



# European forest sinks and climate targets: past trends, main drivers, and future forecasts

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## Abstract

We examine the evolution of European net sinks towards 2030 and the European Union's (EU) climate neutrality target by 2050. The EU's current land use policy for 2021–2030 is divided into two periods: 2021–2025 and 2026–2030. The national inventory data from several databases and statistical analyses are used to examine the trends and drivers and to forecast future forest sinks and the net sinks of the land use, land use change and forestry (LULUCF) sector. Our forecasts suggest that national forest sinks will be short of the agreed forest reference levels in most member states in 2021–2025, with a total of 128 MtCO<sub>2</sub>eq. For 2026–2030, the net sink for the whole EU LULUCF sector will be short of the EU target by 298 MtCO<sub>2</sub>eq. Thus, most member states must design more efficient LULUCF policies to fulfil their national targets. Furthermore, the decreasing trends in the LULUCF sinks also emphasize the need to reduce emissions and to increase the sinks in most member states so that the EU can achieve its climate neutrality goal by 2050.

**Keywords** Climate change mitigation · EU LULUCF regulation · Forest sinks · Panel data analysis · Time series analysis

## Introduction

The European Union (EU) is at the forefront of international efforts to mitigate climate change. In addition to reducing fossil and process-based greenhouse gases (GHGs), the EU also aims to increase the contributions of the land use, land-use change and forestry (LULUCF) sector to the EU's increased overall climate ambition (EU 2018; European Commission 2021). Biogenetic GHG emissions and the carbon sinks of the LULUCF should act as net sinks (i.e., sinks exceed emissions), and their role will increase over time. The EU climate neutrality target requires that by 2050, the net LULUCF sink removes CO<sub>2</sub> from the atmosphere by an amount equal to the remaining fossil and process-based emissions (European Commission 2019). Forests and harvested wood products (HWP) together have removed

up to 11.3% of the EU's annual total GHG emissions (EU + UK + Switzerland + Norway), and the entire LULUCF sector has removed up to 7.6% of the EU's annual total GHG emissions (Eurostat database).

The current regulatory framework for the LULUCF sector covers the period from 2021 to 2030 and is divided into two subperiods. The LULUCF policy for the period from 2021 to 2025 includes accounting rules for afforested land, deforested land, managed cropland, managed grassland, managed wetland, managed forest land, harvested wood products (HWPs), and natural disturbances. For managed forest land and HWP ("forest sinks" in what follows), a combined member state specific reference level is determined ("forest reference level (FRL)" in what follows). Each Member State shall account for emissions and removals resulting from managed forest land with HWPs calculated as emissions and removals in the periods from 2021 to 2025 minus the FRL. FRLs are based on the continuation of sustainable forest management practices from the period from 2000 to 2009 and aim to cancel out the effects of forest age structures because the mitigation potential of existing forests is a function of their age structures, which in turn is a function of historical land management decisions. Summing up the individual FRLs yields the EU27's annual forest and HWPs sink that is about –313 MtCO<sub>2</sub>-eq. in 2021–2025 (note that FRLs are defined

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only for the EU27 countries, i.e., there are no FRLs for UK, Switzerland, or Norway). For the other land accounting categories, the reference periods of accounting are from 2005 to 2009.

Overall, in the 2021–2025 period, member states (MS) are required to achieve a so-called “no debit” rule in the LULUCF sector: the accounted sinks need to be at least equal to the accounted emissions within the sector. In the 2026–2030 period, the overall EU27 target for the LULUCF sector is a total net GHG removal of  $-310$  MtCO<sub>2</sub>-eq. in 2030 (again, this target does not include UK, Switzerland, or Norway). The national LULUCF targets for 2030 are determined by the average LULUCF sinks/emissions in 2016–2018 and also considering the shares of forestland area in each MS. The binding annual targets for net GHG removal during the 2026–2030 period are determined for each MS by using a linear interpolation starting in 2022 (average of GHG emissions/sinks reported during 2021–2023) (European Commission 2021). Thus, in the second period, the LULUCF net sinks in each MS must be equal to or higher than their annual LULUCF targets. As the EU regulation is globally the first binding policy that targets LULUCF sink, it is of interest to examine how MSs can comply with the legislation.

In this paper, we ask whether the trends in the development of forest and LULUCF sinks, and their drivers indicate that the MSs are reaching the EU’s climate change mitigation targets for the LULUCF sector for the 2021–2030 period? Furthermore, we ask where are the greatest challenges and possibilities to promote those targets? The effects of land cover changes on the carbon (C) cycle and contemporary climate are well known (Chazdon et al. 2016; Houghton 2012, 2013), but the roles of other variables, such as forest management, especially at the macro scale, remain less completely understood (Naudts et al. 2016; Benedek and Fertő 2020), which limits predictions of the future evolution of LULUCF sinks (Thomas et al. 2019). Identifying the economic drivers and other factors behind land use changes and recognizing the relationships among them is important for policymakers (Meyer et al. 2003; Lambin and Meyfroidt 2011). We use national inventory data for the period from 1992 to 2020 obtained from several databases to study the past trends of LULUCF and forest sinks and their drivers and use this information to develop univariate and multivariate forecasts for net sinks in each MS. In the 2021–2025 period, we compare the forecasts for forest sinks to the FRLs and forecasts for LULUCF sinks to the “no debit rule”. In the 2026–2030 period, we compare the forecasts for the LULUCF sinks to the annual targets for LULUCF sinks. Our analysis complements many simulation-based analyses for the LULUCF sector (Grassi et al. 2017; Luysaert et al. 2018; Yousefpour et al. 2018; Roe et al. 2019) by providing an empirical analysis based on inventory data

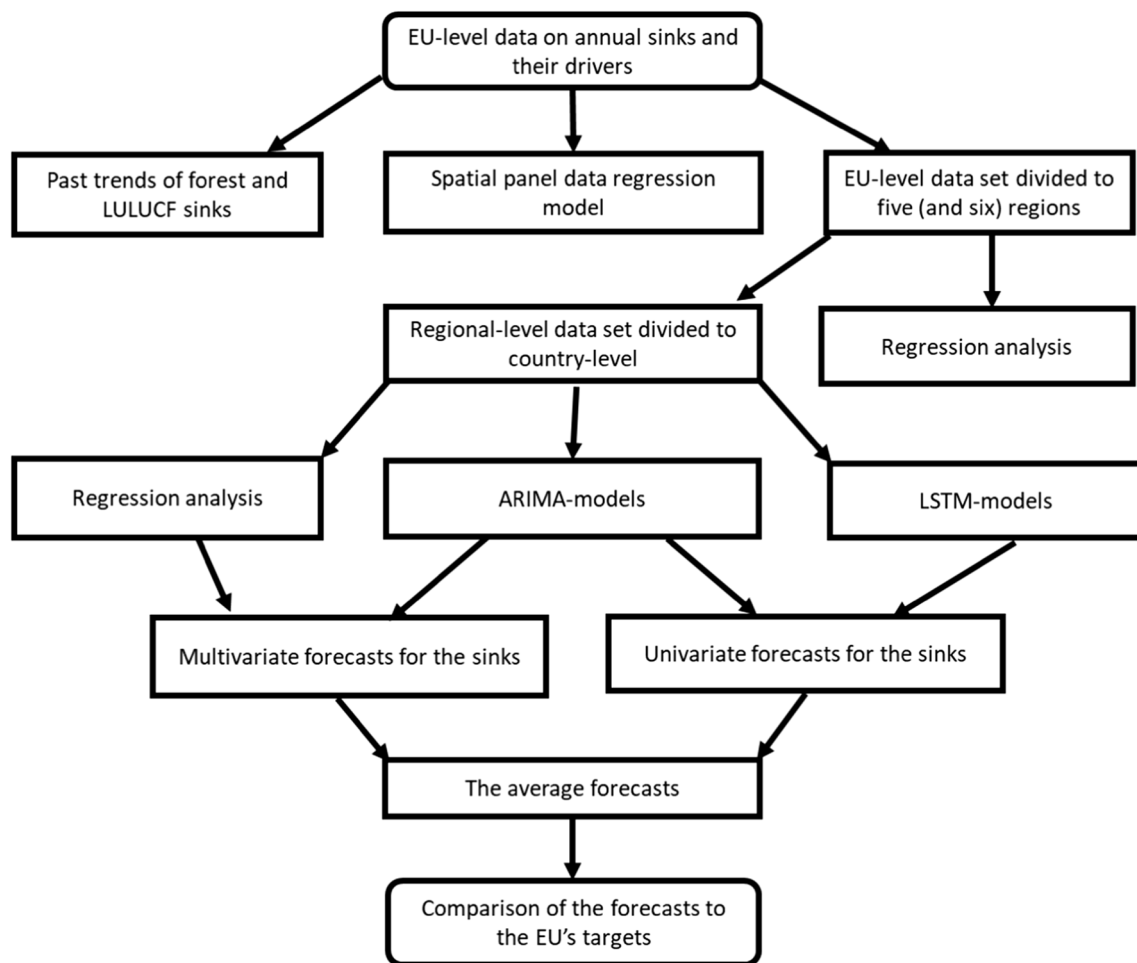
over a relatively long time horizon. Our approach is similar to that of Ciais et al. (2008), who combined European forest inventories and timber harvest statistics for 1950–2000 to assess changes in carbon sinks and Meyer et al. (2003), who used statistical methods to examine the relationships among deforestation and socioeconomic variables for 117 countries. Our approach also resembles that of Ceccherini et al. (2020), who used fine-scale satellite data to determine changes in harvested forest areas and forest biomass over Europe for the period of 2016–2018 relative to 2011–2015. We carry out a panel data analysis and extend the approach for forecasting and studying the LULUCF targets of the EU27.

