, *R. corymbifera*, *Crataegus monogyna* and *Prunus spinosa*. The intensification of agriculture and land reparcelling has led to the destruction of many of these hedges. The recovery of hedgerows has a great interest to restore the landscape, create refuges for wildlife and fix carbon. To calculate the sequestration potential we designed a plantation with *Quercus ilex* (60%), *Q. pyrenaica* (20%) and *Fraxinus angustifolia* (20%),

Table 4
Carbon fixation in afforestation of wasteland pastures (2015–2050).

Species	Tree characteristics				CO ₂ fixed in 35 years					
	DBH37 (cm) ^(a)	Biomass (kg/tree)	Carbon		Per tree (kg/tree)	Per compensation measure				
			(%)	(kg/tree)		Land use	Area (ha) ^(e)	Density (tree/ha)	Per area (t ha ⁻¹)	Total (kt CO ₂)
<i>Quercus ilex</i>	14 ^(b)	135.14 ^(d)	47.5 ^(d)	64.19	235.58	Wasteland pastures	54,783	222	52.30	2865.08
<i>Pinus pinaster</i>	23 ^(c)	166.70 ^(d)	51.1 ^(d)	85.18	312.62			222	69.40	3802.03
										6667.11

^a Diameter at breast height with 37 years.

^b Ximénez de Embún (1963).

^c Río et al. (2006).

^d Montero et al. (2005).

^e Table 1.

Table 5
Carbon fixation in hedgerow planting among cereal crops (2015–2050).

Species	Tree characteristics			CO ₂ fixed in 35 years						
	DBH37 (cm) ^(a)	Biomass (kg/tree)	Carbon		Per tree (kg/tree)	Per compensation measure				
			(%)	(kg/tree)		Land use	Area (ha) ^(f)	Density (tree/ha)	Per area (t ha ⁻¹)	Total (kt CO ₂)
<i>Quercus ilex</i>	14 ^(b)	135.14 ^(e)	47.5 ^(e)	64.19	235.58	2.07% of rainfed crops	3456	266	62.66	216.55
<i>Q. pyrenaica</i>	13 ^(c)	76.78 ^(e)	47.5 ^(e)	36.47	133.85			89	11.91	41.16
<i>Fraxinus ang.</i>	23 ^(d)	446.02 ^(e)	47.8 ^(e)	213.20	782.44			89	69.64	240.68
										498.39

^a Diameter at breast height with 37 years.

^b Ximénez de Embún (1963).

^c Delgado (2009).

^d Modrego and Cisneros (2008).

^e Montero et al. (2005).

^f Table 1.

with a density of 1111 tree/ha and a survival rate of 40%. The average cereal plot size in Castile and Leon, where Segovia is located, is 33.75 ha (INE, 2014). Considering a square plot bordered with a 3 m wide hedge, hedges sum 0.70 ha per plot, 2.07% of the total.

To calculate carbon sequestration in tree planting measures (Tables 3 to 5) we used the tree diameter at breast height (DBH), the biomass in 2050 after 37 years (2 years when planted and 35 growing), the carbon percentage of dry matter and 3.67 as the equivalence among fixed carbon and CO₂ sequestration.

3.2.2. Conservation agriculture

Agriculture, especially tillage, leads to a progressive loss of soil organic carbon (SOC), up to two thirds of the original reserves (Houghton and Skole, 1990; Rasmussen and Collins, 1991; Kinsella and SWCS, 1995; Smith et al., 1996; Loveland and Webb, 2003; Lal, 2004). By contrast, no-tillage (NT) practices, maintaining crop residues on the soil, are more likely to favour an increase in SOC. The first studies on conservation tillage provided enthusiastic results about the capacity of this practice for carbon sequestration (Powlson et al., 2011), mainly because they focused on topsoil. Recent studies analysed the whole soil profile (Baker et al., 2007; Powlson et al., 2011; Dikgwatlhe et al., 2014; Xue et al., 2015; Wiesmeier et al., 2015; Cheesman et al., 2016) and arrive to more cautious estimations.

