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Carbon as the central economic factor in sustainable and profitable grassland management

Barbora Smolkova[1], Petr Blizkovsky[2], Lubor Lacina[3], Jan Vavrina[3], Jiri Skladanka[1], Pavel Knot[1], Pavel Horky[1]* and Frantisek Hrabe[1]

[1]Department of Animal Nutrition and Forage Production, Faculty of AgriSciences, Mendel University in Brno, Zemedelska 1, Brno, Czechia, [2]Faculty of Regional Development and International Studies, Mendel University, Brno, Czechia, [3]Department of Business Economics, Faculty of Business and Economics, Mendel University in Brno, Zemedelska 1, Brno, Czechia

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EDITED BY
Gianni Bellocchi,
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Autonomous University of Barcelona, Spain
Guoxu Ji,
Chinese Academy of Agricultural Sciences, China

*CORRESPONDENCE
Pavel Horky
pavel.horky@mendelu.cz

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To limit the temperature increase to below 2°C by 2100, the Paris Agreement relies on adaptation measures in agriculture and carbon sequestration, including the preservation of permanent grasslands, which store 25%–34% of the world's terrestrial C stock. The experiments were carried out in permanent seminatural grassland at a mesohygrophytic and mesooligotrophic site in the Czech Republic. During our study, data from a 28-year experiment (1992–2019) combining different management techniques were analysed. Management consisted of varying numbers of cuts (two or three cuts) and fertilisation rates (0, 90, 45, 180 N and PK). The data were tested using the economic evaluation of roots and the production of hay, considering the cost of inputs and value of outputs involving C-price. The analyses suggest that hay production as a private good is not profitable regardless of management technique. It was confirmed for both private and public goods that fertilisation affects profitability more than the number of hay cuts. It was found that moderate fertilisation outperforms the no fertilisation option economically but also the high fertilisation option. The profitability of grassland on public and private goods is achieved when the C allowance price reaches at least the range of EUR 20–30 per tonne. The knowledge gained from the experiment can be used to all other grasslands that have comparable traits and grow in similar regions. The dominant plant species in the assessed grassland are spread over the temperate zone. The grass found in the evaluated stand are used for the establishment of cultural grasslands.

KEYWORDS

meadow, carbon, management, economic value, hay, public goods

Introduction

The objective of the Paris Agreement is to restrict the increase in global average temperatures to less than 2°C by the year 2,100, while also enhancing adaptation to the adverse effects of climate change (UNFCCC, 2015). The sequestration of carbon in soil within agricultural areas has been recognised as playing a pivotal role in achieving these goals of the Paris Agreement. In addition, soil carbon sequestration has a collateral benefit associated with various nature-based adaptation measures (Oyesiku-Blakemore and Dondini, 2022; Wollenberg et al., 2016; Bossio et al., 2020). Bengtsson et al. (2019) emphasise the global recognition of extensively managed grasslands for their rich biodiversity and their significant social and cultural values. These grassland ecosystems provide a wide range of ecosystem services, such as carbon sequestration, pollination facilitation, and habitat preservation. Yields and other ecosystem services of grasslands are influenced by fertilisation and cutting management (Van Vooren et al., 2018). The study deals with the analysis of data from a 28-year experiment (1992–2019) on seminatural permanent grassland where different fertilisation and cutting techniques were used (fertilisation and number of cuts). Management consisted of varying numbers of cuts (two or three cuts) and fertilisation rates (0, 90, 45, 180 N and PK). Input and output costs were evaluated, and hay profitability was calculated. At the same time, the C-price balance for inputs/outputs for hay and roots under different grassland management regimens was calculated. Different C prices were used in the analyses and modelled.

Two models were used to measure economic profitability. The first model calculated the profitability of hay as a private good. It measured the cost of inputs and the price of hay. The second model calculated the economic value of the public good of C retention. The monetary value of C retained by hay and roots was determined. The aims of the field experiments were to assess the profitability of hay production, evaluate the impact of public goods (carbon retention) on profitability, identify the most profitable management practices, quantify the contribution of different components to profitability, and determine the sensitivity of profitability to carbon price. The study is intended to provide insight into the economic sustainability of grassland management with respect to both traditional agricultural practices and the emerging role of grasslands in mitigating climate change.

Four research hypotheses (RH) were established:

> *RH1*—private good hay production is not profitable.
>
> *RH2*—more expensive management techniques decrease the profitability of the hay production.
>
> *RH3*—adding the balance of economic value of the C captured and used, the grasslands in total are producing economic benefit.
>
> *RH4*—an economic benefit of C retention is higher with less economic-intense grassland management techniques.

Literature overview

Grasslands can be categorised into various types, such as temperate grasslands, tropical savannas, and alpine meadows, each possessing distinct features and ecological roles. These habitats play a crucial role in carbon sequestration (Laihonen et al., 2022; Hassan et al., 2023). Various types of grasslands still have capacity to store more carbon as they have not yet reached their maximum storage capacity (Pol-van Dasselaar et al., 2019). This additional carbon storage, known as carbon sequestration, plays a crucial role in addressing climate change. The effectiveness of grasslands in extracting additional carbon from the atmosphere and storing it in the soil and vegetation will determine their overall contribution to mitigating the impact of rising emissions.

Fertilisation of grassland, especially with nitrogen, intensifies and increases C sequestration. The application of nitrogen (N) fertilisers can enhance plant productivity, leading to increased biomass and, consequently, greater carbon storage in both aboveground and belowground components. However, excessive fertilisation can lead to a shift in species composition, which can lower carbon storage (Rose et al., 2011; Conant et al., 2017; Ward et al., 2016). Extensification of grassland management has a negative impact on grassland performance. Biomass yield, forage quality, and number of plant species differed among the various management types and that increasing land use intensity resulted in higher biomass yields and forage quality and a lower number of plant species (Van Vooren et al., 2018). Grassland management has impact on soil C and the links to climate change. Intensification, for example, rotational high-intensity grazing in place of free grazing grasslands, increases carbon sequestration and leads to mitigate against climate change while fostering economic and social development (Phukubye et al., 2022). It should also be mentioned that the processes of C sequestration, C storage as soil organic matter, and fluxes of greenhouse gases in grasslands are intimately linked to each other (Kätterer et al., 2012).

It is projected that 0.2–0.8 Gt of CO2 per year could potentially be stored in grassland soils by 2023, assuming CO2 is priced at USD 20–50 per tonne [Intergovernmental Panel on Climate Change (IPCC), 2007]. Although permanent grasslands are not the largest C sink (forests have a larger stock), they contribute 25–34% of the global stock (Liu et al., 2023).

Typology of grasslands

The amount of C contained in stands depends on the type of stand, management practices, and species abundance. According to a study by Rodríguez et al. (2022), C is best deposited in a balance of grasses and forbs with leguminous content of 7–17%. Species abundance strongly depends on soil fertility, type, and intensity of use (Gibson, 2009). For example, mowing is a common management practice in grasslands that can significantly impact carbon storage. Research indicates that appropriate mowing practices can enhance the carbon sequestration potential of grasslands by promoting root biomass accumulation and reducing litter biomass, which is a primary source of carbon in the soil nutrient pool (Laihonen et al., 2022; Hassan et al., 2023).

