Assessing the carbon sink of afforestation with the Carbon Budget Model at the country level: an example for Italy

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In the context of the Kyoto Protocol, the mandatory accounting of Afforestation and Reforestation (AR) activities requires estimating the forest carbon (C) stock changes for any direct human-induced expansion of forest since 1990. We used the Carbon Budget Model (CBM) to estimate C stock changes and emissions from fires on AR lands at country level. Italy was chosen because it has one of the highest annual rates of AR in Europe and the same model was recently applied to Italy's forest management area. We considered the time period 1990-2020 with two case studies reflecting different average annual rates of AR: 78 kha yr^{-1}, based on the 2013 Italian National Inventory Report (NIR, official estimates), and 28 kha yr^{-1}, based on the Italian Land Use Inventory System (IUTI estimates). We compared these two different AR rates with eight regional forest inventories and three independent local studies. The average annual C stock change estimated by CBM, excluding harvest or natural disturbances, was equal to 1738 Gg C yr^{-1} (official estimates) and 630 Gg C yr^{-1} (IUTI estimates). Results for the official estimates are consistent with the estimates reported by Italy to the KP for the period 2008-2010; for 2011 our estimates are about 20% higher than the country's data, probably due to different assumptions on the fire disturbances, the AR rate and the dead wood and litter pools. Furthermore, our analysis suggests that: (i) the impact on the AR sink of different assumptions of species composition is small; (ii) the amount of harvest provided by AR has been negligible for the past (< 3%) and is expected to be small in the near future (up to 8% in 2020); (iii) forest fires up to 2011 had a small impact on the AR sink (on average, < 100 Gg C yr^{-1}). Finally the comparison of the historical AR rates reported by NIR and IUTI with other independent sources gives mixed results: the regional inventories support the AR rates reported by the NIR, while some local studies suggest AR rates somehow intermediate between NIR and IUTI. In conclusion, this study suggests that the CBM can be applied at country level to estimate the C stock changes resulting from AR, including the effect of harvest and fires, though only a comparison with results based on direct field measurements could verify the model's capability to estimate the real C stock change.

Keywords: Afforestation, Reforestation, Carbon Budget Model, Italy, INFC, IUTI

Introduction

In the context of the Land Use, Land-Use change and Forestry (LULUCF) sector of the Kyoto protocol (KP), Afforestation and Reforestation (AR) refers to the direct human-induced conversion of non-forested land (not containing forest on 31 December 1989) to forested land. Specifically, afforestation refers to land that has not been forested for a period of at least 50 years and reforestation for less than 50 years (UNFCCC 2005). Since the same reporting and accounting rules apply to both activities, they are typically treated together (IPCC 2003, 2013).

For the first commitment period of the KP (2008-2012) the accounting of emissions and removals from AR is mandatory for Annex I (so-called developed) countries, *i.e.*, all the carbon (C) stock changes in the five pools (above- and below-ground living biomass, dead wood, litter and soil) and the non-CO$_2$ greenhouse gas (GHG) emissions contribute to the emissions reduction targets by countries. The recently agreed new LULUCF rules (UNFCCC 2011), confirmed the mandatory accounting of AR for the second commitment period of the KP (2013-2020) and introduced important changes (Grassi 2012), including the possibility to exclude from the accounting the emissions and removals related to natural disturbances on forest and AR lands, provided that the respective requirements are met.

Many studies have provided estimates on the C stock changes for Forest Management (FM, *i.e.*, forest existing before 1 January 1990) or for the total forest area at both local (Mund et al. 2002, Masera et al. 2003), national (Karjalainen et al. 2002, Stinson et al. 2011, Pilli et al. 2013) and multi-national scale (Böttcher et al. 2012). For AR, while several studies analyzed C stock changes at the stand or local level (Thuille et al. 2000, Masera et al. 2003, Hoogmoed et al. 2012), extensive estimates based on direct field measures at the country level are lacking.

The contribution of AR removals to the GHG emission reduction targets may, however, be significant and - according to the country reports to the KP - it can be even more important than FM (Grassi et al. 2012). For instance, during 2008-2012 AR offset about 1% of total EU 1990 GHG emissions (EU 2013), and at least a similar contribution is expected for 2013-2020 (Grassi et al. 2012). For this reason, and given the increased reporting requirements set by the new LULUCF rules, a closer look at the emissions and removals from AR lands at the country level is useful from both a scientific and a political perspective.

The main objective of this study was to estimate the stock changes of the five forest C pools for the period 1990-2020, for AR lands and at country level. To this purpose we applied the Carbon Budget Model (CBM) developed by the Canadian Forest Service (Kurz et al. 2009) to AR lands of Italy. Two case studies for AR area were conducted, based on different literature data (Italy 2013, Corona et al. 2012, Marchetti et al. 2012). Italy was considered a good country case-study because it has one of the highest annual rates of AR in the EU and because the same CBM was recently applied to
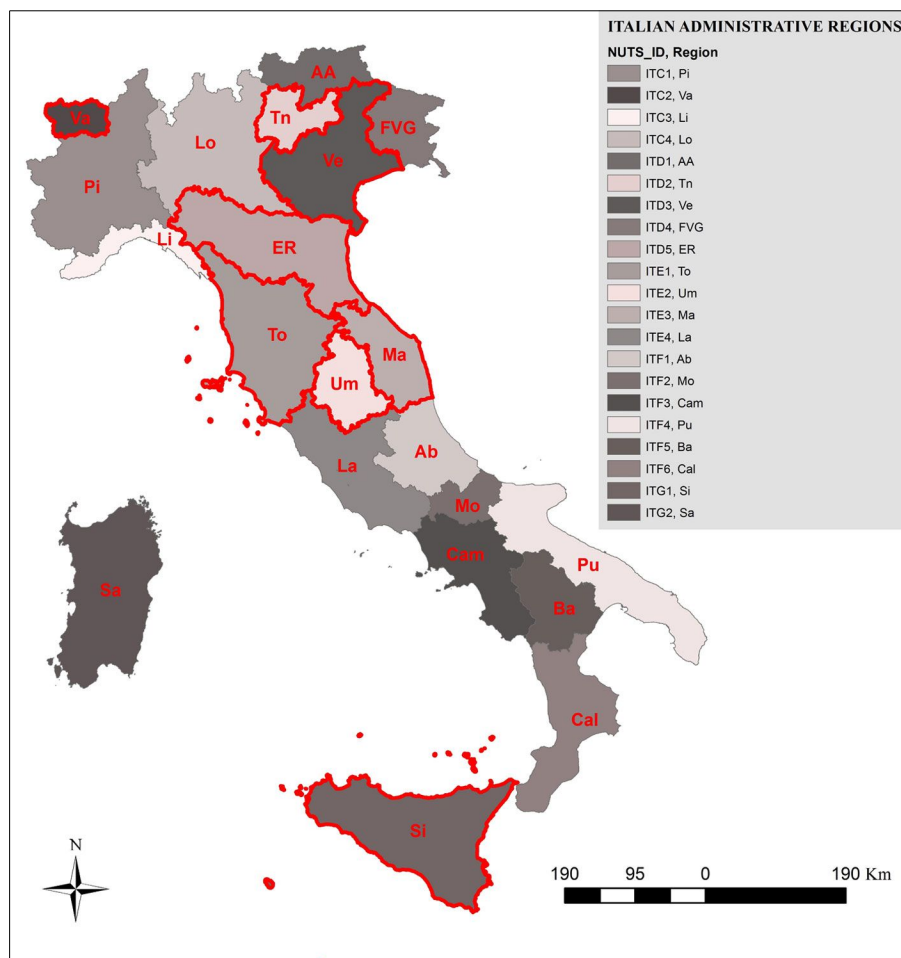
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Fig. 1 - Italian administrative regions and NUTS2 code (*i.e.*, Nomenclature of Territorial Units for Statistics). Regions highlighted by red borders were used to compare national data with regional forest inventories.

the FM area of this country (Pilli et al. 2013). Additional specific questions addressed by this study related to: (i) the impact on the AR sink of different assumptions about species composition (often not well known for many European countries) of AR areas; (ii) the potential contribution of harvest from AR lands, relative to the total harvest at the country level; (iii) the impact of forest fires on the AR sink; (iv) the comparison of AR rates estimated by the two case studies with independent sources (eight regional forest inventories and three local studies).