## Data and methods

We start our analysis by collecting macrolevel data from several databases on annual sinks and their drivers in the EU (Fig. 1). These data are used to study the past trends of forest and LULUCF sinks and to carry out a spatial panel data analysis regarding the drivers of the sinks at the EU level (EU + UK + Switzerland + Norway). Next, we divide the EU into several regions, repeat the regression analysis at the regional level and focus on the effects of harvests on the annual variations in the sinks. We further divide the regional datasets into country-level datasets, which are used to derive several forecasting (multivariate and univariate) models. We use the average of the forecasts obtained with the different models to reduce the effect of model uncertainty on the forecasts and compare the forecasts to the FRLs for the 2021–2025 period and LULUCF targets for the 2026–2030 period. In this part, we only focus on the EU countries, because targets are defined for those. The rest of this chapter provides a more detailed description of the data and methods.

## Data

The Eurostat database provides GHG inventory data and data regarding the potential drivers of the forest sector for the analysis. We focus on the years from 1992 to 2021. In regression analysis, however, we look at the time period from 1992 to 2020, because the time series data that describe the harvests consists of this period. In the Eurostat database, the LULUCF sink/emission data cover the official national GHG inventory data reported to the UNFCCC by the MSs that follow the reporting rules defined by the Intergovernmental Panel on Climate Change (IPCC) reporting guidelines (Eurostat Statistics Explained 2018). The GHG inventory data in the Eurostat database describe how the whole LULUCF net sink varied annually in the period from 1992 to 2021 and how the forest sink, consisting of forest land sink and HWP sink, varied annually in this period. We also



**Fig. 1** Flow chart of the study

examine the annual variations in forest land sinks and HWP sinks. The emissions include CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions, which are measured as Mt CO<sub>2</sub> equivalents. Emissions from croplands, however, include only CO<sub>2</sub> emissions because other GHG emissions are reported in the agriculture sector, which is not part of the LULUCF accounting. We explain the annual variations in sinks/emissions with both human and natural variables, i.e., variables that describe human actions and variables that describe natural conditions and phenomena.

### Variables describing LULUCF management

Annual harvests (the sums of annual harvests (over bark)) are potentially the most important driver of the variations in annual sinks. The annual changes in forest sinks are defined as the differences between forest growth and harvests. Therefore, annual harvests decrease the amounts of annual forest land sinks. On the other hand, annual harvests increase

HWP sinks. Therefore, the net effect on the (combined) forest sinks and LULUCF sinks is determined by the relative sizes of the effects on the forest land sinks and HWP sinks. GDP is included as a macrolevel control variable, which reflects the overall economic condition of the MSs. Previous literature suggests that there is a U-shaped relationship between the GDP per capita and forest carbon sinks (Lin and Ge 2021). Most European countries have relatively high GDPs, and therefore, the expected effect is that the sinks would increase. Agricultural production reflects the intensity of cropland use: when the level of production increases in each MS, the intensity of cropland use increases, and presumably the GHG emissions from croplands increase, or/and the amount of forest sinks decrease through increased deforestation. We sum all the plant products produced in a certain country in a certain year into one aggregate variable, total plant production. We excluded meat products from the analysis to avoid double counting because the effect of meat production on cropland emissions is indirect and occurs through the production of fodder. In the FAO

database, all forestland is divided into planted or naturally regenerated forests. These variables reflect the forest management of each MS: planting is active forest management, whereas allowing the forests to regenerate naturally can be considered as passive management. To avoid perfect multicollinearity, only one of these variables can be used in the regressions. We use planted forests, which reflect the EU's afforestation and reforestation policies. It is measured as the share of forestland that is planted annually, which we convert into hectares. Another potential variable that influences sinks is bioenergy consumption. Bioenergy is included as a potentially important driver of forest sinks because the primary use of wood in Europe is for energy generation (42% of volume) (Nègre 2020). The increased bioenergy consumption requires agricultural expansion, which may lead to decreasing amounts of forest sinks through deforestation. There may also be a direct decreasing effects on sinks if the increased bioenergy consumption is associated with increased fuelwood harvests.

### Variables reflecting natural variations

For the weather variables, we use monthly data for temperature and rainfall, which we average to obtain annual mean values. This implies that the weather variables mainly reflect the general climatic conditions of the countries since most of the variations are lost due to averaging. There are not many annual variations or observable trends in the weather patterns in the observation period. Instead, the spatial variations are great, although countries with similar geographical locations typically share similar weather conditions. The expected effect of temperature on sinks is sink-decreasing because previous findings suggest that at higher temperatures, respiration rates continue to rise while photosynthesis rates decline; therefore, the net effect of temperature on forest sinks is negative (Duffy et al. 2021). Another potentially important driver is forest disturbances, such as storms, park beetle outbreaks, drought, and forest fires. Unfortunately, data on disturbances are scarce because of incomplete reporting by countries. There are some reports, such as Gardiner et al. (2010) and the FAO's Global Forest Resources Assessment database (FAO database 2022), but these data sources do not cover the entire time period of the analysis. Therefore, the effects of forest disturbances on the forest and LULUCF sinks are left to be captured by the yearly fixed effects. We do, however, include forest fires as a separate variable, which are measured as annual burned areas. Moreover, forest disturbances and harvests are not independent of each other: when trees fall because of storms, they are harvested. Typically, the observed peaks in timber production are due to high levels of salvage logging of trees felled by windstorms (Eurostat Statistics Explained 2018). Additionally, droughts or beetle attacks increase harvesting to prevent

disturbances from spreading. The harvest inventory database does not differentiate between normal harvests and salvage logging. Thus, to some extent, the disturbance-related annual variations in sinks are captured by the harvests.

Forest age structures are an important factor that determine the C sequestration potential of forests (Pan et al. 2011; Vilén et al. 2012; Besnard et al. 2018; Pugh et al. 2019; Repo et al. 2021). However, there are no country-specific panel data on European forest age structures for the period from 1992 to 2018. Instead, we use the timber volume as a proxy for age structure, as is commonly done in forest economic studies (Repo et al. 2021) because timber volume is a direct and increasing function of tree ages. For forest accounting purposes (OECD Glossary 2005), age structures are typically expressed in terms of timber volumes, and this relationship is generally accepted in the scientific literature (Chen et al. 2002; Pregitzer and Euskirchen 2004; Peichl and Arain 2006; Goulden et al. 2011; Besnard et al. 2018; Repo et al. 2021). The expected effect on timber volumes is sink-increasing because volumes are an increasing function of forest ages, and the ability of forests to absorb CO<sub>2</sub> increases with age (Stephenson et al. 2014). However, we add the square of the volume as an individual variable to the model with the expected sink-decreasing effect because the literature has found that after several years, the ability of trees to absorb CO<sub>2</sub> decreases and may even become negative if forests emit more CO<sub>2</sub> into the atmosphere through tree respiration and degradation of organic matter in the soil than they absorb through photosynthesis (Gundersen et al. 2021). The timber volume acts by adding a trend to regressions, and therefore, it cannot explain the annual variations but can explain the overall long-term changes in the sinks. Thus, it corrects for the effect of the long-term changes on the effects of harvests and other variables that are potentially important in explaining the annual variations. Table 1 summarizes the information for all variables used in the paper.

## Methods

### Spatial panel data model

To study the driving factors behind the sinks, we fit a spatial panel fixed-effect lag model to the data (Anselin et al. 2006) (Supplementary material S1.1). We use the same model specification for the forest (combined forest land and HWP sinks), forest land, HWP and LULUCF sinks. We focus on the sinks jointly and separately to trace the opposite behaviours of forest land and HWP sinks. We consider the unobserved country-specific characteristics, such as forest ownership types, effects of policies, soil types, and attitudes of landowners, by assigning fixed effects to each MS. We assign fixed effects to each year to account for the

**Table 1** Variables used in the study, summary statistics, expected relationships with sinks, and data sources (upper indices with explanations below the table)

Variable (unit)	min–Mean–max	The expected effect
<b>Dependent variables (the sinks)</b>		
Forest sink (MtCO <sub>2</sub> -Eq. a <sup>-1</sup> ) <sup>a</sup>	–85.6 to –18.5 to 13.1	
Forest land sink (MtCO <sub>2</sub> -Eq. a <sup>-1</sup> ) <sup>a</sup>	–86.2 to –16.9 to 14.8	
HWP sink (MtCO <sub>2</sub> -Eq. a <sup>-1</sup> ) <sup>a</sup>	–16.4 to –1.55 to 1.85	
LULUCF net sink (MtCO <sub>2</sub> -Eq. a <sup>-1</sup> ) <sup>a</sup>	–50.5 to –12.0 to 15.7	
<b>Variables describing LULUCF management</b>		
Harvests (t m <sup>3</sup> ) <sup>a</sup>	0–18,500–114,000	–/+
Financial crisis		–
Per capita GDP (current international t\$) <sup>b</sup>	1100–8300–103,000	+
Planted trees (t ha) <sup>c</sup>	9.0–2008–13,900	+
Total plant production (M t) <sup>c,*</sup>	0.01–25.1–147	–
Bioenergy (t TJ) <sup>b,**</sup>	155–6460–45,600	–
<b>Variables reflecting natural variations</b>		
Volume of the timber stock (M m <sup>3</sup> over bark) <sup>a,***</sup>	0.06–992–3663	+
Squared volume of the timber stock (M m <sup>3</sup> over bark) <sup>a</sup>		–
Temperature (°C) <sup>d</sup>	0.32–8.8–16.0	±
Rainfall (mm) <sup>d</sup>	434–866–1780	±
Forest fires (t ha) <sup>e,****</sup>	0–15.5–540	–

