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The Effect of Alternative Forest Management Models on the Forest Harvest and Emissions as Compared to the Forest Reference Level

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Abstract: Background and Objectives: Under the Paris Agreement, the European Union (EU) sets rules for accounting the greenhouse gas emissions and removals from forest land (FL). According to these rules, the average FL emissions of each member state in 2021–2025 (compliance period 1, CP1) and in 2026–2030 (compliance period 2, CP2) will be compared to a projected forest reference level (FRL). The FRL is estimated by modelling forest development under fixed forest management practices, based on those observed in 2000–2009. In this context, the objective of this study was to estimate the effects of large-scale uptake of alternative forest management models (aFMMs), developed in the ALTERFOR project (Alternative models and robust decision-making for future forest management), on forest harvest and forest carbon sink, considering that the proposed aFMMs are expanded to most of the suitable areas in EU27+UK and Turkey. Methods: We applied the Global Forest Model (G4M) for projecting the harvest and sink with the aFMMs and compared our results to previous FRL projections. The simulations were performed under the condition that the countries should match the harvest levels estimated for their FRLs as closely as possible. A representation of such aFMMs as clearcut, selective logging, shelterwood logging and tree species change was included in G4M. The aFMMs were modeled under four scenarios of spatial allocation and two scenarios of uptake rate. Finally, we compared our results to the business as usual. Results: The introduction of the aFMMs enhanced the forest sink in CP1 and CP2 in all studied regions when compared to the business as usual. Conclusions: Our results suggest that if a balanced mixture of aFMMs is chosen, a similar level of wood harvest can be maintained as in the FRL projection, while at the same time enhancing the forest sink. In particular, a mixture of multifunctional aFMMs, like selective logging and shelterwood, could enhance the carbon sink by up to 21% over the ALTERFOR region while limiting harvest leakages.

Keywords: forest management models; carbon sink; forest harvest; forest reference level; production forests; multifunctional forests; set-aside forests

1. Introduction

The changing climate, increasing biomass demand, requests for wetland restoration, biodiversity conservation and the need for enhancing the carbon sink in forests, lead to an increasing need for alternative forest management models (aFMM). There is a clear need to consider aFMMs that aim at increasing forest multifunctionality while preserving wood production [1]. In particular, within the framework of the ALTERFOR project (Alternative models and robust decision-making for future forest management, https://alterfor-project.eu/), a number of aFMMs have been tested in specific case studies in eight European member states and in Turkey [2,3]. The aFMMs designed in the ALTERFOR project can be aggregated in the following categories: (high productive) clearcut, shelterwood, selective logging, EU habitats (a combination of clearcut forest management with set-aside patches of forest with high biodiversity value), set-aside and combination of the first three listed aFMMs with tree species changes. In this study, we consider these aFMMs from the point of view of the impact on the wood removals (harvest) and the forest carbon sink.

The actual forest management in Europe varies a lot depending on region, tree species, site productivity, forest owner, etc. [4]. The high production clearcut forest management applies relatively short rotations, maximizing mean annual increment [5,6]. Usually, forests in Europe are not managed with the maximum intensity [7]; on average, about 31% of forests are managed intensively and very intensively for wood production [8]. Therefore, the transition of forest with longer rotation to shorter rotation when the objective is to maximize mean annual increment (MAI) leads to an increase in wood removals and a decrease in standing biomass; in contrast, the transition to set-aside management interrupts wood removals and increases the forest biomass accumulation [6]. Selective logging (or continuous cover forestry) is a non-intensive forest management model (FMM) as only single trees that have reached a certain threshold, e.g., stem diameter at breast height (Dbh), are harvested. Under the "EU habitats" forest management high-biodiversity forest patches stay onsite continuously, thus, less forest area is harvested when compared to the forest under clearcut forest management. Transition from clearcut forest management to selective logging forest management or "EU habitats" management leads to an increase in standing forest biomass and a decrease in wood removals [6,9]. Under the shelterwood forest management, the forest is regularly harvested as under the clearcut forest management, however, a share of the forest is left onsite for natural regeneration and protection of the regrowth. Thus, shelterwood logging is an intermediate model between clearcut and continuous cover forest management, as the total biomass is removed in two or more successive stages. Compared to clearcut logging, shelterwood logging is better suited for regenerating some tree species while providing higher biodiversity [10–13] and soil protection, due to the increasing forest biomass and decreasing wood removals since a share of forest stand is left onsite for longer time [14].

As a part of implementing the Paris Agreement, the European Union (EU) set rules for accounting the greenhouse gas emissions and removals from forest land. According to these rules, for each European Member State, the average emissions from forest land in 2021–2025 (compliance period 1, CP1) and in 2026–2030 (compliance period 2, CP2) will be compared to a projected reference level (FRL) [15]. The FRL is estimated by modelling forest development under fixed forest management practices, based on those observed in 2000–2009 (the reference period, RP) [16]. As a result, forest management emissions that occur from pure continuation of RP forest management practices are not taken into account [17]. This approach aims to account only for the impacts of real changes to forest management and the cancelling out of the foreseen decrease in forest sink that is purely due to aging of forests [18]. The FRL estimation criteria allow for different assumptions on the FRL projection, such as flexibility in starting year of projection and determination of the forest management practices within RP to be applied for the projection, and assumptions regarding future climate change [16]. Different assumptions may result in variation of the combined FRLs of EU27+UK by approximately 100 Mt CO_2/year [19].

A number of studies have investigated the effects of implementing aFMMs at different scales. In particular, Schwaiger et al. (2019) [6] studied stakeholder specific landscape-level forest management scenarios (set-aside, multifunctional and wood production oriented) applied in two forest sites, a less productive and a more productive one, in Germany. The studies were carried out under the condition that the whole forest is managed under the same landscape level concept in each scenario. While this implied considerable differentiation at the stand level, it might be summed up as follows:

the multifunctional oriented FMM was characterized by diameter-target harvesting and increasing representation of broadleaved tree species, while the wood production oriented FMM was characterized by increment maximization with conifer monocultures, including the increase in conifer area shares at the expense of broadleaf species. Application of the set-aside FMM led, as expected, to an increase in growing biomass stock in both areas. The multifunctional-oriented FMM resulted in a larger average growing stock than the production oriented FMM in the more productive area, while the effect was opposite in the less productive area. In contrast to the multifunctional management, the production forest scenario resulted in strong oscillations of the harvested timber amounts. This is due to the uneven initial age class distribution at the investigated sites which does not become balanced in the production scenario.

Hynynen et al. (2019) [20] compared growth rate response of even-aged and uneven-aged Norway spruce stands, located in southern Finland, to different cuttings. Even-aged stands were thinned from below while uneven-aged stands were logged selectively. The observation period lasted for about 20 years. The authors concluded that in the conditions of southern Finland the even-aged forest management most likely produces more wood in a long term than uneven-aged forest management, and the growth rate of even-aged stands is likely to be higher than the growth rate of uneven-aged stands.

In 2020, Eggers et al. [21] studied four stakeholder defined scenarios of a large representative forest landscape in Sweden. The scenarios comprised different shares of alternative forest management models: forest reserves, even-aged and uneven-aged management and retention patches. Even-aged forestry with the application of clearcut and shelterwood logging resulted in the largest mean annual harvest, mean annual growth and the least growing stock and low net present value (the sum of future net cash flows discounted to the present). Continuous cover forestry with selective logging resulted in about a 20% lower mean annual harvest and mean annual growth, higher growing stock compared to the even-aged forestry and the largest net present value. The combination of clearcut, shelterwood and selective logging resulted in a slightly lower mean annual harvest, mean annual growth and a higher growing stock than the even-aged forestry, while the net present value was the same. Retention patches that were treated with selection fellings yielded the lowest mean annual harvest, net present value and the largest growing stock compared to the other cases, showing a mean annual growth slightly lower than in the continuous cover forestry.

Vauhkonen and Packalen (2019) [9] studied scenarios of large-scale forest transition to alternative forest management in Finland. They considered a number of scenarios of transition of different shares of forests from even-aged forest management to continuous cover forest management and set-aside management. They found that carbon sequestration, wood removals and harvesting costs depend on the forest type and the share of forest area treated with the alternative FMMs. Transition of forests with low conservation value to the FMM implying continuous cover forestry and set-aside areas resulted in the highest accumulation of carbon stock, a considerable decrease in harvest removals and a moderate increase in harvesting costs. Transition of forests with low conservation value to the FMM implying continuous cover forest management, as well as transition of forests with a high conservation value to the continuous cover forestry (with or without set-aside areas) resulted in a moderate accumulation of carbon stock. Transition to the continuous cover forestry with the establishment of set-aside areas decreases the harvest removals considerably, while the effect of the transition to the continuous cover forestry alone causes more moderate effects. If the uneven-aged FMM is adopted on a large scale, but wood demand remains the same, the harvesting costs with the selective logging becomes considerably higher than with the clearcut (as in even-aged FMM).

However, the effect of large-scale implementation of aFMMs in the whole ALTERFOR region (EU27+UK and Turkey) on wood removals and net forest carbon sink in comparison to the respective FRL levels in CP1 and CP2 has not yet been studied. Therefore, the objective of this study is to estimate the effects of large-scale uptake of the aFMMs, studied in the ALTERFOR project, on forest harvest and forest carbon sink in 2021–2025 and 2026–2030 considering that the proposed aFMMs are expanded to most of the suitable areas in EU27+UK and Turkey. In particular, our results are compared to projections modelling the FRL estimates for EU27+UK (and hypothetical FRL projections for Turkey), thus providing insights into possible opportunities for the EU member states under the new land use, land use change and forestry (LULUCF) regulation. We performed our simulations under the condition that the different countries should still match the harvest levels estimated for their FRLs as closely as possible.

