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New forests and Kyoto Protocol carbon accounting: A case study in central Italy

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Forest expansion into formerly agricultural land plays a relevant role for generating carbon sinks eligible under afforestation activities in the Kyoto Protocol (KP) carbon accounting framework. This paper provides a methodological framework for the multi-temporal assessment of carbon accumulated in these new forest stands, at the reference years of the KP commitment periods: remote sensing analyses, integrating optical imagery and airborne laser scanning data with field survey, are combined with the carbon simulation model CO2FIX to project carbon changes. The approach is applied to a case study in the central Apennines (Italy) to assess the carbon sink associated to these new forests at the years 2008, 2012 and 2020. The approach is based on forest cover change detection and growing stock mapping, while the multi-temporal carbon sink analysis is performed by means of the CO2FIX model. In the considered test area, the results highlight a compound annual rate of forest expansion equal to 0.26% for the period 1990–2012. The overall carbon stored by the new stands is 21.1 Mg ha^{-1} (relative standard error less than 10%) at the year 2012, projected to reach 33.5 Mg ha^{-1} at the year 2020.

1. Introduction

Countries ratifying the United Nations Framework Convention on Climate Change (UNFCCC) Kyoto Protocol (KP) are given the option to meet part of their reduction requirements through the carbon credits generated by afforestation activities after 1990 (Article 3.3). The protocol allows sinks associated with woodland creation in abandoned farmland to be included in the national carbon accounting system to offset emissions, provided that forest expansion can be considered a direct human-induced conversion of land that has not been forested for a period of at least 50 years (UNFCCC, 2001). The possibility to include afforestation as permissible offset activity holds also for the second commitment period of the KP (UNFCCC, 2011).

Italy has expressed a formal position to include the carbon sinks generated by forest expansion as afforestation activities; such a widespread woodland creation phenomenon is regarded human-induced, as it is a natural dynamic that would not otherwise occur without intentional agricultural land abandonment. This phenomenon, widely observed in rural landscapes in Italy (Barbati et al., 2013; Cimini et al., 2013; Corona et al., 2008; Piussi and Pettenella, 2000), is common to many countries of the global north (Beilin et al., 2014). Yet, only few studies have quantitatively analyzed the implications of forest expansion in terms of creation of new carbon sinks (Acosta et al., 2005; Conti and Fagarazzi, 2004; Gils et al., 2008; Mazzoleni et al., 2004).

To bridge this knowledge gap, this paper addresses as a main scientific question the experimentation of a methodological approach, founded on the integration of forest mapping and inventory (Corona, 2010; McRoberts, 2010) with carbon modelling, to assess carbon accumulated in forest stands naturally originated by forest expansion, at the reference years of KP commitment periods (2008, 2012, 2020). Distinctively, simple remote sensing analyses are combined with the carbon simulation model CO2FIX (Masera et al., 2003) to project carbon changes (Fig. 1). The approach allows wall-to-wall mapping of above ground carbon stock, suitable to support decision-making at various administrative levels, from municipality up to subnational scale.

Under such a perspective, the proposed approach has been tested in a case study in central Italy. The experimental framework builds on three steps: (1) forest cover change detection to quantify natural afforestation in the period 1990-2012 by means of optical

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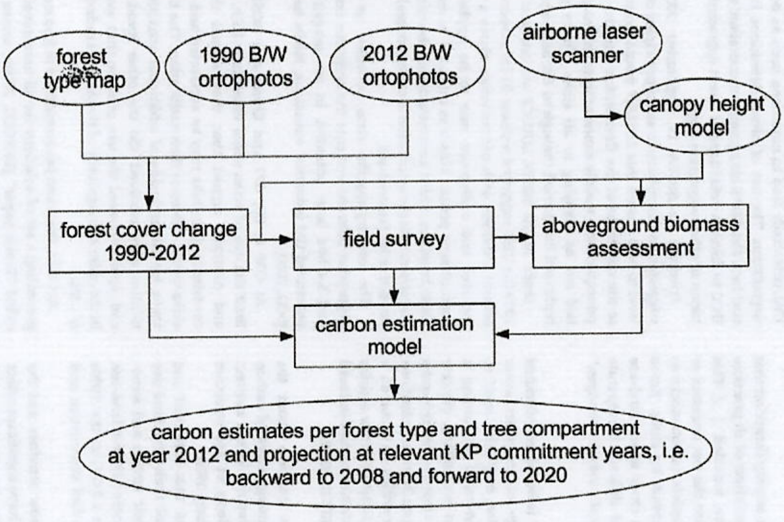

