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RESEARCH

The multiple-use of forests and the ecosystem services may generate higher returns than agricultural land rent in Ukrainian Polissya

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Abstract
Ecosystem service flows are acquiring paramount importance in designing land use policies, the setting local development priorities and social fabric in rural areas. Understanding the dynamics of the monetary value of forest ecosystem services (ES) is important for guiding private landowners in selecting appropriate management alternatives and motivating them to adopt multiple-use forest practices and expand forest cover, according to the New EU Forest Strategy for 2030. In this study, we estimated the spatio-temporal changes in biophysical parameters and the potential annual revenue from four major forest ES within a typical area of the Polissya region, Ukraine. The assessed ES included wood supply, CO_2 sequestration, mushroom and wild berry harvesting, and hunting. We further assessed the competitiveness of income generated under different combinations of ecosystem service utilization and forest regeneration types, comparing it to agricultural land rent using equivalent annual income valuation. We found that the total annual monetary flow from these ES increased by 19.3%, mostly due to forest land expansion and changes in forest structure of study area. On average, provisioning ES (both wood and non-wood forest products) contribute up to 90% of the total annual revenue, with similar contributions from each. This study underscores the competitive potential of forestry utilizing various ES as a viable land-use alternative for local landowners, with the highest expected discount rate of 2.3–3.5%. Our results highlight how forest-based management can serve as a key strategy for increasing forest cover while ensuring economic sustainability at the local level.

Keywords Wood supply · Non-wood forest products, economic value · CO_2 sequestration · Hunting · Harvesting mushrooms and berries

Introduction

Humans receive multiple benefits within natural and cultural landscapes in a form of ecosystem services (ES) (de Groot et al. 2002; Egoh et al. 2007; Meacham et al. 2022). These services change over space and time (Czajkowski et al. 2009; Hansen and Loveland 2012; Cocco et al. 2023) under natural (Delphin et al. 2013), and human (Cademus et al. 2014; Dade et al. 2022) impacts. Land use transitions are an important driver of such change (Fedele et al. 2018; Gomes et al. 2021). Agricultural land expansion as an example of this phenomenon has been extensively studied in relation to tropical rainforest deforestation (Leite-Filho et al. 2021). Meanwhile, many landscapes in temperate biomes have exhibited the opposite process, with cropland abandonment in post-Soviet countries as a clear illustration of this process (Lesiv, et al., 2018b; Stefanski et al., 2014).

Multiple studies on ES focus primarily on their current conditions (Baskent et al. 2008; Adermann et al. 2015; Kangas et al. 2018; Baciu et al. 2021; Soloviy et al. 2021; Taye et al. 2021; Nolander and Lundmark 2024). However, the dynamics of annual flows provided by different services are less represented in literature (Zhang and Li 2022). Land use modification directly impacts the flow of ES (Stürck et al. 2015; Anaya-Romero et al. 2016; Tasser et al. 2024;

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Poturalska et al. 2024), while more alterations can be delivered by climate change (Schirpke and Tasser 2024; Sun et al. 2024).

The importance of addressing the dynamic nature of ES is directly linked to their monetary expression, which has been examined since the 1960s (De Groot et al. 2012). However, still roughly half of scientific publications report ES in a non-monetary way (Acharya et al. 2019), particularly non-market ES (e.g., regulating, cultural). Wood products flows explicitly determine economic annual value of benefits provided by forests (Alberdi et al. 2020; Winkel et al. 2022). Meanwhile, examples of successful implementation of carbon markets assured more considerations for non-wood ES (Zhang et al. 2020). Indeed, the last 15 years have shown a spike in number of these studies (Ojea et al. 2016; Deng et al. 2024; Kuhfuss et al. 2024).

Anthropogenic disasters and military conflicts can significantly shift the value of forest ecosystem services at regional and local scales. War fare deteriorates ecosystem functions and promote land conversion through abandonment, destruction or pollution (Lloyd C. et al. 2023; Lecina-Diaz et al. 2024; Matsala et al. 2024; Myroniuk et al. 2024). Importantly, military impact can limit the economic value of ongoing service flows in direct (e.g., through disruption of local logistic networks) and indirect (e.g., changing market preferences at regional or global scale) ways (Deininger et al. 2025). Forced human migrations from war-affected areas (Reinl et al. 2024) can facilitate land use modifications, thus promoting so-called alternative, or derivative land uses (Carmona-Torres et al. 2023), especially in rural landscapes. Forest areas contaminated by radionuclides in the aftermath of the Chornobyl incident is another factor of risk, which associated with the spatial planning of ecosystem service flows in Polissya (Matsala et al. 2021; Khomutinin et al. 2024). The utilisation of forest wood products (Otreshko et al. 2015; Bilous et al. 2020), none-wood forest products (NWFP) as those delivered by green forest floor and shrubs (Holiaka et al. 2020), and wild animal`s products (Fesenko et al. 2021) in these areas has the potential to pose a significant threat and should be controlled.

Areas in the Polissya region at the northern of Ukraine, along the border with Belarus and Russia, are predominantly rural and forest-covered (Karpiuk et al. 2024; Myroniuk et al. 2024). After the fall of Soviet Union, many lands owned by small private owners were abandoned and naturally afforested by early– (silver birch, *Betula pendula* Roth., and aspen, *Populus tremula* L.) and mid–successional (Scots pine, *Pinus sylvestris* L.) tree species. Meanwhile, in 2010–2020 competition between farms for land resources is growing in Ukraine (Kvartiuk et al. 2024), that encourage landowner recultivates abandoned lands back to croplands (Smaliychuk et al. 2016), even these new forests could even be 30 years old. As for mid-2020s, it is uncertain how the ongoing full-scale invasion by Russia and hostilities along the state border can affect flows of goods and services in agricultural lands compared to forests.

We carried out this research in the rural landscape in the study region. We examined spatio-temporal 10-yr change in flows of both wood and non-wood ES provided by local forests. Our goal was to understand if (i) land use transitions substantially altered the composition of annual ecosystem flows, (ii) non-wood ES can have monetary value comparable to the revenue from wood products supply, and (iii) whether forest owners' revenue from forest ES can be competitive with the rent of land for local agricultural companies as a motivation for private forestry and the preservation of self-seeding forests.

Materials and methods

Study area and forest management planning data

The study site of 4,455.9 ha (Fig. 1) is in the northern part of Chernihiv Oblast, and belongs to the Ukrainian Polissya region (52°30 ‘N, 31°49’E) (Bilous et al. 2017; Lakyda et al. 2019). The Polissya region has temperate continental climate, and its surface is predominantly flat, with the presence of swamplands and bogs (Hensiruk 1992). The average annual temperature in the study region is 7.9 °C (over the last 30 years) with an observed increase of 0.6 °C per decade, while the annual precipitation was roughly 600 mm with tendency of decrease (Karamushka et al. 2023). The dominant tree species in the study area are the Scots pine and silver birch. Additionally, local forests are composed by aspen, black alder *(Alnus glutinosa* L. Gaerth.*)*, and European oak (*Quercus robur* L.).