NT results in an increase of SOC in topsoil with a vertical gradient, but below the tillage depth SOC concentration is higher in conventional tillage (CT). The total amount of SOC appears to be slightly higher in NT versus CT (Lal, 1999; Eve et al., 2002; Arrouays et al., 2002; Kimble et al., 2002; Baritz et al., 2004), although sometimes no differences are found (Carter, 2005; Luo et al., 2010). Some SOC sequestration values for NT are: 0.125–0.515 t ha⁻¹ year⁻¹ (Sommer and Bossio, 2014); 0.306 t ha⁻¹ year⁻¹ (Angers and Eriksen-Hamel, 2008); 0.285 t ha⁻¹ year⁻¹ (Álvarez-Fuentes et al., 2014); 0.226 t ha⁻¹ year⁻¹ (Álvarez-Fuentes and Cantero-Martínez, 2010). The last two values are specifically for Spain.

The SOC sequestration rate is non-linear, with a high growth rate during the first 10–11 years, especially during the first 5 years, and a

stabilization until saturation after 20 years (Watson et al., 2000; West and Post, 2002; Freibauer et al., 2004; Bing et al., 2006; Álvaro-Fuentes et al., 2014). Although SOC increases with the incorporation of crop residues, carbon sequestration depends on the alternative fate of these residues (Powlson et al., 2011).

A risk of NT is the increase in N₂O emissions due to organic matter decomposition (Mackenzie et al., 1998; Smith et al., 2001; Freibauer et al., 2004; Powlson et al., 2011), a GHG with a warming potential 300 times higher than CO₂. However, this emission is only significant in poorly-aerated soils in humid climates (Rochette, 2008), which is not the case of the study area. Zhang et al. (2016) indicates for China that carbon sequestration significantly increased with the application of N-fertilizer, but in Spain authors do not detect relationship between N fertilization and SOC fixation (López-Bellido et al., 2010; Melero et al., 2012).

An advantage of NT versus CT is the reduction in fuel consumption of the machinery, decreasing the emissions from 53 to 29 kg C⁻¹ yr⁻¹ (Kern and Johnson, 1993). In semi-arid regions NT may also favour production due to better moisture conservation (Larney and Lindwall, 1994; Rieger et al., 2008). NT in rainfed cereal crops in Spain is probably more cost-effective than CT, because yield reduction would be offset by lower operating costs (Lacasta and Meco, 2004; Lacasta, 2014). In a Mediterranean climate with summer drought, cereal production depends on precipitation more than on tillage (López-Fando and Almendros, 1995). It is necessary, however, to consider the loss of the income from selling straw.

There is a SOC deficit in agricultural soils under Mediterranean climate (Moyano et al., 1986; Romanyà et al., 2007). The average soil organic matter (SOM) in 258 soil samples of rainfed crops of Segovia (ITA, 2015) was 1.8%; a good situation is 5%, only reached in the best soils. Using a conservative SOC sequestration rate with NT specifically for Spain (0.226 t ha⁻¹ yr⁻¹; see above), and considering a period of 20 years (2015–2035) until stabilization, it is possible to fix 4.52 t ha⁻¹, increasing SOM to 2.01%. Another 0.48 t C ha⁻¹ reduction is possible due to lower fuel consumption, totalling 5 t C ha⁻¹ in 20 years, which in the whole province means 3071 kt CO₂ (Table 6).

Table 6
Carbon fixation in rainfed crop soils with no-tillage.

Carbon sequestration per unit area (ha)			Carbon sequestration in the province (2015–2035)			
SOC ^(a) sequestration ^(b)	Lower fuel consumption ^(c)	Annual carbon sequestration	20 years carbon sequestration	Rainfed cereal provincial area ^(d)	Carbon sequestration	CO ₂ sequestration
(t·C·ha ⁻¹ yr ⁻¹)	(t·C·ha ⁻¹ yr ⁻¹)	(t·C·ha ⁻¹ yr ⁻¹)	(t·C·ha ⁻¹)	(ha)	(kt C)	(kt CO ₂)
0.226	0.024	0.250	5.00	167,365	836.83	3071.15

^a SOC - Soil organic carbon.

^b Álvarez-Fuentes and Cantero-Martínez (2010).

^c Kern and Johnson (1993).

^d Table 1.

Table 7
Cost of carbon fixation in tree planting activities (agroforestry, afforestation and hedgerows) in the period 2015–2050.