Grasslands can be divided into three main types: natural, semi-natural, and improved grasslands. The most typical grasslands in Europe are semi-natural grasslands. They are characterised by management practices that require livestock grazing or hay cutting to maintain their biodiversity (Lemaire et al., 2011; Bullock et al., 2007; Gibson, 2009; Queiroz et al., 2014; Suttie et al., 2005).

Grassland management practices and C sequestration

For effective sequestration of atmospheric CO2, net C needs to accumulate in the soil. This can be achieved by increasing productivity or minimising C losses (e.g., high offtake rates). Ecosystems absorb atmospheric CO2 and essential nutrients, which they then convert into organic material (Johnston et al., 2009; Conant, 2010). The extent of ecosystem services provided by permanent grasslands depends on management practices and environmental factors. For example, more extensively managed stands provide less forage, but there is an increase in biodiversity and they exert a greater potential for C sequestration (Huber et al., 2022).

Increased management of grasslands results in a greater potential for carbon (C) sequestration (Entry et al., 2002; Paul et al., 2020).

Permanent grasslands are identified as a critical ecosystem for sequestering carbon in the soil, as highlighted by various studies (Soussana et al., 2014; Bullock et al., 2007; Lemaire et al., 2011; Smith, 2014; Pilgrim et al., 2010). The specific quantities of carbon sequestered by grasslands are detailed in Table 1.

According to Liu et al. (2023), higher soil C accumulation in species-rich plant communities is not only associated with higher yield and root biomass but also depends on the activity and abundance of the soil microbial community. The same conclusions were reached by Lange et al. (2019). Indeed, it is microbial activity that has a major impact on the C storage capacity of the soil, due to the ability of fungi and bacteria to decompose soil organic matter (Dignac et al., 2017; Panettieri et al., 2017).

In particular, the economic profitability of farmers has a major influence on C sequestration in soil. They make the decisions on cropping and land management. Increasing C sequestration in grassland crops also increases their productivity. On the other hand, harvesting reduces the supply of C to the soil. Therefore, given practices could balance the optimal ratio of C sequestration and the level of farmers' income (Wilts et al., 2004; Lehmann and Hediger, 2004; Conant, 2010; Mishra et al., 2021; COWI Ecologic Institute IEEP, 2021).

One crucial rationale for carbon (C) sequestration in grasslands is that these practices frequently enhance both production and economic returns. Although methods that involve removing forage and disrupt systems may lead to C loss, their objective is to improve forage production. However, the reverse is not always accurate. Actions such as retaining carbon inputs, increasing production, or allocating more resources below ground can contribute to raising soil carbon stocks. Furthermore, practices that boost production also result in increased carbon uptake, enhanced ecosystem carbon stocks, and improved forage production (Conant et al., 2001).

Role of roots and grassland species in C sequestration

Plant roots also play a major role in C sequestration. Root production varies by plant species, with monocots generally producing more root biomass than dicots among herbaceous plants. They also have a higher proportion of fine roots. Root architecture and profile are crucial in the amount and supply of C to the soil (Wilkes et al., 2021; Poorter et al., 2015; Craine et al., 2003). Lange et al. (2019) demonstrated that higher plant diversity increases rhizosphere C inputs.

Hungate et al. (2017) observed that the greatest cumulative marginal values of carbon (C) occurred at low levels of species richness. Increasing plant species richness from five to six resulted in a projected C storage increase of 1.02 metric tonnes of carbon per hectare per species after a 50-year period. However, this change was only 0.15 metric tonnes of carbon per hectare per species when increasing richness from 15 to 16 species. When comparing individual botanical groups, legumes exhibit superior atmospheric nitrogen fixation and are more active in terms of CO2 exchange per unit biomass. Herbs, on the other hand, specialise in storing substantial amounts of nutrients in their roots (Schmid and Hector, 2004; Lipowsky et al., 2015; Herz et al., 2017; Ibañez et al., 2020; Sebastià, 2007; Zhou et al., 2016). According to Rodríguez et al. (2022), the proportion of each component in the mixture is crucial. They found that as the proportion of leguminous species increases, organic C fixation decreases (Hector et al., 1999; Fornara and Tilman, 2008). Furthermore, the presence of a variety of plant species can enhance ecosystem functions, including nutrient cycling and soil health, which are essential for maintaining carbon sequestration processes (Zhou et al., 2019).

Economics of grassland production

Grassland ecosystems contribute multiple services to both farmers and society, collectively known as the 'total economic value of grasslands'. Various grassland management strategies result in short-term increases in both production and carbon (C) sequestration, with practices focused on C sequestration often leading to enhanced income for farmers. Approaches that reduce offtake, whether through grazing or harvest, typically increase C inputs and C stocks (Luong et al., 2018; Conant et al., 2001).

Conant (2010) acknowledges that some C-sequestering practices involve trade-offs, such as reducing forage removal or accepting lower yields. Others require significant investments in equipment such as seedlings or irrigation. However, the primary investments crucial for the successful adoption of such practices are education and knowledge.

Previous studies on the economics of soil C sequestration in the USA estimated that the marginal cost of C ranges from USD 12–500 per metric tonne of CO_2, depending on factors such as the quantity of C sequestered, the type of contract or payment mechanism, and site-specific characteristics (Chambers et al., 2016). Stiglitz et al. (2017) projected a price of USD 50–100 per metric tonne of CO_2 by 2030.

Lehmann and Hediger (2004) consider C sequestration as a functional benefit. In calculating the net benefit of C sequestration, they apply a marginal analysis of land-use change. The net present value is calculated for two flows of hypothetical payments—market production

TABLE 1 C storage of grasslands (Gibson, 2009; White, 2000).

Ecosystem	Total land area (10^6 km^2)	Vegetation	Soils	Total	C stored/area (t C/ha)
Grasslands					
High-latitude	10.9	14–48	281	295–329	271–303
Mid-latitude	20.1	17–56	140	158–197	79–98
Low-latitude	21.7	40–126	158	197–284	91–131
Total	52.6	71–231	579	650–810	123–154

Values are in Gt C and show minimum and maximum estimates. Sources: PAGE calculations based on White (2000).

and a hypothetical C subsidy to be paid to farmers for C sequestration. They conclude that even with higher discount rates, the net present value of C sequestration with extensive grassland management becomes positive, even when the grass is used for feeding animals.

Conant (2010) suggests that all policies, grants, or investments that fund or incentivise certain actions implicitly assume that these actions would not have occurred without policy implementation. C sequestration projects face the challenge of dealing with both human and nature-based changes in C stocks.

Materials and methods

Area and experimental variants

Our experimental field took place in a mesohygrophytic and mesooligotrophic location, as detailed in Table 2. The habitat types are E3.415 Bistort meadows and E2—Mesic grasslands, as classified by the European Environmental Agency (2013). The size of the entire experimental site was 5,000 m^2.