2. Materials and Methods

2.1. Design of the Simulations

In this study, we ran the Global Forest Model (G4M) (spatially explicit model for simulating forest management aimed at satisfying user-defined wood demands [22–24]) with inputs of historical wood demand for 1990–2009 according to FAOSTAT and the results of the Forsell et al. (2019) [19] scenario "A" for the period 2010–2030 (see details in Section 2.3). G4M was developed at the International Institute for Applied Systems Analysis. The model operates on a 0.5 × 0.5-degree grid. In the business as usual scenario (BAU-only) run, we used a standard set of FMMs simulated in G4M (BAU FMMs), i.e., (a) thinning and clearcut logging with different intensities regulated by rotation length or (b) low-intensity logging without clearcut [19]. Since in the standard version of G4M only two categories of FMMs were modelled, (i.e., forest management with clearcuts and without clearcuts), we developed algorithms for simulating other types of FMMs for this study.

In order to estimate the influence of the aFMMs on the harvest and net forest carbon sink (i.e., the terms sink (meaning negative emissions) and emissions are used throughout the text; only increase or decrease in forest stock is considered), we considered (high productive) clearcut, selective logging, shelterwood logging and tree species change which could be combined with clearcut, selective logging and shelterwood logging. We ran G4M by applying four scenarios of spatial allocation of aFMMs: production, multifunctional, balanced and set-aside (see Section 2.2 for their detailed description) and two scenarios for the aFMMs implementation rate: (a) immediate uptake in 2020 and (b) gradual introduction from 2020 to 2030. We then compared the results of the eight scenarios with the BAU-only case. All the scenarios of the spatial allocation of aFMMs are composed of a mixture of aFMMs in locations suitable for the aFMMs and the standard FMMs simulated in G4M in locations not suitable for any aFMM (see Section 2.3 for details).

In all our runs, the G4M was set to match the national wood demand as closely as possible, under the restrictions of the applied aFMMs, in order to reveal the extent of the effect of aFMM introduction on the sink which is not simply explained by decreasing or increasing harvest volumes. That is, we wanted to see if the introduction of the aFMMs can achieve a stronger sink while still satisfying the national demand for wood. Both the variation in harvested wood (dHarvest) and switch of FMMs can influence the forest management emissions, therefore, we developed a linear model for assessing the deviation of the emissions from the BAU-only (dEmissions):

$$\text{dEmissions} = \text{k} \times \text{dHarvest}, \quad (1)$$

In Equation (1), dEmissions is the difference of the forest management emissions under applied aFMMs according to each considered scenario, from the emissions under BAU-only FMMs at every modelling time step (11 modelling time steps in the period 2020–2030). dHarvest is the difference of harvest under the applied aFMMs according to each considered scenario, from the harvest under BAU-only FMMs at every modelling time step. k is the model parameter. Equation (1) was applied over the period 2020–2030 for each scenario of spatial allocation of aFMMs (4 scenarios) and two rates of aFMM introduction, separately (8 scenarios in total). For each scenario (11 modelling time steps), based on the linear model (Equation (1)), we calculated the Pearson correlation and the coefficient of determination (r^2) as a measure used to estimate the share of variance in the emissions explained by the variation of wood harvest. Hence, we assumed that the remaining deviation in emissions, not explained by the change in harvest, (i.e., $1 - r^2$), were caused by the change in FMMs.

2.2. Simulation of FMMs in G4M

There are global and European versions of the model. In the European version of G4M, more detailed available spatial information is used when compared to the global version. From here on, we consider the European version of G4M. In this model, the decisions regarding land use change and forest management are considered from the point of view of a landowner in each grid cell by applying a comparison of the net present values of different management options. In the case of deforestation and/or afforestation decisions, net present value of forestry is compared to the net present value of land use for agriculture plus benefits from selling wood after the clear-cut of the forest. The land use with greater net present value is steadily introduced in the cell. Forest management decisions are modelled to match simulated wood production for each country to exogenously provided wood demands (statistical data for historic period demand and provided by economic partial equilibrium models projections for the future, e.g., GLOBIOM model [25]). The forest management parameters (rotation length and type of forest management, i.e., with clearcutting or without clearcutting) are initialized according to FAO roundwood statistics by countries, while the locations of the forest management practices are initialized using a wood harvest intensity map by Verkerk et al. (2015) [26]. Thus, the standard set of FMMs parameterized to the wood harvest data is representative of the historic forest management in terms of harvest intensity. The aFMMs considered in this study differ from the traditional FMMs by a clearer vision of ecosystem services for which the aFMMs have been designed. For example, the clearcut aFMM is aimed at high wood production, therefore, a rotation close to the one maximizing MAI is applied. The aFMMs aimed at biodiversity include tree species change (in clearcut, shelterwood and selective logging FMMs), a longer regeneration period in shelterwood FMMs, larger targeted Dbh in selective logging FMMs or retention of untouched high biodiversity patches in the clearcut FMM. For this study, G4M was parameterized as in the research on FRL modelling choices [19], while in order to be adequately represented in the G4M, the considered aFMMs required a series of modifications of the standard model, as illustrated in the following paragraphs.

2.2.1. Changing Tree Species

Due to the specifics of G4M, dynamics of only a single tree species can be modelled in one grid cell. In the standard forest management simulation algorithm, the same tree species is planted or regenerated in each cell after its harvest. We modified the algorithm in such a way that the "old" forest is not regenerated after harvesting. However, the same area of another tree species is planted in the "new" virtual forest created in the same grid cell. In the new forest, thinning and final harvest are applied as soon as the size of the trees (Dbh) and the amount of biomass per area (for thinning) and the age of forest stands reach the thresholds defined a-priori for the new tree species. The current tree species distribution in the G4M grid was estimated using a map by Brus et al. (2012) [27], as in [19]. In the aFMMs, coniferous to broadleaves and broadleaves to coniferous tree species transitions were specified. Taking into account the 8 tree species groups used in G4M (fir, spruce, pine, pinus halepensis, birch, beech, oak and larch) and the limited information in the model for discriminating suitable locations for different tree species, the allowed tree species change transitions were defined: fir/spruce/larch to beech; pine/pinus halepensis to oak; birch/oak to pine; and beech to spruce.

2.2.2. Selective Logging in a 1-Canopy Layer Virtual Forest

The simulation of selective logging was obtained by considering the 1-canopy layer in each grid cell. Although G4M is a geographically explicit model, there is no information on location of trees in each grid cell. The trees are grouped in forest stands of similar age, where the age structure of the forests is initialized as defined in [28]. There are two forest management regimes of the virtual forest in a cell in respect to stocking degree—according to forest stand growth tables or according to the natural stocking degree. In the event that the natural stocking degree is reached, a greater stocking biomass per hectare than the growth table stocking can be expected. Thus, we can interpret the natural stocking regime as a forest with undergrowth, i.e., with an uneven aged structure. If in such a forest long rotation time is applied (i.e., the forest is managed to minimize disturbances leading to forest dieback), then most of the wood is harvested with thinning operations (thinning is applied irrespective of age, while Dbh is one of the harvest criteria) that can be interpreted as "selective logging". In a long run or in the case of high wood demand leading to intensive harvesting of such forests, the trees reaching an age greater than a specific rotation time and Dbh greater than a fixed Dbh threshold are also harvested.

2.2.3. Shelterwood Logging

For simulating shelterwood logging, first rotation time (RL) as in a conventional clearcut is determined. Then, the forest area in a grid cell is divided by 1/RL parts for every year, harvesting with additional constraints on tree age (not less than 0.9 × RL), minimum Dbh and wood available for harvesting. However, in contrast to normal clearcut, only one half of the 1/RL area is harvested in each age cohort and the other half is preserved as a shelter for tree regeneration. The preserved shelters are marked and a countdown for the prescribed number of years depending on forest productivity (40% of the rotation length maximizing mean annual increment (MAI)) is initialized for each shelter patch. The shelter patches are clearcut after the countdown reaches zero and the trees are regenerated. The thinning is simulated as in the "standard" G4M. The amount of harvested wood in a particular year can be adjusted by altering RL (RL can vary from the rotation length maximizing MAI to the rotation length maximizing standing biomass (RLmaxBm)) or by changing the time when the shelter is clearcut. The clearcut of the shelter patches can be performed earlier than the initial time set for the shelter, however, not earlier than 80% of the initial time. Otherwise, the clearcut of the shelter patches can be performed later than the initial time set for the shelter, however, the age of the trees should not exceed the age when mortality overcomes increment (RLmaxBm).

2.3. Scenarios for Spatial Allocation of Alternative Forest Management Models in G4M

The scenarios for simulating the aFMM uptake on the European scale were based on the combination of information from a mapping of suitable NUTS2 (nomenclature of territorial units for statistics of the second level) and allocation scenarios which defined objectives of forest management. The EUROSTAT NUTS2 map [29] was used for mapping of the G4M 0.5 × 0.5 degree cells to the NUTS2 regions.

2.3.1. Mapping of Suitable Areas

In this research, we used selected aFMMs from the ALTERFOR case study areas (CSA) located in Germany, Ireland, Italy, Lithuania, Netherlands, Portugal, Slovakia, Sweden and Turkey. The CSA represent forest landscapes of a size of the order of thousand—hundred thousand hectares, providing different ecosystem services [2,3]. Due to the limited representability of the Portuguese CSA of the corresponding NUTS2 region and the lack of appropriate species in G4M, more generalized data were used for Portugal, yet the main management principles were derived from work in the CSA. A description of the selected aFMMs in the CSAs is presented in Table 1.