Materials and methods

Case studies for AR annual rates

Following the relevant IPCC guidance (IPCC 2003, 2006, 2013), to be eligible for AR activities an area of land needs to satisfy a number of criteria, including: (i) the country's definition of forest was not met on 31 December 1989; (ii) trees are growing as a result of direct human-induced activity; and (iii) the trees meet or have the potential to meet the country's definition of forest at maturity.

According to the Italian National Inventory Report (NIR) submitted to UNFCCC and its Kyoto protocol (Italy 2013, 2014), Italy adopted a broad definition of AR, *i.e.*, assuming that AR included all forest expansion after 31 December 1989, including plantations and abandoned pastures and arable lands where forest expanded naturally. In this paper we do not address the criteria to be fulfilled to demonstrate that AR activities are "directly human-induced" (see IPCC 2013, section 2.5).

Until 2013, poplar plantations (considered cropland according to Italian laws) were excluded from AR (NIR 2013); the last Italian NIR (2014), submitted to UNFCCC on 15th April 2014, included poplar plantations under AR activities. All these lands are considered legally bound by national legislation, even prohibiting clear cut activities on these forests (Italy 2013, 2014). Therefore, in Italy the area under AR in the year i (AR_i) is given by the difference between the total forest area in that year (For_i) and the forest area existing by 31 December 1989 (*i.e.*, the FM

area - For_{FM}), minus the total deforestation since 1990 (D_T - eqn. 1):

$$AR_i = For_i - For_{FM} - D_t$$

Due to the lack of data, the annual rate of deforestation occurring on AR cannot be estimated. According to the 2013 Italian NIR (Tab. 7.3 - Italy 2013), between 1990 and 2011 deforestation affected on average about 0.72 kha yr^{-1} (the NIR 2014 reports a higher annual rate of deforestation after 2004).

The estimates of the forest expansion can be provided by two different data sources: the Italian NIR and the Italian Land Use Inventory System (IUTI 2010, Corona et al. 2012, Marchetti et al. 2012). These two data sources were the basis for the two cases study analyzed below.

As first data source, we used the official estimates reported by Italian NIR in 2013 (Italy 2013). In this case (named "official estimates"), based on a total rate of afforestation equal to 1479 kha between 1990 and 2008 (as reported by Tab. 10.10 - Italy 2013), we estimated an average annual rate of AR between 1990 and 2005 equal to 77.8 kha yr^{-1} (this value is consistent with the annual rates of AR reported by Tab. 7.3 - Italy 2013), assumed as a constant annual rate (excluding deforestation). On the 15th April 2014, Italy submitted the 2014 NIR, reporting a total rate of afforestation equal to 1436 kha between 1990 and 2008 and a slightly lower AR (compared to the previous NIR) equal to 75.6 kha yr^{-1} (this value was not considered by the present study).

The value reported in the NIR derives from a linear interpolation between the 2005 total forest area estimated by the last National Forest Inventory (NFI: Italian National Forest and Carbon Inventory, named INFC - Gasparini & Tabacchi 2011), and the first NFI, which refers to 1985 (MAF-ISAFA 1988).

The INFC forest area was equal to about 8759 kha (with a standard error SE = 0.4%) and was based on the FAO-FRA 2000 forest definition (*i.e.*, a minimum forest size equal to 0.5 ha and a crown cover greater than 10% - FRA 2000). The sampling design of the INFC was based on a three-phase inventory. In the first phase, 301 300 sampling points were classified by land-cover/land-use classes through ortophoto interpretation (Tabacchi et al. 2005). In the second phase, a subsample was randomly selected from forest and other wooded land strata, according to the proportion of the land-cover class reported in the 21 Italian administrative regions (Fig. 1). In this phase, approximately 30 000 sample points were surveyed in the field: (i) to verify the previous classification; (ii) to discriminate forest from other wooded land; (iii) to identify different forest types (Fts); and (iv) to collect information on other

the visual interpretation of a set of multi-temporal aerial orthophotos (1990, 2000, 2008 and 2012). Six land-use classes (settlements, cropland, forest land, grassland, wetland and other lands) were detected on geo-referenced points with no field surveys (Corona et al. 2012). The forest land definition applied by IUTI was consistent with both the FAO-FRA2000 (FRA 2000) and the INFC forest definitions (see Tab. 4). Moreover, 301 300 out of 1 206 000 sampling points used by IUTI coincide with the points used in the first phase of the INFC.

According to Marchetti et al. (2012) the total forest land area (excluding all plantations and other wooded lands) increased from 9141 kha (A_{1990}, SE=0.1%) in 1990 to 9470 kha (SE=0.1%) in 2000 and to 9653 kha (A_{2008}, SE=0.1%) in 2008 (Fig. 2, left panel). Based on these data the annual average rate of afforestation was 33 kha yr^{-1} (AR_1) between 1990 and 2000 and 23 kha yr^{-1} (AR_2) between 2000 and 2008 (see Fig. 2, right panel). The regional distribution of these values, applied to the second case study and reported in Tab. 1, can be derived from the data reported by Corona et al. (2012). The figures reported for the period 2000-2008 were assumed constant until 2020.

Estimation of carbon stock changes

The Carbon Budget Model

To estimate the C stock change on AR lands, we used the Carbon Budget Model (CBM) developed by the Canadian Forest Service (Kurz et al. 2009). The model was recently applied to the Italian forests in order to estimate the C sink of the FM area since 1995. The application of the CBM to Italian forests is described in detail by Pilli et al. (2013) and only essential details are summarized below.

The CBM is an inventory-based (*i.e.*, it is based on the information commonly reported by national forest inventories, NFIs), yield-data driven (*i.e.*, the estimates are mainly driven by yield data provided by the user) model that simulates the stand- and landscape-level C dynamics of above- and below-ground biomass, dead organic matter (DOM: litter and dead wood) and mineral soil. The main input data required by model are:

1. The area, further distinguished by age classes, main species and management types (*i.e.*, coppices, even-aged high forests, uneven-aged high forests, etc.). Since the present study focuses on AR, we do not need to define any preliminary age class distribution and management type, but only the forest composition of the afforested area.