The experiment was conducted from 1992 to 2019. The fertilisers used were triple superphosphate (P) 45% P_2O_5, potassium salt (K) 60% K_2O, calc-ammonium nitrate—CAN 27% N, and magnesium sulphate (Mg) 26% MgO. Botanical composition and percentage of cover of each species on site can be found in Supplementary material.

Experiment was established in the already existing seminatural grassland by open-field experimental plots. Each plot was divided into single variant units with a size of 15 m^2 (15 × 10 m). Each of the 13 experimental variants were established in four repetitions.

The experimental variants had two cuts or three cuts. Two-cut and three-cut grass stands included unfertilised variant, P + K variant, P + K + N (90 kg) variant, and P + K + N (180 kg) variant. In addition, three-cut grass stand have P + K + Mg variant, P + K + N (90 kg) + Mg variant, P + K + N (45 kg variant), and P + K + N (135 kg variant) (Table 3).

Root samples

Root biomass samples were taken by the method of monoliths according to Fiala (1987) during the period 1996–2000. Samples were taken once a year from variants F1, F3, F5, and F7 in all their repetitions. The diameter of the sampling cylinder was 5 cm. Sampling was done in the 0–20 cm depth. Root biomass was weighed after the samples had been sluiced through a 0.5 mm sieve, and the biomass was naturally dried.

Economic modelling of hay production profitability

To determine the costs associated with agro-technological operations for hay production, we employed certified methodologies (Kavka, 2006; Voltr et al., 2019). The input costs were aligned with the price levels of 2019, and the same alignment was implemented for the revenue side, i.e., according to the last available data from the field experiments. That alignment allows a consistent transformation of all available field trials´ results into the monetary valuation within the whole time period observed, i.e., time series of years 1996–2019, as further described in this subchapter. The private input costs are involving both the overall variable costs (covering diesel consumption, labour, and fertilisers) and fixed costs (related do depreciation of machinery for the 5-year period) which were adjusted based on the appropriate inflation rates in the EU-27 Member States until year 2019 (OECD, 2023).

To determine the financial worth of the output, we utilised the hay prices provided by the Czech Statistical Office (2023). To calculate the monetary value of the carbon captured by both hay and roots, we derived carbon content estimates additionally also via the methodology outlined by the Soil Quality Knowledge Base (2025). Following this, the carbon content in the hay yield and roots was converted into the weight equivalent of CO_2, using the conversion factor of 0.27 tonnes of carbon per tonne of CO_2 (Brander, 2012).

For the C price, we used the data on primary market auctions of CO_2 allowances on European Energy Exchange AG in the year 2019. We used the mean value for spot prices of CO_2 allowances in 2019 at the value 24.72 EUR/t CO_2 (EEX EUA, 2023) according to the need for field trials' results alignments towards monetary valuation within the period of years 1995–2019.

To establish the monetary valuation proxy, as the indicator considering the input/output balance for the respective field trials, we extended an ultimate concept of the energy and economic balance for crop production (e.g., Fathollahi et al., 2018; Voltr, 2020). In this study, we applied the Gross Monetary Evaluation (GRME) indicator, which we identified as an appropriate tool for assessing the impacts of land use and land use change. A detailed overview of the adopted enumeration model is provided in Figure 1 and Appendix A. The suitability of this approach is further supported by previous research in the field (e.g., Barrow, 2006; Spellerberg, 2013; Jafari et al., 2022).

TABLE 2 Description of the field experiment site.

Site	Location	Year	Mean annual temperature (°C)/rainfall (mm)	Elevation (m a.s.l.)	Soil type	Soil texture	pH
Kameničky (CZ)	49°43′25.866″N, 15°58′40.750″E	1992–2019	6.3/786	630	Stagnosol, acidic and Pleistocene gneiss	Sandy loam soil, slightly gravelly	4.45

Source: Knot et al. (2015).

TABLE 3 Grassland management techniques used in the field experiment.

Number of cuttings	Term of cut	Fertilisation
2H (2 hay cuts)	Middle June Middle September	F1 (unfertilised) F3 [P + K (30 kg P + 60 kg K)] F5 [P + K + N (90 kg)] F7 [P + K + N (180 kg)]
3H (3 hay cuts)	Beginning June Beginning August Beginning October	F1 (unfertilised) F2 [P + K (30 kg P + 60 kg K) + Mg (30 kg)] F3 (P + K) F4 [P + K + N (90 kg) + Mg] F5 [P + K + N (90 kg)] F6 [P + K + N (180 kg) + Mg] F7 [P + K + N (180 kg)] F8 [P + K + N (45 kg)] F9 [P + K + N (135 kg)]

Estimate of the indicator GRME of the hay production regarding the assumptions of private model according to the type of grassland management

The estimated monetary effect per year is based on calculation of the indicator GRME as it can be seen in formula (1) that provides an insight into a financial remuneration of inputs in the hay production management approaches according the long-term field experiments while considering its applicability to agricultural enterprises.

$$\text{GRME}_{hay\_private,i} = \text{Revenue}_{hay,i} - \text{Total\_Normative\_Cost}_{hay,i} \quad (1)$$

where $\text{GRME}_{hay\_private,i}$ is the Gross Monetary Evaluation of the hay production in private model regarding type of the grass management (i) in EUR/ha/year, $\text{Revenue}_{hay,i}$ is the revenue of a parameterised hay production and type of the grass management (i) according to the field trials in EUR/ha/year, and $\text{Total\_Normative\_Cost}_{hay,i}$ is the total normative cost of hay production and type of the grass management (i) in EUR/ha/year as defined in formula (2).

$$\text{Total\_Normative\_Cost}_{hay,i} = \text{TVC}_{operations,i} + \text{TVC}_{machines,i} + \text{TFC}_{machines,i} \quad (2)$$

where $\text{TVC}_{operations,\,i}$ is the total variable cost of technological operations without machines and type of the grass management (i) in EUR/ha/year as defined in formula (3). $\text{TVC}_{machines,\,i}$ is the total variable cost of machines for operations and type of the grass management (i) in EUR/ha/year as defined in formula (4). $\text{TFC}_{machines,\,i}$ is the total fixed cost of the type machinery sets needed for conducting agri-technological operations according to the type of the grass management (i) in EUR/ha/year.

$$\text{TVC}_{operations,i} = \text{cost of labour force} + \text{cost of fertilisers} \quad (3)$$

$$\text{TVC}_{machines,i} = \text{cost of diesel consumption} + \text{cost of other support material} \quad (4)$$

Estimate of the indicator GRME of the hay production regarding the assumptions of public–private model according to the type of grassland management

The estimated monetary effect is based on calculation of adjusted indicator GRME as can be seen in formula (5) that provides an insight into a financial remuneration of inputs in the hay production management approaches, taking into consideration pricing of carbon on the revenue and inputs side for the given approaches according to the long-term field experiments.

$$\text{GRME}_{hay\_public\_private,i} = \left(\text{Revenue}_{hay,i} + \text{Carbon}_{MP\_out,i}\right) - \left(\text{Total\_Normative\_Cost}_{hay,i} + \text{Carbon}_{MP\_in,i}\right) \quad (5)$$

where variables $\text{Revenue}_{hay,\,i}$ and $\text{Total\_Normative\_Cost}_{hay,i}$ are already defined in formula (1) and others as following: $\text{GRME}_{hay\_public\_private,i}$ is the Gross Monetary Evaluation of the hay production in the public–private model regarding type of the grass management (i), including pricing of carbon (all values in EUR/ha/year), $\text{Carbon}_{MP\_out,\,i}$ is the market price of captured carbon amount regarding CO_2 conversion equivalent (see also Figure 1), $\text{Carbon}_{MP\_in,\,i}$ is the market price of carbon equivalent of production inputs via CO_2 conversion (see also Figure 1).