It is important to consider the multi-purpose nature of the forest when assessing the dynamic relationships between ES. These relationships can vary considerably, ranging from synergistic to neutral, competitive and alternative (mutually exclusive) (Bennett et al. 2009; Aryal et al. 2022; Pan et al. 2022). The primary forest ES within the study area for the local citizens are as follows: wood-based forest products supply; hunting; harvesting of non-wood forest products. By "primary" we meant the services that are present on the market and generate real monetary flows. Mushrooms and wild berries are main harvestable NWFP in Ukraine (Stryamets et al. 2015). Additionally, we estimated flows of carbon sequestration, focusing on stocks stored in forest biomass. We did not include many regulation services in this study, such as soil erosion control and water protection, due to plain local topography, small human population and absence of ravine formation processes. Cultural ES such as

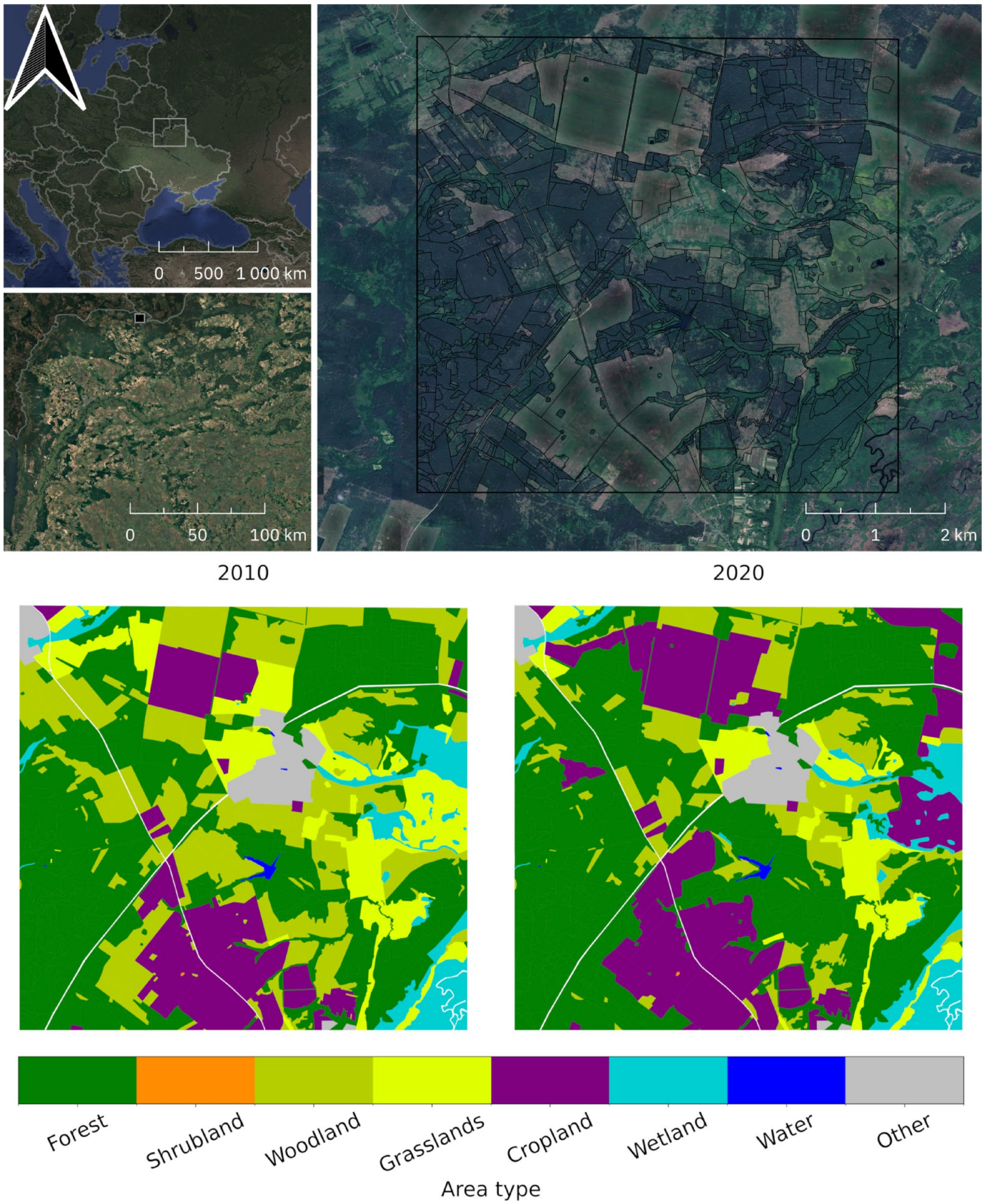

Fig. 1 Location of the study area and land use distribution based on forests management and planning (FMP) data

tourism were also not accounted due to poor local development of corresponding activities.

We conducted an independent inventory within the study area following the practices of forest management

Table 1 Distribution of forest sites by tree species in the study area

Common name	2010 year		2020 year	
	Area, ha	Area, %	Area, ha	Area, %
Black alder	240.8	12.7	259.2	11.8
Silver birch	711.0	37.5	722.2	32.8
Scots pine	877.0	46.3	1095.8	49.8
Common aspen	11.9	0.6	13.7	0.6
Common oak	12.8	0.7	15.5	0.7
Other species	19.4	1.0	23.0	1.0
Unstocked	21.4	1.1	69.9	3.2
Total	1894.0	100.0	2199.3	100.0

and planning in Ukraine. We delineated forest stands and other land use types (Table A1), and estimated mean stand characteristics (e.g., diameter at breast height, height, relative stocking, age) and tree species composition through in situ visual and measuring observations. All forests within the study area were surveyed in 2010 (Bilous et al. 2017; Lakyda et al. 2019) and revisited in 2020, updating the delineated land use map and forest stand classifications (Table 1). Besides stocked forest stands, we also estimated biometric characteristics for temporarily unstocked forest lands (regenerated clear-cuts) and naturally afforesting lands (woodlands). Temporarily unstocked lands were included to forest areas. Naturally afforesting abandoned lands that fulfilled the FAO (2018) definition of «forest» (canopy cover exceeding 10%, a minimum average stand height of 5 m, and a minimum area of 0.1 ha) were classified as forest and analysed accordingly; otherwise, these lands were classified as woodland. We did not analyse wood supply and carbon sequestration ecosystem services for woodlands; however, these lands were relevant for the hunting ecosystem service due to their influence on habitat quality distribution across the study area. Lands with woody species, such as willow, that were unable to reach the forest definition we classified as shrublands.

Assessment of ecosystem service flows

We estimated the annual flow of four forest ES during 10-yr based on field collected data as for 2010 and 2020 that equals the typical forest management planning period. Additionally, we used site-specific data, derived from either our experiments established in situ or guidelines published in scientific sources, to link stand average characteristics from FMP data with wood and non-wood service estimates (Fig. 2).