Measure	Area (ha)	Planting density (tree/ha)	Planting cost (€/ha) ^(a)	Maintenance cost (2 years) (€/ha) ^(a)	Production loss (35 years) (€/ha) ^(b)	Incentive (35 years) (€/ha) ^(c)	Total cost (35 years) (€/ha)
Agroforestry	Cereal	167,365	25	125.00	100.00	146.46	1836.11
	Pasture (<i>Q. ilex</i>)	103,609	100	450.00	400.00	35.00	1235.00
	Pasture (<i>Fraxinus</i>)	25,902	100	450.00	400.00	35.00	1235.00
Afforestation	Wasteland	54,783	1111	3100.00	1100.00	1750.00	6125.00
Hedgerows	Cereal	3456	1111	3100.00	1100.00	14,646.48	20,311.13

^a Estimated by market data.

^b Agroforestry 1%, afforestation and hedgerows 100%.

^c Proposed 10% of total production or lease rent.

3.3. Compensation costs

To estimate the costs of the measures (Tables 7 and 8), all for 2015, we used 2014 data on production of grain and straw, and grain prices for Segovia (JCYL, 2015a), and contrasted market prices for straw, planting and maintenance. Agroforestry occupy 1% of the land and afforestation and hedges 100%, so it is necessary to offset the current production; crop production is based on grain and straw yield, and livestock in land rental prices, 100 €/ha in meadows and 50 €/ha in pastures. Straw remains on the ground and will no longer be sold, requiring compensation. We added a 10% of the current land revenue as a benefit to incentivize landowners to undertake these measures.

The sequestration after applying all the defined measures would be 15,690 kt CO₂, more than twice the road carbon emissions between 2015 and 2050. The efficiency and costs per tonne of CO₂ vary greatly among the different measures. To calculate the compensation budget we have studied three scenarios: (1) optimization of costs, using the measures with cheaper cost per tonne of CO₂; (2) equitable use of all the measures; the compensation required is 49% of the possible, so each measure is used in this percentage; (3) most expensive combination, using first the measures with higher cost per tonne of CO₂. Depending on the scenarios the compensation budget varies from 316 to 785 million € (Table 9).

3.4. Compensation funding

The main funding option proposed is the application of a tax on fuels. The emission of diesel is 2.660 kg CO₂/l, and for petrol 2.325 kg CO₂/l (EPA, 2005); fuel sales in Spain in 2015 were 82.4% of diesel and 17.6% of petrol (CORES, 2015) so the weighted emission mean is 2.601 kg CO₂/l. The average fuel price in Spain in 2015 (MINETUR, 2015) was 1.19 €/l for diesel and 1.33 €/l for petrol; using sales percentages the weighted mean is 1.21 €/l. The estimated total emissions, 7670 kt CO₂, are equivalent to a consumption of 2949 million litres of fuel. Depending on the compensation scenarios the average impact on fuel price is 0.11 to 0.27 € per litre, 9 to 22% (Table 10).

4. Discussion

In the studied area, agroforestry, afforestation and conservation agriculture can offset road traffic CO₂ emissions in the medium term without changes in the economic activities related to land use, providing important ecological and scenic advantages; the main challenge is funding.

The most effective measure is hedgerow planting, with great ecological benefits, although it is expensive and has a limited potential because implies farmland occupation, competing with agriculture. Agroforestry in cereal crops is not very effective because *Quercus ilex* grows slowly, making the measure expensive, although it produces long-term absorption because these species live hundreds of years. In pastures, agroforestry is more effective because it allows higher tree density and land production is lower, which reduces compensation costs. In moist soils *Fraxinus angustifolia* has a much faster growth, making their use more efficient.

Afforestation can compensate 87% of total CO₂ emissions only through the plantation of wasteland pastures with marginal livestock use, so the economic impact is minimal. Moreover, the investment can be profitable because it provides a source of renewable energy (Graham, 2003).

Carbon sequestration in soils through conservation agriculture has limited efficiency and is not cheap, but has the advantage that payments are annual, not requiring initial investments. It would be a transitional measure until vehicle efficiency increases, alternative energy sources are sought (Lal, 2004) and tree plantations grow. Moreover, NT probably is more profitable in this area than CT, so payments could be gradually reduced and disappear eventually. Sommer and Bossio (2014) conclude that this measure cannot be considered as a climate stabilization wedge, but Lassaletta and Aguilera (2015) disagree, arguing that it still deserves important attention for scientists, managers and policy makers.

We note that the slow tree growth under Mediterranean climate can be a major concern, because also slows down carbon sequestration and makes compensation more expensive, but not infeasible; in more rainy climates sequestration is greater, although the cost of compensation will

Table 8
Cost of carbon fixation in conservation agriculture (no-tillage).