2. The gross merchantable volume production by age classes, main species and (eventually) management types, defined by yield tables (YTs) provided by the user. These data represent the stand-level volume accumulation in the absence of natural disturbances and management practices. Tables can be directly inferred by the volume and increment data provided from NFIs or from the literature.

The present study focuses on young (less than 30 years old) forests. However, the INFC reports increment and volume data for the age classes < 20 years for only 39 out of 253 groups of forest types and regions. We

therefore derived the YTs library from a large species-independent database (Pilli et al. 2013), including about 1460 equations derived from the European forest yield tables database (AFOLU database - Teobaldelli et al. 2007) and from an Italian literature review (Castellani 1982). Because these tables were based on direct field measurements, we assumed that they can also adequately represent the evolution of standing volume in young stands, where inventory data are missing and silvicultural tretaments generally have a lower impact. We selected the equation having the minimum relative difference from the average volume per hectare reported in the INFC (considering the entire range of available age classes) for each FT and region. These equations were used to compile the YTs library applied during the model run, including 90 different YTs, based on the volume reported by INFC and the equations derived by the species-independent database.

The CBM spatial framework conceptually follows Reporting Method 1 (IPCC 2003) where, for the purpose of estimation and reporting, the spatial units (SPUs) are defined by their geographic boundaries and all forest stands are geographically referenced to SPUs. The intersection between the administrative and ecological boundaries (defined as Climatic Units in case of Italy) yielded 168 unique SPUs (Fig. 3).

In the present study, we considered 21 administrative units, 24 climatic units (CLUs), as defined by Pilli (2012), and 17 forest types (FT, reported in Tab. 2), assumed as pure forests according to the main species reported by INFC (detected from the Tab. 7.16-7.32 reported by Gasparini & Tabacchi 2011). Assuming all the FTs as pure forests, may be a quite rough assumption but in many cases the natural expansion of forests is driven (at least in the first stage) by few species with a higher seed dispersal capacity (*i.e.*, pioneer species - Oldeman 1990) and this process may favor the formation of almost-pure forest stands (see Tab. 2 and the following section).

Specific equations were selected to fit the species-specific values of biomass reported in the INFC and to convert the merchantable volume into aboveground biomass (Boudewyn et al. 2007). A detailed analysis on the calibration of stand level equations is reported by Pilli et al. (2013, Appendix D). Belowground biomass was calculated using the equations provided by Li et al. (2003) and the annual dead wood and foliage input was estimated as a percentage applied to the standing biomass stock (Kurz et al. 2009).

To estimate the decomposition rate of each DOM pool, the base decomposition rates defined at 10 °C for each pool is adjusted in the CBM based on the mean annual temperature in each SPU. For forested lands, DOM pools (dead wood and litter) and soil are ini-
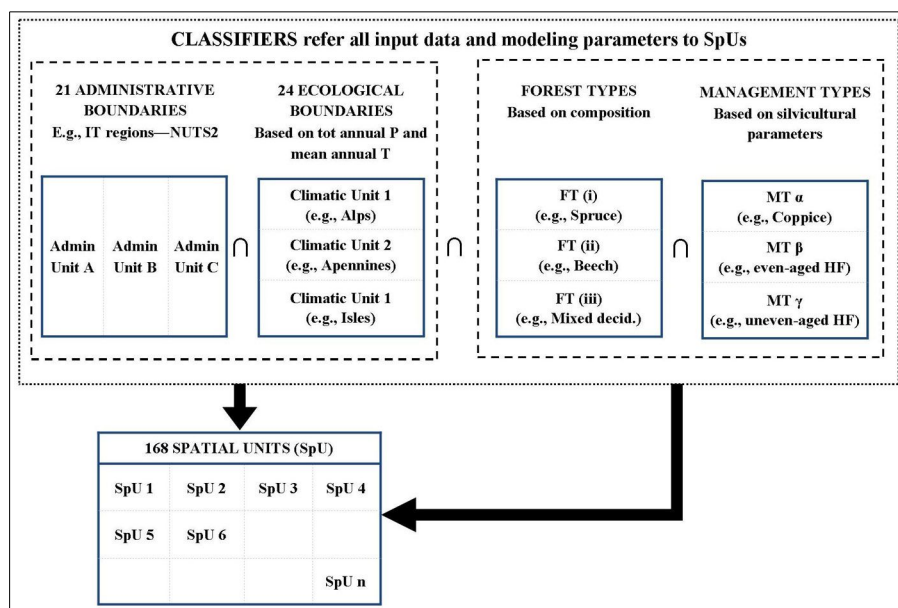

Fig. 3 - Schematic representation of the main input data required by CBM in order to define the Spatial Units (SPUs). The dashed line identifies the general classifiers and the dotted line delimits the information provided by the forest inventory, split between each SpU (by Pilli et al. 2013).

tialized using a procedure that takes into consideration site productivity, temperature-dependent decomposition rates and disturbance history (Kurz et al. 2009).

For the initialization of the non-forested lands, the user can define the initial C content (before afforestation) of the living biomass (*i.e.*, merchantable, foliage, roots, etc.) and DOM pools.

Forest expansion in Italy is mainly related to process of natural re-colonization of abandoned areas (Corona et al. 2005, De Natale et al. 2007, Dalla Valle et al. 2009), moving from grasslands or pastures to forested lands, through the progressive establishment of tree species. Therefore, for the initialization of the non-forested lands we assumed that:

1. the initial soil C stock was equal to the average soil C content of grassland, *i.e.*, 78.9 Mg C ha^{-1} as reported by the Italian NIR (Italy 2013);

2. the average C stock of the living biomass sub-pools before AR was equal to 3% (*i.e.*, a total living biomass C stock equal to 2 Mg C ha^{-1}) of the average C stock estimated by CBM for the FM area between 1995 and 2010, as reported by Pilli et al. (2013).

The user can define annual natural and anthropogenic disturbances such as fire, insects or storms and partial or clear-cut harvesting which may be applied during the model run (Kull et al. 2011). Afforestation and deforestation can be represented as disturbance types with their own disturbance matrices and transitions to and from forest land.

The model provides annual predictions on C stocks and fluxes, such as the annual C transfers between pools, from pools to the atmosphere and to the forest product sector, as well as ecological indicators such as the net primary production. The model also reports land areas and C pools in the appropriate UNFCCC and KP land categories.

Model scenarios

The annual rate of afforestation reported in Fig. 2 - and distributed at the regional level according to Tab. 1 - was further distributed for both case studies between 17 FTs (see Tab. 2). Due to the different classification systems, the forest composition reported by the two inventories is not comparable. The proportion of each FT at regional level was therefore based on the FT distribution reported by INFC, taking into account the following considerations:

1. The total forest area detected by INFC can be distinguished between different management types (defined according to the silvicultural system and the forest structure): coppices (further distinguished between simple coppice, coppice with standards, coppices in transition to high forests, etc.), even-aged high forests, uneven-aged high forests, not-defined class and not-classified

Tab. 2 - Main species associated to each forest type (FT), seed dispersal capacity assigned to each FT (1: anemochory/wind-dispersed species; 0: non-anemochory species; 0.5: mixed groups of species), light tolerance index based on Ellenberg & Leuschner (2010) and the total weighting factor (equal to the sum of the previous indexes) assigned to each forest type.