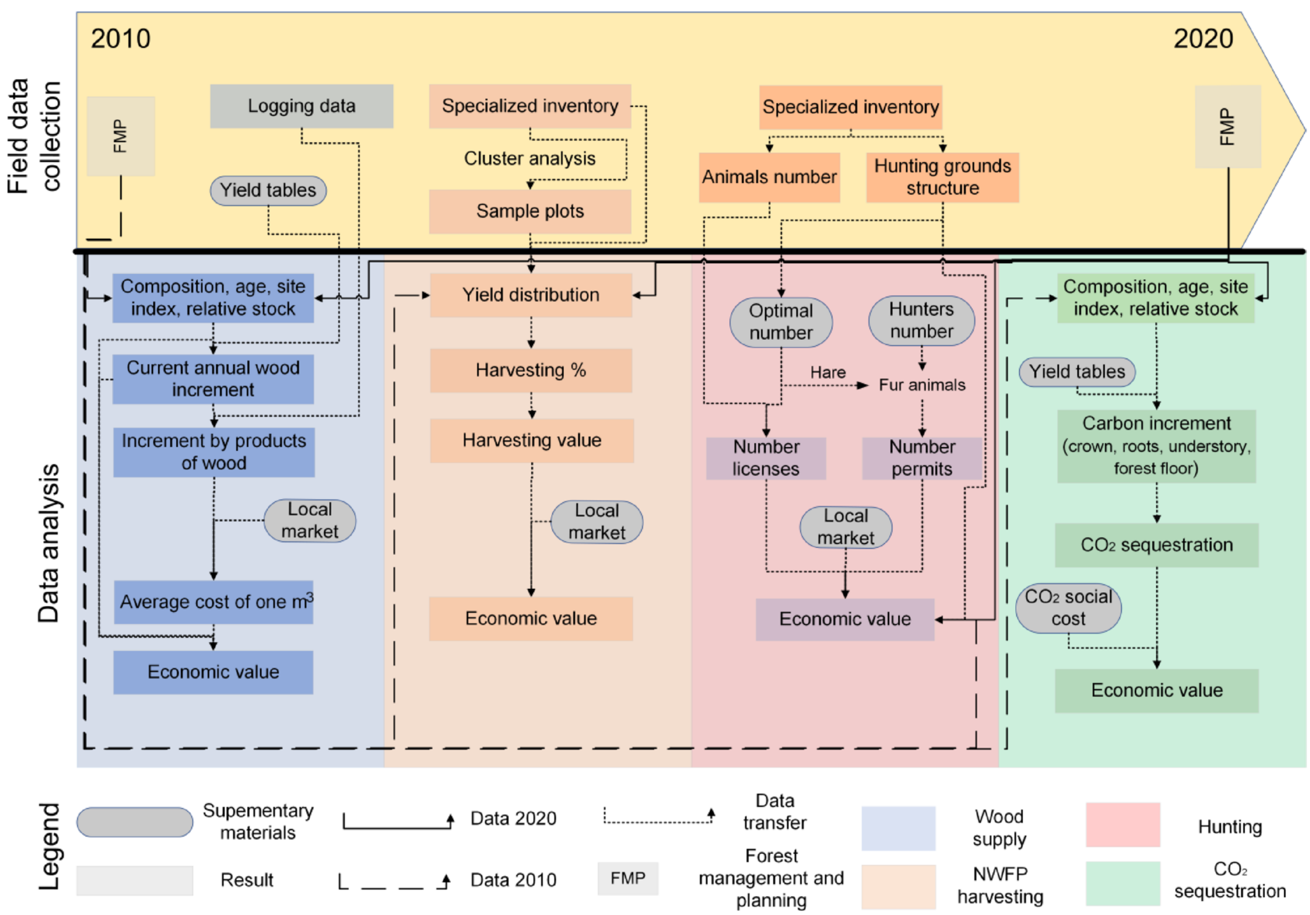

Fig. 2 A conceptual flowchart of the study of ES value

The evaluated monetary value of forest ES has been converted from UAH to USD using annual currency exchange rates. The monetary values of ES products were obtained from local markets between 2010 and 2020. The same average price of products was utilised for both study periods, thus excluding any fluctuations due to supply and demand. Afterwards, the USD values were converted to USD in 2020 via inflation rates.

Wood supply

The annual value of wood-based products increment was estimated using FMP data, growth and yield tables (NUBIP 2013), and local reports on wood qualitative structure resulting from thinning and final felling conducted within the study area in 2010s (Fig. A1). The annual increment of wood products volume for each forest site was calculated based on tree species composition, stand origin, site index, age, and relative stocking (by basal area) of forest stands (Table A2).

The revenue generated by timber and firewood was estimated using local average market prices at forest road and local reports on timber qualitative structure resulting from thinning and final felling by local forest enterprises. In general, the average estimated price of 1 m^3 of wood production increment (cubic meter corresponds to the average wood structure by quality for the age class of stands) in the study area by 2020 was about 17.4 USD. The evaluated average price per 1 m^3 of wood in Scots pine stands was found to range from 1.9−6.9 USD in young stands to 33.2−42.0 USD in middle-aged, immature, and mature stands.

CO_2 sequestration

The annual carbon increment in live forest biomass values was estimated for each forest site and study period separately utilizing growth and yield tables of biomass (Shvidenko et al. 2008; Lakyda et al. 2018). The annual carbon sequestration was estimated for the aboveground tree biomass, tree roots, understory vegetation (undergrowth shrubs and young trees), and green forest floor (mosses, lichens and herbaceous vegetation). Then, we excluded carbon in stem biomass as we consider these forests managed, thus primarily deriving their value through timber supply during thinning and final felling. We obtained the part of stemwood carbon in total stand carbon increment, which was 65–66% in both young and immature forests, 67% in middle-aged forests, 62% in mature forests, and 45% in unstocked forest lands.

The economic value of carbon sequestration service was defined as the cost of carbon emissions using the avoided abatement cost method (Schaubroeck et al. 2016) and utilizing the conversion (from C to CO_2) factor 3.67 (IPCC 2006). Based on statistical estimates of CO_2 monetizing value for 2020, the cost of one tonne of CO_2 was set at 14.0 USD (IWG 2021).

Hunting

We conducted a specialized field inventory of forest hunting grounds in the study area, focusing on determining of the number of game animals. The inventory was performed using two total count methods: noisy chase out and track counting on snow. Data on tree species composition, canopy cover, stand age group, and understory density was used to estimate a site index of hunting grounds within their inventory. Additionally, we estimated this index for non-forest land uses within the study area. The value of the site of hunting grounds ranges specifically for a targeted game species, from 1 (optimal habitat) to 5 (avoided habitat) according to On the Approval of the "Regulations for Organizing Hunting Grounds" (2007).

As a result of field inventory, we counted the number of moose (*Alces alces* L.), roe deer (*Capreolus capreolus* L.), wild boar (*Sus scrofa* L.), European hare (*Lepus europaeus* L.), and European pine marten (*Martes martes* L.). In addition, the number of beavers (*Castor fiber* L.), and muskrats (*Ondatra zibethicus* L.) within permanent water bodies of the study area was inventoried by the sample counts method. Still, muskrats were not included in the ES assessment since this species was not hunted during this period, and the cost of possible licenses is unspecified. However, it can be a potential additional service within hunting. The inventory revealed the presence of a black grouse (*Tetrao tetrix* L.) in the study area, with a total count of 80 birds. This species, a traditional hunting bird in Eurasia. We excluded black grouse and moose from the hunting ES assessment due to their inclusion in the Red Data Book of Ukraine (national list of threatened species). This exclusion commenced in 2019 for moose and throughout the entire period for black grouse.

The optimal number of animals for each targeted game species within the study area was estimated using mean values of the site index of hunting grounds. Subsequently, the number of hunting licenses (permits) for each game species was calculated as a difference between the inventoried number of animals (field data) and the optimal number of animals (calculated) of each species (Table 2).

The study area plays host to an annual hunting season for waterfowl (ducks and geese, etc.), field birds (partridges and quail, etc.), and forest birds (woodcocks and pigeons, etc.), as well as fur animals. Hunters must purchase a seasonal permit to hunt birds and separate permit for fur animals.

Table 2 Distribution parameters of evaluated game species across the study area

Game species	Average site hunting index	Total number of individuals	Number of hunting permits	Cost of permit, USD
Moose	3.1	13	1	1273.5
Roe deer	3.1	80	9	340.9
Wild boar	3.3	30	7	235.1
Hare	2.5	200	117	5.9
Marten	4.3	20	2	78.4
Beaver	–	20	2	78.4

Table 3 Number of sample plots where NWFP estimation were conducted

Forest composition	Age group				
	young	middle	immature	mature and overmature	total
Penny bun					
Birch	1	1	3	9	14
Mixed	1	1	3	6	11
Pine	0	1	1	3	5
Slippery jack					
Birch	4	0	0	0	4
Mixed	9	1	0	0	10
Pine	15	1	0	0	16
Girolle					
Birch	1	1	5	6	13
Mixed	1	1	5	6	13
Pine	1	1	1	1	4
Red raspberry					
Birch	6	0	0	0	6
Mixed	6	3	3	3	15
Pine	12	3	3	3	21
Wild strawberry					
Birch	12	6	6	6	30
Mixed	12	6	6	6	30
Pine	18	6	6	6	36

Thus, the total amount of benefits from hunting in the study area was calculated using the designed formula:

$$H = \sum_{i=n}^{n} (Na_i \cdot l_i) + Nh_1 \cdot Pf + Nh_2 \cdot Pb \quad (1)$$

where, H – the annual payment from hunting, USD; Na_i – the number of animals permitted for hunting per year; l_i – the game animal hunting license cost, USD; *Nh* – number of hunters on study area; *Pf* – the hunting permit cost for the fur game species, USD; *Pb* – the hunting permit cost for the gamebird species, USD.

