



SUPER-G

SUSTAINABLE PERMANENT GRASSLAND

Deliverable 3.10

Benchmarking & testing - Final synthesis report

This report only reflects the views of the author(s).

The Commission is not liable for any use that may be made of the information contained therein.

Project funded under the Horizon 2020 Research and Innovation Programme

Dissemination Level

PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Contact Details

Name of Contact: Paul Newell Price

Address: ADAS Gleadthorpe, Meden Vale, Mansfield, Notts – NG20 9PD, UK

Telephone: +44 (0) 1623 844331

Mobile: +44 (0) 7774 281 253

Email: paul.newell-price@adas.co.uk



Contents

Summary	4
Abstract	7
1. Introduction & objectives.....	8
2. Permanent grassland management datasets and farm networks	9
3. Co-innovation farm workshops	18
4. Synergies and trade-offs	22
5. Assessment of PG innovative management options.....	26
6. Modelling selected indicators for ES from farm data on PG characteristics and management	36
7. Road testing	41
8. Discussion and conclusions	42
9. References.....	45



Summary

Project Number: 774124

Project: SUPER-G – Developing SUSTainable PERmanent Grassland systems and policies

Duration: 5 years 9 months

Start date of Project: 1st June 2018

Project management: RSK ADAS LIMITED

Person in charge: Paul Newell-Price

Deliverable: D3.10

Due date of deliverable: February 2024

Actual submission date: February 2024

Work package (WP): WP3

WP Leader: Marija Klopčič

Person in charge: Paul Newell Price

Author(s): Paul Newell Price, Francis Lively, Jason Rankin, Nina Buchmann, Frances Titterington, Sjaak Conijn and Marija Klopčič

Contributor(s): Bailey G, Báldi A., Barberis D., Benschop M., Bianchi F., Bihaly A.D., Boughton C., Bouten M., Brown S., Buchmann N., Bufe C., Buijs S., Cañada M.C., Dămătîrcă C., Dekker C., Dik P., Dokic M., Dubljevic R., Feigenwinter I., Fernández-Habas J., Fernández-Rebollo P., Francksen R., García-Moreno A.M., Geerts R., Gies E., Gómez-Giráldez P., González-Dugo M., Gordon A., Grinnell N., Hadden R., Hadden S., Hamidi D., Hamidi M., Hassink J., Hidalgo-Fernández M.T., Hilhorst G., Hiron M., Hollewand F., Holohan C., Horn J., Hoving I., Hütt C., Isselstein J., Jindo K., Kempenaar C., Klootwijk C., Komainda M., Kovács-Hostyánszki A., Langley J., Leal-Murillo J.R., Lellei-Kovács E., Lively F., Lombardi G., Lonati M., Mainetti A., Markovic B, Markovic M, Máté A., Mendez P., Meurs B., Milazzo F., Milazzoc F., Molnár C., Moretti B, Newell Price P., Nishikawa H., Noij G.J., Nota G., Oenema J, Ozinga W., Pagani R., Palme R., Patterson D., Petrella F., Piross I.S., Pittarello M., Platt S., Pomp M., Quero J.L., Radonjic D., Rankin J., Ravetto Enri S., Real D., Rhymer C.M., Riesch F., Schils R.L.M., Schmitz A, Schöppner A.K., Siede C., Sijbrandij F., Soltész Z., Somay L., Standen J., Szigeti V., Thompson S., Tonn B., Ungaro F., Vajna, F., Van der Vlugt P., Van Os J. Vanwalleghem T., Verloop, J., Wagenaar, J.P., Wahlund L., Westerink J., Whittingham M.J., Williams J., Wolter S., Zavattaro L.

Communication level: Public

Version: V1





The SUPER-G project (Grant Agreement No.: 774124) has received funding from the European Union Horizon 2020 Research and Innovation Programme. The views and opinions expressed in this report does not represent the official position of the European Commission and is entirely the responsibility of the authors.