If the expected effect is negative, the variable decreases the sink, and if the effect is positive, the variable increases the sink

a = Eurostat database (national statistics were used for Denmark, Germany, and UK, and FAO database for Croatia), b = World Bank database, c = FAO database, d = World Bank Climate Change Knowledge Portal (World Bank Group 2021), e = Copernicus database

\*This variable includes crops; fruits; vegetables; root crops; seeds; and legumes. They are all summed together to reflect the country's total plant production

\*\*Renewable and bioenergy consumption

\*\*\* We fill missing values by using the FAO's Global Forest Resources Assessment database (FAO database 2022). The data points for timber volumes are available for 1990, 2000, 2010, 2015, 2016, 2017, and 2018. We use linear interpolation to obtain the data points for the missing years. Linear interpolation is reasonable in this case since the changes in general age structures at the country level are a slow and a trend-like process

\*\*\*\* These data are also quite incomplete, with full series for only 14 countries (e.g., 1992–2018), while five countries are missing the entire series (e.g., Ireland, Denmark, Belgium, Iceland, and the Netherlands). We complete the series with data from reports on forest fires in 2017 and 2018 (San-Miguel-Ayanz et al. 2017, 2019, 2020, 2022). If there is no value for a certain year in a certain MS, we assume that the amount of burned area is low and is modelled as zero

overall unexplained annual variations in sinks across the EU (+ UK + Switzerland + Norway). The model estimations were carried out with RStudio and the *splm* package (Millo and Piras 2012). We use a spatial panel model to obtain an EU-wide overview of the drivers behind the forest and LULUCF sinks. Therefore, we must consider the fact that the EU consists of very different countries, but neighbouring countries tend to be similar with similar demographics, political institutions, and natural endowments. Countries that are close to each other may interact in many ways through trade and policies and natural phenomena. In addition, neighbouring countries often belong to the same vegetation zone, which determines the type of natural forest. Correct modelling of the underlying spatially dependent

error structure of the data is essential for understanding both the drivers and geographic distributions of forest sinks. After the EU-wide analysis, we divide the dataset into country groupings (cf. Nabuurs et al. 2013) and repeat the estimations on these subsamples to obtain a better understanding of the regional effects of harvests on forest sinks.

## Forecasting models

We use the past trends of forest and LULUCF sinks and harvests and other explanatory variables to empirically forecast the future sinks in the EU27 (only the actual EU countries, for which there are FRLs and LULUCF targets). Because

forecasting is a notoriously uncertain activity and each forecasting method has its pros and cons, we use several models to produce forecasts of both forest and LULUCF sinks for each MS for the period from 2019 to 2030 and, following the previous literature, average the forecasting results (Steel 2017; Dormann et al. 2018) (Supplementary material S1.2). The models are (1) autoregressive integrated moving average (ARIMA) models (Yule 1927; Box and Jenkins 1970), which are the most well-known models in time series forecasting; (2) long short-term memory (LSTM) networks, which are regarded as more generalizable and superior compared to ARIMA and multivariate regression models (Hochreiter and Schmidhuber 1997); and (3) multivariate regression models, which may be more reliable than ARIMA models in the case of long-term forecasts (1–15 years), which is the case here (e.g. Mohamed and Bodger 2005; Ekonomou 2010), and in which forecasts of a given variable will be based not only on its own past but also on the past and present values of other time series related to it. When we compare the forecasts to the EU27 targets, we use only the forest forecasts for the 2021–2025 period, but the forecasts for the LULUCF sinks are used for both periods (e.g., 2021–2025 and 2026–2030). In the first period, the LULUCF forecasts are used to examine the attainability of the “no debit” rule, and in the second period, the LULUCF forecasts are compared to the annual targets.

## Results

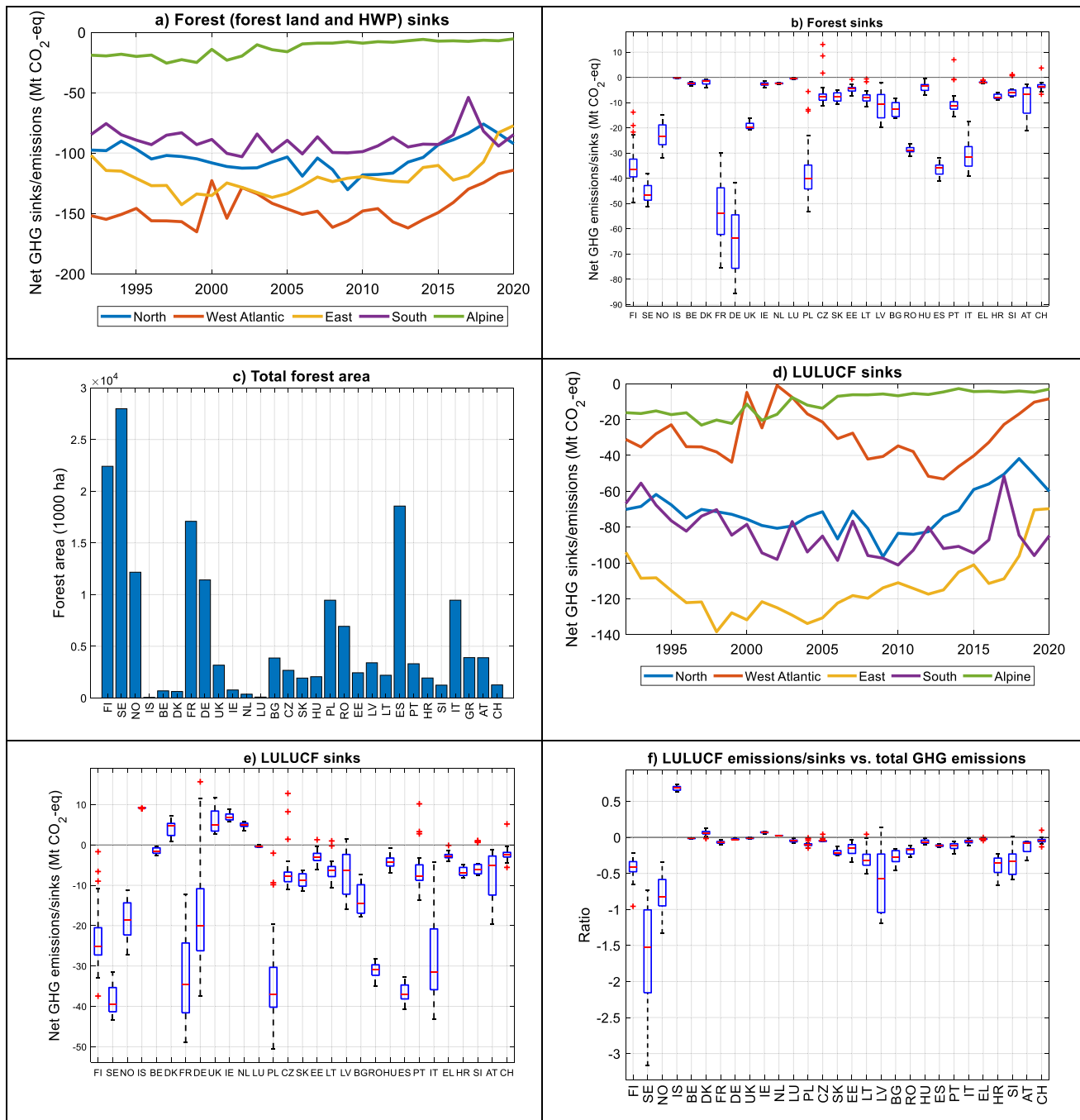
### Past trends of the sinks and emissions of the land use sector

We analyse the past (1992–2020) development of the sinks and emissions of the land use sector in each MS to obtain an overview of the trends and spatial heterogeneity of the sinks/emissions (see Supplementary material S2 for a more detailed analysis). The annual forest and LULUCF sinks vary greatly across MSs, and we employ country groupings for MSs with similar geographical locations (cf. Nabuurs et al. 2013). Focusing first on the trends in the regional forest sinks, we observe that in northern and western Atlantic Europe, the sinks increased from the 1990s onwards in a similar fashion, but after the 2008 financial crisis, the trends decreased (Fig. 2a). Development has been similar in southern Europe, although considerably smoother. Antonarakis et al. (2022) suggest two reasons for this trend. First, the global demand for wood products increased after the financial crisis, leading to the increased use of residual wood as a source of energy. Second, countries may have focused on reversing the economic downturn and diluted their climate change mitigation policies. In eastern Europe, the trend initially increased but began to decrease in the late 1990s. In

the alpine zone, there was a decreasing trend in the sinks throughout the observation period.