Main species	FT	Seed dispersal capacity	Light tolerance	Weighting factor
Larch and stone pine forests	LD	1.0	1.0	2.0
Norway spruce forests	PA	1.0	0.5	1.5
Silver Fir forests	AA	1.0	0.0	1.0
Scots pine and Mountain pine	PS	1.0	1.0	2.0
Black pine forests	PN	1.0	1.0	2.0
Mediterranean pine forests	PM	0.0	0.5	0.5
Other coniferous forests	OC	0.5	0.5	1.0
Beech forests	FS	0.0	0.5	0.5
Oak forests (*Quercus* spp.)	QR	0.0	1.0	1.0
Turkey Oak forests	QC	0.0	1.0	1.0
Chestnut forests	CS	0.0	0.5	0.5
Hornbeam forests	Oca	1.0	0.5	1.5
Riparian forests	RF	1.0	1.0	2.0
Mixed deciduous broadleaved forests	OB	0.5	0.5	1.0
Holm oak forests	QI	0.0	0.5	0.5
Cork oak forests	QS	0.0	0.5	0.5
Other evergreen forests	OE	0.5	0.5	1.0

for the management type/system forest area (see Table 7.4 in Gasparini & Tabacchi 2011).

2. We assumed that the new forests detected during the field measurements of the INFC should have been included in the not-defined class (INFC 2004). Indeed, (i) the areas classified as coppice (3673 kha and 3663 kha reported by the first and the second NFIs, respectively) and even-aged high forest (1176 kha and 1509 kha, reported by the first and the second NFIs, respectively) by the two inventories are similar; (ii) the area reported in the not-defined class by INFC (*i.e.*, about 886 kha, also including some other forests types), covers about 55% of the total forest area established between 1985 and 2005 (*i.e.*, about 1600 kha); the remaining amount of natural forest expansion (about 757 kha) was probably reported as not-classified for the management type/system or under some

other category (*i.e.*, uneven-aged high forests).

3. The original FTs percentage distribution estimated at the regional level and based on the not-defined plus not-classified forest area was applied to the annual rates of AR defined for the official estimates, as a first possible share of species. This distribution, named "FT distribution 1", was used to test the effect of the species composition on the model output.

4. Since the previous forest area (*i.e.*, not-defined + not-classified group) also included some FTs with a low seed dispersal capacity, such as beech and chestnut, we further corrected the FT distribution 1 according to a weighting factor (*i.e.*, a multiplier applied to the original distribution) based on the seed dispersal capacity and the light tolerance of each species (Tab. 2). This correction generally increased the share of larch and conifers and reduced the share of
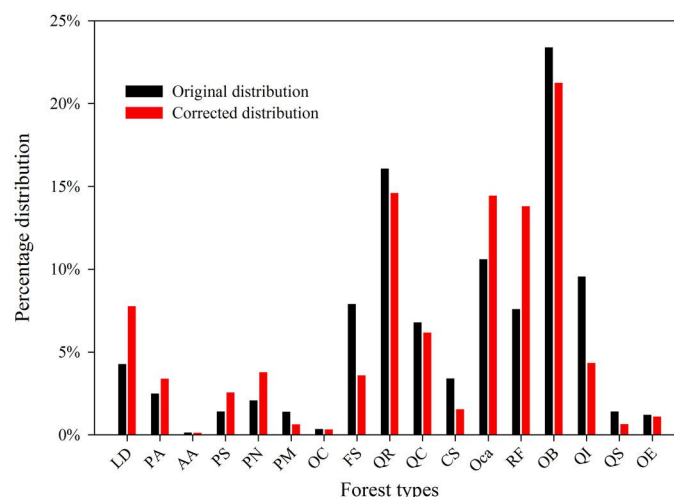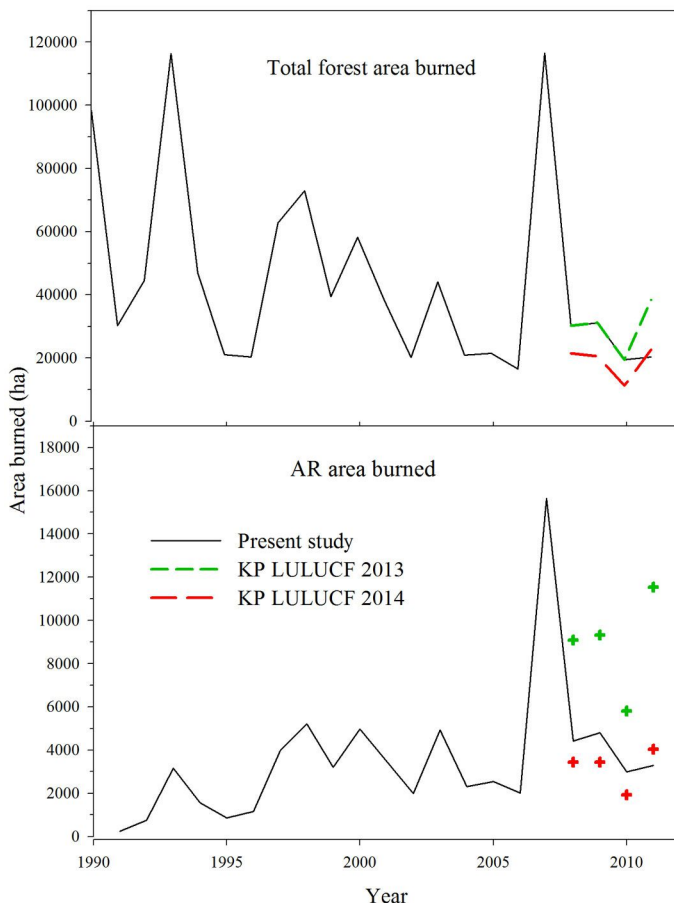

Fig. 4 - Comparison between the FT distribution 1 (based on the FT distribution of the INFC not-defined plus not-classified forest area) and the FT distribution 2 (based on the previous distribution corrected according to the weighting factors reported in Tab. 2) percentage distribution at national level. The FTs acronyms are reported in Tab. 2.

Fig. 5 - (Upper panel): total amount of area burned (black line) reported by official statistics (CFS 2010, 2012) and used by our study to estimate the amount of AR area burned between 1990 and 2011, applied during the model run in official estimates (black line on the lower panel). The upper panel also highlights the total amount of area burned reported by the KP LULUCF tables submitted to UNFCCC in 2013 (green line) and 2014 (red line). The lower panel highlights the AR area burned reported by the KP LULUCF tables submitted to UNFCCC in 2013 (green points) and 2014 (red points).

beech and chestnut (Fig. 4). The resulting FT distribution 2 was applied to the annual rate of AR defined in both case studies. A comparison between the FT distribution 1 and 2 is reported in Fig. 4.

To provide an estimate of the future potential C sink related to AR, the model was run to 2020, assuming a constant annual rate of afforestation between 2011 and 2020 (see Fig. 2). Since our study focuses on AR, deforestation was not considered. Two additional disturbances were applied to the new forest area:

(1) We estimated the potential (*i.e.*, maximum) C stock of harvested wood products provided by AR: we applied a 15% commercial thinning rate to conifer forests older than 20 years, and a 20% commercial thinning rate to broadleaved forests older than 15 years. According to Italian law, no clearcut activity was applied to these forests (Italy 2013).