Cereal	Area	Production (kg/ha)		Price (€/100 kg)		Compensation (€/ha)			
		Grain ^(a)	Straw ^(a)	Grain ^(a)	Straw ^(b)	Loss from straw sales	Incentive ^(c)	Total annual	Total 2015–2035
Wheat	66,615	2207	1119	17.44	3.00	33.57	41.85	75.42	1508.34
Barley	86,827	1868	959	15.25	4.50	43.16	32.80	75.96	1519.15
Oats	1337	1312	672	16.11	3.00	20.16	23.15	43.31	866.25
Rye	11,666	1465	752	15.36	3.00	22.56	24.76	47.32	946.37
Triticale	920	1968	1000	17.00 ^(c)	3.00	30.00	36.46	66.46	1329.12
	167,365	1971	1006	16.15	3.78	37.65	35.78	73.43	1468.66

^a JCYL (2015a).

^b Estimated by market data.

^c Proposed 10% of total (grain + straw).

Table 9
Costs per tonne of CO₂ and total compensation budget for different scenarios.

Measure		CO ₂ sequestration			Compensation scenarios					
		Maximum sequestration (kt CO ₂)	Efficiency per unit area (t CO ₂ /ha)	Cost per tonne (€/t CO ₂)	1. Optimizing cost per tonne		2. Equitable use of measures		3. Most expensive combination	
					(kt CO ₂)	(M €) ^a	(kt CO ₂)	(M €) ^a	(kt CO ₂)	(M €) ^a
Agroforestry	Cereal	985.78	5.89	311.73	0	0	481.69	150.16	985.78	307.30
	Pasture (<i>Q. ilex</i>)	2441.02	23.56	52.42	0	0	1192.77	62.52	2441.02	127.96
	Pasture (<i>Fraxinus</i>)	2026.59	78.24	15.78	2026.59	31.98	990.26	15.63	0	0
Afforestation		6667.11	121.70	50.33	5640.10	283.87	3257.78	163.96	670.35	33.74
Hedgerows		498.39	144.17	140.84	0	0	243.53	34.30	498.39	70.19
Conservation agriculture		3071.15	18.35	80.04	0	0	1500.67	120.11	3071.15	245.81
		15,690.04	74.03	71.31	7666.69	315.85	7666.69	546.68	7666.69	785.00

^a Millions of €.

not necessarily be reduced, due to the higher opportunity cost of eliminating existing agriculture. For example, Hobbs et al. (2016) show differences in the mean sequestration rate of tree dominating plantings depending on the mean annual rainfall in South Australia, ranging from 2.94 t CO₂ ha⁻¹ year⁻¹ with a mean rainfall of 251–350 mm, year⁻¹ to 44.59 t CO₂ ha⁻¹ year⁻¹ with more than 750 mm year⁻¹; multiplying rainfall by 2.5 means increasing sequestration 15 times.

By contrast, an advantage of Spain is its large extension and a lower population density compared to the EU average, with large agricultural extensions, productive and marginal, where it is possible to act. This binomial, climate-land availability, determines the possibilities of compensation, and may lead to significant differences in feasibility and costs between regions and countries. In addition, variability in productivity within a region can be an opportunity to improve efficiency, locating appropriately the landscape modifications to achieve a maximum sequestration benefit, reducing opportunity losses and compensation costs; for example, in the studied area the humid soils of the piedmont have the maximum sequestration potential, coupled with the highest ecological value.

The sequestration measures recommended are effective to reduce atmospheric CO₂ concentration in a very short span of time on geologic scale, but no permanently. The CO₂ sequestered by photosynthesis is fixed in lignocellulosic products, which eventually decompose and release CO₂ back into the atmosphere. Consequently, a durable sequestration should involve monitoring and management actions maintained over time, ensuring that the release of CO₂ by decomposition does not end up neutralizing the sequestration achieved.