Fig. 1. Methodology approach adopted for the case study.

imagery; (2) above-ground forest carbon stocks estimation in afforested areas at the year 2012, by coupling airborne laser scanning (ALS) data and field survey; (3) estimation of carbon stocks at the years 2008 and 2020 by means of the CO2FIX model. This paper describes and discusses the methodology applied and the results. Highlights on management issues that may become relevant for the second commitment period of the KP are also outlined.

2. Materials and methods

2.1. Study area and available data

The study area is located in the mountain ranges of Gran Sasso e Monti della Laga National Park and covers 26 km^2 (Fig. 2).

Available remotely sensed imagery for the study area was two sets of orthocorrected airborne photos dated 1990 (spring) and 2012 (summer); the 1990 images are black and white one meter/pixel resolution orthophotos, while the 2012 images are half meter/pixel resolution in true-color. A digital terrain model (DTM) and an upper canopy height model (CHM) with pixel size of 1 m^2 were developed from an ALS discrete-return dataset (average data density = 1.5 points m^{-2}; laser wavelength = 1064 nm; light beam width = 1 cm; vertical accuracy = 15 cm) acquired in the spring of 2012.

As further ancillary data, the forest types map of the Gran Sasso e Monti della Laga National Park, dated 2012, was also available; this map adopts the forest definition of the Food and Agriculture Organization of the United Nations (FAO, 2004), with minimum mapping unit of 0.5 ha (nominal scale 1:10,000).

2.2. Forest cover change detection and field survey

Forest cover change in the period 1990–2012 was quantified by the intersection of 1990 and 2012 land cover maps, digitized by on-screen interpretation of the orthophotos. Land cover was mapped into four broad classes: grazing land, forest land, shrub land, other land. The forest class was delineated with a minimum mapping unit of 0.5 ha. The new forest stands at the year 2012 included patches with forest tree vegetation already existing at the year 1990 but whose size was smaller than 0.5 ha at that time.

The National Park forest type (sensu Barbati et al., 2007) map (Fig. 3,Table 1) was applied to stratify the new forest stands, established after year 1990 in the study area, into four physiognomic types: mixed broadleaf forest stands, Turkey oak (*Quercus cerris* L.) stands, European beech (*Fagus sylvatica* L.)

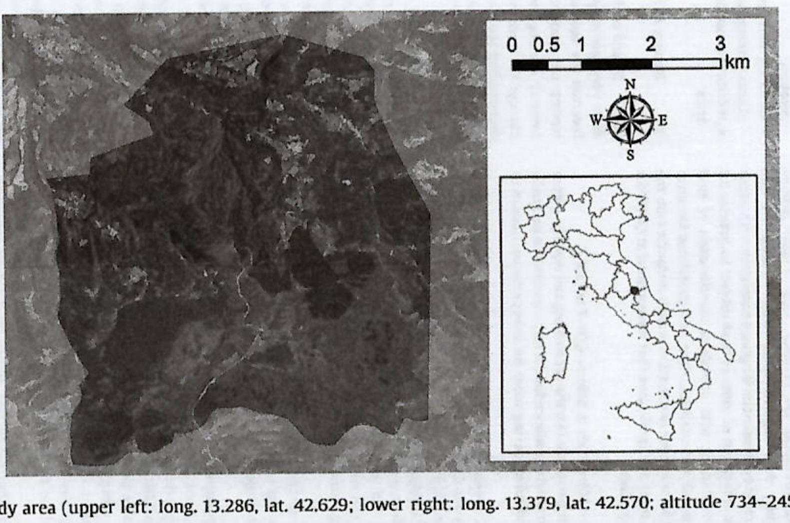

Fig. 2. Study area (upper left: long. 13.286, lat. 42.629; lower right: long. 13.379, lat. 42.570; altitude 734–2458 m a.s.l.).