(2) Since fire is the main natural disturbance affecting Italian forests (Italy 2013), we estimated the amount of afforested area affected by fire for each *i*-year (*Burned_AR*ᵢ) as follows (eqn. 3):

$$Burned \_ AR_i = Fire_i \cdot \frac{Tot \_ AR_i}{FM_{1990} + Tot \_ AR_i}$$

where *Fire*ᵢ is the total amount of forest area affected by fires (in ha) reported at the national level (CFS 2010, 2012), *Tot_AR*ᵢ is the total amount of afforested area in *i*-th year (*i.e.*, the cumulative AR area since the base year) and *FM*₁₉₉₀ is the forest management area in 1990 (the base year), equal to 7450 kha in official estimates. Even if specific data on the amount of area affected by fire at

regional level are available, to be consistent with the approach applied for the FM area, the total amount of area burned each year (reported in Fig. 5) was distributed between different regions, forest types and climatic units, according to the assumptions reported by Pilli et al. (2013). This approach was applied to the data reported in official estimates for the period 1990-2011.

A summary of the different scenarios analyzed by CBM is reported in Tab. 3.

Results and discussion

Carbon stock changes of AR land

The C stock change estimated by CBM is reported in Fig. 6. The total C stock change estimated in 1991 (*i.e.*, at the first time step) applying the FT distribution 2 was equal to 191 Gg C yr⁻¹ and 77 Gg C yr⁻¹, using the official and the IUTI estimates, respectively. Excluding the effect of harvest, in 2011 these values grow to 2418 Gg C yr⁻¹ (official estimates) and 870 Gg C yr⁻¹ (IUTI estimates). Between 1990 and 2011, with a total amount of afforestation equal to 1640 kha (official estimates) and excluding any disturbance (*i.e.*, no harvest and no fire), the living biomass stock (aboveground and belowground) increased on average to 957 Gg C yr⁻¹ (0.58 Mg C ha⁻¹ yr⁻¹), dead wood, litter and soil increased on average to 179 Gg C yr⁻¹ (0.11 Mg C ha⁻¹ yr⁻¹) and the resulting total increase was 1136 Gg C yr⁻¹ (0.69 Mg C ha⁻¹ yr⁻¹). Applying the FT distribution 1 to official estimates and excluding any disturbance, we detected a negligible percentage difference with the FT distribution 2, equal to about 0.6% of the living biomass stock.

As expected, using IUTI estimates (excluding harvest and fire) with a total amount of afforestation in 2011 of 579 kha, we estimated a lower average C stock change of 370, 63 and 433 Gg C yr⁻¹ for the living biomass, DOM and soil and total pools, respectively. This last figure is about 60% lower than the value from the official estimates.

Assuming a constant annual rate of AR after 2012 and excluding disturbance events, CBM estimated a total C stock change in 2020 equal to 3839 and 1298 Gg C yr⁻¹ in official estimates (AR = 78.8 kha yr⁻¹) and IUTI estimates (AR = 22.9 kha yr⁻¹), respectively. Applying the FT distribution 1 to official estimates, we still detected a negligible percentage difference (1.5%) with the FT distribution 2 for the living biomass stock in 2020.

Adding the effects of the potential harvest provided by AR land to these runs, the 2020 total C stock change decreased to 3237 and 1065 Gg C yr⁻¹, using the official and IUTI estimates, respectively. The total amount of harvest provided using the official estimates increased from about 325 400 m³ in 2005

Tab. 3 - Summary of the scenarios analyzed by CBM, based on different assumptions about the annual rate of AR (case studies 1 and 2), FT distribution (Original and Corrected) and disturbance events (potential harvest and fire).

AR assumptions	Case study	FT share	Harvest	Fire
NIR	1	Corrected	No	No
NIR	1	Original	No	No
NIR	1	Corrected	Yes	No
NIR	1	Original	Yes	No
NIR	1	Corrected	Yes	Yes
IUTI	2	Corrected	No	No

Fig. 6 - C stock change (Gg C yr⁻¹) estimated by CBM for official estimates (based on the NIR's assumptions) and IUTI estimates (based on the IUTI's assumptions). The figure reports the (i) living biomass, (ii) litter, dead wood (DOM) and soil, and (iii) total C stock change, excluding disturbances (no harvest and no fire) and including the potential amount of harvest provided by AR (reported in the right panels in Gg of dry matter yr⁻¹). The vertical dotted line in the left panels divides historical data (before 2011) and the future AR rate used in our study.
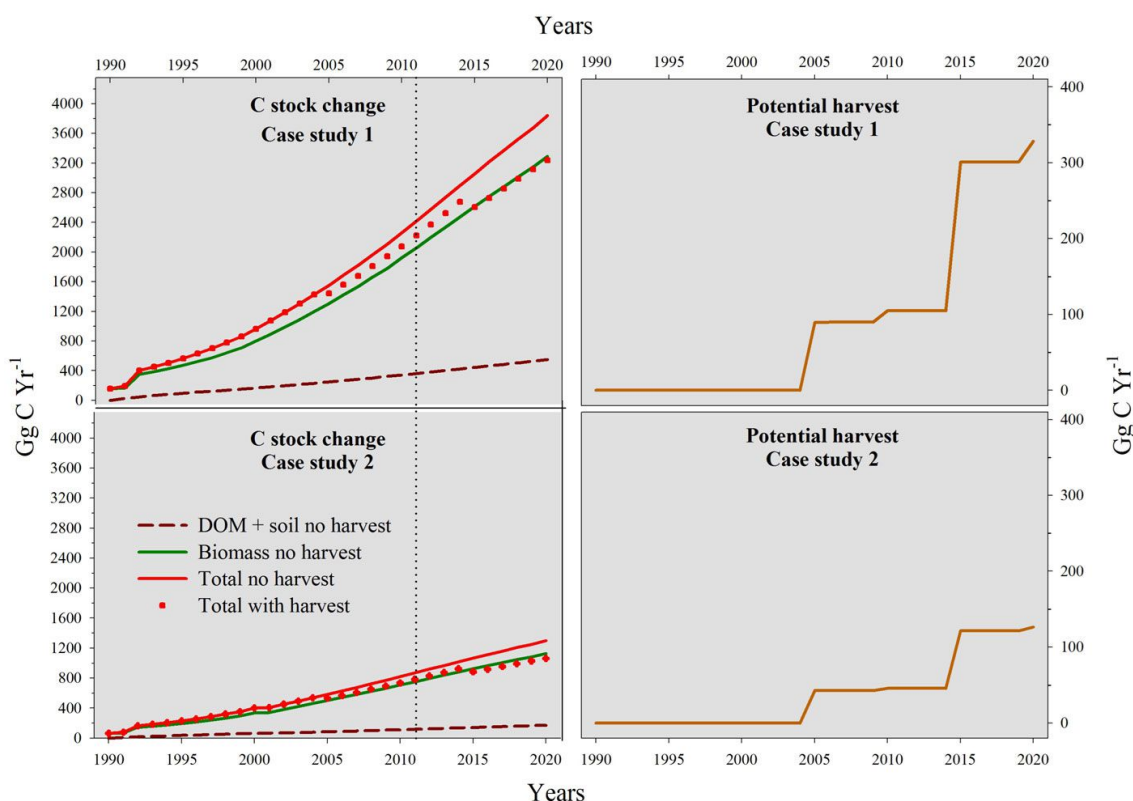
(totally provided by broadleaves) to about 1 200 000 m³ in 2020. Due to our assumptions, about 85% of this amount was provided by broadleaves in 2020. This highlights that the silvicultural treatments applied to the new forest lands, excluding any kind of clearcuts, may decrease the potential 2020 C stock change by about 15-17% compared to the runs with no disturbance.