In Northern Europe, the largest forest sink is in Sweden (Fig. 2b). This is partly because the forested area in Sweden is the largest, although the forest area share is largest in Finland (Fig. 2c). In western Atlantic Europe, the largest sinks are in Germany and France. The Alpine region (Austria and Switzerland only) has relatively small forest sinks, although the forestry sector is important for both countries. In Eastern Europe, Poland, Romania, and Bulgaria have large forest sinks. At the European level, France, Germany, and Poland have large forest sinks, although the forest areas in these countries are notably smaller than those in Sweden and Finland or even in Spain (Fig. 1c). In Southern Europe, Spain and Italy have large forest sinks. The forest sinks in Spain have been quite stable, although the average number of forest fires has increased considerably since the 1960s (Schelhaas et al. 2003). In Portugal, in contrast, forest fires significantly decreased the sinks, particularly in 2003, 2005, and 2017 (Turco et al. 2019). In general, forest disturbances can cause significant sudden drops in the sinks (Supplementary material S2). Consider, for instance, the storms “Lothar” and “Martin” that caused large sudden drops in forest sinks in many countries in 2000 (Gardiner et al. 2010). In some cases, the disturbances lasted several years due to the insect attacks that followed the storms (Schelhaas et al. 2003).

Turning to the entire LULUCF sector, the annual variations, and overall trends of the LULUCF sinks closely followed those of the forest sinks, mainly because the GHG emissions from other land use sectors were rather constant (Fig. 2d, Supplementary material S2). This suggests that the main drivers of the annual variations in LULUCF sinks are those that drive the annual variations in forest sinks. Nevertheless, the emissions from other land uses affect the levels of LULUCF sinks, which were considerably lower than the forest sinks, particularly in western Atlantic Europe. The countries with large forest sinks also had the largest LULUCF sinks: Sweden, Finland, and Norway in northern Europe; France and Germany in western Atlantic Europe; Spain and Italy in southern Europe; and Poland and Romania in eastern Europe (Fig. 2e). However, large net sinks exist in these countries because these countries have large land areas. The greatest LULUCF net sinks relative to land areas are in Slovenia, Luxembourg, Slovakia, Hungary, Poland, and Bulgaria (Supplementary material S2, Figure S10). Similarly, the forest sinks relative to total land areas are the largest in Luxembourg, Slovenia, Germany, and Latvia (Supplementary material S2, Figure S11). In Germany, the LULUCF sinks were considerably smaller than the forest sinks because of the large emissions from grasslands and croplands (Supplementary material S2, Figures S6 and S7). The relative sizes of the emissions/sinks of the LULUCF sector compared with the total national GHG emissions are



**Fig. 2** Panel **a** shows the annual variations in net GHG sinks/emissions from the forestlands and HWPs in country groupings in Europe (EU + UK + Switzerland + Norway) from 1992 to 2020. GHG emissions are presented as positive numbers, whereas sinks are presented as negative numbers, which is consistent with the GHG inventory reporting. Country groupings include western Atlantic Europe: BE, DK, FR, DE, UK, IE, NL, and LU; northern Europe: FI, NO, SE, and IS; eastern Europe: BG, CZ, SK, EE, LV, LT, PL, RO and HU; southern Europe: HR, EL, IT, PT, SI and ES; and alpine areas: AT and CH. Panel **b** shows the minimum, maximum, quartiles and median values of net GHG emissions (+) and sinks (–) from the forestlands and HWPs in each MS in 1990–2018. Panel **c** shows the forest

areas in each MS measured in 1000 hectares in 2018. Panel **d** shows the annual variations in net GHG sinks/emissions from the entire LULUCF sectors in geographical clusters in Europe in 1990–2018. The blue boxes describe the first and third quartiles, and red spots are extreme values. Panel **e** shows the net GHG emissions from the LULUCF sector in each MS in 1990–2018. Panel **f** shows the share of LULUCF sink/emissions of the each country’s total GHG emissions. The inventory data are obtained from the Eurostat database, and forest area data are obtained from the World Bank (2020). Negative net emissions indicate sinks, and positive net emissions indicate emissions

large only in northern Europe (Sweden in particular) and Latvia (Fig. 1f). These results support the findings described in the previous literature that suggest that although the LULUCF sector and forests have a role in climate change mitigation, large GHG emission reductions are also needed in other sectors (Grassi et al. 2017; Luysaert et al. 2018; Popkin 2019).

### Driving factors of forest and land use sector sinks at the EU level

We studied the driving factors behind the annual variations in the forest (combined forest land and HWP), forest land, HWP and LULUCF sinks using 11 predictors (Table 1). A statistically significant spatial autoregressive coefficient confirms that the data are spatially correlated (Table 2). Recall that a negative effect means that the variable increases the sink, and a positive effect means that the variable decreases it because sinks are described as negative emissions. Annual harvests are significant and affect sinks with the expected signs and sizes: 0.28 tCO<sub>2</sub>-eq/m<sup>3</sup>a<sup>-1</sup> for forest sinks; 0.45 tCO<sub>2</sub>-eq/m<sup>3</sup>a<sup>-1</sup> for forest land sinks; -0.18 tCO<sub>2</sub>-eq/m<sup>3</sup>a<sup>-1</sup>

for HWP sinks; and 0.36 tCO<sub>2</sub>-eq/m<sup>3</sup>a<sup>-1</sup> for LULUCF sinks. The financial crisis had a significant negative effect on the HWP sinks, possibly due to decreased trade: when trade decreases, harvests decrease, and therefore, the production of HWPs decreases, and consequently, their sinks decrease. The effect was opposite for forest land sinks: the effect of harvests on the sinks decreased, which is logical since harvests have a strong decreasing effect on forest land sinks. Overall, the effects were statistically insignificant when we examined the forest and LULUCF sinks, probably because the financial crisis had opposite effects on the HWP and forest land sinks.

Forest fires have been a significant driver of sinks, except for the HWP sinks: 0.033 MCO<sub>2</sub>-eq/ha a<sup>-1</sup> for the forest sinks, 0.034 MCO<sub>2</sub>-eq/ha a<sup>-1</sup> for forest land sinks; 0.038 MCO<sub>2</sub>-eq/ha a<sup>-1</sup> for the LULUCF sinks. The volume of timber stock, which captures the annual trends related to the changing age structures, significantly increased the sinks (except the HWP sinks): 0.027 tCO<sub>2</sub>-eq/m<sup>3</sup> a<sup>-1</sup> for forest sinks; 0.026 tCO<sub>2</sub>-eq/m<sup>3</sup> a<sup>-1</sup> for forest land sinks; and 0.027 tCO<sub>2</sub>-eq/m<sup>3</sup> a<sup>-1</sup> for LULUCF sinks. The effect size of the volume is quite small due to the trend-like evolution of the

**Table 2** Parameter estimates and standard errors for the drivers explaining the annual variations in the forest sinks, forest land sinks, HWP sinks, and LULUCF sinks provided by the spatial panel fixed-effect lag model

Driver	Forest sink (MtCO <sub>2</sub> -Eq. a <sup>-1</sup> )	Forest land sink (MtCO <sub>2</sub> -Eq. a <sup>-1</sup> )	HWP sink (MtCO <sub>2</sub> -Eq. a <sup>-1</sup> )	LULUCF sink (MtCO <sub>2</sub> -Eq. a <sup>-1</sup> )
Spatial autoregressive coefficient	-0.78 (0.13)***	-0.68 (0.13)***	-0.42 (0.11)***	-0.82 (0.13)***
Intercept	-25.3 (9.8)**	-21.2 (10.7)*	6.5 (1.7)***	-20.2 (14.1)
Harvests (1000 m <sup>3</sup> )	2.8E-04 (4.8E-05)***	4.5E-04 (5.0E-05)***	-1.8E-04 (8.4E-06)***	3.6E-04 (5.0E-05)***
Financial crisis dummy* harvests (1000 m <sup>3</sup> )	-1.7E-05 (2.6E-05)	-8.0E-05 (2.7E-05)**	6.4E-05 (4.6E-06)***	-1.1E-05 (2.7E-05)
Volume of the timber stock (M m <sup>3</sup> over bark)	-2.7E-02 (4.6E-03)***	-2.6E-02 (4.8E-03)***	-1.8E-04 (8.1E-04)	-2.7E-02 (4.8E-03)***
Squared volume of the timber stock (M m <sup>3</sup> over bark)	5.6E-06 (1.1E-06)***	6.4E-06 (1.1E-06)***	-8.1E-07 (1.9E-07)***	5.9E-06 (1.1E-06)***
Log of per capita GDP (current international \$)	-5.8E-01 (9.1E-01)	-1.6E-01 (9.5E-01)	-3.9E-01 (1.6E-01)*	6.3E-02 (9.5E-05)
Temperature (°C)	8.6E-01 (4.8E-01)	8.2E-01 (5.0E-01)	-4.6E-02 (8.4E-02)	9.4E-01 (5.0E-01)
Rainfall (mm)	1.1E-03 (1.8E-03)	1.2E-03 (1.9E-03)	-2.6E-05 (3.2E-04)	1.2E-03 (1.9E-03)
Forest fires—burned area (1000 ha)	3.3E-02 (5.9E-03)***	3.4E-02 (6.2E-03)***	8.2E-05 (1.0E-03)	3.8E-02 (6.2E-03)***
Planted trees (1000 ha)	-1.8E-03 (6.8E-04)**	-1.5E-03 (7.1E-04)*	-2.5E-04 (1.2E-04)*	-1.4E-03 (7.1E-04)*
Total plant production (M t)	1.5E-01 (5.0E-02)**	1.7E-01 (5.2E-02)***	-2.2E-02 (8.8E-03)*	2.1E-01 (5.2E-02)***
Consumption of bioenergy (t TJ)	-3.1E-05 (7.4E-05)	-6.7E-05 (7.7E-05)	3.5E-05 (1.3E-05)**	-3.6E-04 (7.7E-05)***