None-wood forest products harvesting

The NWFP harvesting data was collected for the following major species of mushrooms in study area: slippery jack (Suillus luteus L.), penny bun (Boletus edulis Bull. Ex Fr.), girolle (Cantharellus cibarius Fr.). Red raspberry (Rubus idaeus L.) and wild strawberry (Fragaria vesca L.) presented the major berry species that local people harvested yearly. As a result of the specialized forest inventory, forest plots that yield mushrooms and/or berries were identified (Table 3). The random selection of sample plots for data collection on the volume of mushrooms and berries was based on cluster analysis by type of forest, tree species composition, and stand age.

The study of mushrooms' performance was conducted using rectangular sample plots (20 × 20 m) during the main yield season: August-October for slippery jack, August–September for penny bun, June–September for girolle.

For all types of mushrooms and the raspberry, up to 3 sample plots per hectare were established in a diagonal configuration, with up to 6 plots per hectare for the wild strawberry. Initially, the standard harvesting of NWFP was performed in each sample plot, which was then followed by a detailed examination of their full performance. The examination of the raspberries comprised the quantification of the number of fruiting shoots and the number of berries per shoot. The yield was then determined in accordance with the Forest Mensuration Handbook (NUBIP 2013).

Using the first-person harvesting imitation approach, the potential NWFP harvesting rates were estimated as 0.5 for mushrooms, 0.25 for raspberries, and 0.1 for strawberries. To exercise control over the estimated value of NWFP productivity in the study site, a survey was conducted of three local receiving stations and 62 local citizens who collect NWFP for their own needs. In order to exercise control over the estimated value of NWFP productivity in study site, a survey was conducted of local receiving stations, and local citizens who collect NWFP for their own needs. The empirical data of the harvested volume of NWFP on sample plots were used to assess the volume of mushrooms and berries in study areas with the relevant stand age and composition of tree species (Table 4).

The calculated annual NWFP prices at receiving stations were established at 0.5 USD·kg^{-1} for slippery jack, 3.2 USD·kg^{-1} for penny bun, 2.5 USD·kg^{-1} for Girolle, 1.5 USD·kg^{-1} for red raspberry, and 2.0 USD·kg^{-1} for wild strawberry.

Table 4 Overall productivity of NWFP

Species	Common criteria of NWFP yield distribution	Average yield, kg·ha^{-1}·year^{-1}
Slippery Jack	Clear pine stands with the best yield in young stands and decline during aging	100–25
	Mixed pine-birch stands, yield decline due to ageing of stands and increasing % of leaf species (birch and aspen, oak) in the composition of stands	60–5
Penny bun	Birch stands, with a trend of higher productivity in the oldest age	25–10
	Pine stands, lower yield at the young age	7–5
	Other stands except for alder, black locust	2–1
Girolle	Birch and aspen stands, a higher yield after 30 years old	65–50
	Pine stands (higher yield in young age)	10–5
Red raspberry	The highest yield was in the areas after clearcut and in temporary unstocked forest sites	360–300
	Forest cowered lands with higher value in after 40 years old	50–20
Wild strawberry*	Temporary unstocked birch and mixed forest lands, woodlands	40–35
	Temporary unstocked areas, and young forest with gaps	30–15
	Middle aged and mature forest stands with gaps	5–2

*Except alder stands

Table 5 Average forestry local costs

Description	Average cost, USD	Unit	Period, years
Plantation establishment	171.5	UDS ha^{-1}	0
Plantation tending	84.0–144.2	UDS ha^{-1}	1–4
Thinning in the youth period	99.9–153.4	UDS ha^{-1}	5–20
Thinning	10.5–11.8	UDS m^{-3}	> 20
Final harvest	9.4	UDS m^{-3}	The end of rotation
Administrative costs	5.7	UDS ha^{-1}	Annual
NWFP harvesting	80% of revenue	USD kg^{-1}	Annual
Hunting	95% of revenue	USD	Annual

Estimating of annual income of pine forest lands under management scenarios

We determined the competitive potential of lands with pine forest as alternative to rent the same land for agricultural production utilizing Equivalent annual income (EAI) formula (Brukas et al., 2001; Lula et al., 2021). The following assumptions concerning land use scenarios were made in conducting the EAI calculation:

Assumption 1 Landowners manage artificially established forests as classical forest enterprises, generating revenues solely from wood supply. We included costs from plantation establishment and silvicultural (e.g., thinning).

Assumption 2 Landowners manage artificially established forests and generate revenues not only from wood supply, but also obtain annual revenue from hunting and NWFP harvesting. As in Assumption 1, plantation establishment and silvicultural costs are included.

Assumption 3 Landowners manage naturally regenerated forests and obtain revenues solely from wood supply. We supposed that no plantation establishment or thinning costs occur during the first 10 years of forest growth.

Assumption 4 Landowners manage naturally regenerated forests and generate revenues from wood supply, hunting, and NWFP harvesting. According to Assumption 3, no plantation establishment or thinning costs occur during the first 10 years.

The selection of dominant pine forest sites based on the site index was carried out to estimate revenue within the study area. It was assumed that four thinning operations, each with an intensity of 20%, were conducted over the rotation period. The price per cubic metre of wood harvested through thinning, as estimated according to Section “Wood supply revenue”. The volume of the final harvest were estimated as the weighted average of the mature forest sites within the study area. The costs associated with tree planting, thinning treatments, protection, felling and annual administrative expenses over the 80-year rotation period were obtained from four local state forestry enterprises (Table 5). The costs and revenues that were applied in the computation are located at the forest landing site, tax liability. Furthermore, annual costs and income were incorporated values into the net present value (NPV) calculation as the annual series (Bullard & Straka, 2011; Sills et al., 2017). Administrative costs were included under all four assumptions, as these expenses are directly linked to forest management and occur regardless of the revenue structure. In contrast, Assumptions 1 and 3 represent classical forest enterprise models limited to wood production without supplementary income streams. Income from hunting and NWFP was incorporated only under Assumptions 2 and 4, since these scenarios explicitly account for revenues beyond wood supply. The income of NWFP harvesting was estimated with the exclusion of the financial burden of harvesting which was found to account for 80% of revenue. The hunting service accounted for approximately 95% of management costs. To account for the fact that hunting service requires very large forest areas and as well as NWFP harvesting is characterized by a high degree of spatial heterogeneity, we applied average annual revenues estimated at our study site. This approach aggregated productivity of stands with different age classes and parameters, rather than assuming age-dependent revenues for individual plots. The revenue from carbon sequestration was excluded from the calculation of the net present value on the basis that a carbon marker was not available. Under all four assumptions, forest management costs (thinning, final cut costs etc.) were included. However, in the case of naturally afforested forests (Assumptions 3 and 4), costs related to plantation establishment and thinning during the first 10 years of stand development were excluded, as these do not apply.