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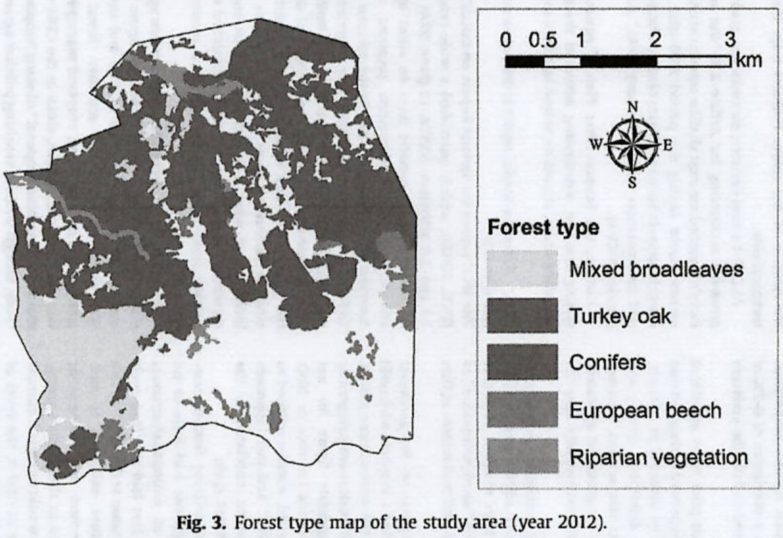

Fig. 3. Forest type map of the study area (year 2012).

stands, and riparian stands. A sample of 22 survey points was selected by stratified random sampling from the population of the newly established forest stands.

The survey points were geo-referenced by GPS post-processing differential correction with an estimated accuracy of the point coordinates ranging from 0.1 to 0.3 m. Field sampling plots, centered on each survey point, were shaped as two concentric circles of radius 6 m and 13 m, respectively. The diameter at breast height of all tree stems falling within the sampling plot was measured, using a minimum threshold of 2.5 cm for the inner circle and 9.5 cm for the outer one. In addition, a random sample of 30 trees, stratified by stem diameter, was chosen on each sampling plot for tree height measurement. The age of each sample plot was established by tree ring analysis, carried out on the cores collected from two tree stems of mean diameter. The growing stock was computed by allometric equations developed for the National Forest Inventory (Tabacchi et al., 2011), having national-wide applicability.

2.3. Above-ground forest carbon stock at the year 2012

The above-ground forest carbon stock at the year 2012 was assessed by integrating ALS data and field plot sampling. ALS data are valuable for the spatial estimation of several dendrometric parameters, including growing stock (Barbati et al., 2009; Corona and Fattorini, 2008; McRoberts et al., 2013; Nilsson, 1996; Parker and Evans, 2004; Ståhl et al., 2014; Wallerman and Holmgren, 2007) and biomass (Dubayah and Drake, 2000; Lefsky et al., 1999; Lim et al., 2003; Means et al., 1999; Naesset, 1997).

Forest growing stock mapping at the year 2012 was carried out through the ALS-based CHM approach proposed by Cartisano et al. (2013). The total growing stock (T_A, m^3) over a given area (A, e.g. the area covered by a given forest type) is estimated as:

$$\hat{T}_A = \hat{k} T_{xA} \tag{1}$$

Table 1
Forest type area at the year 2012.

Forest type	Area (ha)
Mixed broadleaves	300.2
Turkey oak	931.2
Conifers	174.1
European beech	87.3
Riparian vegetation	49.8
Total	1542.6

where

$$T_{xA} = \sum_{j=1}^{N} h_j \tag{2}$$

$$\hat{k} = \frac{\overline{T}}{\overline{P}} \tag{3}$$

with h_j is the upper canopy height provided by the CHM for the j-th pixel; N is the total number of CHM pixels over the given area A

$$\overline{T} = \frac{1}{n}\sum_{i=1}^{n} T_i \tag{4}$$

$$\overline{P} = \frac{1}{n}\sum_{i=1}^{n} P_i \tag{5}$$

where T_i is the growing stock (m^3) measured in the i-th sampling plot, n is the number of sampling plots and P_i is the total of the heights (m) provided by CHM over the set of the CHM (§ 2.1) pixels belonging to the i-th sampling plot.