The costs per CO₂ tonne in our proposal are above the usual voluntary carbon markets prices in Spain (usually 5 to 15 €) due to the indicated climatic limitations, and because are designed with ecological criteria and as incentives for landowners, and do not seek only for the maximization of carbon sequestration. Also, offsetting in a developed country, such as Spain, is much more expensive than in a developing country, where many carbon markets have their projects. Rodríguez-Entrena et al. (2012) calculate a cost of 17 € per tonne of CO₂ sequestered in olive grove soils, while Lubowski et al. (2006) establish a cost between 8 and 164 USD (7.65–156.92 €) depending on the discount rates, which is closer to our results. Benítez et al. (2007) note that

tree-planting activities within 20 years could offset 1 year of carbon emissions in the energy sector, considering a carbon price of 50 USD per tonne (47.84 €), near to our results for afforestation (50.33 €). However, price depends on the climate and the standard of living of the countries, so is not possible to make global comparisons. Also, the actual carbon price and the expected price for the society could be so different; TaeWoo et al. (2014) indicates that South Korean firms are willing to pay between 5.45 and 7.77 USD/t CO₂ in domestic and overseas projects, well below 50 USD per tonne.

Taking into account the strong price differences between measures, there is a risk of using only the cheapest ones, although all of them are desirable. This requires the intervention of the public administrations to regulate these compensations, avoiding imbalances.

Applying the polluter pays principle, it is possible to assume a fuel tax as funding source for road traffic CO₂ offset, so that those who emit, drivers, face the cost of compensation. However, this can lead to a sharp increase in fuel costs, up to 22%, with macroeconomic implications. An option to avoid an excessive increase of fuel price is charging only the cost of using afforestation, the most common measure, in this case 50.33 €/t CO₂, which implies 0.13 €/l, 11% of fuel price. The rest of the funds should come from different sources, taking into account the social and ecological advantages of these measures. Agroforestry and agricultural measures should be linked to the aids of the Common Agricultural Policy to promote a more ecological agriculture. Also, it is possible to link State or EU aids for biodiversity improvement. Further, the inclusion of the LULUCF sector in the national GHG accounting by the 2030 EU Climate and Energy Framework (EC, 2015) would make that offsetting road traffic CO₂ emissions in the own country helps to achieve the national emission targets.

The idea of offsetting for unavoidable environmental damage is widely accepted, although in practice limited, because rarely is a legal obligation. Environmental compensation depends on the political will of each country. An example is the compensation of wetland damages established by the United States Clean Water Act of 1972 (GPO, 2016), which has favoured the development of specific mechanisms, such as mitigation banks. Similarly, it would be possible to require compensation of GHG emissions associated with the construction of development projects, or even further, to their operation.

Table 10
Cost of compensatory measures per litre of fuel in different scenarios.

Total CO ₂ emission (kt CO ₂)	Fuel emission (kg CO ₂ /l)	Fuel consumption (Million l)	Compensation scenarios					
			1. Optimizing cost		2. Equitable		3. Most expensive	
			Total cost (Million €)	Cost per litre	Total cost (Million €)	Cost per litre	Total cost (Million €)	Cost per litre
				(€/l) (%)		(€/l) (%)		(€/l) (%)
7669.69	2.601	2948.75	315.85	0.11 8.9	546.68	0.19 15.3	785.00	0.27 22.0

5. Conclusions

Offsetting CO₂ emissions generated by road traffic through LULUCF activities is possible in Central Spain, and probably on other regions and countries; in fact, the potential compensation offer in this area is twice the required for road emissions.

The feasibility of these measures depends on land availability and traffic, and the costs on climate, which determines the growth of the vegetation, and the standard of living, which determines the costs of execution, compensation and incentive. The proposed measures are specifically designed for the study area, and could be extrapolated to a large part of the Mediterranean Region; however, in each case, it is necessary to determine the usable species, their growth and the local costs to calculate the effectiveness and cost of application.

The costs are higher when carbon sequestration, biodiversity improvement and rural development objectives are integrated than when seeking only to maximize the sequestration. However, an integration of all these objectives is a win-win strategy with climate, ecological, social and scenic benefits. There are also important cost differences between measures, with reforestation being the most efficient extensive one, although it should not be the only option.

According to the polluter pays principle, the main source of funding should be a fuel tax, since it is the fuel consumption that results in the emission of GHG in the operation of the roads. Depending on the measures the cost impact on fuel price could be between 9 and 25%. However, taking into account the social and ecological benefits of these actions, it would be logical to integrate other funding channels, such as the Common Agricultural Policy in the EU or government funds for the improvement of biodiversity and landscape, reducing the impact on fuel price.

Consequently, the main challenge is funding, which depends largely on the political will and the awareness of the citizens.

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