Estimate of the indicator GRME of the hay production regarding the assumptions on inclusion of roots in the public–private model according to the type of the grass management

The estimated monetary effect is based on calculation of adjusted indicator GRME as can be seen in formula (6) that provides an insight into the financial remuneration of inputs according to the hay production management types including specifically also the dry matter of roots from field trials, taking into consideration market pricing of carbon effects on the revenue and input side for the given grass management approaches.

$$\text{GRME}_{hay\_roots\_public\_private,i} = \left(\text{Revenue}_{hay,i} + \text{Carbon}_{MP\_hr\_out,i}\right) - \left(\text{Total\_Normative\_Cost}_{hay,i} + \text{Carbon}_{MP\_in,i}\right) \quad (6)$$

where variables $\text{Revenue}_{hay,\,i}$, $\text{Total\_Normative\_Cost}_{hay,\,i}$, and $\text{Carbon}_{MP\_in,i}$ are already defined in formulas (1), (5) and the others as following: $\text{Carbon}_{MP\_hr\_out,\,i}$ is the market price of captured carbon amount in hay and root dry matter regarding CO_2 conversion equivalent in Figure 1.

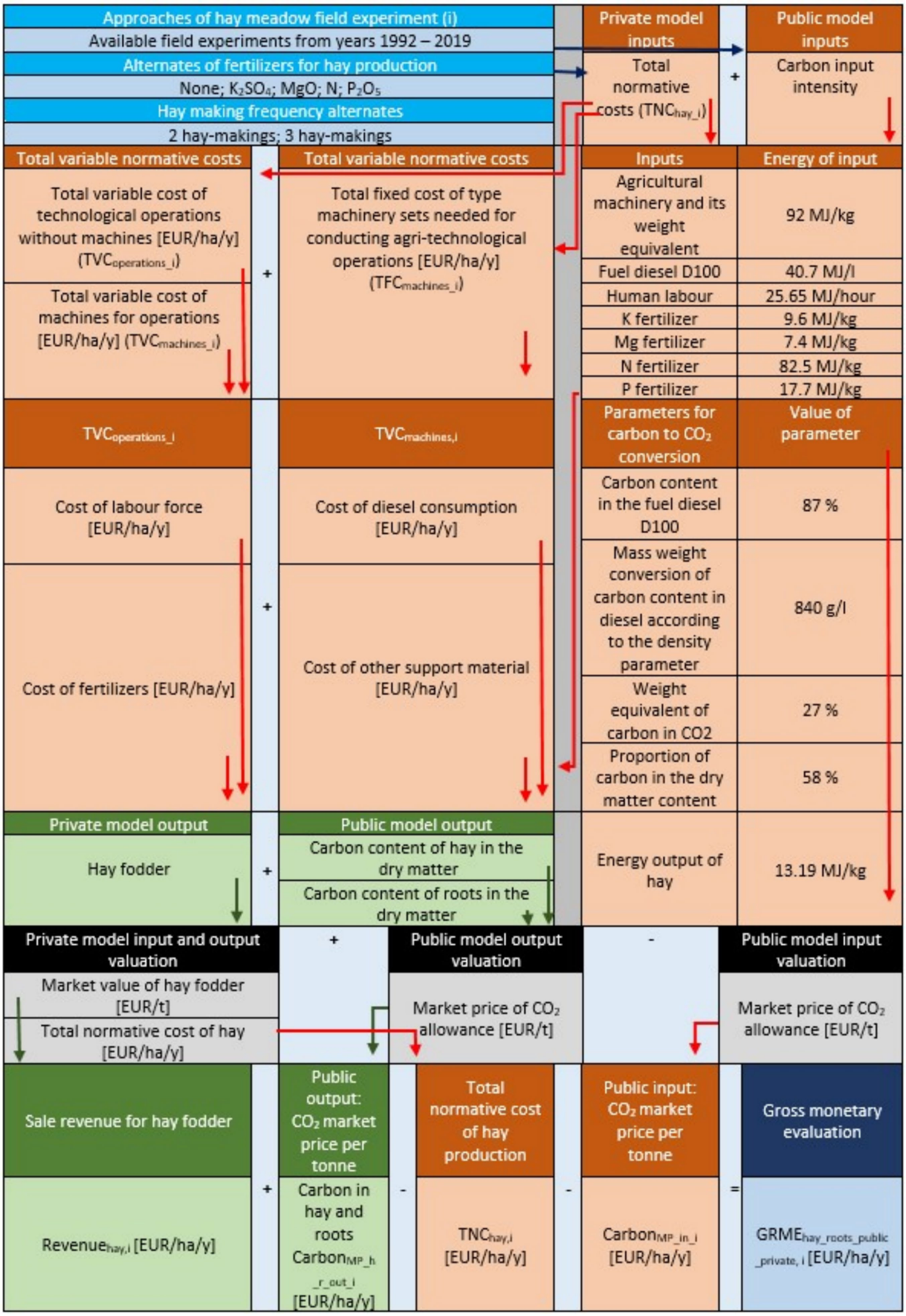

FIGURE 1
GRME model of public and private goods produced by grassland.

Finally, we run a C-price sensitivity test in which we aimed at establishing the minimum C price for tested options to be at zero profitability. We established regression function where the CO_2 allowance market price as the proxy for C-price is the independent variable and GMRE the dependent variable.

Results and discussion

Economic profitability of the hay production in private good model

The results show that the hay production as a private good was not profitable in all tested grassland management options (Figure 2). Overall, it resulted in a mean loss value of 243 to 39 EUR ha^{-1}. The economically best-performing grassland management was the NPK fertilised/two-cut option (Figure 2D), followed by the lower input management option with 2 hay cuts and fertilisation (Figure 2G). It additionally resulted in smaller profitability variation, specifically fertilisation with NPK (Figure 2D) and 3 hay cuts without fertilisation (Figure 2F). The absence of N resulted in year-to-year profitability fluctuation. The use of Mg brought no positive effect on profitability outcome. The impact of a higher frequency of hay cuts on the profitability was negative. The profitability of the two hay cuts without fertilisation was negative and in the range of −60 to −163 EUR ha^{-1} (Figure 2E) while for three hay cut without fertilisation it was approximately −200 EUR ha^{-1} (Figure 2F). Similar pattern was observed for the two and three hay cut options with fertilisation (Figures 2G,H).