The standard error of $\hat{T}_A$ is estimated as:

$$\hat{e} = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}\left(cT_i - \hat{k}cP_i\right)^2} \tag{6}$$

where, $c = A/a$, with a equal to the sampling plot size (expressed in the same measurement unit of A).

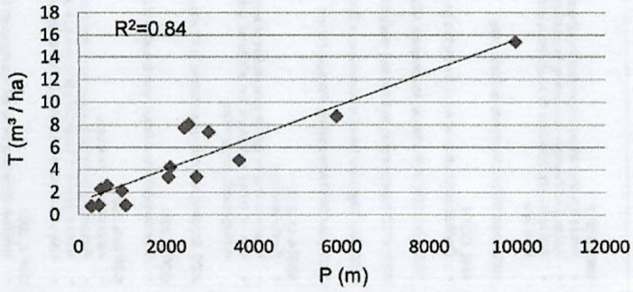

Fig. 4. Relationship between the observed growing stock (m^3 ha^{-1}) and the total of the upper canopy heights (m) provided by the CHM on each sampling plot.

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The approach builds on the general assumption that growing stock is positively correlated with upper canopy height as measured by ALS data (Corona et al., 2012b; Montaghi et al., 2013), which is the case for this study too (Fig. 4).

2.4. Stocks estimates to 2008 and 2020

The carbon sequestration by afforestation projects and forest management can be efficiently assessed through models like CO2FIX (Masera et al., 2003), FullCAM (Richards, 2001), GORCAM (Schlamadinger and Marland, 1996) and Formica (Böttcher et al., 2008). Specifically, the CO2FIX carbon model is characterized by high level of input parametrization and modularity, allowing separate analysis for the carbon compartments and simulation of various management scenarios.

CO2FIX was preferred over the other models because: (a) it does fit the analysis on mixed forests with its "cohort model" approach (Reed, 1980), where the cohort is defined as a group of individual trees or species that exhibit similar growths and are therefore treated as single entities (Alder, 1995); (b) it has a more widespread use than the other models, comparing the number of results of Google Scholar searches; (c) it has a detailed biomass module, based on current increment data.

The CO2FIX projections were here based on the input parameters summarized in Table 2; for each forest type the mean increment (I_m) was computed as:

$$I_m = \frac{\hat{T}_A}{Y_m A} \tag{7}$$

where, $\hat{T}_A$ is the total growing stock (§ 2.3) over a given area (A) and Y_m is the mean age based on the field survey data (§ 2.2). The ages of the expanded forest area was computed as mean age of the sample plots (Table 3).

The model was applied to project the 2012 carbon stock to the other relevant KP commitment years, i.e. backward to 2008 and forward to 2020. For each KP commitment year, the amount of carbon stored in the aboveground biomass pool of new forest stands was computed as balance between prior biomass, biomass increment, mortality and turnover of foliage, branches and roots.

The area of new forest stands was projected backward (2008) and forward (2020) by linear scaling, on the basis of the measured 1990–2012 annual rate of forest expansion.

A couple of input data simplifications was adopted to run CO2FIX with respect to the original model version: (a) the mean volume increment (Eq. (7)) was used instead of the current annual increment; (b) we assumed soil organic carbon and litter carbon equal to zero because of the young age of the considered new forest stands and the lack of reliable local data on soil and litter carbon content on former agricultural land recolonized by forest vegetation. The carbon assessment proposed is therefore conservative: these pools are equivalent to the carbon of the living biomass in many forest biosystems (Krug et al., 2012). According to the Italian National Forest Inventory (Gasparini and Tabacchi, 2011), in central Italy forest soil organic carbon and litter carbon stocks amount in average to 80 Mg ha^{-1} (relative standard error between 4 and 8%, according to the region).