Removals (sinks) and emissions (sources) are represented as negative and positive values, respectively; therefore, a negative sign implies that the variable increases a sink, and a positive sign implies that a variable decreases a sink. For each driver, there is an estimate of the effect and standard error (in brackets). Significance marks refer to the p values of the t-tests. Panel data set consists of 25 countries (including UK, Switzerland, Norway, and excluding Lithuania, Belgium, Luxembourg, and Greece due to the missing values) and years 1992–2020

Significance codes: \*\*\* means < 0.001; \*\* means < 0.01; \* means < 0.05; . means < 0.1; and ' ' means > 0.1

stocks. In addition, the squared volume had a decreasing (and insignificant, except for the HWP sinks) effect on the sinks, although the effect size was marginal:  $0.0056 \text{ CO}_2\text{-eq/m}^3 \text{ a}^{-1}$  for forest sinks;  $0.0064 \text{ CO}_2\text{-eq/m}^3 \text{ a}^{-1}$  for forest land sinks;  $0.0059 \text{ CO}_2\text{-eq/m}^3 \text{ a}^{-1}$  for LULUCF sinks; and  $-0.00081 \text{ CO}_2\text{-eq/m}^3 \text{ a}^{-1}$  for HWP sinks. The effect of volume on forest land sinks becomes negative (sink-decreasing) when the volume is approximately 2 billion cubic metres (Supplementary material S3, Figure S12). The negative effect is non-existent for HWP sinks, and therefore, the turning point for forest sinks occurs later, at approximately 2.5 billion cubic metres. For LULUCF sinks, this point occurs at approximately 2.3 billion cubic metres. In Finland, Sweden, Germany, Poland, France, and Romania, the volume of timber stock has already exceeded 2 billion cubic metres, suggesting that, to some extent, observed declining mitigation potential of existing forests may be related to the age structures of the forests.

Our results also suggest that planting trees has increased the sinks significantly:  $-1.8 \text{ tCO}_2\text{-eq/ha a}^{-1}$  for forest sinks;  $-1.5 \text{ tCO}_2\text{-eq/ha a}^{-1}$  for forest land sinks;  $-0.25 \text{ tCO}_2\text{-eq/ha a}^{-1}$  for HWP sinks; and  $-1.4 \text{ tCO}_2\text{-eq/ha a}^{-1}$  for LULUCF sinks. Plant production also exerted statistically significant effects on the sinks:  $0.15 \text{ tCO}_2\text{-Eq. a}^{-1}$  for forest sinks;  $0.17 \text{ tCO}_2\text{-Eq. a}^{-1}$  for forest land sinks;  $-0.022 \text{ tCO}_2\text{-Eq. a}^{-1}$  for HWP sinks; and  $0.21 \text{ tCO}_2\text{-Eq. a}^{-1}$  for LULUCF sinks for Mt of total plant production. The effect size due to plant production is naturally statistically more significant and greater in magnitude when the whole LULUCF sink is considered because increasing agricultural production also implies higher GHG emissions from croplands and grasslands in addition to increasing deforestation. Regarding local weather conditions, rainfall did not have a significant effect on the sinks. However, temperature had a decreasing effect on the

forest, forest land, and LULUCF sinks, although this was significant only at the 10% level. The effect of temperature on the sinks originates from the emissions of land uses other than forest land, which are typically increasing functions of temperature (Jones et al. 2004; Schaufler et al. 2010; Koffi et al. 2020; Chang et al. 2021). All the annual and most of the spatial fixed effects, were insignificant (Supplementary material S3).

## Regional and MS-wise effects of harvests on forest sinks

We next apply regression analyses for the five regions in Europe (EU + Norway, Switzerland, and UK) but focus only on the impact of harvests on sinks. The sink-decreasing effect of harvests on the forest sink and forest land sink is greatest in the Alps ( $1.96 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$  for forest land sinks and  $1.64 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$  for forest sinks); second greatest in western Atlantic Europe ( $1.0 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$  for forest land sinks and  $0.74 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$  for forest sinks); and third greatest in northern Europe ( $0.51 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$  for forest land sinks and  $0.38 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$  for forest sinks) (Table 3). The effect is insignificant in southern and eastern Europe. In southern Europe, forest fires appear to be the most significant driver of the annual variation of the sinks ( $0.030 \text{ MCO}_2\text{-eq/ha a}^{-1}$  for forest and forest land sinks, and  $0.032 \text{ MCO}_2\text{-eq/ha a}^{-1}$  for LULUCF sink). Moreover, if we divide eastern Europe into a block consisting of the Baltic countries (block 1) and a block consisting of the other eastern European countries (block 2), we find that the effect of harvests on forest land sinks is significant in the Baltic block ( $0.52 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$  for forest land sinks). The effect of harvests on HWP sinks is significant (and sink-increasing)

**Table 3** The effects of harvests on the sinks ( $\text{tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$ ) on the combined forest and HWP sinks, forest land sinks, HWP sinks, and LULUCF sinks in different regions of Europe

Region	Effect of the harvest on the sinks ( $\text{tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$ )			
	Forest and HWP sink	Forest land sink	HWP sink	LULUCF sink
Northern Europe	0.379 (0.063)***	0.505 (0.089)***	-0.126 (0.032)***	0.384 (0.072)***
West Atlantic Europe	0.735 (0.150)**	1.00 (0.149)***	-0.310 (0.0273)***	0.688 (0.165)***
Alps	1.64 (0.181)***	1.96 (0.169)***	-0.314 (0.034)***	1.70 (0.186)***
Southern Europe	0.143 (0.207)	0.304 (0.195)	-0.161 (0.037)***	0.109 (0.266)
Eastern Europe	-0.109 (0.195)	0.0175 (0.196)	-0.127 (0.015)***	-0.058 (0.111)
Eastern Europe 1. block (Baltics)	0.369 (0.192)	0.524 (0.203)*	-0.155 (0.023)***	0.461 (0.193)*
Eastern Europe 2. block	-0.178 (0.274)	-0.076 (0.276)	-0.101 (0.0168)***	-0.116 (0.268)

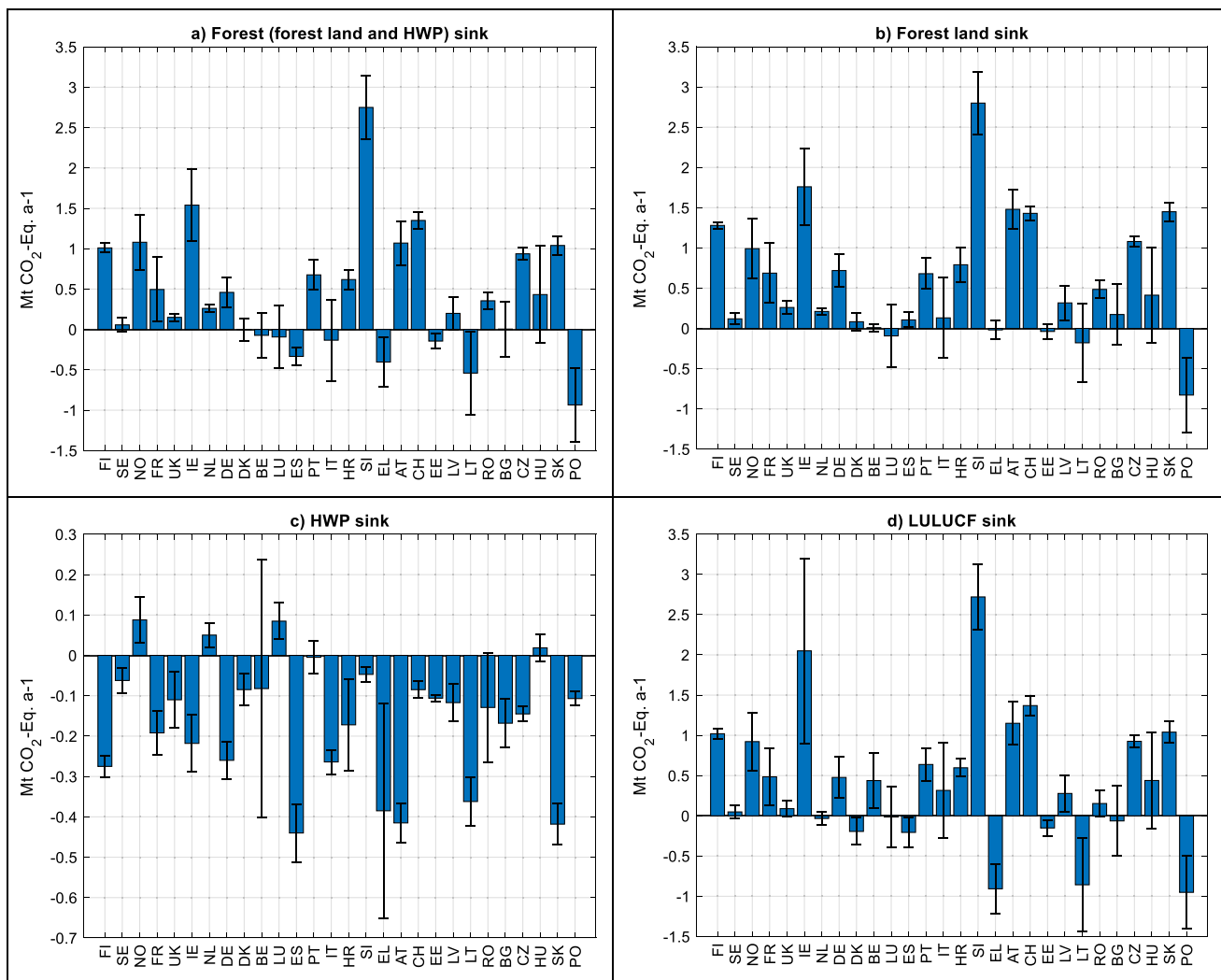
The regions are northern Europe (Finland, Sweden, and Norway); western Atlantic Europe (France, UK, Ireland, Netherlands, Germany, Denmark, and Belgium); the Alps (Austria and Switzerland); southern Europe (Spain, Portugal, Italy, Croatia, Slovenia, and Greece); eastern Europe (Estonia, Latvia, Lithuania, Romania, Bulgaria, Czech Republic, Slovakia, Hungary, and Poland); eastern Europe 1. block (Estonia, Latvia, and Lithuania); and eastern Europe 2. block (Romania, Bulgaria, Czech Republic, Slovakia, Hungary, and Poland). Positive signs indicate sink-decreasing effects, and negative signs indicate a sink-decreasing effects