The results suggest that fertilisation intensity plays an important role for the economic profitability of the grasslands. In the private model, the hay production is non-profitable under all management methods (Figure 3). However, for the two-hay management, the medium intensity fertilisation levels, such as F3 and F5, are the best economically performing techniques. It is followed by high-intensity (F7) and no-fertilisation (F1) options. The similar pattern applies also for the three-cut grassland management. This can be explained by an economic balance of the cost invested for fertilisation and the increase of the hay quantity produced.

The economic profit of expenses for the increased number of the cuts is smaller than the benefit one receives from the fertilisation. Figures 2, 3 suggest that all two-cut options were more profitable that all three-cut ones. It is more profitable for the farmers to opt for fertilisation rather than into number of cuts. However, the limitation of the finding is that we do not consider the quality—and thus higher price—of the hay which is likely to improve the economic profit with the number of cuts.

Economic profitability of the hay production with C retention (public-private good model)

The economic profitability of the hay production with calculating the C retention median values was in the range of −136 to 38 EUR ha^{-1} (Figure 4). The medians of all tested management options were in the negative or close-to-zero profitability. In the option without fertilisation, the profitability was in the range of −150 to −5 EUR ha^{-1} (Figure 4A), while using the NPK fertilisation, the profitability slightly increased (Figure 4D) and was stable over years. Options with PK and PKMg fertilisation showed lower levels of profitability compared to NPK fertilisation with −136 to 12 EUR ha^{-1} (Figures 4B,C). The effect of hay cut frequency for the profitability was negative. Without fertilisation, two hay cut option resulted in −90 to 66 EUR ha^{-1} (Figure 4E) and the three cuts in −187 to 4 EUR ha^{-1} (Figure 4F). The effect of fertilisation in combination with higher cuts frequency was negative. The two-cuts with fertilisation option reached −6 to 35 EUR ha^{-1} (Figure 4G) while the three cuts only −175 to −30 EUR ha^{-1} (Figure 4H). In addition, adding one more cut increased the volatility of the economic profitability. The results showed that the economic balance of the value of the C cost to of the inputs and value of the C retention by hay is significantly positive in economic terms, compared to the private model option. However, the profitability levels are still largely negative. Unlike in the private model, in the private and public goods, model with the C retention in hay makes hay production from the societal perspective more profitable.

It is worth discussing the effect of fertilisation on the profitability in case of the public–private model. If counting the monetary value of the C used for inputs and C captured by the hay and roots, the moderate use of fertilisers proven to be from the economic perspective the best performing management methods although still with a negative profitability (Figures 3–5). It also stabilises the economics profitability over the years. Spending more cost in the form of higher hay cut frequency was not economically profitable. As for the farmers, for the society the preferred grassland management techniques also comprise the moderate fertilisation and two cuts.

Economic profitability of the hay and root production with C retention (private-public good model)

The economic profitability of the hay grassland management has substantially increased when measuring the potential of C capture by the roots regarding the field experiments within years 1996–2000, which allowed inclusion of root biomass dry matter content into our analysis. None of the grassland management option demonstrated negative profitability (Figure 5). In the option without fertilisation, the median profitability was approximately 813 EUR ha^{-1}. Adding PK fertilisation improved the profitability marginally to 836 EUR ha^{-1}. Moderate N fertilisation (90 kg ha^{-1}) with low PK fertilisation resulted in the further profitability increase to 1,036 EUR ha^{-1}. However, high N fertilisation (180 kg ha^{-1}) with the PK was economically less profitable, and the profitability was below 700 EUR ha^{-1}. The addition of the public good of the retention of C by roots had a robust positive effect on the grassland profitability. The profitability further increases with a moderate input addition in the form of fertilisation. Higher fertilisation levels proven not to bring profitability increase.

We expected that the moderate fertilisation stimulates the creation of the grassland root biomass to the certain level. Above such a level, the root biomass stagnates which can be explained by either the lower root biomass production or a higher rate of root biomass microbial decomposition in the presence of more nutrition. This has not been proven by the results, and our study does not offer enough insight on the biological mechanism behind the roots' formation and decomposition under various types of grassland management.

FIGURE 2
Financial balance of input and output from the grassland based on the private goods assumptions using the Gross Monetary Evaluation (GRME) indicator values.

Return on cost analysis of the hay production in the private good model

The return on cost was negative for all options under the private goods model. We also found out a negative regression between the cost of the input and the economic value of the hay produced (Figure 3A). Every additional input of 100 EUR ha^{-1} decreased the GRME by 337 EUR ha^{-1}. The low-to-moderate input (2HF3 and 2HF5 options with inputs between 400 and 500 EUR ha^{-1}) reached the least negative GRME of approximately −80 EUR ha^{-1}. GRME reached by a high-intensity options with NPK and PKMg fertilisation where the inputs were between 500 and 700 EUR ha^{-1}