Table 1. Description of selected alternative forest management models (aFMMs) in the ALTERFOR case study areas (CSA) and their grouping for further modeling in the Global Forest Model (G4M).

Country/CSA	NUTS2 *	aFMM Characteristics	aFMM Highlights for G4M Modelling	aFMM Group
Germany/Brandenburg	DE30-DE40	Scots pine timber and energy forest	Shelterwood, short rotation from 60 years; pine	shelterwood
		Biodiversity centered management of pine	Selective logging; change species from pine to oak	selective logging species change
		Oak biodiversity set-aside	No use; for oak	set-aside
Germany/Bavaria	DE21-22-23-24-25-26-27	Norway spruce timber and energy forest	Shelterwood; for spruce; short rotation from 60–70 years	shelterwood
		Biodiversity centered management of spruce	Selective logging (diameter at breast height (Dbh): 40–45/60 cm); species change from spruce to beech	selective logging species change
		Beech biodiversity set-aside	No use; for beech	set-aside
Ireland	IE01-IE02	Lodgepole pine fiber	Clearcut; for pine; rotation: 65–80 years	clearcut
		Lodgepole pine wilderness	No use; pine	set-aside
		Sitka spruce under birch nurse, on blanket bog	Clearcut; spruce; rotation from 40 years	clearcut
		Bog restoration	No use;	set-aside
		Lodgepole pine—Nephin	No use; pine	set-aside
Italy	IT32	Recreational selective	Selective	selective logging
		Uniform shelterwood and coppice	Shelterwood and coppice; rotation of 80–100 years for shelterwood and 35 years for coppice	shelterwood
Lithuania	LT00	Adaptive rotation	Normal clearcut; coniferous	clearcut
		Care for broadleaves	Normal clearcut; change species from coniferous to deciduous and vice versa, stop the change when half-half	clearcut species change
		Potential EU habitats	Clearcut with untouched patches	EU habitats

Table 1. *Cont.*

Country/CSA	NUTS2 *	aFMM Characteristics	aFMM Highlights for G4M Modelling	aFMM Group
The Netherlands	NL11-12-13-21-22-23-31-32-33-34-41-42	Wood mass forest	Clearcut; rotation: 20–30 years for very productive forests	clearcut
		High value timber	Shelterwood; Dbh: 45–60 cm	shelterwood
		Park management	Selective	selective logging
		Climate resilient management	Selective	selective logging
Portugal	PT11 **	Pure maritime pine	Clearcut; pine halepensis; rotation: 40–60 years	clearcut
		Pure oak forest sawlog	Clearcut; oak; rotation: 40–60 years	clearcut
		Oak for cork production	Selective	selective logging
Slovakia	SK01-02-03-04	Even aged mixed	Shelterwood; rotation: 90 years; change species: from deciduous to coniferous/from coniferous to deciduous, stop the change when half–half	shelterwood species change
		Uneven aged mixed	Shelterwood; regeneration period up to 60 years; change species: from deciduous to coniferous/from coniferous to deciduous, stop the change when half–half	shelterwood species change
Sweden	SE09	Sitka/Douglas	Clearcut; spruce or fir; rotation: 40–70 years	clearcut
		Spruce/pine/birch mixture	Clearcut; spruce, pine or birch; rotation: 40–70 years	clearcut
		Selection	Selective; spruce	selective logging
		Stand edge management	No use	set-aside
Turkey		Continuous cover forestry	Selective; beech	selective logging

* Nomenclature of territorial units for statistics of the second level (NUTS2) for which the case study areas (CSAs) were considered to be representative. ** In the case of the Portuguese CSAs, they have limited representability of the NUTS2 region because of high diversity in the region, however, the management principles derived from the CSA are used in this study.

The CSAs were considered to be representative for the forest conditions in the NUTS2 regions where they were initially selected. We identified other NUTS2 regions which we could also assume to be reasonably represented with the following approach: We collected a set of variables describing key forest properties, i.e., forest and forest management characteristics, for each NUTS2 region. Then, we compared, with regard to these variables, all NUTS2 regions without a CSA to those containing a CSA using an appropriate similarity metric (see below). Any NUTS2 region which was sufficiently similar to a NUTS2 region that contained a CSA was considered to be represented. The variables we used for describing the forest and forest management conditions were:

- Forest area share covered by conifers;
- Tree species diversity, expressed by the Shannon diversity index [30,31] based on the NUTS2 regions' tree species area shares;
- Management type, expressed by the area share of high forest (as opposed to coppice);
- Standing wood volume per unit area, expressed in m^3 merchantable wood per ha;
- The regions' potential forest productivity, expressed by the climate-vegetation-productivity (CVP) index by Paterson (1956) [32].

The input data for calculating the first four variables were provided by the European Union's Joint Research Center in Ispra, Italy. For calculating the CVP index, temperatures are required in daily resolution, as well as the annual precipitation and the latitude of the location of interest. See [32] for details of the calculation. The temperature and precipitation data were obtained in a 25 × 25 km resolution from the EU's AGRI4cast resource portal (https://ec.europa.eu/jrc/en/scientific-tool/agri4cast-resources-portal). Based on these data we calculated an aggregated CVP value for each NUTS2 region and the decade from 2005 to 2014 (which was the last documented year at the time of the download).

As an appropriate measure for similarity or dissimilarity between the NUTS2 regions with regard to the five forest variables, we used the Mahalanobis distance [33], which has the advantage of being scale-invariant and taking account correlations in the data. In order to determine an acceptable threshold value for accepting or refusing sufficient similarity, we calculated the Mahalanobis distances for each NUTS2 region against each other, and fitted an empirical density function to their distribution (Figure 1). As the cutoff point, we chose the leftmost inflection point of this density function (i.e., the maximum of its first derivative), because this is the point where the dissimilarity increases quickest. This point is at a Mahalanobis distance of 1.93, which indicates that all NUTS2 with a smaller distance to a CSA-covered NUTS2 are to be accepted. The outcome of this procedure suggests that 96 NUTS2 regions are sufficiently comparable to 1 of the 9 NUTS2 which contain a case study area. This means that we come to a coverage of 105 out 132 European NUTS2 regions. This result was accepted after a careful check for plausibility according to the following procedure: We mapped the Mahalanobis distances on NUTS2 level and visually checked for high similarities that would contradict accepted knowledge about forest and forest management conditions in Europe. If this were the case, we would have had been forced to assume that the set of variables we based the comparison on was not sufficiently complete. This would have been the case e.g., if a NUTS2 region in Sweden had a close similarity to one in central Italy, or one in Slovakia to one in the United Kingdom.

In the case of Poland, we chose the third closest case study NUTS2 for the grid cells with pine, because the first and the second closest case study NUTS2 considered only spruce-specific aFMMs, while the prevailing tree species in Poland is pine. In Greece and Finland, where there were no CSAs in the ALTERFOR project and shared indicators for the Mahalanobis distance similarity approach, similarity indicators from the neighboring countries, southern Italy for Greece and central-northern Sweden for Finland, were used, respectively.

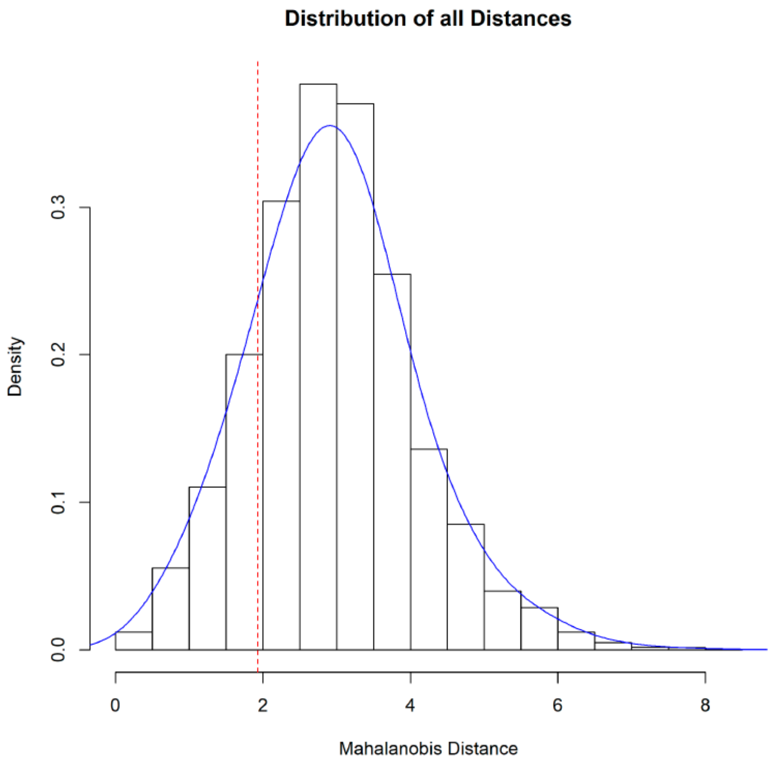

Figure 1. A histogram of the Mahalanobis distances of all NUTS2 regions against each other. The blue line is a fitted empirical (non-parametric) density function; the red line is at the maximum of the first derivative, i.e., a distance of 1.93.

2.3.2. Allocation Scenarios for aFMMs

Since all the ALTERFOR case study regions, except the one in Turkey, consider a few distinct aFMMs (from 2 to 5), we developed four scenarios, differing on the assumptions on how the section of the aFMMs is prioritized within each suitable NUTS2 region.