Significance codes: '\*\*\*' means  $<0.001$ ; '\*\*' means  $<0.01$ ; '\*' means  $<0.05$ ; '.' means  $<0.1$ ; and ' ' means  $>0.1$

in all regions. This effect is greatest in the Alps and in western Atlantic Europe ( $-0.31 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$ ); second greatest in southern Europe ( $-0.16 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$ ); and third greatest in northern and eastern Europe ( $-0.13 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$ ). The effects of harvests on LULUCF sinks are greatest in the Alps ( $1.70 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$ ); second greatest in western Atlantic Europe ( $0.69 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$ ); and third greatest in northern Atlantic Europe ( $0.38 \text{ tCO}_2\text{-eq/m}^3 \text{ a}^{-1}$ ). This effect is insignificant in southern and eastern Europe.

We next apply the same model specification for each MS except that we omit the country fixed effects and replace the yearly fixed effects with the trend of the dependent variable (except for the case of southern Europe) and make some minor modifications (see Supplementary material S1.4). We focus again on the effects of harvests on the sinks. Figure 3

shows how much the sinks decrease ( $\text{Mt CO}_2\text{-eq}$ ) when the harvests are increased by one  $\text{Mm}^3$ , that is, the marginal effect of the harvests on sinks in each MS ( $\text{tCO}_2\text{-eq/m}^3$ ). The sink-decreasing (i.e., positive sign) effects on forest land sinks are greatest in Slovenia, Ireland, Austria, Slovakia, Switzerland, Finland, Czech Republic, and Norway (Fig. 3b). In these countries, the  $\text{tCO}_2\text{-eq/m}^3$  effects of the harvests are more than one and even two (Slovenia). The effects are smallest in Poland, Lithuania, Luxembourg, Estonia, Greece, Belgium, Denmark, Spain, and Sweden. We may also observe that some marginal effects are associated with great uncertainties and are therefore insignificant, i.e., could also be zero. In some of these cases, we may even observe sink-increasing effects (Poland, Lithuania, Luxembourg, Estonia, and Greece) on forest land sinks. When



**Fig. 3** Marginal effects of harvests on forest and HWP sinks (a), forest land sinks (b), HWP sinks (c), and LULUCF net sinks (d) in each MS obtained from the MS-wide regressions. Bars show the levels of the effects, and the black lines show the 95% confidence intervals.

The effects show by how many  $\text{Mt CO}_2\text{-eq}$  the sinks decrease when the harvests are increased by  $\text{Mm}^3$ , i.e., what is the  $\text{tCO}_2\text{-eq/m}^3$  effect of the harvests

examining forest sinks (e.g., forest land + HWPs), the countries with the greatest effects are the same, but the order is slightly different (Fig. 3a). In addition, in most cases, the effects of harvests are smaller for forest sinks than for forest land sinks. The effects of harvests on LULUCF sinks are rather similar to those on forest sinks (Fig. 3d). Harvests have the greatest sink-decreasing effects on the LULUCF sinks in Slovenia, Ireland, Switzerland, Austria, Slovakia, Finland, Czech Republic, and Norway, whereas the greatest sink-increasing effects occur in Poland, Greece, Lithuania, Spain, Denmark, Estonia, Bulgaria, and the Netherlands (sink-increasing effects are associated with great uncertainties and could therefore also be zero). These effects are nearly same magnitude as those for forest sinks but are lower than those for forest land sinks. Harvests increase the HWP sinks in almost every country, except Norway, the Netherlands, Luxembourg, and Hungary (Fig. 3c). The greatest effects can be found in Spain, Slovakia, Austria, Greece, Lithuania, and Finland.

### Forecasts for forest and land use sector sinks and their comparisons to the EU27 targets

We now turn to the main question of how the forecasts for the forest (forestland + HWPs) sinks and LULUCF sinks compare to the FRLs in 2021–2025 and to the EU targets for the LULUCF sector in 2026–2030. Therefore, we focus on the EU27 targets, implying that we exclude Switzerland, UK, and Norway. We use the derived ARIMA, regression, and LSTM network models to forecast the national forest and LULUCF sinks for the period from 2021 to 2030 (Supplementary material S1.1–S1.4). We first look at the forecasts for the forest and LULUCF sinks for the country groupings and all of EU (Fig. 4). Overall, the forecasts up to 2025 and 2030 suggest declining forest and LULUCF sinks, respectively, which is in agreement with the previous literature (Ceccherini et al. 2020). This declining trend is modest in southern Europe, where the forests are least intensively managed. On average, the forecasted forest sinks fall short of the FRLs in all the regions, except in southern Europe and in Alpine (only Austria). In addition, the forecasted forest sinks are below the FRLs only by a small amount in eastern Europe. FRLs exceed the forecasted forest sinks the most in west Atlantic and northern Europe. In total, forecasted forest sinks undercut the FRLs in EU27 in 2021–2025. The forecasted LULUCF sinks lie below the annual EU targets in all the regions. The difference is greatest in west Atlantic and northern Europe and smallest in southern Europe. At the EU-level, LULUCF sinks clearly fall short of the EU targets in 2026–2030, and the difference between actual and target sink increases every year. In addition, because the forest sinks continue their decreasing trend, the difference between the LULUCF sinks and the EU targets in 2026–2030 is

greater than the difference between the forest sinks and the FRLs in 2021–2025.

We ask next how the forecasted forest sinks relate to the FRLs in each MS in the period from 2021 to 2025. The main finding is that the forecasted sinks exceed the FRLs in most MSs, especially in Southern Europe (Fig. 5a and Supplementary material S4), which supports the estimation by the European Commission (2021). The forecasted sinks exceed the FRLs most notably in Germany, Hungary, Romania, Italy, and Sweden. However, in total the forest sinks in 2021–2025 fall short of the FRLs by approximately 128 MtCO<sub>2</sub>eq. The primary reason for this result is that the forecasted forest sinks are very much lower than the national FRLs in France, Finland, and the Czech Republic.