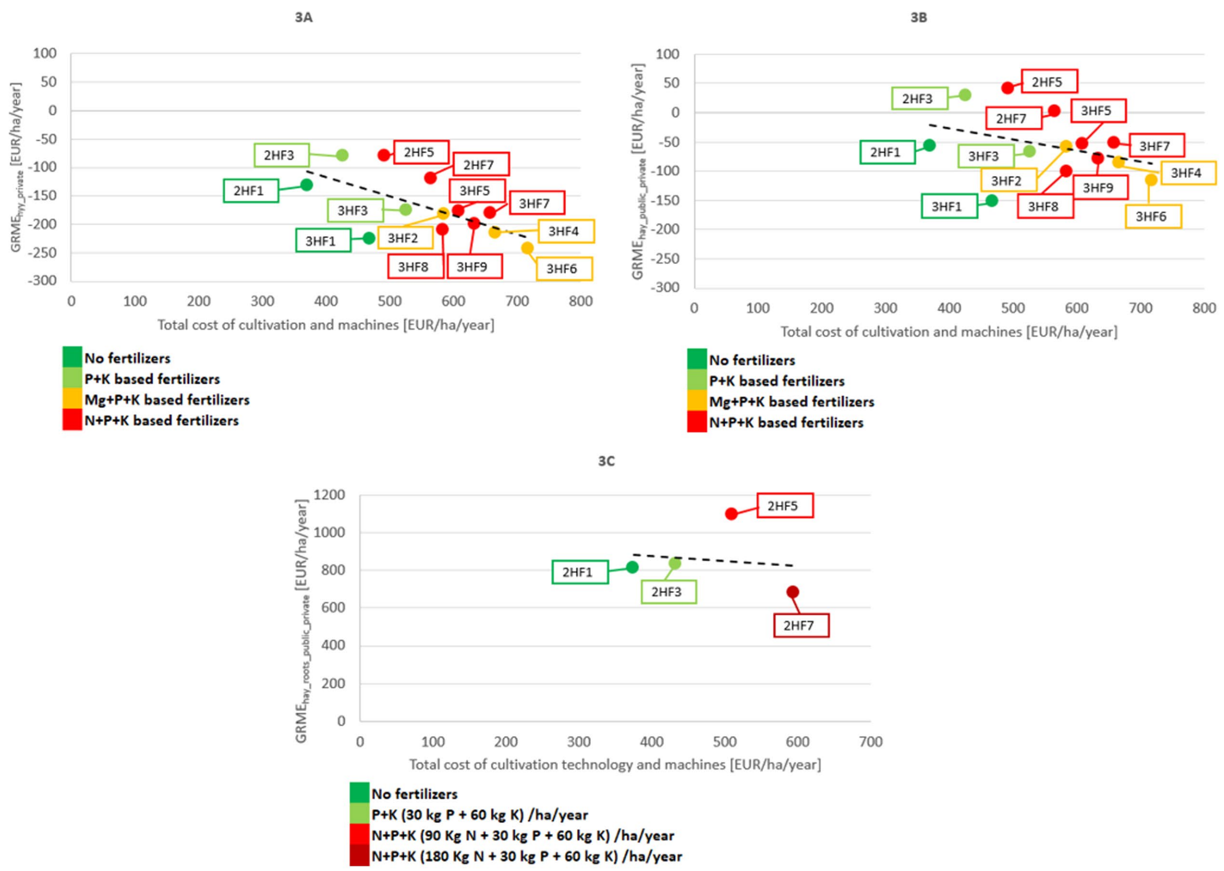

FIGURE 3
Return on cost of inputs for grassland management (private goods model for hay).

and profitability was low and reached −183 and −244 EUR ha^{-1}. Options without fertilisation and without N fertilisation (2HF1, 3HF1) demonstrated even lower profitability. This means that a moderate fertilisation and especially with N had a positive economic effect on the private good production. The results therefore show that the extensive and low-input options are economically sounder in the private model.

Return on cost analysis of the hay production with C retention in hay and root (private-public goods model)

While adding also into consideration the price of the C retention in hay, the grassland production has proven to be slightly profitable to negative (Figure 3B). However, the return of cost was more positive than in the private goods model. Every additional input of 100 EUR ha^{-1} further decreased the GRME by 19.1 Eur ha^{-1}. The effect of various forms of input was largely like the one of the private models. Options with only 2 cuts and a moderate PK fertilisation (2HF3) or moderate NPK fertilisation (2HF5) resulted in a positive GRME. High-input options (such as 3HF6) had the most negative return on cost. The results show that moderate-input options are economically sounder also in the private–public model. Extensive option without demonstrated fertilisation (2HF1) was among the least economically profitable options.

Once considering the price of C captured also by the roots (in addition to hay), the return of investment of grassland management was highly positive (Figure 3C). The median analysis showed all studied options were economically profitable and ranged between 679 and 1,096 EUR ha^{-1}. However, increasing cost had a negative effect on the return of investment. Every additional input of 100 EUR ha^{-1} further decreased the GRME by 27.4 EUR ha^{-1}. The results showed that low-input options were economically most profitable.

Sensitivity test of C price in the private–public model

With the sensitivity test, we also answer to the question of what the minimum market price of C for the return on cost to be positive. Considering hay only (Figure 6), the results are similar for three out of the four tested aggregated options (the high N and PK fertilisation, the moderate NPK fertilisation and the PK fertilisation options), and the C price should be above 19.7 to 22.1 EUR/t for the GRME to be above zero EUR ha^{-1} y^{-1}. For the remaining non-fertilised option, the C price should be above 33.4 EUR/t. In addition, the parameters of the regression lines suggest that in the latter option, the GRME is more sensitive to the C price than in the three other options.

While adding roots into consideration, the minimum market price of C allowing the zero profitability is significantly lower. The C price is close for all four aggregated options and reaches 2.1 and 3.1

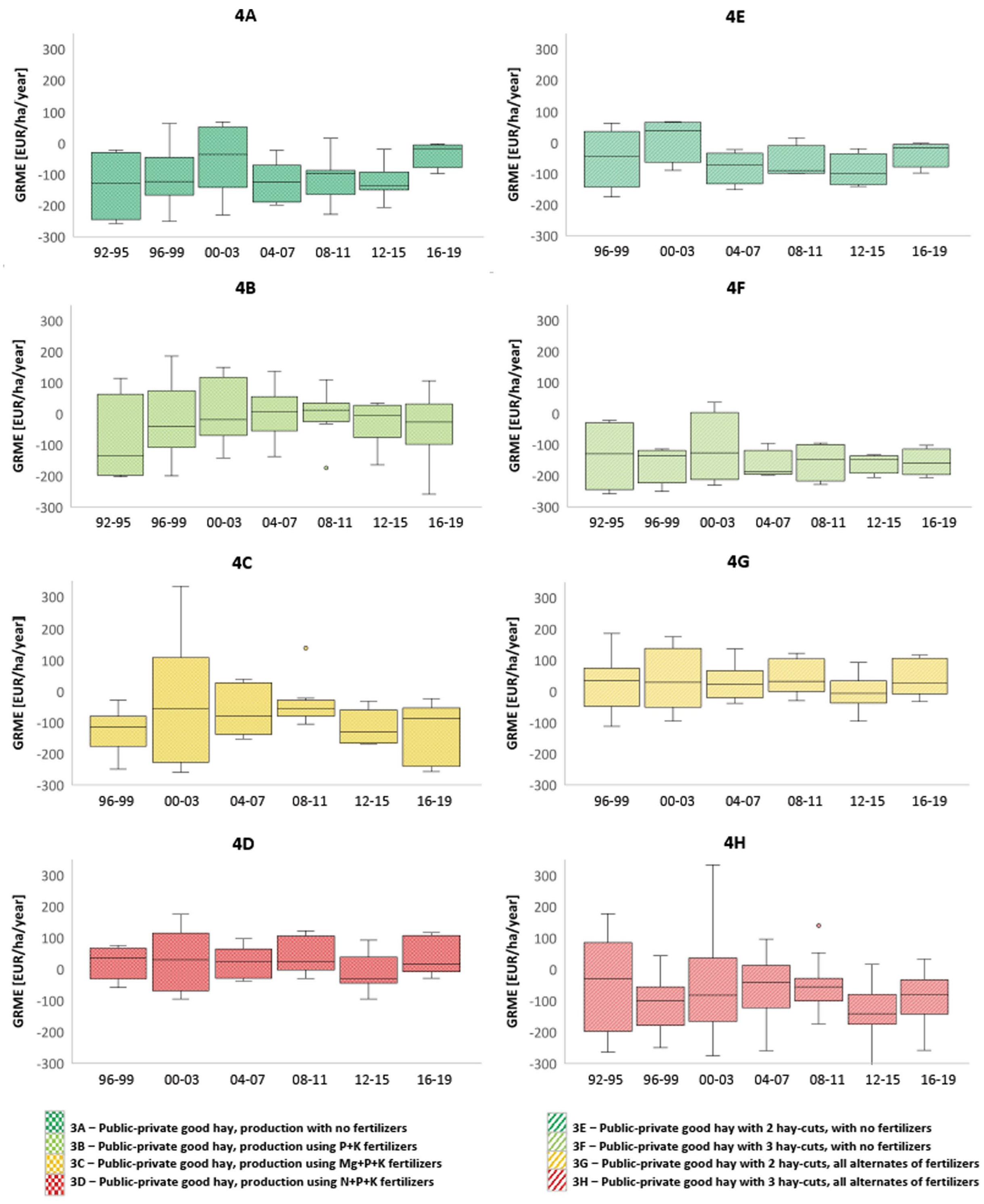

FIGURE 4
Financial balance of input and output from the grassland based on private and public goods of hay using the Gross Monetary Evaluation (GRME) indicator values.