The following four scenarios are considered:

- Production forestry (aFMMs aimed at wood production, i.e., clearcut and shelterwood logging are prioritized);
- Multifunctional forestry (aFMMs aimed at multifunctional forest use, including selective logging, high production aimed forest management with untouched patches (hereinafter referred to as EU habitats) or with species change are prioritized);
- Balanced forestry (all aFMMs are allowed equally, for trying to achieve a harvest close to the BAU-only case);
- Set-aside forestry (aimed at biodiversity, wilderness, restoration, stand edge management and other nature protection low-intensity management).

When allocating aFMMs to the model grid cells within each suitable NUTS2 region, we also took into account the information on prevailing tree species, increment (estimated using a potential net primary production map [34] and scaled at country level to match [35]), harvesting and transportation costs [36], and forest share in neighboring grid cells. The tree species information is important for selecting only the aFMMs developed for a particular species or group of species. The information on increment is important for "production" aFMMs, as well as for any FMM when the diameter at breast height (Dbh) or rotation is specified as a target (i.e., the target Dbh should be reachable before the forest stand starts losing biomass, while the target rotation should not be shorter than the one maximizing MAI and no longer than the one maximizing standing biomass). The increment, harvesting and transportation costs, forest location and the neighboring grid cell information are important for the set-aside aFMMs (e.g., biodiversity set-aside, wilderness, forest edge). In particular, a combination of the tree species and increment information was used for the allocation of set-aside aFMMs aimed at the biodiversity protection, while a combination of harvesting and transportation costs (the costs generally are greater for remote forest), forest location and the neighboring grid cell information was used for the set-aside FMMs aimed at forest edge protection. The "EU habitats" aFMM is an intermediate between production and set-aside-oriented forest management, therefore, it was prioritized under the set-aside and the multifunction scenarios.

In the production scenario, we first selected all suitable areas (in terms of tree species and high increment) for the clearcut and shelterwood logging and then assigned the remaining suitable areas to the selective logging aFMMs. Among the shelterwood and the clearcut aFMMs, the priority was given to the aFMMs without tree species change. Only low-productive forests (increment below country average), which were not intensively managed in the past [37], were set-aside for biodiversity or wilderness, and remote (with the harvest and transportation costs greater than country average) low-productive edge forests were set-aside for forest edge management.

In the multifunctional scenario, we first selected all suitable areas (in terms of tree species and target diameter) for the selective logging aFMMs, then chose the remaining areas for the shelterwood and on the last turn for the clearcut aFMMs. Among the shelterwood and the clearcut aFMMs, the priority was given to the aFMMs with tree species change. The set-aside aFMMs were considered as in the production scenario.

In the balanced scenario, we applied rules as in the multifunctional scenario. However, when selecting suitable units for the selective logging aFMMs, in locations characterized by high increment, the priority was given to the shelterwood and clearcut aFMMs. The set-aside aFMM were considered as in the production scenario.

In the set-aside scenario, all areas suitable for the set-aside aFMMs (with tree species, for which a particular set-aside aFMMs was designed, increment below country average and, in the case of edge forest management, that are remote and at the forest edge) were selected first and allocated to the set-aside aFMMs; the remaining units were allocated as in the multifunctional scenario.

2.4. Application of G4M for Estimating the FRL

Forsell et al. (2019) [19] estimated the forest reference levels for the 28 EU member states under different assumptions that are justifiable according to the LULUCF regulation and the FRL Guidance [16] (12 scenarios were considered). For the FRL estimation, G4M was run twice. First, the model was run in usual mode (i.e., simulating forest management aimed at satisfying exogenous wood demand) and the forest management was determined and recorded for each model grid cell (i.e., 0.5×0.5 degree simulation unit) during the reference period (2000–2009), and the forest state (i.e., age structure, age-related biomass, diameter and height) was recorded at the end of 2009. In the second run, G4M was initialized with the forest state data in the end of 2009, while the forest management parameters (rotation length and FMM), recorded in the first run, were fixed during the whole simulation length. The simulation was performed from the starting year of the FRL simulation until the end of the second FRL commitment period (CP2, 2026–2030). The scenarios considered by Forsell et al. (2019) [19] differed from each other in terms of the year of starting the FRL simulation, stratification, spatial allocation of forest management models, timing of individual forest management activities and accounting of climate change. All scenarios were constructed to be compatible with the instructions provided in the guidance documentation published by the European Commission [13]. In this study, we used the results of a scenario, where the FRL simulation started in 2010, the forests were stratified by the tree species and productivity, and the forest management parameters used for the FRL simulation (spatial allocation of the forest management and timing of the activities) were determined in each model cell as an average for the reference period, while climate change was not taken into account (scenario "A" in [19]). In addition, we estimated the FRL for Turkey in a similar manner.

In this study, we grouped the countries similarly as in [19] (central-east, central-west, northern and southern regions), except the southern region where Turkey was additionally included (Table 2).

Table 2. Grouping of the countries in study regions, number of grid cells and forest area considered in the study.

Region	Countries	Number of Grid Cells Considered in the Regions	Forest Area Considered in the Regions, kha
Central-East	Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia	357	21,579
Central-West	Austria, Belgium, France, Germany, Ireland, Luxembourg, The Netherlands, The United Kingdom	653	33,236
Northern	Denmark, Estonia, Finland, Latvia, Lithuania, Sweden	556	50,801
Southern	Croatia, Cyprus, Greece, Italy, Malta, Portugal, Slovenia, Spain, Turkey	460	37,921

3. Results

3.1. Spatial Allocation of aFMMs under the Scenarios

In G4M, the aFMMs were applied to 34–43% of the total studied forest area depending on the aFMM allocation scenario (the sum of shares of all non-BAU FMMs, Table 3). The largest share of aFMMs was applied to the set-aside scenario (44.3%), mostly due to promotion of the set-aside aFMMs in this scenario. The uptake was decreasing in the production scenario where the set-aside aFMMs were not applied and the selective logging and EU habitat aFMMs were taken up less than the production oriented aFMMs. Across regions, the largest share of aFMMs were applied in the central-east region, (over 60% of the forest area), where most types of aFMMs were present due to a better match between the aFMM application requirements (Table 1) and local site characteristics represented with the minimum Mahalanobis distance (below the 1.93 threshold) at the NUTS2 level and with the tree species and increment at the grid-cell level. Sixteen NUTS2 regions in the central-west region, 13 in the southern region and 7 in the central-east region did not match the requirements for the aFMM application (the Mahalanobis distance is greater than 1.93). In Turkey (southern region), the only matching aFMM targeted the beech forests that makes about 8.5% of the national forest area (https://ogm.gov.tr/lang/en/Pages/Forests/StatisticalInfo.aspx). In the northern region, low forest increment was the limiting factor for allocation of the clearcut and selective logging aFMMs.

Table 3. Share of FMMs implemented within the total forest area in each region for the aFMM allocation scenarios (business as usual (BAU)—only standard G4M FMMs are applied; sc indicates that tree species change is applied in the considered aFMM; colors highlight the relative shares of FMMs within each region, from the lowest (red) to the highest (green)).

Scenario	Region	BAU	Clearcut	Clearcut sc	Shelterwood	Shelterwood sc	Selective	Selective Sc	EU Habitats	Set-Aside
Set-Aside	Central-East	37.80%	1.20%	13.30%	1.30%	8.60%	6.60%	5.30%	25.70%	0.10%
	Central-West	60.80%	4.80%	0.00%	1.30%	0.90%	11.50%	15.70%	3.50%	1.50%
	Northern	56.50%	1.20%	3.40%	0.00%	0.00%	16.80%	0.00%	7.30%	14.80%
	Southern	60.20%	2.70%	0.00%	6.60%	0.00%	14.70%	0.00%	11.70%	4.10%
	All regions	55.70%	2.40%	3.20%	2.20%	1.50%	13.50%	4.40%	10.30%	6.70%
Multifunction	Central-East	38.00%	1.20%	13.30%	1.30%	8.60%	6.60%	5.30%	25.70%	0.00%
	Central-West	62.70%	4.90%	0.00%	1.40%	0.90%	10.90%	15.70%	3.50%	0.00%
	Northern	66.30%	2.00%	3.40%	0.00%	0.00%	16.80%	0.00%	7.30%	4.20%
	Southern	63.80%	2.70%	0.00%	6.60%	0.00%	14.20%	0.00%	11.70%	1.10%
	All regions	60.60%	2.80%	3.20%	2.20%	1.50%	13.20%	4.40%	10.30%	1.70%
Balanced	Central-East	38.00%	21.70%	16.10%	6.90%	8.60%	3.50%	2.80%	2.40%	0.00%
	Central-West	63.70%	4.90%	0.80%	9.60%	0.90%	9.60%	7.80%	2.70%	0.00%
	Northern	70.50%	7.00%	2.10%	0.00%	0.00%	16.80%	0.00%	3.50%	0.00%
	Southern	63.80%	11.70%	0.90%	10.90%	0.00%	9.90%	0.00%	1.70%	1.10%
	All regions	62.30%	10.00%	3.60%	6.10%	1.50%	11.30%	2.20%	2.70%	0.30%
Production	Central-East	38.00%	21.70%	16.10%	9.70%	8.60%	3.50%	0.00%	2.40%	0.00%
	Central-West	64.20%	4.90%	0.80%	14.20%	0.90%	9.10%	3.20%	2.70%	0.00%
	Northern	79.80%	7.00%	2.10%	0.00%	0.00%	7.50%	0.00%	3.50%	0.00%
	Southern	65.20%	11.70%	0.90%	10.90%	0.00%	9.50%	0.00%	1.70%	0.00%
	All regions	66.00%	10.00%	3.60%	7.60%	1.50%	7.80%	0.70%	2.70%	0.00%