This effect was null before 2004 (Fig. 6, right panels) since we assumed that stands younger than 15 years were not affected by harvest. The harvest considerably increased after 2010, when new conifers stands (older than 20 years) were affected by commercial thinnings. In 2015 a second thinning was applied to the broadleaves area afforested in 1990 (*i.e.*, 25 years old in 2015): this area had a first thinning in 2005, when it was 15 years old and, based on our assumptions, the same area may have a second thinning after 10 yrs. (*i.e.*, in 2015). Since the annual rate of AR was constant between 1990 and 2005, during the following 5 years the same amount of area is available (every year) for a second thinning applied to broadleaves. In 2020, a further increase on harvest is due to an additional amount of forest area available (both for broadleaves and for conifers) for a second thinning.

A different FT composition (based on the FT distribution 1 applied to official estimates) may reduce the total amount of harvest by less than 4% on average.

The total amount of harvest provided by

AR using the official estimates increases from about 89 Gg of dry matter in 2005 (42.5 Gg using the IUTI estimates) to about 328 Gg of dry matter in 2020 (127 Gg using the IUTI estimates). These figures account for about 3% (1% in IUTI estimates) of the total amount of harvest provided in 2005 by Italian forests, equal to about 6550 Gg of dry matter (Pilli et al. 2013) and they only represent a potential (*i.e.*, maximum) amount of harvest that could be provided by these new forests. This suggests that in the past 20 years the total amount of harvest at the national level was almost entirely provided by the existing forests, *i.e.*, the FM area. The contribution of harvest from AR is also likely relatively small for the near future: assuming for 2020 a level of harvest of about 15 million of m³ at the country level (Pilli et al. 2013), the future contribution from AR appears to be approximately 8%. Of course, our assumptions did not consider the site productivity and other parameters (such as accessibility, slope, etc.) further reducing the potential amount of harvest provided by AR. The future harvest assumed by Pilli et al. (2013) is consistent with the assumption made by Italy for the Forest Management Reference Level.

The possible amount of harvest provided by plantations is also small. Indeed, the total amount of plantations (excluding poplar) reported at the national level by INFC is equal to about 56 kha. The inventory also detected the total amount of plantations (including

poplars) established after 1990 equal to about 60% of the amount of plantations (accounting also for the not classified area). This suggests that, even assuming that these new forests are totally represented by not-poplar plantations, the total amount of plantations established between 1990 and 2005 is equal to about 33 kha, *i.e.*, less than 3% of the total amount of AR estimated by NIR until 2005.

In order to directly compare our results with the values reported by NIR, we reported in Fig. 7 the total C sink estimated by CBM in Gg CO₂ yr⁻¹ (according to IPCC reporting guidelines negative values represent a terrestrial C sink and positive values a C source). The effect of fire emissions on AR does not considerably decrease the total C sink estimated by CBM in official estimates. The average C sink estimated to 2012, was equal to -4396 Gg CO₂ and -4167 Gg CO₂, excluding any disturbance event and including harvest and fire, respectively. As expected, since the total amount of afforested area and the amount of C accumulated on this area increase with time, so do the emissions related to fire on AR land. In 2007, when the total amount of burned area at the national level was equal to about 116 kha and, according to our assumptions, 15 kha of the AR area burned, fire emissions on AR were about 400 Gg CO₂ eq.

In Fig. 7, the estimates provided by CBM are compared with the figures reported by Italy in the KP LULUCF tables (Tab. 5(KP-
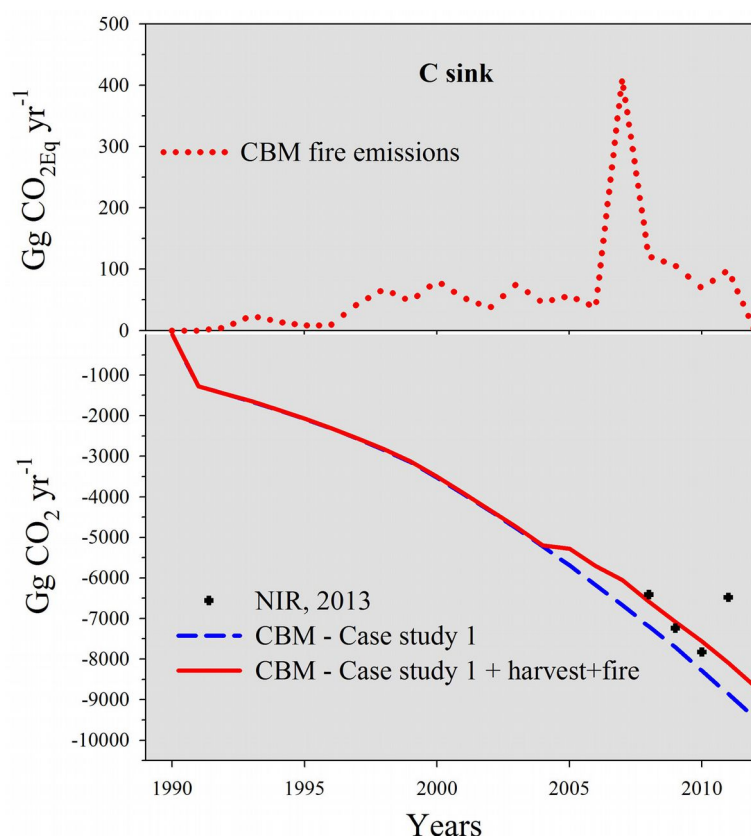
Fig. 7 - Comparison between the total C sink (in Gg CO_2 yr^{-1}) estimated by CBM with the official estimates (based on NIR assumptions, Italy 2013), excluding the harvest (dashed line) and including the effect of harvest and fires (red line). The figure also reports the emissions (in CO_{2Eq}, upper panel) related to fire disturbances on the afforested area. Due to the different assumptions about the annual rate of AR, the data reported by the official estimates cannot be compared with IUTI estimates. According to the IPCC Guidance (IPCC 2013) negative values highlight a C sink and positive values a C source to the atmosphere.

Tab. 4 - Reference year and main parameters defining the forest definition (minimum area, forest cover, width and potential tree height) applied by the National forest inventories, by IUTI and by the regional inventories reported in Tab. 3. Further information on the data sources is reported in the last column. (1): the regional forest area reported includes coppices, high forests, plantations and temporary gaps; (2): the regional forest area reported includes coppices, high forests and plantations; (3): the area reported for 1992 includes only the productive forests.