Van der Voet (Nabuurs et al., 1993) reported an uncertainty analysis of the model CO2FIX for the Norway spruce forest type in central Europe. The Author assessed the total carbon stock with a standard deviation of 12% and concluded that the major sources of variability were referable to the litter and humus carbon pools and to the carbon content of dry matter. The sensitivity analysis of Nabuurs et al. (2008) lead to a complete different result: the stem parameters (including the carbon content) had the most influence on carbon stock assessment.

In the present study a very conservative approach was followed, excluding these carbon pools from the analysis and assuming as if forest expansion does not occur in the period 2012–2020. The variability of the growing growing stock is explained by Eq. (6). This parameter is directly related to the mean increment of the stem volume, which is one of the most relevant parameters according to Nabuurs et al. (2008).

3. Results

Forest stands originated by natural afforestation in the period 1990–2012 amount to nearly 90 ha, corresponding to compound annual rate of forest expansion equal to 0.26% (Fig. 5). The new stands are characterized by 41.5% of mixed broadleaves, by 40.8% of Turkey oak, by 16.8% of European beech, and by 0.9% of riparian vegetation. Such new stands show a great diversity of conditions, between and within each forest type, as to density, tree species composition, forest age and growing stock (Table 3), thus revealing a kaleidoscopic pattern of stages of forest succession after farmland abandonment.

The growing stock of these new stands amounts to 7655 m^3 at the year 2012, with an average of 88 m^3 ha^{-1} (standard error = 7.1 m^3 ha^{-1}). The huge ecological variability is reflected by the wide range of average growing stock per forest type (Table 4), from 45 m^3 ha^{-1} (mixed broadleaved forests) up to 120 m^3 ha^{-1} (Turkey

Table 2
Input parameters applied to the CO2FIX biomass module.

Source type	Parameter	Reference	Forest type	Value
Bibliography	Wood basic density (Mg m^{-3})	Giordano (1981)	European beech	0.41
			Turkey oak forest and other forest types	0.69
	Biomass ratio between tree compartment and stem	Brown et al. (2002)	European beech	Foliage: 0.075 Branches: 0.132 Roots: 0.524
		Apadula (2003)	Turkey oak forest and other forest types	Foliage: 0.041 Branches: 0.326 Roots: 0.383
	Mortality rate	Romano et al. (2009)	All forest types	0.0117
This study	Age (years)	Table 3	European beech	17
			Turkey oak	22
			Mixed broadleaves	15
			Riparian formation	26
	Mean increment of the stem volume (m^3 ha^{-1} year^{-1})	Table 4	European beech	6.34
			Turkey oak	4.03
			Mixed broadleaves	2.21
			Riparian formation	1.63

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Table 3
Data summary from field sampling plots.

Parameter	Range	Mean
Mixed broadleaved forest (A=47.7 ha; n=9)		
N (stems/ha)	303–625	525
B ($m^2 ha^{-1}$)	3.9–11.4	7.7
H_m (m)	6.2–11.4	8.7
GS ($m^3 ha^{-1}$)	14.8–49.4	30.9
Age of forest patches (years)	14–18	15.3
Tree species composition (%)		
European black pine	0–23.6	5.9
European silver fir	0–39.1	9.8
European spruce	0–37.3	9.3
European wild pear	0–27.4	6.9
Turkey oak	0–100	59.9
Wild cherry	0–33.1	8.3
Turkey oak forest (A=35.5 ha; n=8)		
N (stems/ha)	926–6603	3272.4
B ($m^2 ha^{-1}$)	11.4–28.1	19.8
H_m (m)	7.6–10.9	9.3
GS ($m^3 ha^{-1}$)	40.1–165.0	103.0
Age of forest patches (years)	18–28	22.4
Tree species composition (%)		
Aspen	0–20.7	3.1
Common hawthorn	0–37.5	6.3
Common hazel	0–70.1	10.0
European wild pear	0–100	16.6
Field elm	0–25.1	3.6
Goat willow	0–1.2	0.2
Turkey oak	0–100.0	56.3
Wild cherry	0–17.9	3.9
European beech forest (A=15.4 ha; n=4)		
N (stems/ha)	196–2113	1437.7
B ($m^2 ha^{-1}$)	2.5–44.8	21.4
H_m (m)	9.5–14.0	10.9
GS ($m^3 ha^{-1}$)	16.7–289.2	131.1
Age of forest patches (years)	10–24	17
Tree species composition (%)		
Aspen	9.5–92.0	45.6
Goat willow	8.0–63.0	39.2
Turkey oak	0.0–43.7	14.6
Riparian forest (A=0.9 ha; n=1)		
N (stems/ha)	–	309
B ($m^2 ha^{-1}$)	–	3.2
H_m (m)	–	8.7
GS ($m^3 ha^{-1}$)	–	16.5
Age of forest patches (years)	–	26
Tree species composition (%)		
European black pine	–	4.6
Field maple	–	4.6
Turkey oak	–	83.1
Wild cherry	–	7.8