The NPV was estimated using formula 2:

$$NPV = -C + \frac{E_T}{w^T} + \sum_{t=1}^{T} \frac{D_t}{w^t} - \sum_{t=1}^{T} \frac{P_t}{w^t} + \sum_{k=1}^{K} A_k^b - A_k^c \frac{w^T - 1}{rw^T} + \frac{L_T}{W^T} \tag{2}$$

where w=1+r; r – discount rate; *T* – end of rotation period, year; E_T – revenue minus cost (net income) from final logging at end of rotation, USD; *Di* – revenue minus cost (net income) from thinning at age t_i, USD; *C* – the plantation establishment cost at year 0; P_i the plantation tending cost at age t_i, USD; USD; A – average annual costs (*c*) and incomes (*b*) by type *k* (administrative, hunt, NWFP harvesting), which are time- and age-invariant, USD; *K* – total number of annual costs and incomes; L_T – scrap value at the end of the first rotation period *T*.

The Faustmann framework (Faustmann 1849, Samuelson 1976) was applied to estimate the land expectation value (LEV) for the assumed post-harvest forest management scenarios, which represent a scrap value of land at the end of rotation under the applied management strategy (formula 3). The LEV calculation includes plantation establishment costs as well as costs and revenues from thinning operations and final harvest. In the multifunctional forestry scenario, LEV additionally includes annual incomes from hunting and NWFP harvesting, consistent with the corresponding assumptions. For scenarios involving naturally regenerated forests, it was assumed that after the final harvest, the stand is artificially regenerated, and the LEV is therefore calculated based on the corresponding post-harvest management assumptions.

$$L_T = LEV_{planted} = \frac{-C + \frac{E_T}{w^T} + \sum_{t=1}^{T} \frac{D_t}{w^t} - \sum_{t=1}^{T} \frac{P_t}{w^t} + \sum_{k=1}^{K} A_k^b - A_k^c \frac{w^T-1}{rw^T}}{1 - w^{-T}} \tag{3}$$

To compare forest land use scenarios with agricultural land renting, the terminal value of agricultural land must also be taken into account. Although the EAI derived from a constant annual agricultural rent remains unchanged with discounting, the scrap value of rented agricultural land is sensitive to the discount rate. Therefore, the corresponding land expectation value for agricultural land was calculated and discounted using formulas 4 and 5.

$$NPV_{agriculture} = A^b \frac{w^T - 1}{rw^T} + \frac{L_T}{W^T} \tag{4}$$

$$L_{agriculture} = LEV_{agriculture} = \frac{A^b}{r} \tag{5}$$

The average annual forest land income was estimated using formula (6), by expressing the net present value as the equivalent annual income (Hseu and Buongiorno 1997; Bullard and Straka 2011):

$$EAI = NPV \frac{r}{1 - w^{-T}} \tag{6}$$

We opted to use a discount rate of 2% for EAI calculation, which the basis for the comparison of current income with long-term income in the context of sustainable forest management (Nijnik et al. 2012; Merganič et al. 2022).

Results

Change in land use conversion

The most notable alterations in land type within the study decade were area reduction of woodland and grassland area, which declined by 10.9% and 5.0%, respectively (Fig. 3). Conversely, the forest area exhibited a 6.8% expansion, while cropland increased by 9.6%. The cropland area increased by 426.1 ha (considered as 100% of transition), of which nearly 57% of the increased area of cropland was related to deforestation in young self-seeded forests (11%) and woodlands (46%), both naturally occurred on abandoned farmlands.

The conversion of 301.9 ha of woodlands (6.8% of the study area) into forest cover occurred within 10 years

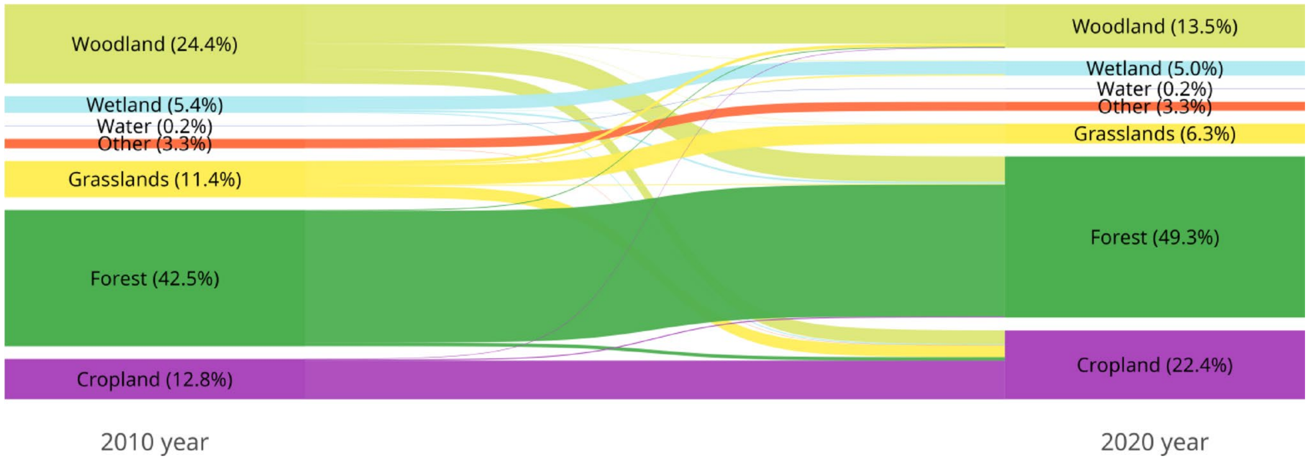

Fig. 3 Land cover transitions within the study area in 2010–2020

Table 6 Distribution of the annual average revenue of each forest ES, divided by study periods

Age group	Area, ha	The annual revenue of ES, USD·ha^{-1} year^{-1}				
		Wood supply	NWFP harvesting	CO_2 sequestration	Hunting	Total
2010 year (total forestry lands – 1894.0 ha)						
Unstocked	21.4	4.0±1.7	139.0±46.5	19.0±4.2	2.3±1.2	163.3±53.5
Young	767.4	6.6±2.1	65.4±29.7	16.7±3.5	2.5±1.3	91.1±36.6
Middle	368.1	113.6±17.8	49.0±20.1	13.2±2.5	2.0±1.0	177.8±41.4
Immature	652.1	96.9±14.5	60.4±26.0	8.1±1.4	1.3±0.7	166.7±42.7
Mature	85.0	55.7±8.4	99.4±40.0	8.8±1.6	1.5±0.8	165.4±50.8
Average	–	60.6±9.7	62.8±27.2	12.7±2.5	2.0±1.0	138.1±40.4
2020 (total forestry lands – 2199.3 ha)						
Unstocked	69.9	3.4±1.4	129.7±39.5	20.9±4.6	1.6±0.8	143.9±46.4
Young	906.5	38.6±7.8	55.8±26.6	23.2±4.7	1.6±0.9	119.2±39.9
Middle	324.1	71.8±13.4	63.5±26.4	17.7±3.5	1.4±0.7	154.3±43.9
Immature	342.6	117.8±17.7	53.4±23.1	9.1±1.5	1.0±0.5	181.4±42.7
Mature	556.2	67.7±10.2	68.7±29.9	6.0±1.0	1.0±0.5	143.9±41.7
Average	–	62.1±10.6	62.2±27.3	15.8±3.1	1.4±0.7	141.5±41.6

compared to 2010. Additionally, an increase in mean average diameter at breast height was observed in young stands (from 5 to 9 cm), as this group was predominantly comprised of recently established plantations in 2010 (including replanted and natural expanded forests). Meanwhile, for diameter at breast height decreased within middle-aged forest (from 22 to 16 cm), without significant changes in other age groups.

Composition of monetary flow

We observed a substantial increase in monetary flow derived from forest ES within the decade: from 262 k USD·year^{-1} in 2010 to 311 k USD·year^{-1} in 2020. This flow per 1 ha of forest land had increase from 138 USD·ha^{-1}·year^{-1} in 2010 to 142 USD·ha^{-1}·year^{-1} in 2020.