The clearcut (with and without species change) and the EU habitat aFMMs were applied in all regions in different shares. The largest shares of both aFMMs were in the central-east region, the share of the clearcut aFMM reached 38% in the production and balanced scenarios, while the EU habitat aFMM reached 25.7% under the set-aside and multifunction scenarios. The large share of the clearcut and EU habitat aFMMs in the region was due to a good match of the CSA in Lithuania considering the clearcut (with and without species change) and EU habitat aFMMs with the characteristics of the most forests in Poland (Figures 2 and A1, Figures A2 and A3). The three aFMMs from this CSA were assigned to the same forest area depending on the allocation scenario and the grid-cell characteristics. The shelterwood aFMM (with and without species change) was applied in all regions with the share reaching 11–18% in the production scenario, except the northern region where the share was close to zero. The selective logging aFMM (with and without species change) was present in all regions with the largest share (27.2%) in the central-west region, followed by the northern and southern regions with the shares reaching about 15–17%. The set-aside aFMM was present in all regions only under the set-aside scenario with the largest share in the northern region (14.8%) and much lower shares in the other regions (0.1–4.1%) (Table 3). In the northern region, most of the NUTS2 regions had the lowest Mahalanobis distance to the CSA in Sweden where the clearcut, selective and set-aside aFMMs were considered. In the central-west region, most NUTS2 regions had the lowest Mahalanobis distance to the CSAs from Germany and the Netherlands where the high-productive clearcut, selective and set-aside aFMMs were considered (Table 1). A map with the spatial explicit allocation of the FMMs under the production scenario is presented in Figure 2, while maps with the other considered scenarios are presented in Appendix A (Figures A1–A3).

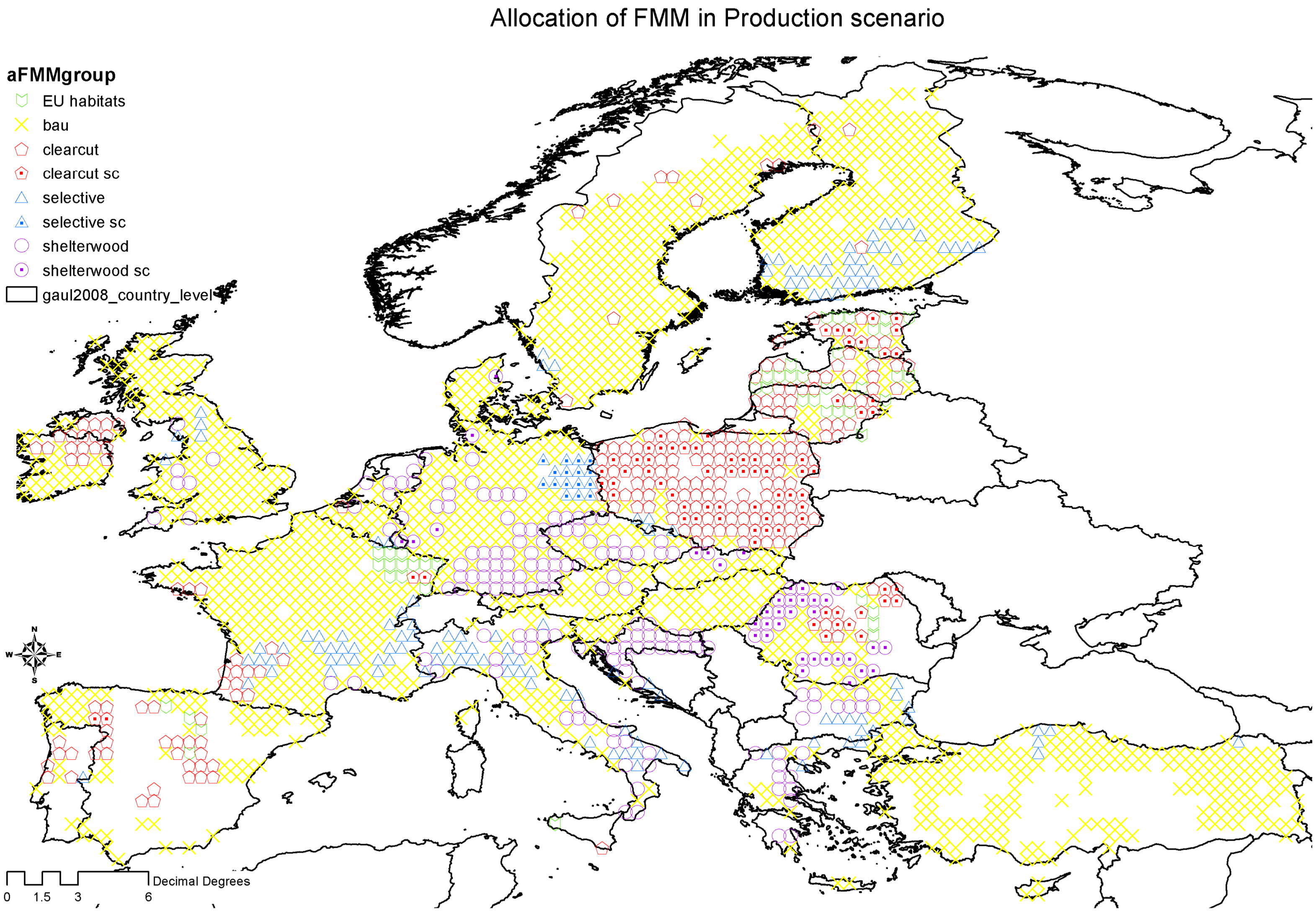

Figure 2. Allocation of the forest management models in the production scenario.

3.2. Influence of the aFMMs on the Harvest

When considering the results aggregated for the whole studied territory (EU27+UK and Turkey), the application of the aFMMs resulted in a slight decrease in harvested wood, with a maximum of 1.1% in CP1 and 0.92% in CP2, contrasting to BAU-only case across all scenarios (Tables 4 and 5). As expected, the largest decrease in harvest occurred under the set-aside aFMM allocation scenario, followed by multifunction (0.84% in CP1 and 0.54% in CP2) and balanced (0.78% in CP1 and 0.52% in CP2), with the smallest decrease in the production scenario (0.67% in CP1 and 0.34% in CP2). The impact of the aFMM introduction was greater in CP1 than in CP2 because the model required some time to adapt the harvest to the new FMMs. The wood demand was growing during the CP; in CP2 the wood demand was 1.5% greater than in CP1. During CP1, in the scenarios with immediate introduction of the aFMMs, the decrease in harvest was generally slightly greater than in the respective scenario with gradual introduction. However, the difference was on an order of 0.01%. In CP2, the impact of the immediate introduction of the aFMMs was about 5 times less than the impact of the gradual introduction, however, the impact in general was lower than in CP1 (except the set-aside scenario, where the impacts of the gradual introduction of the aFMMs were almost similar) (Tables 4 and 5). In the case of the gradual introduction of aFMMs, the model simulated the harvest for satisfying the demand under continuous changing of the FMMs, thus, it had to adapt the harvest in the different locations to fulfill the increasing demand.

In the central-east region, the introduction of aFMMs resulted in slight increase in harvest (0.16%) under the production and balanced scenarios during CP1 and in all scenarios during CP2. This can be explained by the largest share of the clearcut aFMMs introduced in the region (Table 3). In the northern region, the immediate introduction of aFMMs resulted in a slight increase in harvest in CP2, whereas the immediate introduction of the selective logging and set-aside aFMMs was compensated by rapid intensification of harvest in other places. While the mobilized harvest in CP1 allowed keeping the wood removals close to the BAU-only values, the mobilized harvest in CP2 contributed to the overshooting of the BAU-only values, because more trees in these areas have reached the harvesting threshold (e.g., target Dbh) of the selective logging aFMM, which increased wood removals.

The largest decrease in harvest was observed in the northern region under the set-aside scenario in CP1 with immediate and gradual introduction of aFMMs, and in CP2 with gradual introduction of aFMMs (Tables 4 and 5), given that considerable forest area was set-aside for forest edge management, restoration or biodiversity protection, and converted to selective logging (Table 3). In the case of the gradual introduction of aFMMs, the model intensified harvest in less additional areas than in the case of the immediate introduction of aFMMs because the shortage of the harvest was lower. The introduction of both the shelterwood and selective logging aFMMs in the central-west and southern regions (Table 3) was the reason why the harvest under the introduced aFMMs was below BAU-only FMMs. Massive introduction of the shelterwood logging aFMM, where considerable forest areas are left onsite (the harvest is postponed), may cause shortage of harvest in the short term, especially if they are not compensated by intensification of harvest in other areas.

Table 4. Annual harvest of roundwood and net forest emissions for the BAU-only scenario across the different regions.

Period	Region				
	Central-East	Central-West	Northern	Southern	All Regions
Roundwood Harvest (Thousand m^3/Year) *					
Reference 2000–2009	91,801	160,786	172,221	67,373	492,181
CP1 2021–2025	102,942	165,668	185,365	68,135	522,110
CP2 2026–2030	105,888	171,835	182,505	69,917	530,145
Net Forest Emissions (Mt CO_2/Year) **					
Reference 2000–2009	−83	−127	−94	−140	−445
CP1 2021–2025	−60	−126	−76	−127	−388
CP2 2026–2030	−54	−117	−77	−119	−366

* In "m^3 over-bark". ** Negative emissions (or sink) denote removal of carbon dioxide from the atmosphere.

Table 5. Deviation of annual roundwood harvest and net forest emissions from BAU-only scenario in the considered scenarios, in thousand m^3/year (overbark) and Mt CO_2/year, respectively, in the studied regions averaged for CP1 and CP2 (a positive number for the harvest implies that the harvest is larger in the considered scenario as compared to the BAU-only scenario, and a negative number for the emissions implies that the emissions are lower (i.e., the sink is larger) in the considered scenario as compared to the BAU-only scenario). (Prod = production, Multi = multifunction).