A: area of the new forest stands at the year 2012; n: total number of survey points; N: number of stems; B: basal area; H_m: height of the tree of mean basal area; GS: growing stock.

oak). The map of aboveground growing stock (Fig. 6) evidences the relevant spatial variability, with values ranging from 5 to 10 $m^3 ha^{-1}$ up to nearly 300 $m^3 ha^{-1}$ for the oldest and most productive forest patches.

The overall amount of carbon stored in the new forest stands is estimated about 1834 Mg (21.1 Mg ha^{-1}) at the year 2012, with projections to the 2008 and the 2020 KP commitment years amounting, respectively, to 1055 Mg (14.7 Mg ha^{-1}) and 3922 Mg (33.5 Mg ha^{-1}) (Fig. 7).

4. Discussion

4.1. Relevance of new forest stands as carbon stocks

The rate of forest expansion measured in the study area is very close to the national mean in Italy (compound annual rate equal to 0.30%) reported by IUTI (Inventario dell'Uso delle Terre d'Italia) inventory for the years 1990–2008 (Corona et al., 2012a); therefore, data provided by the case study are in line with the magnitude of the phenomenon of woodland expansion that has been occurring on abandoned rural lands in the last decades in Italy. Forest area in Europe has expanded as well during the past twenty years, but at a higher rate: by 0.41% per year in Europe (without Russian Federation), and 1.1% per year in South-West Europe (Forest Europe, 2011).

The carbon stocks generated by afforestation are not negligible; the carbon stored in the above ground biomass of relatively young forest patches, aged from 10 to 28 years, is in the order of 17% (beech) to 40% (mixed broadleaved, Turkey oak, riparian species) of the regional mean stock values of the corresponding forest types estimated by the Italian National Forest Inventory (Gasparini and Tabacchi, 2011). The reliability of the obtained estimates is quite acceptable, since, despite the few field plots, the exploitation of the ALS-derived CHM data as suitable covariates has allowed to keep the relative standard error of the growing stock lower than 10%. The annual carbon sequestration rate is also consistent, around 1 Mg ha^{-1} $year^{-1}$ at the year 2012 and predicted to double by the year 2020.

4.2. Potential of the tested approach

Visual interpretation of very high resolution remotely sensed images was here used to estimate the changes of forest cover. This method has proven accurate for the estimation of forest expansion on a small-scale spatial scale in the study area (Cimini et al., 2013).

The ALS-based approach to assess the forest growing stock in the study area has provided reliable results in terms of accuracy, comparable to previous experiments carried out in Italy (Barbati et al., 2009; Corona et al., 2014a, 2014b). From an estimation point of view, such experiments have shown a linear relationship between the height values provided by CHM and the values of forest growing stock, like in the case here presented. This kind of trend is in accordance with the statistical model of ratio estimation, which has the interesting property of preserving the proportionality parameter at any spatial grain (Corona et al., 2014b). It is worth to be stressed that, at least in Europe, ALS surveys are often committed on large territories by governmental (national or local) administrations for purposes like topographical or hydrogeological investigations, and CHM data are then usually released to the general public at low or no cost (the so called open data): in the light of this, free CHM data represent an effective information source to support forest estimation, even at large scale (Cartisano et al., 2013; Corona et al., 2012b; Montaghi et al., 2013).