The annual revenue derived from the wood products increment was evaluated as almost 44% of the total annual monetary flow, which varied from between 114 k USD·year^{-1} in 2010 to 136 k USD·year^{-1} in 2020 (61 USD·ha^{-1}·year^{-1} and 62 USD·ha^{-1}·year^{-1}, respectively). Wood supply revenue Increment is dominant in middle and immature aged stands due to the high growth rate. The most significant change was in young forests, where the average value of current increment of wood rose almost sixfold (Table 6, Table B1) due to changes in the distribution of mean diameter, resulting in the output of more expensive wood products. The above-average ES value of unstocked areas (clear-cut areas) is primarily due to the NWFP harvesting and yield of raspberries (Table 4), which alone supply 90 USD·ha^{-1}·year^{-1}.

On average, the harvest of non-wood forest products (mushrooms and wild berries) constituted similar value of annual monetary flow to than revenue from wood increment. In 2010, this revenue was valued at 45.5% of the total flow (63 USD·ha^{-1}·year^{-1}), while in 2020 its proportion slightly declined to 43.9% (62 USD·ha^{-1}·year^{-1}) (Table 6, Fig. 4, Table B3). Although the obtained revenue from NWFP harvesting was on average higher in unstocked forest lands

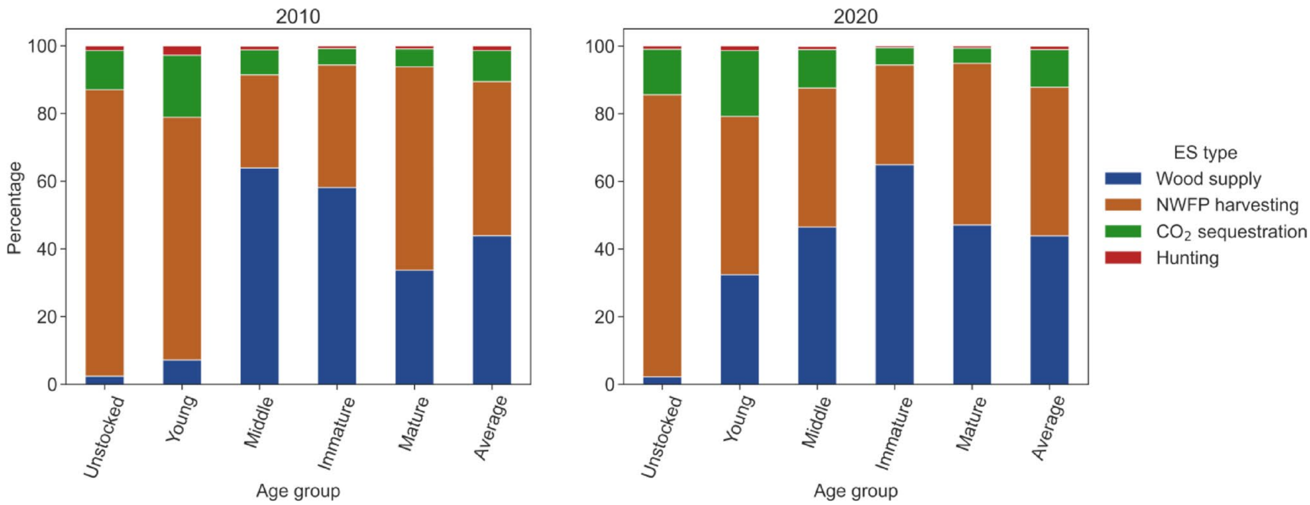

Fig. 4 Relative distribution of monetary flow by stands of different age groups at the beginning and end of the study period

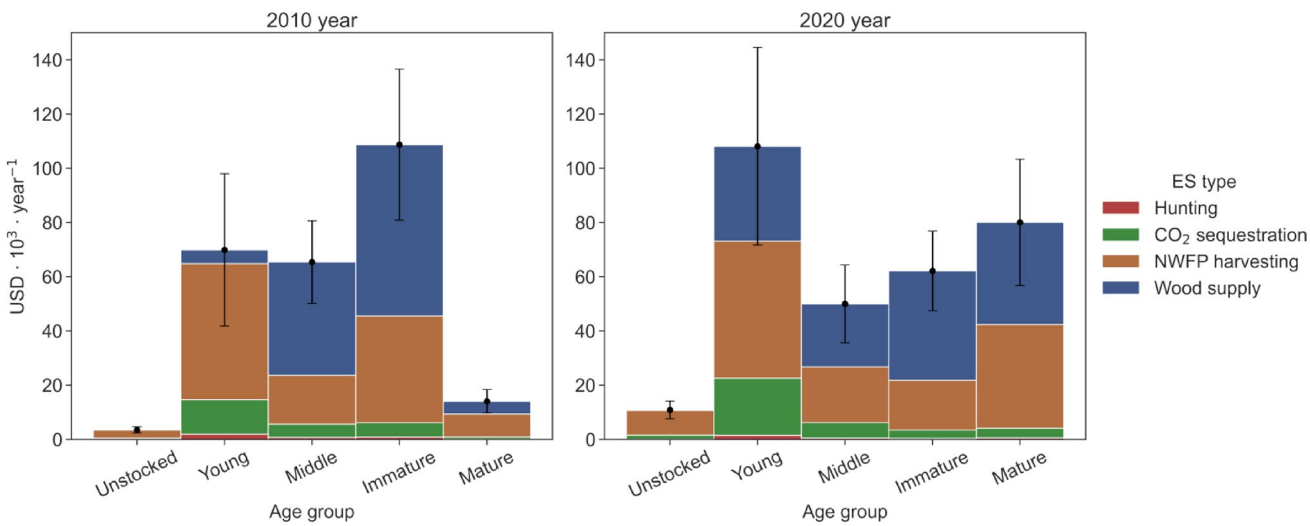

Fig. 5 The total annual monetary flow provided by forest ES within study area

(139 in 2010 and 130 in 2020, USD·ha^{-1}·year^{-1}), it represented only 2.5% (2010) and 6.6% (2020) of the total revenue generated in the study area (Fig. 5).

The CO_2 sequestration monetary value (Fig. 4, Table B2) constituted 9.2% in 2010 and 11.2% in 2020 of the total annual flow, with the annual value of CO_2 sequestrations amounting between 13 and 16 USD·ha^{-1}·year^{-1}, respectively. Unstocked forest lands sustained 18 USD·ha^{-1}·year^{-1} in 2010 and 21 USD·ha^{-1}·year^{-1} in 2020 due to their high net biomass growth.

The proportion of revenue from hunting service of the total annual monetary flow was approximately 1.2%. The evaluated total revenue derived from hunting was 3.7·10^3 USD·year^{-1} (average revenue – 2.0 USD·ha^{-1}·year^{-1}) in 2010 and 3.0·10^3 USD·year^{-1} (average revenue – 1.4 USD·ha^{-1}·year^{-1}) in 2020. This type of ES displayed the most homogeneous temporal and spatial characteristics, with a minor divergence of revenue between forest sites. This divergence can be explained by changes in hunting ground's structure and its quality (stand age distribution, tree species composition, understory availability etc.). The factors influencing the management of game land have a stronger impact on the number of game species (e.g. permits for certain species, the impact of illegal hunting) than on the characteristics of forest stands. The value of this ecosystem service at the site has declined by 30% due to the prohibition on moose hunting throughout Ukraine, despite the study area having a high number of these animals.