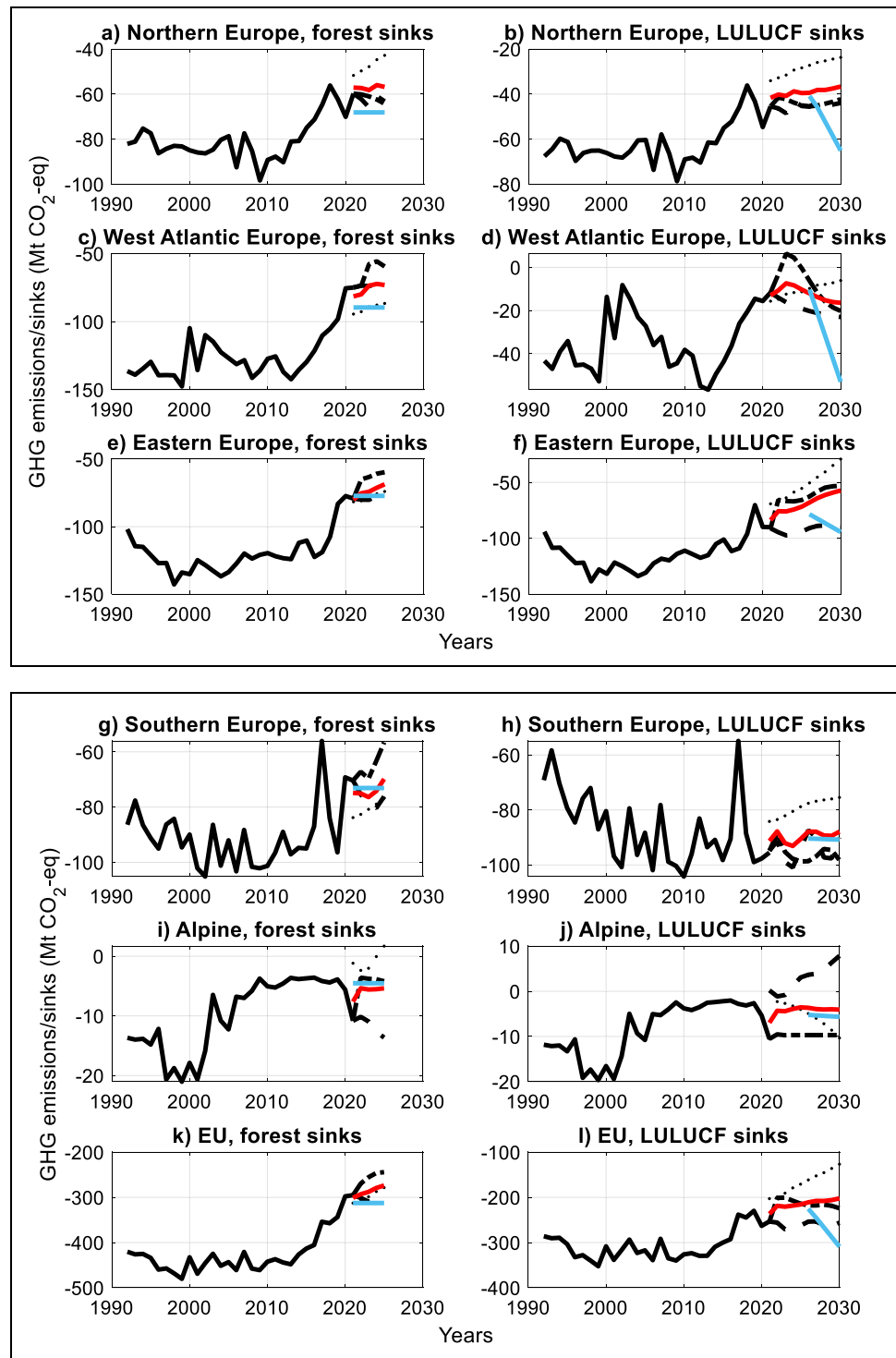
For the 2026–2030 period, we compare the forecasts for the LULUCF sinks to their national annual targets set by the EU. We use our forecasts to establish the starting points for the linear trajectories of the annual binding targets for each MS. The comparisons show that in most MSs, the forecasted net sinks are below the target trajectories (Fig. 5b). At the EU level, the LULUCF sink is -203 MtCO<sub>2</sub>eq in 2030, indicating that the sink is 107 MtCO<sub>2</sub>eq less than the 2030 target. The only MSs in which the annual sinks exceed the targets are Portugal, Denmark, Netherlands, Slovenia, Hungary, and Romania. In Portugal, this is the case because the 2030 target is low. Thus, active measures are needed in nearly all MSs to increase the sinks or reduce the emissions from the LULUCF sector. The sinks are most notably below the annual targets in Poland, France, Finland, Spain, Sweden, Germany, Latvia, and Italy. The targets for 2030 are quite high for Sweden, Spain, Poland, France, Italy, and Germany, because in these countries, the LULUCF sinks were at high levels in the reference period (2016–2018) (Supplementary material S4). The high targets for the net LULUCF sinks are the primary reason for not reaching the targets. In Finland, on the other hand, the sinks were very low in 2016–2018 due to the high harvesting rates. The total cumulative difference between the targets and the LULUCF sinks from 2026 to 2030 is 298 MtCO<sub>2</sub>eq.

## Discussion and conclusions

We examined the variables affecting the variations in LULUCF sinks and used them to predict the future evolution of national forests and LULUCF sinks. This facilitated comparisons of the predicted sinks to the national forest reference levels (2025) and to the LULUCF targets (2030). This analysis reveals the greatest challenges and possibilities to promote sinks for the 2021–2030 EU policy.

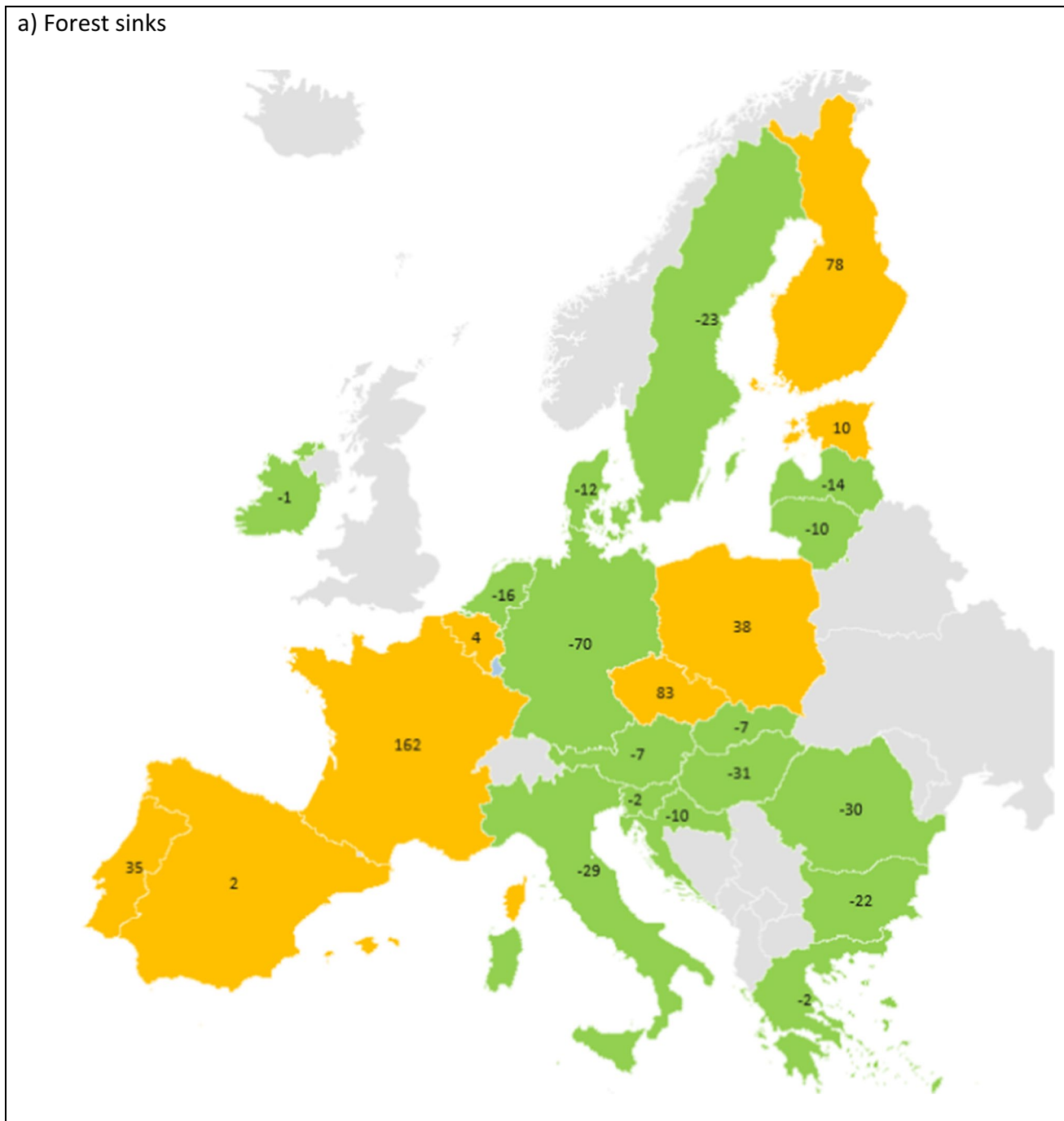
The first set of results shows that annual harvests are the main factor that explain the variations not only in forest sinks but also in LULUCF sinks in the entire EU, its

**Fig. 4** Observed and reported GHG inventory data for forest land and HWP and the LULUCF sector for 1992–2018 (Eurostat database), forecasts provided by the ARIMA models (2019–2030) (black dashed lines), LSTM models (2020–2030) (black dash-dotted lines), regression models (2019–2030) (black dotted lines), the averages of the models (2020–2030) (red solid lines), and the national FRLs and LULUCF targets (blue solid lines) for the country clusters (i.e., geographic regions) and all of Europe. The time series used for estimating the regression models consist of the years 1992–2020, whereas the time series used for estimating the ARIMA and the LSTM models consist of the years 1992–2021. Therefore, the forecasts obtained with multivariate and the univariate methods start at different points. Inventory data are obtained from the Eurostat database



regions and member states. The soils and other emissions from agriculture and land-use change have been rather stable but affect the levels of LULUCF sinks. Furthermore, afforestation, bioenergy use, and forest fires play significant roles in the variations in forest and LULUCF sinks. Interestingly, increased harvesting increases HWP sinks, which moderates the impact of harvests on forest and LULUCF sinks.

Naturally, this suggests that increasing the share of long-lived wood products would alleviate the harvesting effect on the sinks. The sensitivity of forest and LULUCF sinks to harvests, as measured by the magnitude of the effect, varies greatly across the MSs, which is mostly related to the intensity of forest utilization. Thus, member states and regions are, after all, quite heterogeneous.