The reliability of CO2FIX projections here obtained cannot be assessed against literature data, since, to the best of our knowledge, no comparable results on new natural forest stands are available (probably, most of the results are not published nor are they accessible). However, the obtained carbon figures have the same magnitude of those reported by Phillips (2002) for artificial afforestation in Romania.

5. Final remarks

Afforestation plays a key role in the forest carbon challenge, i.e. under the strategies to increase the total carbon benefits from forest and wood product storage (Kolström et al., 2011). An accurate estimation of the area affected by forest expansion is essential for providing reliable figures on the spatial extent of sinks associated with woodland creation on abandoned farmland. The present case study provides evidence that afforested lands resulting from woodland creation after withdrawal of farming show a complex pattern of forest successional stages and, Alessandrini et al 2016

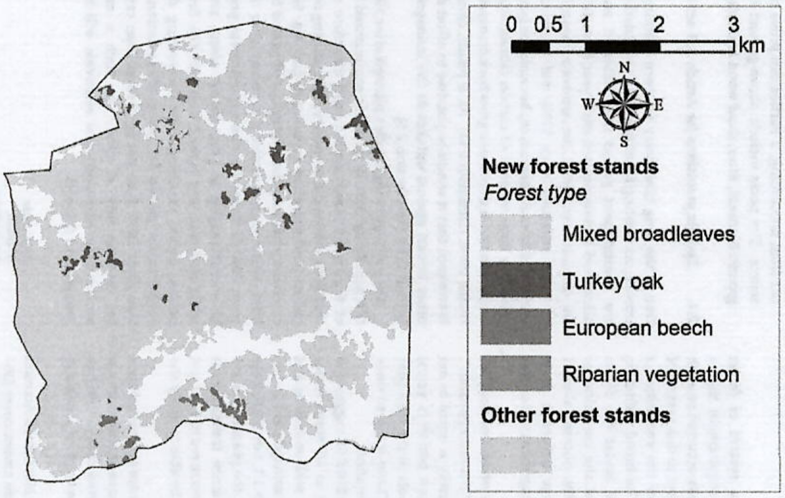

Fig. 5. Forest cover expansion between the year 1990 and the year 2012.

Table 4
Growing stock of the new forest stands at the year 2012.

Forest type	Area (ha)	Total above-ground growing stock (m^3)	Above-ground growing stock per hectare ($m^3\ ha^{-1}$)	Stem growing stock per hectare ($m^3\ ha^{-1}$)	Mean increment of stem growing stock per hectare ($m^3\ year^{-1}\ ha^{-1}$)
Turkey oak	35.3	4250.1	120.4	88.6	4.0
European beech	14.6	1730.1	118.5	107.8	6.3
Mixed broadleaves	36.0	1623.6	45.1	33.2	2.2
Riparian formation	0.9	51.8	57.6	42.4	1.6

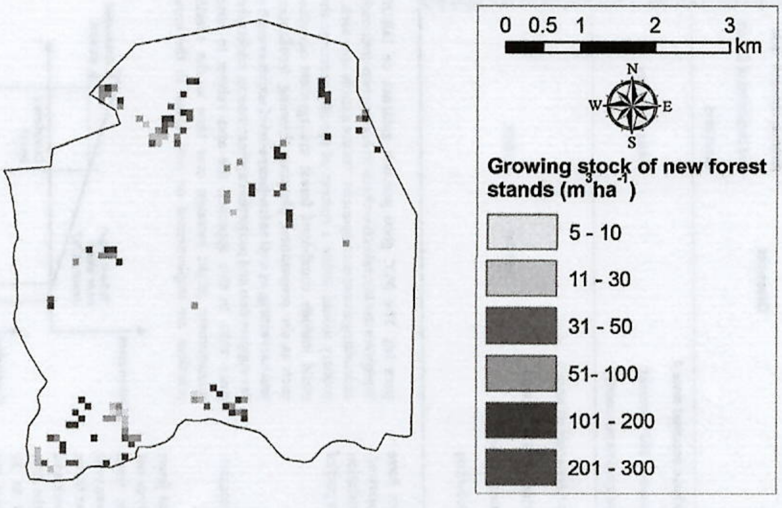

Fig. 6. Growing stock ($m^3\ ha^{-1}$) of the new forest stands in the study area.

accordingly, high variability in the amount of carbon stored in these carbon sinks. In this context, carbon sequestration assessment requires methodologies able to quantify the variability of the key parameters that count for carbon sequestration (size of the new stand, tree species, age, mean annual increment) also linked to the existence of infrastructure, access to skills and services, on a relatively small spatial scale (minimum mapping unit not larger than 0.5 ha).