THIS PROJECT HAS RECEIVED FUNDING FROM
THE EUROPEAN UNION' HORIZON 2020 RESEARCH
AND INNOVATION PROGRAMME
UNDER GRANT AGREEMENT N. 774124

Partners in the SUPER-G project are:

Organisation	Acronym	Country
University of Newcastle upon Tyne	UNEW	UK
RSK ADAS Limited	ADAS	UK
The University Court of The University of Aberdeen	UNIABDN	UK
Mendelova Univerzita V Brne	MENDU	CZ
Magyar Tudomanyos Akademia Okologiai Kutatokozept	HUN-REN ÖK	HU
Javna Ustanova Univerzitet Crne Gore Podgorica	UOM	ME
Sveriges lantbruksuniversitet	SLU	SE
Universita Degli Studi Di Torino	UNITO	IT
Stichting Wageningen Research	WR	NL
Eidgenoessische Technische Hochschule Zuerich	ETHZ	CH
Szkola Glowna Gospodarstwa Wiejskiego	WULS	PL
Georg-August-Universitat Gottingenstiftung Offentlichen Rechts	UGOE	DE
Agri-food & Biosciences Institute	AFBI	UK
Consulai, Consultoria Agroindustrial, Lda	CONSULAI	PT
Universidad de Córdoba	UCO	ES
Univerza V Ljubljani	UL	SI
Chambre Régionale d'Agriculture De Normandie	CRAN	FR
Association Normande de la ferme expérimentale de La Blanche Maison	LBM	FR
The Northern Ireland Agricultural Research and Development Council	AgriSearch	UK
CRA GRAND EST	CRAGE	FR
Wageningen University	WU	NL
Forschungsinstitut fur Biologischen Lanbau Stiftung	FIBL	CH

Abstract

Permanent grasslands can be defined as “any land dominated by grasses or herbaceous forage that can be grazed/mown and has not been included in the crop rotation of a holding for five years or more”. They have the capacity to deliver multiple ecosystem services such as food production, supporting biodiversity, storing carbon, supplying clean water and providing valued landscapes. However, datasets and management surveys indicate that they are under threat from intensification, abandonment, urbanization and conversion to arable land. Permanent grasslands by their very nature can be challenging to manage and this was confirmed in co-innovation workshops with farmers and advisers who identified multiple factors and constraints to production such as stony soils, steep slopes, high/low temperatures, high/low rainfall, increased frequency of extreme weather events and short tenancies. Nevertheless, there was significant interest from farmers in improving their understanding of sward and grassland management (e.g. grazing and cutting strategies); the costs and benefits of sward renewal; nutrient management; integrating trees into grassland landscapes; and improving grass quality and productivity. Many farmers were also interested in communicating to the general public and demonstrating how their permanent grasslands can deliver a range of ecosystem services and public goods. There was generally less interest in high technology solutions, although some farmers were keen to investigate the use of GPS collars and virtual fencing to improve their monitoring and implementation of grazing management. Demonstration and experimental work indicated that, with technical and financial support (e.g. capital grants), these and other technologies have potential for wider adoption among farmers open to these opportunities. Sward renewal, including the integration of multi-species swards containing grasses, deep rooting herbs and legumes, has potential for more widespread adoption, although our co-innovation work in this project indicated that more research is needed to provide better agronomic support for the management of such swards. PG management survey data for specialist dairy farms indicated that rental charge was a significant driver of intensification in terms of milk production, manufactured nitrogen fertiliser use and amounts of purchased feed. Increasing manufactured nitrogen fertiliser application rates also correlated with lower plant species richness, an indicator of biodiversity decline. Further work is needed to determine how to decouple the need for increased meat and milk production (alongside increasing amounts of purchased feed) from high land rental charges and other factors driving intensification. Nevertheless, given sufficient technical, financial and societal support alongside a continual process of co-innovation with advisers and researchers, grazing livestock farmers can provide multiple public goods alongside food production.



1. Introduction & objectives

The existence and management of permanent grasslands (PG) is key to the delivery of multiple ecosystem services (ES) across Europe. The overall objective of the SUPER-G project was to co-develop sustainable PG systems and policies with farmers and policy makers that are effective in optimising productivity, whilst supporting biodiversity and delivering a number of other ES. The third project work package (WP) focused on gathering data from and working with farmers that manage PG. Through survey work, co-innovation workshops, trials, demonstrations, field experimentation, road testing and modelling it was possible to gain a better understanding of how the implementation of innovative management options can influence the profitability and sustainability of PG and how different management strategies affect the synergies and trade-offs in ES delivery.