Period	Scenario							
	Prod 2020	Prod 2020–2030	Balanced 2020	Balanced 2020–2030	Multi 2020	Multi 2020–2030	Set-Aside 2020	Set-Aside 2020–2030
Central-East								
CP1 harvest	167	149	155	66	−52	−374	−96	−375
CP1 emissions	−9	−6	−11	−7	−17	−12	−17	−12
CP2 harvest	321	87	220	−28	326	156	343	158
CP2 emissions	−8	−6	−10	−8	−16	−13	−16	−13
Central-West								
CP1 harvest	−820	−638	−854	−572	−1045	−704	−1335	−871
CP1 emissions	−9	−8	−19	−12	−35	−23	−37	−24
CP2 harvest	−443	−709	−476	−684	−811	−1042	−1495	−1261
CP2 emissions	−8	−9	−20	−17	−39	−33	−41	−34
Northern								
CP1 harvest	−2086	−1324	−2622	−2633	−2569	−2593	−3550	−2766
CP1 emissions	−9	−3	−16	−6	−20	−9	−19	−9
CP2 harvest	271	−763	229	−1560	314	−1737	37	−3645
CP2 emissions	−8	−5	−14	−7	−18	−10	−15	−12
Southern								
CP1 harvest	−770	−732	−727	−722	−711	−640	−717	−669
CP1 emissions	−4	−3	−4	−3	−5	−3	−5	−3
CP2 harvest	−491	−427	−508	−503	−408	−238	−373	−123
CP2	−5	−3	−5	−3	−6	−4	−6	−4
All Regions								
CP1 harvest	−3510	−2545	−4048	−3860	−4376	−4310	−5697	−4682
CP1 emissions	−31	−19	−49	−28	−77	−47	−78	−48
CP2 harvest	−343	−1811	−535	−2774	−579	−2861	−1489	−4870
CP2 emissions	−29	−23	−49	−36	−79	−60	−78	−62

3.3. Influence of the aFMMs on Forest Emissions

The introduction of the aFMMs strengthened the carbon sink in forest biomass in each particular region and in the whole studied territory under all scenarios when compared to the BAU-only scenario (Tables 4 and 5). For the whole territory, the sink increased from 5% under the production scenario with gradual introduction of aFMMs up to 20–21% under multifunction and set-aside scenarios with immediate introduction of aFMMs in CP1, and from 6 up to 21% in CP2 under the same scenarios. The largest increase in the sink occurred in the central-west region, that is, 30% in CP1 and 35% in CP2. In particular, this improvement in the forest sink was achieved under the multifunction and set-aside scenarios with immediate introduction of aFMMs. The same scenarios resulted in about a 30% increase in the sink in the central-east region, a 23–26% increase in the northern region and a 4–5% increase in the southern region in CP1 and CP2, respectively. The multifunction and set-aside scenarios with gradual introduction of aFMMs resulted in about a 20% increase in the sink in the east- and west-European regions in CP1 and a 25–29% increase in CP2; in the northern region, the increase was 11% in CP1 and 14–15% in CP2; in the southern region, the increase was about 2% in CP1 and 3% in CP2.

The impact of the production scenarios on the increase in the sink was about two times smaller than the impact of the multifunction and set-aside scenarios in the central-east and the northern regions in CP1 and CP2; in the central-west region, the production scenarios resulted in about a 3–4 times lower increase in the sink in CP1 and CP2; in the southern region, the difference was below 1% (Tables 4 and 5). The inclusion of Turkey in the southern region reduced the relative effect of the aFMM introduction on the sink by two-fold. The reason is that Turkey was contributing to about a half of the sink in the southern region and the aFMM applied in Turkey concerned only beech forests, occupying about 8.5% of the forested area in the country (https://ogm.gov.tr/lang/en/Pages/Forests/StatisticalInfo.aspx). As a result, the difference between the BAU-only and the aFMM application scenarios was not as notable as in the other regions. This also explains the little relative difference between the forest sink under the production, the multifunction and the set-aside scenarios in the southern region.

3.4. The Correlation of the Harvest and Net Forest Sink and Its Implications for the aFMMs

Wood harvest influences the carbon sink in forest biomass [28,38]. Therefore, in order to separate the effects of the wood harvest from the change in forest management, we tested the correlation between the deviations of the wood removals and the forest emissions from the BAU-only levels when introducing the aFMMs. In this comparison, we can ignore cases when the correlation is negative, i.e., the increase in wood harvest occurs together with the reduction in emissions (increase in the sink), because it does not make our analysis weaker. Therefore, we considered only positive correlation at a significance level of 5%. The found correlation was significant and positive for the production scenario with immediate introduction of aFMMs in the central-east, central-west and southern regions, as well as for the whole studied area (Table 6). In some other regions, the correlation was also significant and positive. These regions are as follows: the southern region for all scenarios with the immediate introduction of aFMMs, the northern region for the set-aside scenarios with immediate and gradual introduction of aFMMs and the central-west region for the multifunction scenario with gradual introduction of aFMMs.

By combining the Tables 5 and 6 and reducing the emissions deviation (from Table 5) by $1 - r^2$ (from Table 6) for respective regions and scenarios, in the cases of positive and significant correlations, we can obtain a more robust estimate of the effect of aFMM introduction on the net forest carbon sink. In all the cases of significant correlations, over 50% of increase in the sink was connected with the decrease in the wood harvest according to the selected level of significance, except the multifunction scenario in the central-west region. In this last case, the decrease in the wood harvest was responsible for about 49% of the increase in the sink (Table 6).

Table 6. Pearson correlation for the deviation of roundwood harvest and net forest emissions from the BAU-only scenario in the considered scenarios in 2000–2030 (r), coefficient of determination (r^2) and p-values for the correlation * (positive correlation implies that the increase in harvest occurs together with the increase in net forest emissions, and negative correlation implies that the increase in harvest occurs together with the reduction in net forest emissions). (Prod = production, Multi = multifunction).

Item	Scenario							
	Prod 2020	**Prod 2020–2030**	**Balanced 2020**	**Balanced 2020–2030**	**Multi 2020**	**Multi 2020–2030**	**Set-Aside 2020**	**Set-Aside 2020–2030**
				Central-East				
r	0.02	0.56	0.20	0.40	−0.25	−0.09	−0.21	−0.08
r^2	0.00	0.32	0.04	0.16	0.06	0.01	0.05	0.01
p	0.945	0.071	0.565	0.217	0.457	0.799	0.526	0.824
				Central-West				
r	0.80	0.22	0.48	0.17	−0.17	0.70	−0.17	0.56
r^2	0.63	0.05	0.23	0.03	0.03	0.49	0.03	0.31
p	**0.003**	0.525	0.133	0.627	0.611	**0.017**	0.618	0.072
				Northern				
r	0.40	−0.43	0.32	−0.70	0.44	−0.55	0.98	0.93
r^2	0.16	0.18	0.10	0.49	0.19	0.30	0.95	0.86
p	0.218	0.189	0.331	0.016	0.180	0.080	**0.000**	**0.000**
				Southern				
r	0.97	−0.08	0.97	0.16	0.83	−0.12	0.80	−0.01
r^2	0.95	0.01	0.95	0.03	0.69	0.01	0.64	0.00
p	**0.000**	0.826	**0.000**	0.634	**0.002**	0.721	**0.003**	0.966
				All Regions				
r	0.67	−0.76	0.39	−0.76	−0.53	−0.90	−0.35	0.36
r^2	0.45	0.58	0.16	0.57	0.28	0.82	0.12	0.13
p	**0.024**	0.006	0.230	0.007	0.091	0.000	0.294	0.278

* r varies between −1 and 1 and indicates the strength and the direction of the correlation; r^2 indicates the share of the variance in the dependent variable, net forest emissions, that is explained by the independent variable, the roundwood harvest; $p < 0.05$ are marked bold as they indicate that the correlation is significant according to the chosen probability threshold.

4. Discussion

4.1. Impact of the Introduction of the aFMMs on the Harvest and Net Forest Sink

The changing of an FMM in a certain part of the forest impacts the local harvest in the year of the aFMM introduction and may change the average harvest over a longer period. If the aFMM was introduced in a large territory, the wood removal in the country or region is affected and should be compensated by the adaptation of FMM parameters in other places within the region, in order to still satisfy the total wood demand. In the case of switching from the clearcut to the shelterwood logging aFMM, the removals are reduced in the year of the aFMM introduction, because a share of the forest stand, which would be harvested in the case of the clearcut aFMM, is left onsite for regeneration. Therefore, in the years when shelters are removed, the total harvest can be larger when compared to the clearcut FMM [14]. Carbon sequestration in forest biomass is greater than in the forests treated with clearcut logging, because a number of older trees are present onsite in the shelters. In the case of switching from the clearcut to the EU habitat aFMM, the removals are reduced in the year of the aFMM introduction and, in the long run, the carbon sequestration in forest biomass is larger because a share of the forest stand, which would have been removed in the case of the clearcut aFMM, is left onsite for biodiversity protection [39]. In the case of switching from the clearcut to the selective logging aFMM, the removals are reduced in the year of the aFMM introduction and, in the long run, the carbon sequestration in forest biomass is larger. In the case of switching from the clearcut to the set-aside aFMM, the removals are reduced in the year of the aFMM introduction as well as in the long run because the logging is not carried out. The dynamics of the wood removals and the carbon sink is in line with the study by Vauhkonen and Packalen (2019) [9], Eggers et al. (2020) [21] and the high-productive case from Schwaiger et al. (2019) [6].