Equivalent annual income of pine forest stands under different management assumptions

We obtained EAI value (discount rate of 2.0%) of 57.9 USD·ha^{-1}·year^{-1} for Assumption 1 and 74.2

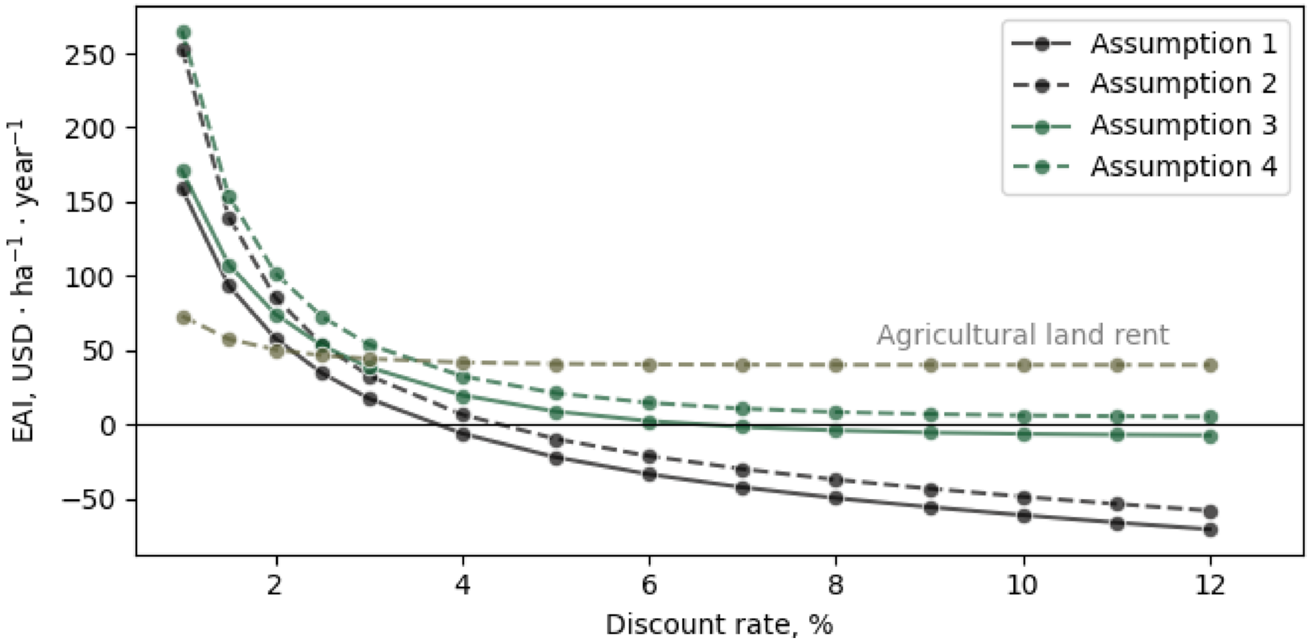

Fig. 6 Sensitivity analysis of the EAI under different assumptions to discount rate

USD·ha^{-1}·year^{-1} in case of Assumption 3 (NPV values were estimated of 2299.7 and 2949.5 USD·ha^{-1} respectively). For an discount rate value of 2.3% (2.9% for natural afforested lands) or less the forest land is competitive with the 40 USD·ha^{-1}·year^{-1} rent of agricultural land rent. Results of our study indicate that adopting of discount rate of 3.7% and higher would make the cultivation of pine wood unprofitable under Assumption 1. In the context of the assumptions 3, the threshold of profitable discount rate increases to 6.5%.

Considering multifunctional forestry, the ES complex (Assumption 2) in planted forest will be competitive with the agricultural land rent value using the discount rate value of 2.8% (3.5% considering Assumption 4). The estimated EAI values (discount rate of 2.0%) were 85.5 USD·ha^{-1}·year^{-1} (101.8 USD·ha^{-1}·year^{-1} for Assumption 4)

(Fig. 6).

The threshold for a profitable discount rate increases to 4.3% for assumption 2. Consequently, there is no break-even discount rate for naturally afforested lands (assumption 4), as the diversification of annual income from multiple activities keeps the EAI positive, in contrast to scenarios where forest was planted or where NPV derived solely from wood production.

Discussion

Land-use conversion and changes in forest ES

The analysis of potential income from forest ES is of primary importance for justifying land use changes. The decision of landowners depends on reliable and up-to-date information on environmental and economic benefits (Renard et al. 2015; Pan et al. 2024), especially in the context of intensive land use change (Feng et al. 2023). Our study showed that the conversion of young stands to arable land did not reduce the total ES value, while natural forest expansion increased ES value by almost 20% during the decade. However, the relatively small size of our study area limits the representativeness of land-use conversion within the region. Although fluctuations in the total ES value were observed, the average estimated economic value per ha remained nearly stable, suggesting that changes were mainly driven by transitions between forest age classes. An exception was carbon sequestration economic value, where increase of this ES was recorded due to the expansion of young stands with higher biomass increment.

Private forestry and agricultural land use in the context of forest expansion

The Ukrainian government aims to expand forest areas in line with the New European Forest Strategy for 2030 (ES 2021) for climate change mitigation. Yet, a major challenge is finding land for afforestation. Mentioned above climate change is not favourable for most agroforestry landscape which occupy vast areas: in the 2010s, the arable land in Ukraine covered 79% (EPRS, 2024) of the total area of agricultural land (41.3 Mha), that is one of the highest national values of the globe. The Russian aggression in Ukraine destroyed the system of shelterbelts and other forest protective components of agricultural landscapes in the southern regions (Matsala et al. 2024). All together, this has generated a problem which calls for urgent need of optimizing the spatial land-cover structure of forestry and agricultural landscapes. Estimates suggest 2.9–4.0 Mha of abandoned lands divided across citizens (Smaliychuk et al. 2016; Lesiv et al. 2018a; Kvartiuk et al. 2024), some with low productivity. Meanwhile, potential to increase in agricultural production through yield intensification is greater than that achieved through the recultivation of abandoned land (Deppermann et al. 2018). According to Ukrainian law, agricultural landowners cannot change land use to forestry, leaving naturally regenerated forests in a legal grey zone (Kvartiuk and Herzfeld 2019). At the study site, only a minority of private landowners rented their arable land to agricultural companies and farms during 2010–2020 with an average revenue of 40 USD·ha^{-1}·year^{-1} (Kvartiuk et al., 2022). Resolving this conflict and creating capabilities for private forestry could significantly increase forest cover and provide new revenue opportunities.

The primary rationale for landowners considering forestry on abandoned land is the potential financial gain from private forestry as an alternative land use option, compared to ranting land to agricultural enterprises. Land rent provides annual income without effort, while forestry offers long-term income from wood supply (Figs. B1, B2), NWFP harvesting, hunting, and carbon sequestration requires management costs. Under the given assumptions, foresty did not outperform agricultural land rental at discount rates above 2.3–3.5%. However, strategies combining afforestation with carbon credits could enhance profitability, especially on marginal lands.

A limitation of our assessment is that it represents rather conservative estimates based on traditional forest management practices in Ukraine, with a specific emphasis on naturally regenerated forests as a separate category. These estimates do not account for alternative management strategies, compared to state forest owner private forestry consider maximisation of profits, which might yield higher EAI values under different scenarios (Brukas et al. 2001). Various forest management scenarios could therefore provide a broader perspective on the potential profitability of forestry adjusting their rotation lengths (Pasalodos-Tato and Pukkala, 2007). Lula et al. (2021) showed that planting Scots pine stands is the most reliable regeneration strategy, which contrasts with our findings because our assessment focused only on existing naturally regenerated stands without considering rotation-based scenarios. In addition, recent research on improved forest reproductive material of Scots pine demonstrates that genetic improvements could simultaneously enhance growth and resistance to diseases, thereby significantly increasing timber production and financial returns under future climate scenarios (Saraev et al. 2025). Similar results were obtained in Sweden, where an assessment of seven silvicultural measures (including the use of improved regeneration material, fertilization, and species change) demonstrated that most of them were highly profitable, with NPV increases substantially exceeding the additional investment costs (Simonsen et al. 2010). This highlights that intensification strategies can improve long-term benefits in our conservative estimates.