EUR t^{-1} (Figure 6B). The option with the high fertilisation input is the most sensitive to the C price.

One of the key findings of the study is the hay production as the private good only is non-profitable and different management methods lead to economic losses. When including the public goods production in the form of the C retention in the hay and C price needed to produce the hay, the economic balance is still only marginally positive or negative depending on the grassland management (Figures 3, 4). However, as the sensitivity test (Figure 6) shows, this outcome depends on the C price. Interestingly, with the increasing C price, the more input-intensive management techniques are more economically profitable for the society. This can be explained by the fact that the amount of C captured by hay is outweighing the amount of C input. The higher the C price is, the bigger is the amount of public and private goods produced.

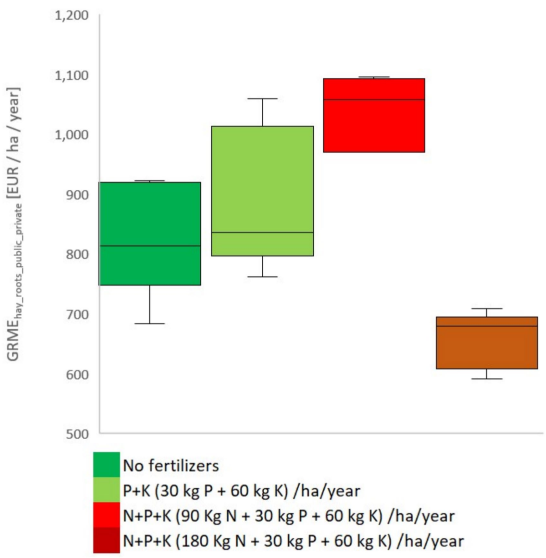

FIGURE 5
Economic profitability of the hay and root production with C retention within 5 years under two hay cut option using the Gross monetary evaluation (GRME) indicator.

A relative monetary compositions of the inputs and outputs for the private–public model with roots

Finally, we quantified what relative proportion of the inputs was represented by private cost of machines and technology and what relative proportion of public cost were represented the cost of C for the machines and technology production. Similarly on the output side, we calculated a relative proportion regarding the price of the hay as the private output and a relative proportion regarding the price of the C retained by the hay and roots (Table 4).

For the inputs, the private cost of the machinery and operations including fertilisers was by far the most important (between 95 and 99% of the total cost). The input public cost of the price of the C needed for the respective grass management, i.e., the machinery and technology, was relatively low (5 to 1% of the total cost). The more intensive input in the form of fertilisers, the higher percentage proportion of the public cost was observed.

For the outputs, a relative proportion regarding the monetary value of the private good (hay) was relatively small (20 to 35%) of all valuable outputs. The remaining 65 to 80% of a relative proportion regarding monetary value of the output was represented by the C retained in hay and roots. The dry matter carbon capture ability of roots was represented by far the largest part of the monetary valuable output (50 to 70%), while hay accounted only for a relative proportion approximately 10%. With increasing fertilisation inputs, the private goods production output was increasing. The public good valuable output clearly outperforms the private part of the valuable grassland production output. The underground part of the grasslands contributes most to the public good profitability of the grasslands.

We noticed different profitability effects of the higher inputs compared to the hay-only scenario. The best economically performing techniques are moderate and no-fertilisation ones. The high-intensity fertilisation decreases the public and private goods profitability. The explanation for this finding is linked to the production and decomposition dynamics of the roots.

It is worth discussing the time question of the C retention by the hay and roots. As the above and below surface biomasses are subject to decomposition, humification, and mineralisation, the captured C would be partly back to the atmosphere. The use of the hay can be food for domestic animals, composting or leaving it on the grassland. Every of the three possible uses will affect the biomass decomposition and C time retention. The question not covered by our research is therefore to what extend the public goods production needs to be decreased by counting the C part which is freed back to the atmosphere and to what extend this can be influenced by grassland management. For the roots, the question of private goods is not existing, but the understanding the biomass composition is even more complex.

Discussing the financial incentives for C storage, Huber et al. (2022) stress that policymakers have to be careful with policy incentives, as if they are set incorrectly, they will not lead to increase C sequestration. Policies to encourage adoption of practices that sequester C in extensively managed grasslands lag behind policies for forest and intensively managed agricultural lands. Smith (2014) in his study concludes that on existing grassland, only through improving the grassland management, soil C can be sequestered, so where grassland management is poor, policy should seek to improve it. Since there is much more C to be lost from grasslands than can be gained, protecting large grassland C stocks should be a policy priority.

Our findings concerning the negative correlation between the higher cost of the input and the economic profit for the public good (C capturing balance) correspond to the findings of Paul et al. (2020).

The market prices of hay are too low for hay from grasslands to be profitable. Therefore, providing support for the C sequestration and for other environmental services is one possible way forward. As noted by Conant (2010), providing support or incentivising some action implicitly assumes that the action would not have taken place in the absence of policy implementation. An alternative way is to introduce grassland certification that will allow farmers to enter grasslands into the system of the C Removal Certification Framework and to participate in C trading system.

The C sequestered in hay has just a short-term effect. Hay is later used as fodder or other way which later releases the C back to the air. Methods of long-term C sequestration in harvested hay have to be discussed in context of grassland management alternatives.

Research hypothesis

Our research hypotheses (RH) as established above were fully (RH1, RH4) or partially (RH2, RH 3) confirmed. RH1 is confirmed. The private good production of hay is not economically profitable. The RH2 is valid but with the exception on the non-fertilised option which has proven not to be the most economically profitable. The RH3 limitation is that in case of hay production, the hypothesis was confirmed only for exceptional years and specific management techniques but not generally. When adding the balance of economic value of the C retained and used the grasslands in total are producing economic benefit. In case of hay production, the hypothesis was confirmed only for exceptional years and specific management techniques but not generally. When adding the economic balance of the C price captured by the roots RH3 was confirmed. RH4 was