The multifunction scenario in the northern region can be compared to the MUCL (multi-use conservation landscapes) scenario with 20% share of continuous forest cover and set-aside forest management (p = 20%) from the study by Vauhkonen and Packalen (2019) [9] for Finland, while the balanced scenario can be compared to the MUL (multi-use landscapes) scenario with 15% share of continuous forest cover forest management (p = 15%) and the production scenario to the MUL scenario (p = 5–10%). In our study, similar to [9], the increase in the share of the set-aside and continuous cover forest management leads to accumulation of forest biomass and a decrease in harvest removals.

The changing of tree species does not affect the amount of wood removals in CP1 and CP2 sharply, as the new species are introduced gradually and will reach the harvesting thresholds after CP2. However, in the longer period, the FMM parameters will be adapted to the properties of the new tree species (e.g., harvesting Dbh threshold is 40–45 cm for spruce but 60 cm for beech in the CSA in Bavaria, Table 1; the rotation length maximizing MAI depends on the shape of the growth curve) that affects the harvest. The share of coniferous and non-coniferous roundwood will change as well, which in the long run can impact the wood processing industry [40].

4.2. aFMM Scenarios Minimizing the Reduction in Harvest and Maximizing the Increase in Sink

From the point of view of minimizing the reduction in roundwood harvest compared to the BAU-only, the production or balanced scenarios are the preferable ones. In most cases, the immediate introduction of aFMMs had a greater impact on harvest during CP1, while the gradual introduction of aFMMs had a greater impact in CP2. The impact varies from a slight increase in wood removals (0.3%) in the central-east region to a slight decrease, up to 1.1%, in the other regions.

From the point of view of maximizing the enhancement of the sink in forest biomass in CP1 and CP2, the multifunction or set-aside scenarios of aFMM allocation with immediate introduction of the aFMM had the largest effect in all regions (from 5% in the southern to 35% in the central-west region). The gradual introduction of aFMMs reduced the effect by approximately 40% in CP1 and by 20% in CP2 (Table 5). Taking into account the correlation between wood harvest and the carbon sink (i.e., combining information from Tables 5 and 6), in the northern region and the allocation of aFMMs according to the multifunction scenario in the southern region, the multifunction or set-aside scenarios with gradual introduction of aFMMs are the preferable ones for maximizing the carbon sink.

When comparing the impact of the aFMM introduction, we may highlight scenarios which cause a minimal reduction in wood removals and a large increase in the carbon sink. Such scenarios are optimal from both points of view, because this way, both the impact on the wood processing industry and the enhancement of the carbon sink in forest biomass are considered. Under these considerations, in the central-east region, the allocation of the aFMMs following the balanced or multifunction scenarios with immediate or gradual introduction of the aFMMs are the preferable ones (Table 5). Meanwhile, the multifunction scenario is preferable in the central-west and northern regions. At the same time, the multifunction or set-aside scenarios are better performing in the southern region. In fact, the multifunction scenario shows good performance in all regions.

However, considering the correlation of the wood removals and the carbon sink in our study (Table 6), a significant share of the sink increase was connected to reduction in wood removals. This can be observed in the central-west region, under the multifunction scenario with gradual introduction of aFMMs, and in the southern region, under the multifunction and set-aside scenarios with immediate introduction of aFMMs. Thus, the effect of management in these cases was secondary compared to the effect of reducing the harvest.

In general, the immediate introduction of the aFMMs resulted in over 1.5 times greater increase in the sink than the gradual introduction under CP1 and over 1.2 times under CP2. These results indicate that adopting aFMMs has potential to provide a possibility for EU member states to gain accounting credits under the LULUCF regulation. However, the decision of introducing the aFMMs should be taken fast to greater effect on the carbon sink in CP1 and CP2.

4.3. Caveats in This Study

The relatively small number of CSAs and their locations reduce the representativeness of the CSAs for larger regions, especially in NUT2 with high diversity like in the case of Portugal. Another dimension of the representativeness is the mapping of the NUTS2 where the CSAs are located in the other NUTS2 using a statistical similarity. Finally, we applied a computer model operating on a $0.5 \times 0.5°$ grid (approximately 50×50 km) initialized with one prevailing tree species group in each grid cell and applying forest stand growth functions generalized for eight tree species groups. However, we can argue that the results of this study are likely to present a conservative estimate of the potential of the aFMMs because of a possible underestimation of the potentially suitable areas. The reason is that in the first stage, we chose only the "most similar" NUTS2 region according to the Mahalanobis index. However, there could be other NUTS2 regions, apart from those where the Mahalanobis scores are within the similarity range, which may include forests composed of tree species for which a particular aFMM is designed, or having productivities fitting some of the aFMMs. The rough spatial resolution of the model and the use of only one prevailing tree species group in each cell filtered out possible suitable locations for aFMMs that were targeted for some specific tree species. Besides that, within one selected NUTS2 region, there are a few aFMMs which can be applied equally in the same location. Another uncertainty is in the time of switching to an aFMM which can influence the harvest and the net forest carbon sink. Since the spatial allocation of aFMMs is not unique and the time of aFMM application is uncertain, we developed four different scenarios of spatial allocation and two different scenarios for the time of aFMM introduction.

The application of aFMMs resulted in a slight decrease in harvested wood, with a maximum of 1.1% in CP1 and 0.92% in CP2, contrasting to BAU-only FMMs (Tables 4 and 5). The largest decrease in harvest occurred under the set-aside aFMM allocation scenario, followed by multifunction (0.84% in CP1 and 0.54% in CP2) and balanced (0.78% in CP1 and 0.52% in CP2), with the smallest decrease observed in the production scenario (0.67% in CP1 and 0.34% in CP2). However, we consider as baseline the harvest level resulting from the application of the FMMs as in the RP (according to the FRL definition). In reality, wood demand may be greater, for example, the EU Reference Scenario 2016 [41] projects a harvest increase in EU27+UK by more than 15% in CP1 and CP2 (compared to about 7–8% increase in the current study). In the case of the larger wood demand, we expect a shortage of wood under set-aside scenarios, in particular in the northern region.

The future climate, atmospheric CO_2 concentration and nitrogen deposition were not taken into account in this study. However, this should have a limited effect on the results within next 10 years. In addition, we did not consider in this study the contribution to the sink which can be obtained through harvested wood products. A change in management could have a possible impact on the share of different assortments being harvested and therefore on their different capacity of storing carbon over time, with a potential climate impact of the aFMMs. This aspect would need further explorations in the future.

5. Conclusions

The introduction of the aFMM enhances the forest sink in CP1 and CP2 in all studied regions within the EU27+UK and Turkey area. This is an interesting result from the EU LULUCF regulation viewpoint. Our results suggest that if a balanced mixture of aFMMs is chosen, a similar level of wood harvest can be maintained as in the forest reference level, while at the same time enhancing the forest sink. In particular, our results suggest that promoting a mixture of multifunctional aFMMs, such as the ones based on selective logging and shelterwood, could enhance the carbon sink while limiting harvest leakages in the considered regions. In specific regions, such as the Central-East EU, promoting a mixture of aFMMs including all types of harvest (clearcuts, shelterwood and selective logging) could have positive effects on both carbon sequestration and availability of wood for forest industries. In other regions, in particular the southern region, it could be beneficial to first and foremost increase the share of set aside management together with the multifunctional one. The faster the aFMMs are adopted, the larger their impact on the carbon sink within the timeframe of the LULUCF regulation and its CP1 and CP2.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