PG management approaches for different ES were co-developed, assessed and evaluated; and emerging technologies and innovative PG management approaches were tested and validated on commercial farms and experimental platforms and then 'road-tested' to enable knowledge exchange across six biogeographic regions of Europe. The specific objectives of WP3 were to:

- O3.1a Establish a range of farm networks across the biogeographic regions.
- O3.1b Compile and synthesise existing data on farm performance in relation to PG & ES delivery from the farm networks within and between biogeographic regions.
- O3.2 Co-develop innovative and integrated approaches for PG management in farm workshops and test them out on farms and experimental platforms; focusing on cost-effectiveness, environmental impacts and practicalities for farmers and land managers.
- O3.3 Improve our understanding of trade-offs and synergies associated with the management of PG for ES delivery.
- O3.4 Co-develop and test innovative practices and emerging technologies at selected experimental farms and research stations.
- O3.5 Evaluate by modelling the integrated and innovative approaches for PG management through critical assessments on profitability and sustainability.
- O3.6 'Road test' and demonstrate the innovative practices and emerging technologies for practicability, profitability and sustainability on commercial farms, considering farmers' acceptance.
- O3.7 Prepare a synthesis of all outputs from Tasks 1 to 6.

This report addresses objective 3.7 by synthesising and summarising the activities carried out across the 23 SUPER-G farm networks and 17 experimental platforms. Farm surveys were carried out in 2019 and 2023 to characterise the farms within the farm networks and assess what has changed in the intervening four years. The data from the first survey was used to investigate relationships between PG management, the cost base of production and ES delivery, focusing on specialised dairy farms to produce an ES delivery model for these farms. Co-innovation workshops were held within each of the farm networks, initially to understand the key challenges associated with managing PG and the management options that farmers and advisers were most interested in testing on farm. Subsequent workshops were an opportunity to view the trials, demonstrations and experiments and to discuss the results in terms of practicality, profitability and sustainability. This was complemented by work on experimental platforms that carried out more detailed measurements to improve our understanding of how PG management affects ES delivery. The most promising management options were 'road tested' on commercial farms with a focus on practicality and social, economic and environmental sustainability.

2. Permanent grassland management datasets and farm networks

The first objective of WP3 was to establish a range of farm networks across six biogeographic regions in Europe and to compile and synthesise existing data on farm performance in relation to PG and ES delivery.

Deliverable report 3.2 provided an overview of PG management datasets at European and national level. The list of European datasets was not exhaustive but provides an indication of where useful information can be found. The European statistical survey sources include the:

- Farm Structural Survey (FSS)
- Survey on Agricultural Production Methods (SAPM)
- Farm Accountancy Data Network (FADN)
- Eurostat compilation of crop and land use statistics
- Land Parcel Information System (LPIS): the spatial register within the Integrated Administration and Control System (IACS)
- Land Use and Cover Area frame Survey (LUCAS)
- Greenhouse gas (GHG) emission inventory submissions, including a record of emissions from land use, land use change and forestry (LULUCF)
- Organisation for Economic Cooperation and Development (OECD) Environmental data compendium (including grassland categories divided between temporary and permanent grassland; irrigated and non-irrigated; and the area under organic farming)
- OECD Environmental Performance of Agriculture dataset (1990-2004)

European-level study-based information includes the:

- **Pasture Knowledge Base (PASK)**, developed for the MARS (Monitoring Agriculture with Remote Sensing) STAT Action at the EC Joint Research Council (JRC)
- **FAO country pasture profiles**: an initiative of the FAO *Grassland and Pasture Crops Group*
- **Biodiversity data centre (BDC)** managed by the European Environmental Agency (EEA)
- **High Nature Value farmland (HNV)** map, which presents the geographic distribution of HNV farmland in the EU

European land cover data include the:

- European Space Agency (ESA) **GlobCover** Land Cover Map
- **GLC2000** Global Land Cover map
- **CORINE** (CO-ordination of INformation on the Environment) Land Cover (CLC) inventory
- **GMES** (Global Monitoring for Environment and Security) initiative, headed by the European Commission (EC) in partnership with the European Space Agency (ESA)

More recent developments include the EU Grassland Watch project, which aims to support the monitoring and management of Natura 2000 sites using Copernicus earth observation data with a focus on grasslands to “*assess the health of protected areas / ecosystems through time*”: [Home \(cop4n2k.eu\)](http://cop4n2k.eu)



Deliverable report 3.2 also summarised national datasets on PG area and/or management from 11 European nations (namely: Czech Republic, England, France, Italy, Northern Ireland, The Netherlands, Portugal, Slovenia, Spain, Sweden and Switzerland) and provided an overview of trends in PG area and management. PG now covers 48 million hectares across the EU-27 and accounts for 30.5% of the total Utilised Agricultural Area (UAA) (Eurostat 2023), although there are large differences between countries in terms of proportion of UAA, spatial fragmentation and distribution (Figure 1).