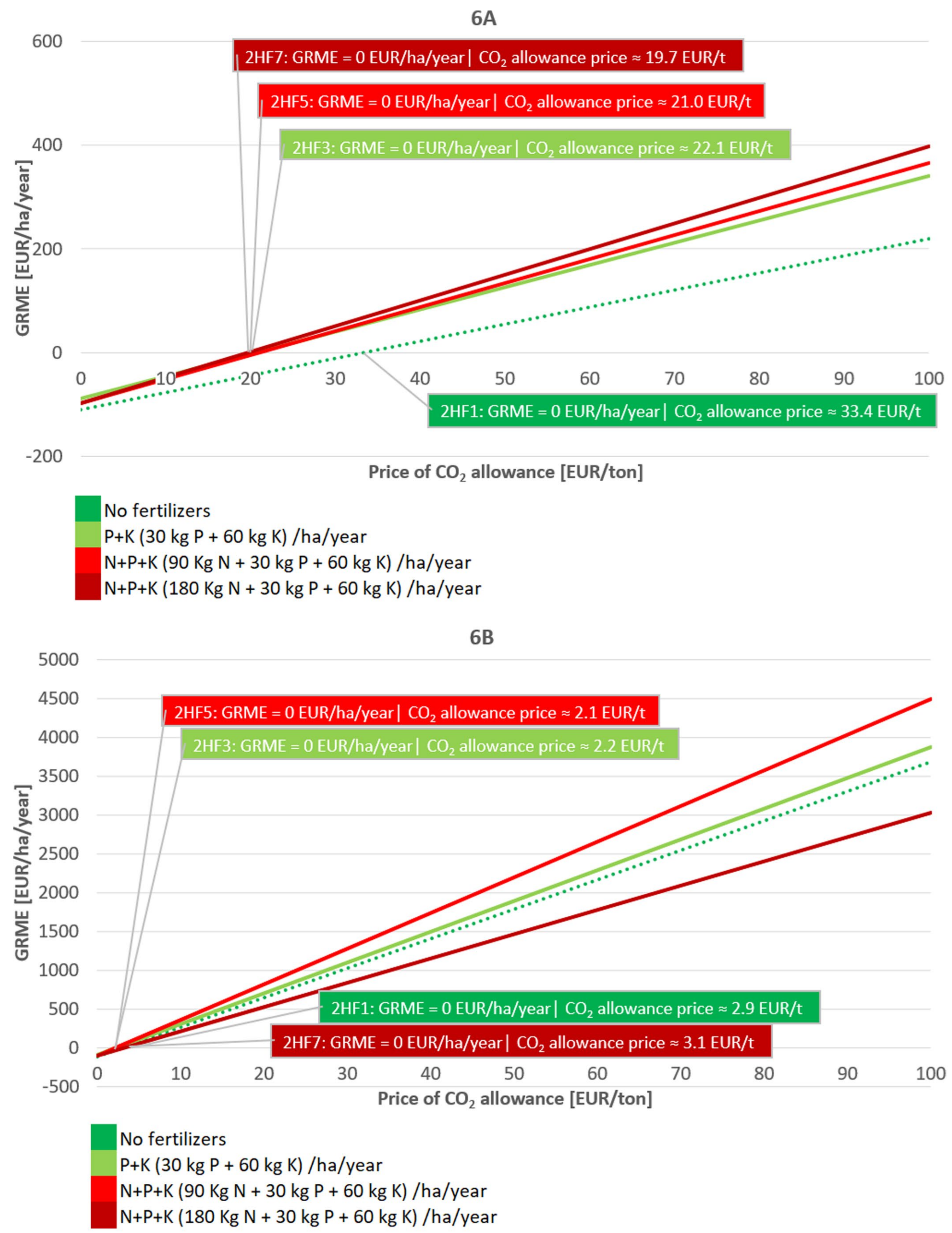

FIGURE 6
Sensitivity test of CO_2 price in the public–private model for hay **(A)** and for hay and roots **(B)**.

confirmed. The economic benefit was higher with less economic-intense grassland management techniques. The regression lines for the economic profit as a function of economic input were descending for private hay model production, for the public-private hay model and for the public-private hay and roots model.

Conclusion

Our field experiments conducted in a selected location with lower agricultural land fertility indicate that hay production lacks profitability regardless of the management technique employed. However, economic viability improves when accounting for the public goods generated in the form of carbon (C) captured by hay. When incorporating the economic balance of C prices for both input and output, grasslands were marginally profitable in specific years and under certain management techniques, while remaining largely non-profitable in other years and techniques. In both private and public goods analyses, fertilisation has proven to have a more significant impact on profitability than the number of hay cuts. Among various fertilisation options, moderate fertilisation economically outperformed non-fertilisation and high-fertilisation options. Roots emerged as the most substantial

TABLE 4 Monetary valuation of the balance of the private and public share on total inputs and outputs for 2 hay cuts management grassland.

Proportion in inputs (I) and outputs (II)	0% 20% 40% 60% 80% 100%
IA. Private input: Cost of cultivation and machines	……………………………………………………………………………….1 ……………………………………………………………………………….3 ………………………………………………………………………………5 ……………………………………………………………………………7
IB. Public input: CO_2 in monetary valuation for cultivation and machines	.1 .3 ..5 ….7
IIA. Private output: Revenue for hay	……………….1 …………………..3 …………………..5 …………………………7
IIB. Public output: CO_2 in monetary valuation for hay	…..1 ……3 ……5 ……..7
IIC. Public output: CO_2 in monetary valuation for roots	…………………………………………………….1 ……………………………………………………3 ……………………………………………………5 ………………………………………7

Field experiments within years 1996–2000, 2019 prices, CO2 at market price in 2019. Grassland management: …1 = 2HF1, no fertilisers; …3 = 2HF3, fertilisers P + K (30 kg P + 60 kg K)/ha/year; …5 = 2HF5, fertilisers N + P + K (90 Kg N + 30 kg P + 60 kg K)/ha/year; 2HF7; …7 = 2HF7, fertilisers N + P + K (180 Kg N + 30 kg P + 60 kg K)/ha/year.

component of grassland profitability when considering C retention, contributing to 50 to 70% of both public and private grassland outputs. The price of hay ranked second, contributing 20 to 35% of public and private grassland outputs. The price of C captured in hay represented less than 10% of both public and private grassland outputs. The sensitivity analysis revealed that, depending on the management technique, a C price represented by the CO_2 allowance market price of 20 to 30 EUR per tonne makes grasslands profitable from both private and public goods perspectives. If the contribution of roots to C capture is considered, a C price of approximately 5 EUR per tonne results in the economic profitability of grasslands.

Author's note

PB also serves as the Secretary General of the Committee of the Regions (CoR). This text reflects only the opinion of the author and does not necessarily represent the opinion of the CoR.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found at: https://mendelu.sharepoint.com/:x:/r/sites/Article_meadows_February_2023/_layouts/15/Doc.aspx?sourcedoc=%7B35F3AF5A-B075-42E3-84E2-017CFB679BBC%7D&file=Appendix_A_Dataset_article_C_ver_270623_0349pm%20(1).xlsx&action=default&mobileredirect=true.

Author contributions

BS: Writing – original draft. PB: Conceptualization, Methodology, Writing – review & editing. LL: Formal analysis, Resources, Writing – review & editing. JV: Conceptualization, Investigation, Methodology, Writing – original draft. JS: Methodology, Supervision, Validation, Writing – review & editing. PK: Conceptualization, Investigation, Methodology, Writing – original draft. PH: Conceptualization, Supervision, Validation, Writing – original draft. FH: Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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