Inventory	Reference year	Min. area (m^2)	Forest cover (%)	Min. width (m)	Min. tree height (m)	Reference
INFC	2005	5000	10	20	5	Gasparini & Tabacchi 2011 [1]
NFI	1985	2000	20	20	-	Castellani et al. 1988 [2]
IUTI	1990, 2000, 2008	5000	10	-	5	Corona et al. 2012, Marchetti et al. 2012
Emilia Romagna	1985	5000	10	20	5	Regione Emilia Romagna 2008
Marche	2000	2000	20	20	-	Regione Marche 2008
Sicilia	2009	5000	10	20	5	Regione Sicilia 2014
Toscana	1991-1993	5000	10	20	5	Puntelli 2009 [3]
Trentino	2003	5000	10	20	5	Tonolli & Salvagni 2007
Umbria	1991	2000	20	20	-	Regione Umbria 2014
Val d'Aosta	1993	2000	20	20	-	Pasquettaz 2014
Veneto	1986	5000	10	20	5	Anfodillo et al. 2006

I) A.1.1) submitted to UNFCCC in 2013 and 2014 (UNFCCC 2013, 2014). The country's estimates on the living biomass are based on the For-est model also applied to the FM area (Federici et al. 2008). In this model, the initial growing stock volume is based on the 1985 NFI data; the biomass current annual increment is computed through derivative Richard's functions derived by an Italian yield table collection, further corrected to account for losses due to harvest, mortality and fire; dead wood and litter C pools are estimated using country specific emission factors and equations correlated to the living biomass pool (Italy 2013).

For the period 2008-2010, including the effect of fire and harvest (red line in Fig. 7), our estimates are consistent with those reported by Italy (UNFCCC 2013, 2014). For 2011, Italy reported a marked reduction of the total C sink (-20% compared to 2010), not estimated by our model. Due to the relevant recalculations reported by the NIRs 2013 and 2014, we cannot clearly identify the reason of this reduction. Indeed, (i) in 2013 and 2014 there was some relevant recalculation on the litter and dead wood C pools (Italy 2013, 2014); (ii) in 2014 there was a relevant recalculation (about -25% compared with NIR 2013) of the AR annual rate, due to the data provided by the new NFI and to the inclusion of poplar plantations into forest (Italy 2014); (iii) between 2013 and 2014, the total burned forest area and the AR burned area reported by Italy for the period 2008-2011 considerably decreased (see Fig. 5, based on data reported by Tab. 5(KP-II)5 of the KP LULUCF submissions 2013 and 2014). Despite these recalculations, the KP LULUCF tables submitted in 2013 and 2014 report the same C sink for the period 2008-2011, with a percentage difference lower than 2% between the values reported by the two submissions. Therefore, we can speculate that: (i) the reduction on the total C sink reported in the 2013 KP LULUCF tables may be due to a higher burned area (+251% compared with our assumptions); (ii) the reduction on the total C sink reported in the 2014 KP LULUCF tables may be due to the lower annual rate of AR assumed in 2014 (about -25% compared with our assumptions), while the AR burned area reported by these tables is consistent with our assumptions (Fig. 5, lower panel). Despite the different AR rates and burned area, however, the estimates provided by our model, by the 2013 KP LULUCF tables and the 2014 KP LULUCF tables for the period 2008-2010 are still quite similar. This suggests that further parameters, related for example to different implied emissions factors, are involved.

Other differences may be due to the effect of fire on the dead wood and litter pools. Indeed, as highlighted for the FM area, due to

the approach applied by Italy (based on a linear regression with the aboveground biomass), a reduction in biomass C pool due to fire causes a corresponding reduction in the dead wood pool which represents an immediate release to the atmosphere. In the CBM model, fire disturbances move part of the living biomass to the dead wood pool where it will slowly be released to the atmosphere through decay (Pilli et al. 2013).

Annual rate of AR

The differences between the annual rates of AR based on the official estimates and IUTI reflect the difference in the trend of total forest area reported by the two NFIs (used by official estimates) and estimated by IUTI. For IUTI, based on the data reported by Marchetti et al. (2012), the total forest area in 1985 (A_{1985}) can be estimated as (eqn. 4):

$$A_{1985} = A_{1990} - (AR_1 \cdot 5) = \\ = 9479 - (33 \cdot 5) = 9305\, kha$$

where A_{1990} is the forest area in 1990 and AR_1 the annual rate of afforestation for the period 1990-2000. Applying the same approach to A_{2005} (9653 kha) and AR_2 (23 kha), the total forest area estimated by the IUTI for 2005 (A_{2005}) is equal to about 9584 kha.

By contrast, the forest area estimated by the NFIs, excluding shrub lands, other wooded lands and poplar plantations, is equal to 7089 kha (*i.e.*, -24% compared with A_{1985}) and 8693 kha (*i.e.*, -9% compared with A_{2005}) for 1985 and 2005, respectively. Therefore, the difference in annual rates of AR provided by the two studies is mainly related to the higher (+24%) amount of forest area estimated by the IUTI for 1990 and, derived from this, for 1985 (see Fig. 2). In contrast, the difference on 2005 forest area is lower (<10%) and probably related to different methodological assumptions, as discussed by Marchetti et al. (2012).

Since both these studies also provide detailed information at the regional level, the total forest area reported for 1985 (by the first Italian NFI), 1990 (by IUTI), 2000 (by IUTI), 2005 (by INFC) and 2008 (by IUTI) can be compared with the estimates provided by regional forest inventories available for 8 of 21 administrative regions (Fig. 1). As highlighted in Fig. 8, for all these regions the differences between the NFI's forest area and the IUTI's forest area are higher for 1990 and 2000, and are lower for 2005 and 2008. From this figure it emerges also a much higher AR rate (*i.e.*, slope of the lines) in the NIR approach compared to IUTI.

Despite the differences in the forest definitions applied at the regional level (reported in Tab. 4 and largely discussed by Tosi & Marchetti 1998 and Tosi & Monteccone 2004), the forest areas estimated by the regional forest inventories are generally con-
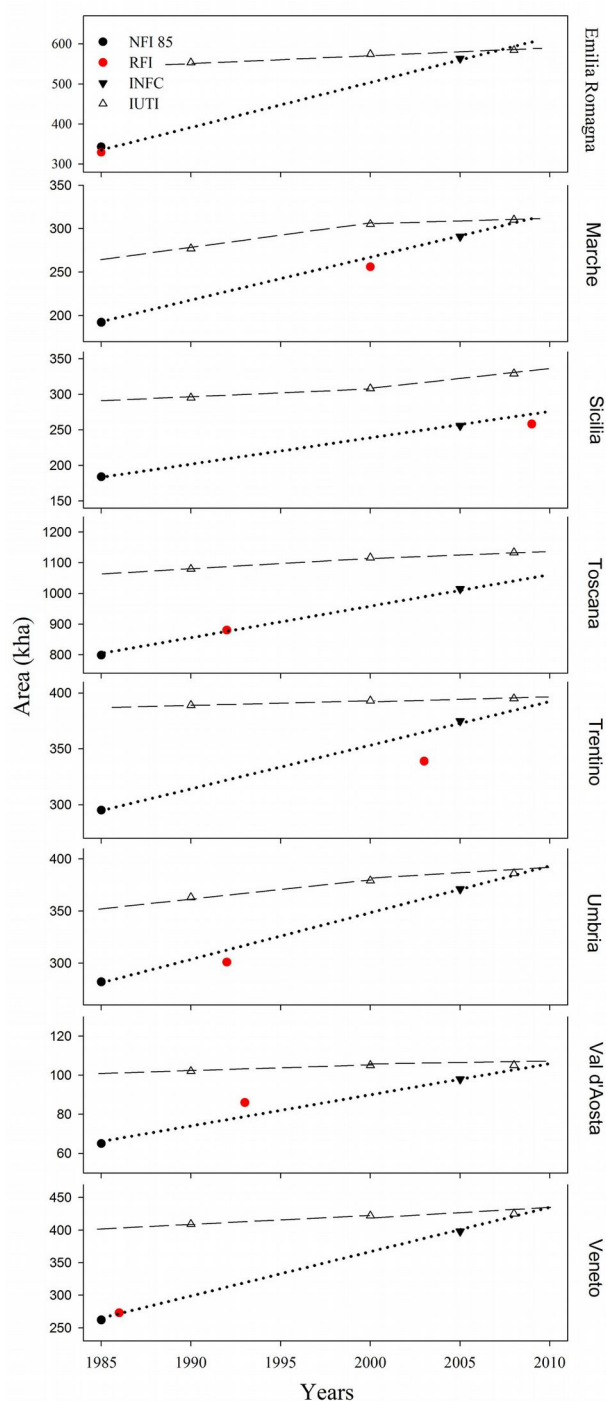
sistent with the estimates provided by the NFIs or with the linear interpolation between the 1985 and 2005 figures (dotted lines in Fig. 8). This suggests that the differences in the estimates of the forest area related to the two forest definitions are negligible, as suggested by De Natale et al. (2003). In contrast, for all these regions we detected larger differences in the estimates provided by IUTI (especially for 1990) with the linear interpolation between these data (dashed lines in Fig. 8). As discussed by Marchetti et al.