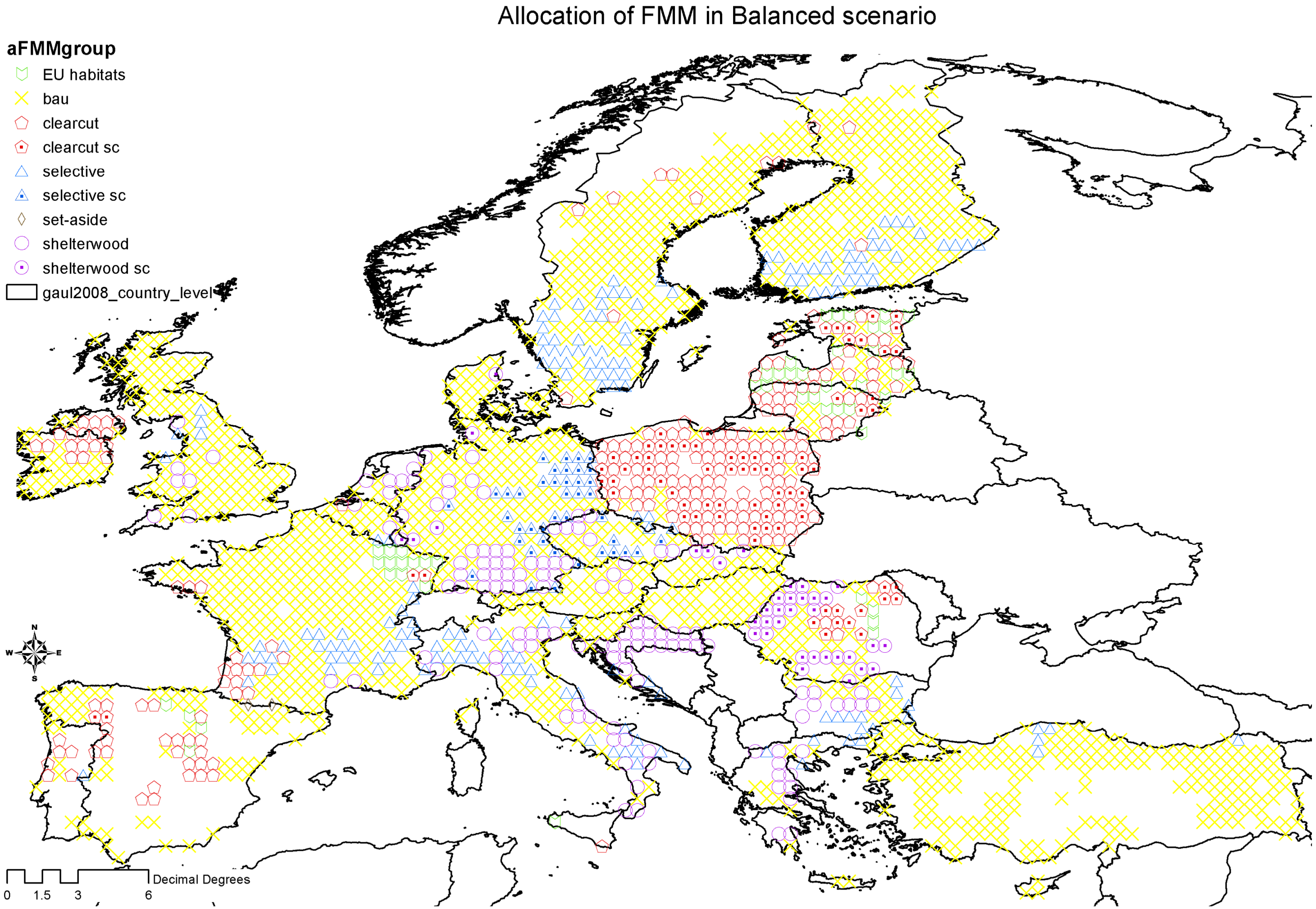

Figure A1. Allocation of the forest management models in the balanced scenario.

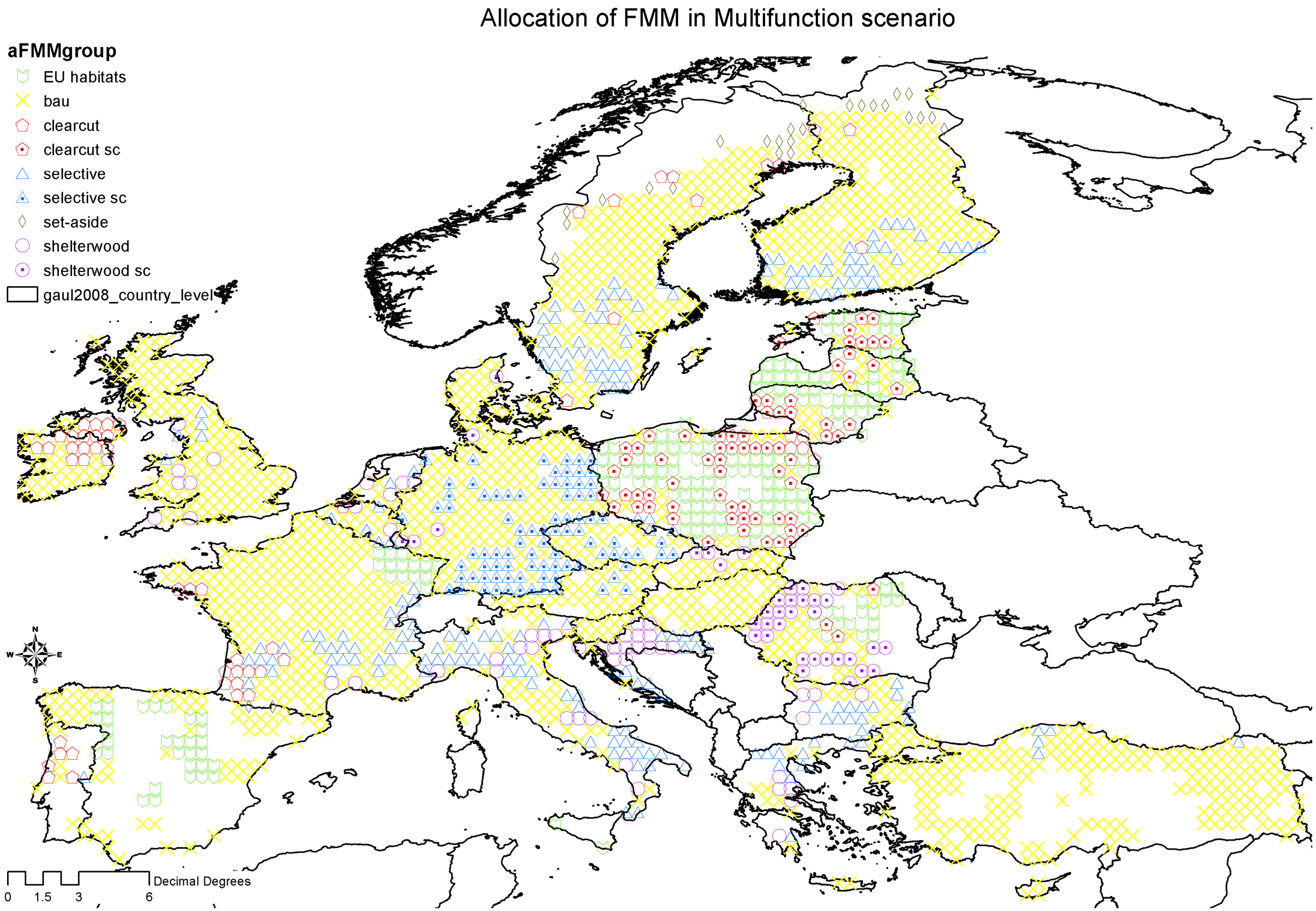

Figure A2. Allocation of the forest management models in the multifunction scenario.

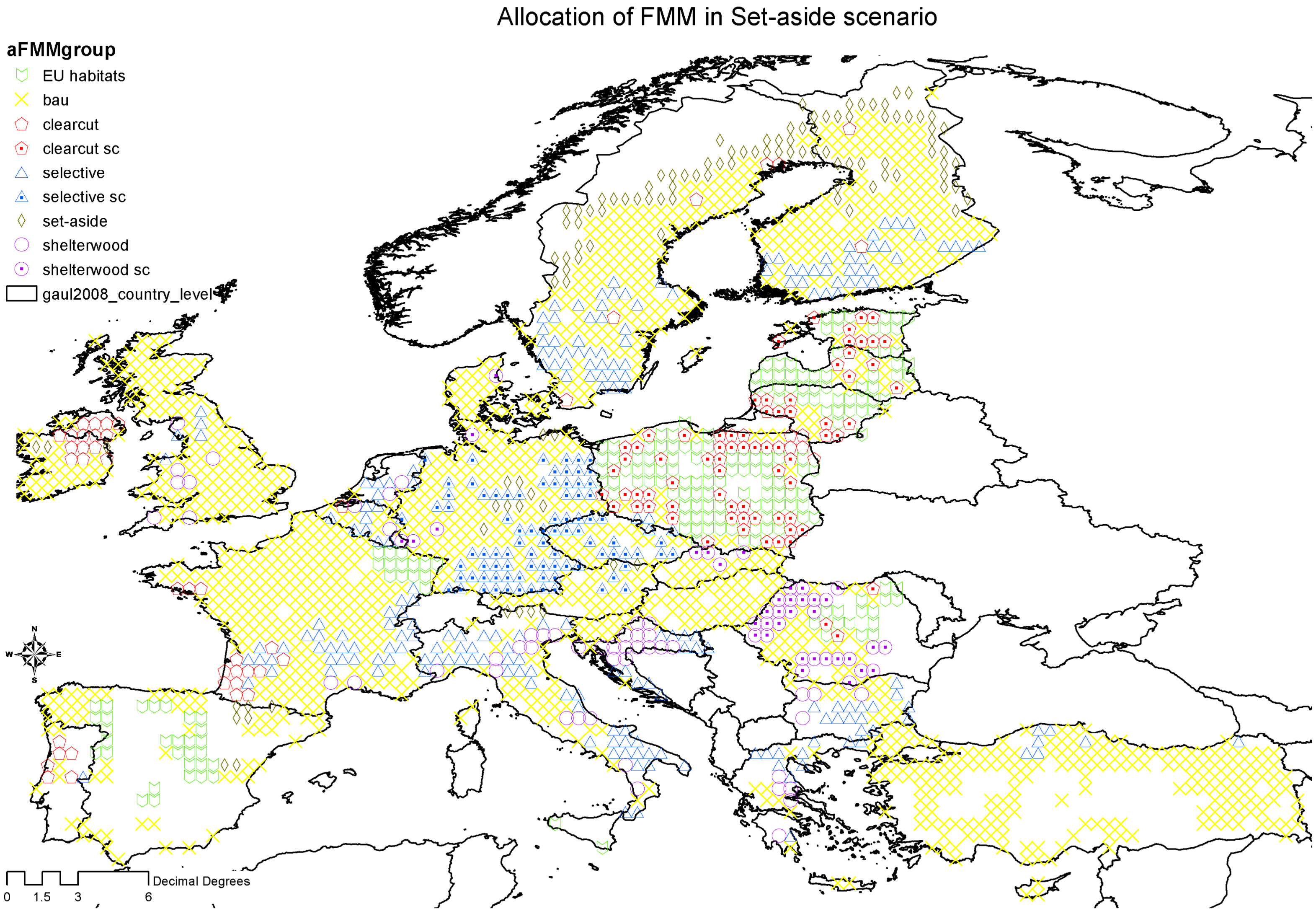

Figure A3. Allocation of the forest management models in the set-aside scenario.

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