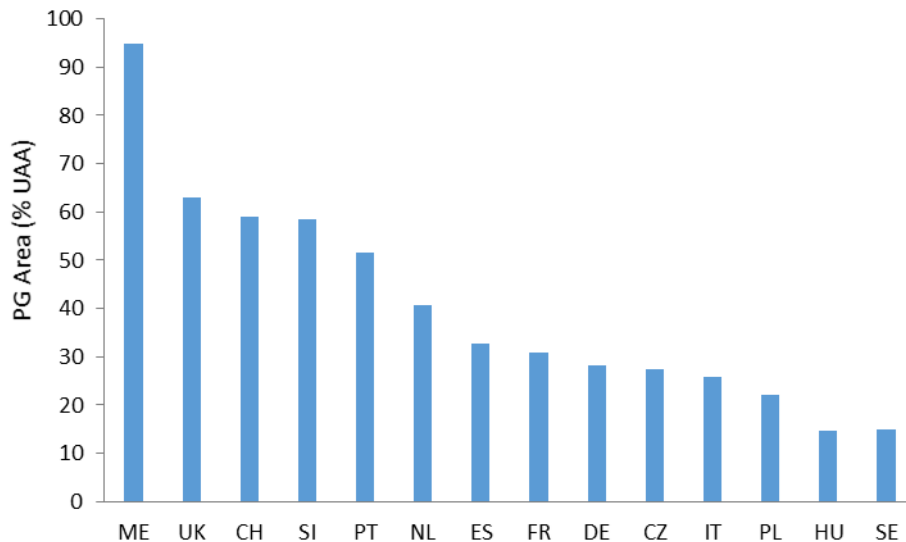


Figure 1. Permanent grassland as a percentage of UAA in SUPER-G partner countries. Eurostat 2016 data, extracted on 17.02.2021

Across Europe there has been a trend for a decrease in PG area. Across the EU-6 (Belgium, Denmark, Germany, France, Italy and Luxembourg), between 1970 and 2010, permanent grassland losses are estimated at around 30%, i.e., a loss of c. 7 million ha (European communities, 2000 & Eurostat 2017). More recently from 2005 to 2013, across the different biogeographical regions EU countries have reported both increases and decreases in PG area. For example, within Hungary (Pannonian region) the proportion of PG area has increased by 50% (or 234,000 ha) whereas Sweden (Boreal region) has seen a 13% (or 66,000 ha) reduction in PG area. In terms of total hectares, the largest increase in PG area was reported for the UK (Atlantic region) with an increase of 983,000 ha whilst the largest decrease in PG area was reported for Spain (Mediterranean region) at almost 700,000 ha.

In 2018-19, the 23 SUPER-G farm networks were confirmed (Table 1) and a detailed PG management survey questionnaire was designed to gather information on farm characteristics and PG management practices, intentions and outlook from farmers participating in the networks (Mulvenna *et al.*, 2021). It covered the following areas:

- Farm information
- Permanent Grassland information
- Soil management
- Grass management
- Sward management and grass yields
- Ecosystem services
- Farm economics
- Innovations and Knowledge Exchange

Table 1. Table of farm networks involved in SUPER-G

Farm network	Bio-geographic region	Country	Lead partner	Type of Agriculture	ES investigated	Livestock type
Equinet	Alpine/ Continental	DE	UGOE	Con & Org	P B Animal Welfare	D B H
Association of dairy cattle farmers	Alpine/ Continental/ Mediterranean	SI	UL	Con & Org	P C B W E	D B
Association of sheep and goat farmers	Alpine/ Continental/ Mediterranean	SI	UL	Con & Org	P B E	S G
Association of Mountain Agrarian Communities	Alpine/ Mediterranean	SI	UL	Con & Org	P B C W E	D B S
Associazione Regionale Gruppi Coltivatori Sviluppo	Alpine and Continental	IT	UNITO	Con & Org	P B C W	D B
Cows and Opportunities	Atlantic	NL	WR	Con	P C W	D
Proeftuin veenweiden (grassland on peat soils)	Atlantic	NL	WR	Con & Org	P B C W	D
Northumberland Grazing Group	Atlantic	UK	ADAS	Con & Org	P B C F	D B S
GrassCheck	Atlantic	UK(NI)	Agri- Search	Con	P C W	D B S
Lamb from Grass (Upland Component)	Atlantic	UK(NI)	AFBI	Con	P B C	S
Normandy grass growth observatory	Atlantic	FR	CRAN	Con & Org	P B C E	D
SVFA	Boreal	SE	SLU	Con & Org	P B W	D B S H
AGRIPOPES	Boreal	SE	SLU	Con & Org	P B C F	B
Green Network ("Réseau vert")	Continental	FR	CRAGE*	Con & Org	P B C W	D B
Grass Network ("Réseau Herbe")	Continental	FR	CRAGE*	Con & Org	P B C W	D B