(2012), these differences may be related to the lack of a field survey in IUTI to distinguish forests and other wooded lands; by contrast, the estimates of forest area provided by the two Italian NFIs are based on field surveys, which are the sole source of information in the first NFI and a key data source in the second NFI (Tabacchi et al. 2005). This may help to explain a possible overestimation of the total forest area reported by IUTI for 1990 and a consequent lower estimate of the annual rate of AR since

Fig. 8 - Comparison between the forest area reported by 8 regional forest inventories (RFI), by the first (NFI 85) and the second (INFC) Italian NFIs and by IUTI (for 1990, 2000 and 2008). The dotted line highlights the linear interpolation between the two NFIs (approach used by the NIR) and the dashed lines highlight the linear interpolations between the 1990-2000 and the 2000-2008 IUTI estimates. Tab. 4 reports further details on the reference year and the forest definition applied by each study.

1990.

The different AR rates could also be partially due to a possible underestimation of the 2005 forest area reported by the second NFI, due to the omission, in the second stage of the INFC, of field surveys on points classified as not-forested during the first stage (Marchetti et al. 2012). However, to avoid this underestimation of the forest area as a consequence of the lack of field surveys on non-forest sampling units, the second NFI implemented a procedure to control omission classification errors referred to forest sampling units that would not be classified as forest in the first phase (Gasparini & Tabacchi 2011, p. 29).

Furthermore, the localization of the forest border, the possibility to distinguish young trees from shrubs in orthophotos, the question whether actual or potential minimum tree heights are assessed, the training of the personnel conducting the assessments, as well as other issues specified in the field protocols and assessment instructions, have to be considered in an exhaustive comparison of the two studies (Tab. 4).

Additional information to analyze AR estimates of NIR and IUTI is provided by three local studies on forest expansion. For the Trentino region, De Natale et al. (2007) estimated an annual rate of forest expansion equal to 0.11% for the period 1973-1999; for the Abruzzo region, Corona et al. (2005) estimated an annual rate of forest expansion equal to 0.23% for the period 1990-2002; for the Veneto region, Salvadori et al. (2006) and Dalla Valle et al. (2009) estimated an annual rate of forest expansion between 0.04% and 0.26% for the period 1991-2003. All these estimates are considerably lower than the values inferred by NFI data (*i.e.*, 0.64%, 0.75% and 0.37%, for Trentino, Abruzzo and Veneto region, respectively), but sometimes higher also than the values detected from IUTI. These differences may be also due to the specific methodological assumptions of these studies:

1. The observation period is different and particularly for the Trentino region the initial year (1973) could affect the resulting AR, as afforestation is not a linear phenomenon.
2. The case study of Veneto is limited to a portion of the region.
3. The three studies are based on photointerpretation without field data, and the diachronic classification of the ortophotos could have led to an overestimation of forest area for the past.

Overall, the comparison of AR rates reported by the 2013 NIR and IUTI with other independent sources for the period 1990-2005 gives mixed results: the regional forest inventories seem to support the AR rates reported by the NIR, while the local studies suggest AR rates somehow intermediate between NIR and IUTI. Based on the data provided by IUTI, recently confirmed by the preliminary results provided by the new Italian NFI, it is likely that the annual rate of AR in Italy in the last decade is decreasing compared with the '80s and the '90s.

Conclusions

We used the CBM to estimate the C stock changes resulting from AR activities in Italy for the period 1990-2020, including the potential effect of harvest and natural disturbances. We ran the model for two cases studies, based on different sources of data: an average annual rate of AR of about 78 kha yr^{-1} (using the 2013 official estimates, reflecting the Italian National Inventory Report) and 28 kha yr^{-1} (using the IUTI estimates, based on Italian Land Use Inventory System). Furthermore, we compared these two different AR rates with independent sources: eight regional forest inventories and three local studies.

The average C stock change estimated by our model between 1990 and 2020, excluding harvest or natural disturbances, averaged 1738 Gg C yr^{-1} (official estimates) and 630 Gg C yr^{-1} (IUTI estimates). The results based on the official estimates are consistent with the estimates reported by Italy for the period 2008-2010. Due to a different amount of area burned and AR rate, as well as to different model assumptions on the dead wood and litter pools, the C sink estimated by CBM for 2011, was about 20% lower than the C sink reported by the KP LULUCF tables (UNFCCC 2013, 2014).

Furthermore, our analysis suggests that:

1. the rates of AR are a major source of uncertainty in the estimation of AR stock changes; CBM results are comparable with NIR's ones when the same AR rate is used;
2. the different assumptions about the forest composition of AR area have a small impact on estimates of the AR sink;
3. due to the young age of the new forests, the potential amount of harvest provided from AR land has been negligible for the historical period (likely less than 3% of the total harvest in 2005) and is expected to be small in the near future (up to about 8% in 2020);
4. forest fires for the historical period, distributed by year according to the relative proportion of the AR area compared to the total forest area, had a relatively small impact on the AR sink (on average, emission from forest fires were less than 5% of the sink);
5. the selection of the yield tables applied by the model was based on the volume data reported by the INFC for even-aged forest; the same selection could also be based on increment data reflecting the current growth of forest, but this requires more specific information on these stands;

6. the comparison of NIR and IUTI estimates for AR with eight regional forest inventories confirms the afforestation rate of NIR for the period 1990-2005, while the comparison with three local studies suggests AR rates somehow intermediate between NIR and IUTI; based on the data provided by IUTI, recently confirmed by the preliminary data provided by the new Italian NFI, it is likely that the annual rate of AR in Italy in the last decade is decreasing compared with the '80s and the '90s.

In conclusion, this study suggests that the CBM can be applied at the country level to estimate the C stock change related to AR, including the effect of harvest and natural disturbances, even if only a comparison with results based on direct field measurements could verify the model's capability to estimate the real C stock change.

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