Composition of monetary flow

At present, the ES of wood supply and carbon sequestration are closely interlinked, making their trade-offs and synergies a particularly pressing issue for decision-making in forest management, as they determine which service becomes the primary target of management strategies. If forest owners rejected logging and focused on the ecological value of the forest (prioritized CO_2 sequestration service over wood supply), the mean revenue of CO_2 sequestration would increase to 37.5 USD·ha^{-1}·year^{-1} in 2010 and 46.4 USD·ha^{-1}·year^{-1} in 2020. The economic value of carbon sequestration would constitute 61.9 and 74.7% of the revenue from wood product increments, respectively. This finding contradicts similar research, where the annual value of regulation services was dominant (Ninan and Inoue 2014; Roces-Díaz et al. 2021). The supply of ES strongly depend on the characteristics of forest stands and, in turn, on forest management (Vangi et al., 2025). This applies not only to wood supply or CO_2 sequestration, but also to services related to soil and water protection, as well as to the provision of food products (Roces-Díaz et al. 2021). We reported a 24% change in the economic value of CO_2 sequestration within one decade, driven by both land use conversion and change in forest age structure. Since the estimated monetary value of CO_2 sequestration depends on state policies, the potential revenue from CO_2 sequestration is not equal to its monetary value on the global market. In this case, a realistic revenue could be obtained through the voluntary carbon market, which was valued approximately equal or 2–7 times lower than carbon cost rates in 2020 (Forest Trends' Ecosystem Marketplace 2021). The price of wood forest resources is subject to considerable fluctuation. For example, the average price per 1 m^3 of timber production in Ukraine has nearly doubled over the last decade. The revenue derived from total ES is comparable to the median value presented in the study by Taye (2021) in temperate continental forest. It exceeded a median value of 90 USD·ha^{-1}·year^{-1} (at the 2017 price level), meanwhile wood products supply ES exceeds regularization services.

The revenue derived from hunting ecosystem service was not commercially attractive (1.4–2.0 USD·ha^{-1}·year^{-1}) because it consisted primarily of payments from members of a local hunting organization and depended on license prices. However, there is potential to increase revenue from this ecosystem service if non-local hunters are involved in commercial hunting and if hunting is combined with other types of forest recreation. In the study by Häyhä et al. (2015), the annual monetary flow from hunting services in Alpine forests was evaluated at 10 EUR·ha^{-1}·year^{-1}, while tourism value was 77 EUR·ha^{-1}·year^{-1}. Croitoru (2007) estimated the value of hunting services in 18 Mediterranean countries, ranging from 7 to 149 USD·ha^{-1}·year^{-1}.

The results of our study support the hypothesis that revenue from NWFP harvesting can be comparable to the revenue of wood production (Alexander et al. 2002). Differentiation between commercial and self-consumption NWFP harvesting by Ukrainian citizens is a challenging task. While they are permitted to freely harvest NWFP for personal use, the commercial harvesting of the most sought-after NWFP for sale at receiving stations has become a common supplementary household revenue source. We reported estimates for annual revenue derived from NWFP significantly higher than the average 27 USD·ha^{-1}·year^{-1} for temperate forests (Taye et al. 2021). Our economic values of NWFP harvesting are similar to the spatially closest estimates in the European region (Brander et al. 2025), with values reported for mountain forests of 67 USD·ha^{-1}·year^{-1} in the Carpathians (Popa et al. 2016), and 53 and 25 USD·ha^{-1}·year^{-1} in the Northern (Paletto et al. 2015) and Southern Alps (Häyhä et al. 2015), respectively. Meanwhile, Kovalčík (2014) reported that income from this ES could reach a third of the respective income provided by wood sales. In study by Šišák (2006), this proportion was found to be 20%. Indeed, later pan-European studies provided similar estimates, i.e. 20% of the annual value of forest ES is supplied by non-wood products (Lovrić et al. 2021).

We assume that likely the areas with high NWFP yield are probably unattractive for tourism. Importantly, we calculated NWFP productivity at 28.9 kg·ha^{-1}·year^{-1} for mushrooms and 10.5 kg·ha^{-1}·year^{-1} for wild berries. These figures differ significantly from estimates reported by Šišák (2006) in Czech Republic, i.e. 8.2 kg·ha^{-1}·year^{-1} for mushrooms and 15.6 kg·ha^{-1}·year^{-1} for wild berries. It may explain why we achieved so high annual revenue from NWFP in our study area. The productivity of NWFP is highly variable, and depends on the type of forest, soil properties, and forest management practices. In addition, the availability and list of NWFP differ considerably across climatic zones and forest types within the country. Another important factor is the legislative regulation of NWFP harvesting, which may complicate both its accounting and the registration of related income. In Ukraine, for example, citizens are legally entitled to collect mushrooms and berries in state-owned forests free of charge. However, in practice, a large share of these products is harvested by individuals and subsequently sold to collection points, often without being officially recorded or taxed. This situation may explain the discrepancies in reported values and the comparatively high annual revenues obtained in our study area. However, it is noteworthy that the yield of NWFP in the study area corresponded to the lowest values of mushrooms and berries within the last half-century (NUBIP 2013). It is reasonable to hypothesize that the yield of NWFP will decline in the future due to climate change.

Conclusions

ES are fundamental in multifunctional and diversified use of forests and in transition to sustainable development of forests and forest management as a whole. We evaluated spatio-temporal changes in the annual monetary flow of four major ES in the border region of Ukrainian Polissya, closing an existing gap in knowledge on the economic values of forest ES in Eastern Europe. Together, two provisioning services (wood supply and NWFP) deliver about 90% of monetary revenue from local forests. Furthermore, NWFP harvesting, as well as hunting, can generate revenue on an annual basis, unlike wood supply, thereby diversifying production and reducing risks for landowners. Our results can be used for planning strategies of forest development to mitigate climate change, in particular for substantiating investments in private forestry in Ukraine, which has a significant potential for expanding forest cover.

A comprehensive assessment of potential monetary flows from ES and analyses of the EAI demonstrates to private landowners the potential advantages of forestry as an ecological and economic asset, compared to renting land for agricultural use under discount rate of not more than 2.3–3.5% under low soil fertility of Polissya lands. Moreover, private forestry have potential to reach higher profitability utilizing economically efficient approaches compared with conventional forestry practices. In the face of climate change challenges posed, Ukraine has the potential to significantly expand forest cover and diversify forestry practices. This can be achieved by promoting the legalisation of self-seeding forests on abandoned lands and disseminating best practices in private forestry.

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Author contributions Andrii Bilous: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Writing—original draft, Supervision. Roman Zadorozhniuk: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing—original draft. Valentyn Bilous: Conceptualization, Formal analysis, Investigation. Petro Diachuk: Investigation, Writing—review and editing. Oleksandr Labenko: Conceptualization, Formal analysis, Methodology, Writing—review and editing. Svitlana Bilous: Conceptualization, Investigation, Formal analysis. Andrii Lashko: Investigation. Yaroslav Kovbasa: Investigation. Oleksandr Hrytsenko: Investigation. Dmitry Schepaschenko: Conceptualization, Data curation, Methodology, Project administration, Supervision, Writing – review and editing. Fulvio Di Fulvio: Conceptualization, Formal analysis, Writing—& editing. Anatoly Shvidenko: Conceptualization, Data curation, Methodology, Supervision, Writing—review and editing. Florian Kraxner: Conceptualization, Methodology, Supervision, Writing—review and editing. All authors contributed to the final version of the manuscript.

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Data availability Data is available upon request.

Code availability Research core is available upon request.

Declarations

Conflicts of interest The authors confirm that there were no known competing interests that influenced the findings of the study.

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