The tested methodological approach (Fig. 1) is suitable for providing reliable quantification of forest cover change and carbon sequestration in landscapes characterized by afforestation dynamics and to generate projections of future carbon sequestration. Albeit focusing on natural afforestation dynamics specific to Italy, it might be relevant also for countries sharing similar KP reporting requirements, i.e. assessing changes in carbon stocks following afforestation and reforestation activities.

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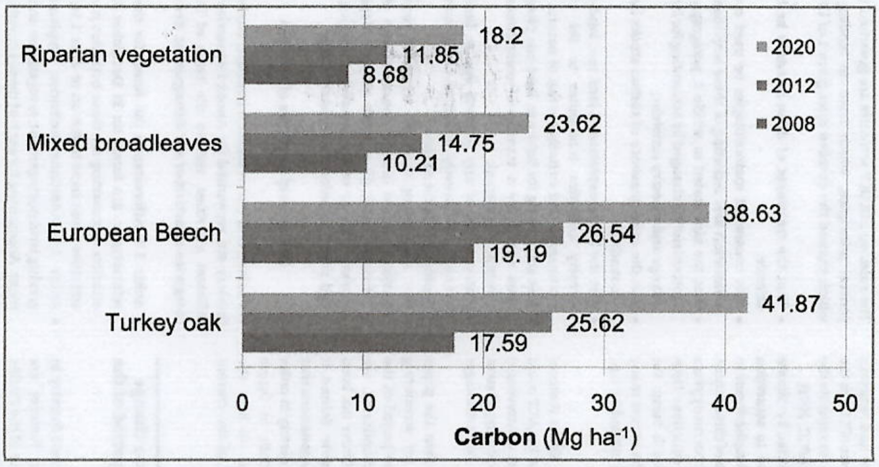

Fig. 7. Estimate of the total carbon amount in the new forest stands, by forest type and reference year.

The approach is not novel as concerns its components (see Fig. 1), but the advancement here proposed is the integrated use of multisource data (ALS data, optical imagery, plot sampling) and the CO2FIX model. The quality of input data represents a critical issue: in the present application, the forest cover change map was derived by on-screen interpretation of high resolution airborne orthophotos, with the support of ancillary data. Future refinements of the methodology will include the implementation of an automatic forest mapping algorithm, in order to achieve improved efficiency in forest cover change detection at larger spatial scales. As far as wood above-ground forest carbon stock assessment is concerned, the main critical point is the field survey, considering the high variability of growing stock within the new forest stands, often associated to small-scale differences in tree species composition. To this end, the methodological framework here tested would require experimentation on other study cases, characterized by different forest types, vertical structures and tree densities. Further methodological development may also consider stratification on unsupervised classification maps, based on data fusion between ALS and multi-spectral satellite data.

A general lack of active forest management was observed in the considered new forest stands; this may constitute a threat if carbon credits generated by afforestation are used to meet reduction requirements in the next application phase of KP politics. In fact, the absence of early thinning in these dense stands may increase the risk of forest fires and may have negative implications in terms of provision of wood products; this last issue deserves attention for the second commitment period of the KP, as the life cycle of carbon stored in harvested wood products is expected to count for national carbon inventories. From the management point of view, one of the most serious threats may be the spread of disturbances, especially wildfires; this might jeopardize the natural capital accumulated in few decades: not only carbon credits, but ecosystem services related to the conservation key resources such as soil and water. Future incentive policies of forest management with a landscape planning approach may both decrease these risks for carbon long-term accounting and enhance the ecosystem services of forests.

In this perspective, the tested approach, by providing accurate spatial information on the variability of tree density, species composition and growing stock, can be an effective tool even for the zoning of the incentives and the simulation and assessment of alternative options for sustainable management of afforestations.

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