**Fig. 5** Cumulative differences between the national forest reference levels and the forest and HWP sinks in 2021–2025 (upper panel) and the LULUCF sinks and national linear target trajectories in 2026–2030 (lower panel). The numbers indicate the actual cumulative differences, which are averaged between the models and are measured

in MtCO<sub>2</sub>-eq. Positive numbers indicate that the cumulative net sinks are below the reference level or the target trajectories (orange countries), and negative values indicate that the cumulative net sinks exceed the reference level or the target trajectories (green countries)

Harvests are the main driver of the annual variations in forest sinks, which is also well established in the previous literature (cf. Holtmark 2010, 2012; Hudiburg et al. 2011; Achat et al. 2015; Naudts et al. 2016; Ceccherini et al. 2020), but their positive impacts on HWP sinks have not

received much attention. Additionally, the trade-off found between bioenergy use and sinks is in line with the results presented in the previous literature (cf. Holtmark 2010, 2012; Schulze et al. 2012), although it has been argued that the net result depends on the specific characteristics

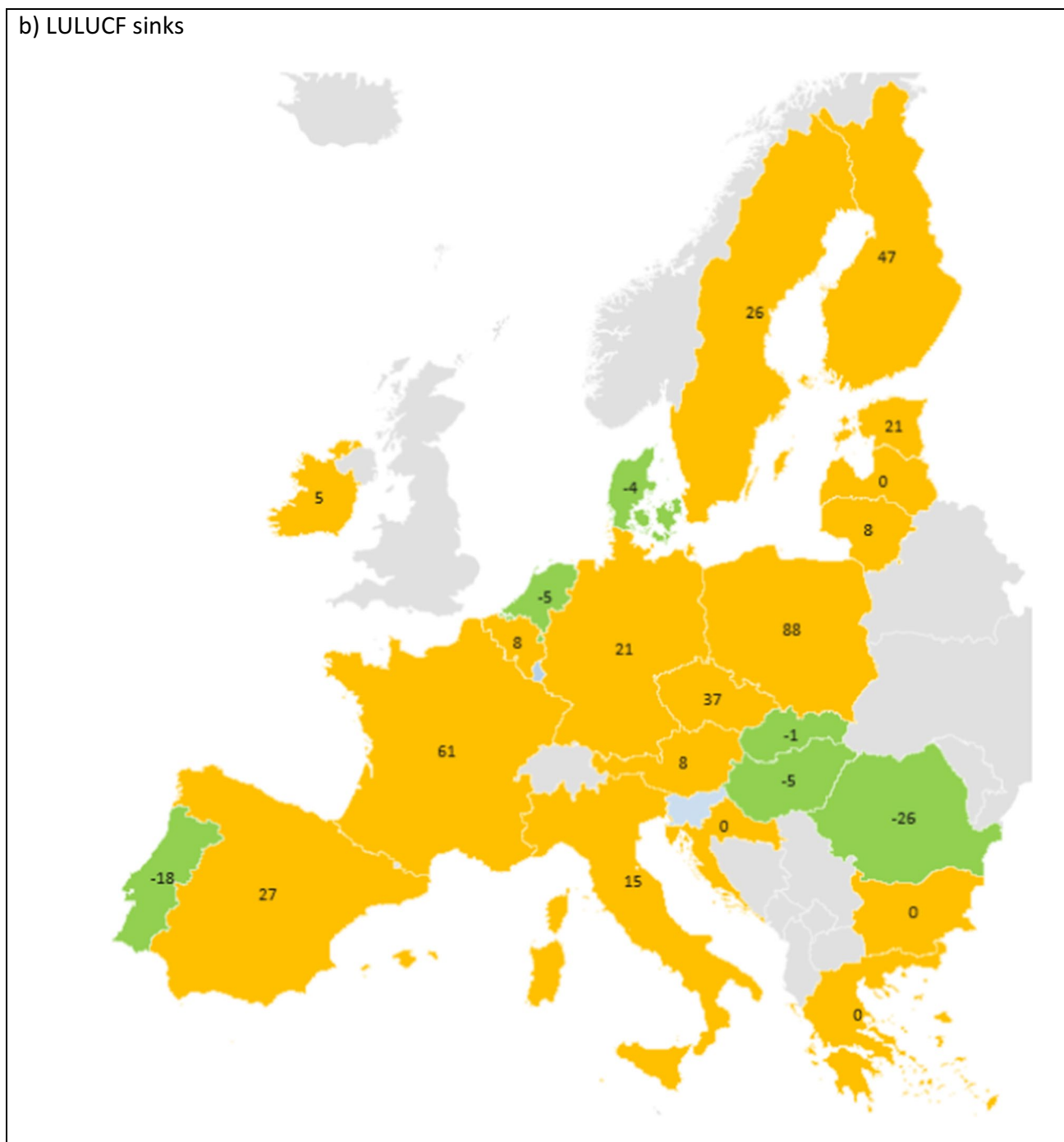


Fig. 5 (continued)

of the forest system under analysis, the fuels manufactured and the timeframe of the analysis (Searchinger et al. 2009; Johnson 2009; Holtmark 2010; Hudiburg et al. 2011; McKechnie et al. 2011; Zanchi et al. 2011; Mitchell et al. 2012; Schulze et al. 2012; Sterman et al. 2018; Seppälä et al. 2019; Favero et al. 2020).

Previous literature has noted that harvest effects differ across regions in Europe (cf. Marland and Schlamadinger 1997; Duncker et al. 2012; Schelhaas et al. 2018; Yousefpour et al. 2018). We complement this with insights about country-wise harvest sensitivities. They are important for understanding the current and future challenges of the EU's

LULUCF policy. Given that determining forest reference levels does not reflect these sensitivities and that they are a function of forest utilization rates, the current policy creates an uneven burden on member states. For countries with high harvesting sensitivities, increasing sinks by decreasing harvesting is easy but probably costly. Countries with low harvest sensitivities must rely more on reductions in soil emissions, which may be cheaper if agricultural support instruments are wisely tailored for emissions reduction.

Our analysis shows that for most countries, the forest reference levels (FRLs) have been set at notably low levels compared to the past development of forest sinks, even during the “reference period” of 2000–2009. The FRLs are high only for a few member states, including Finland, France, Portugal, and the Czech Republic. Thus, the MSs are in rather unequal positions regarding the forest sink targets in 2021–2025. Nevertheless, our forecasts suggest that the forest sinks will fall short of the FRLs in total by 128 Mt CO<sub>2</sub>-eq in 2021–2025, mainly due to the declining development of the sinks in the countries with high FRLs, implying that there will be shortage of sink units in this period for trading. The emerging number of sink units for trading depends on the two factors. Firstly, the accounted results of managed forest land with HWPs and other land accounting categories determine the fulfilment of the EU27 LULUCF’s target, and the result offer a starting point to assess the potential amount of sink units that we could not assess in this study. Secondly, it is unclear how sink units will be used for offsetting emissions in the effort-sharing regulation (ESR) in countries with the surplus results of LULUCF in 2021–2025.

For the 2026–2030 period, our forecasts suggest that most MSs will find it very challenging to reach their LULUCF targets. In total, the MSs fall short of their targets by 298 Mt CO<sub>2</sub>-eq. In particular, we predict that Finland, Poland, and France will have large deficits. Trading of sink units will not provide a feasible solution during this period either, as the number of selling countries (six) is limited. It should be noted, however, that national targets may still change, even though the overall target will remain fixed at 310 Mt CO<sub>2</sub>-eq in 2030.

In any case, the conclusion from our predictions is that member states need to design more effective policies to strengthen the LULUCF sinks. Most likely, both forest and agricultural policies must be sharpened by introducing economic incentives for carbon sequestration in forests and cultivated land (Roe et al. 2019). The responsibility belongs to the MSs. For some countries, peatlands provide a large mitigation potential provided drainage is halted and drained peatlands are rewetted (Tanneberger et al. 2021). Agricultural practices can be shifted towards carbon farming, and national forest policies must be complemented by sink-increasing instruments, such as subsidy schemes for

sequestration (see, e.g., Gren and Aklilu 2016; Lintunen and Uusivuori 2016; Lintunen et al. 2016; Niinimäki et al. 2013; Pihlainen et al. 2014; Pohjola and Valsta 2007; Pohjola et al. 2018).

We employed a set of statistical models to derive the results. The main limitation in our analysis relates to the data. The inventory data are uncertain due to weak inter-institutional arrangements and data gaps. Furthermore, the reporting practices, classification systems and assessment methods may vary across countries (Grainger 2008; Ceccherini et al. 2020). There are also uncertainties that are related to the models we used for forecasting (see Supplementary material S.1.2). Thus, following the suggestions in the past literature, we averaged the forecasts obtained with the different models with equal weights (Steel 2017; Dormann et al. 2018). For future research, explicit consideration of forest disturbances such as windthrow and insect outbreaks (which we were forced to exclude from the model due to data limitations) would be insightful since they can have notable annual effects on forests and their sinks (Schelhaas et al. 2003; Kurz et al. 2008; Seidl et al. 2014; Seidl et al. 2017; Yamanoi et al. 2015; Ziemblińska et al. 2018; Forzieri et al. 2021). Another interesting topic for future research is the relative cost-efficiency or trade-off between harvest reductions and emissions reduction from other land uses. This kind of analysis would require different kinds of data (finer spatial resolution) and approaches (possibly optimization).

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**Author contributions** MO, MH, and JS planned the research. MH gathered the data, carried out the estimations, forecasts and calculations, and produced all results. MH wrote the main manuscript text. MO and JS wrote some sections of the manuscript. All authors analysed the results. All authors reviewed the manuscript. All authors revised the manuscript.

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**Declaration**

**Conflict of interest** The authors have no competing interests as defined by Springer or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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