Farm network	Bio-geographic region	Country	Lead partner	Type of Agriculture	ES investigated	Livestock type
Bohemian Moravian Highlands	Continental/ Pannonian	CZ	MENDU	Con & Org	P W F E	D B
Biodehesa network	Mediterranean	ES	UCO	Con & Org	P B C E	B S P
Association for the Defence of the Heritage of Mertola (ADPM)	Mediterranean	PT & ES	CONSULAI	Con (low input)	P B C E	P S G
BioBio	Pannonian	HU	MTA OK	Con (low intensity) & Org	B C W	D S
Lorraine Grass Network	Continental	FR	CRAGE*	Con & Org	P B C W	D B
Observatoire de la croissance de l'herbe	Atlantic	FR	CRAN	Con & Org	P	D B S
The Farmers Association "Producers of Durmitor's skorup"	Alpine	ME	UOM	Con & Org	P B	D B S H
Polish dairy farmers association	Continental	PL	WULS	Con	P B	D

* CRAGE also implies one or more of their linked third parties (CA88, CA54, CA55 and CA57)

Ecosystem services (ES) investigated: P = food production, B = biodiversity, C= carbon sequestration and greenhouse gas (GHG) mitigation, W = water quality, F = flood control, E = erosion control.

Type of Agriculture: Con = conventional, Org = organic

Livestock types: S = sheep, D = dairy, B = beef, H = horses, P = pigs, G = goats

The surveys were conducted by trained extension officers across six biogeographic regions: Alpine, Atlantic, Boreal, Continental, Mediterranean, and Pannonian. Respondents were provided with a farmer information sheet that ensured interpretation and responses between farm networks and biogeographic regions were consistent. The survey and the farm information sheet are presented in SUPER-G deliverable report 3.2 (Mulvenna *et al.*, 2021).

Responses were collated and standardised in an anonymous datafile for analyses. Statistical analysis was conducted using R-3.6.3 (R Core Team, 2020) to investigate differences between farm networks in the contrasting biogeographic regions by ANOVA. Chi-square tests were used to look for differences in the proportions of responses to questions concerning various aspects of PG management, including farmer target yields from cutting and grazing swards, and challenges when trying to improve grassland performance. The significance threshold was $P < 0.05$.

Target yields for PG were dependent on the exploitation system, with different targets for grazed land and land cut for hay or silage. The target grass dry matter yield ($\text{t DM ha}^{-1} \text{ year}^{-1}$) on improved grazing land varied between regions ($\chi^2 = 55.987$, $df = 15$, $P < 0.001$). Atlantic region farmers had the highest expectations for their improved PG, with 60% targeting a yield of 10-15 t ha^{-1} , and 1% targeting 15 $\text{t DM ha}^{-1} \text{ yr}^{-1}$. The target grass dry matter yield on PG improved for cutting also varied between biogeographic region ($\chi^2 = 29.227$, $df = 15$, $P < 0.05$). Most farmers in the Alpine, Atlantic and Continental networks targeted 5-10 $\text{t DM ha}^{-1} \text{ yr}^{-1}$, while most farmers in the Pannonian network targeted up to 5 $\text{t DM ha}^{-1} \text{ yr}^{-1}$. In the Boreal and Mediterranean networks, most respondents reported a target of 5-10 $\text{t DM ha}^{-1} \text{ yr}^{-1}$ (37.5% and 40%). Some farmers in the Atlantic (10%), Mediterranean (10%), Alpine (6%), and Continental (1%) networks targeted more than 15 $\text{t DM ha}^{-1} \text{ yr}^{-1}$ on their cutting land. These higher targets are reflected in the organic manure use, with the Atlantic region applying 57.2 t ha^{-1} to improved PG silage ground, significantly more than Alpine (39.0 t ha^{-1}), Boreal (20.8 t ha^{-1}) or Continental (29.6 t ha^{-1}) respondents. This increased use of organic manure on silage ground could be reflective of the increased target, or the higher stocking rate in this region leading to a greater availability of organic manure.

Grazing yields varied between biogeographic region ($\chi^2 = 19.64$, $df = 10$, $P < 0.05$). Grazing yields of 0-5 $\text{t DM ha}^{-1} \text{ yr}^{-1}$ were reported by the majority of all respondents in all regions other than the Atlantic networks where 55% of respondents reported yields of 5-10 $\text{t DM ha}^{-1} \text{ yr}^{-1}$. A small proportion (3%) of farmers in the Continental networks reported yields of 10-15 $\text{t DM ha}^{-1} \text{ yr}^{-1}$. Reported cutting yields also varied between biogeographic regions ($\chi^2 = 25.35$, $df = 10$, $P < 0.001$), with most farmers in Alpine, Boreal, Continental, Mediterranean and Pannonian networks reporting yields of 0-5 $\text{t DM ha}^{-1} \text{ yr}^{-1}$. By contrast, in the Atlantic networks, 82% of respondents reported cutting yields of 5-10 $\text{t DM ha}^{-1} \text{ yr}^{-1}$. The results confirm the higher grass yield potential in Atlantic regions and indicate that many farmers are not achieving their target grazing and cutting yields.

When asked about any changes in the intensity of PG management in the past 10 years, 49% of respondents stated that management intensity had increased; 41% reported that management intensity remained unchanged; and 10% had reduced management intensity. There were some significant differences between the farm networks representing the six biogeographic regions in trends in improved PG management intensity ($\chi^2 = 33.50$, $df = 10$, $P < 0.001$; Figure 2), with a majority of farmers in the Alpine, Atlantic and Mediterranean farm networks reporting that management intensity had increased. The majority of farmers in the Continental and Pannonian networks reported that management intensity had not changed, whereas farmers in the Boreal networks reported that PG management intensity had decreased over the last 10 years.



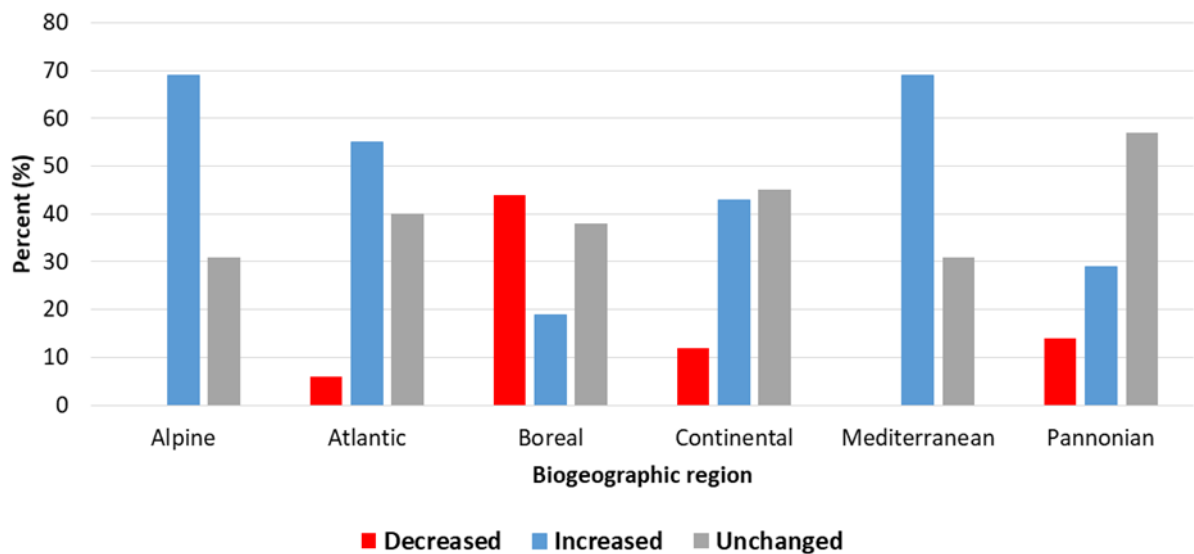


Figure 2. The views of farmers surveyed (%) in each biogeographic region on changes in the intensity of improved permanent grassland management over the previous 10 years.

Farmers were asked what environmental features, activities and environmental restrictions they had on their farm that provide ES (Table 2). The perception of features like ‘hedgerows’ and ‘species-rich grassland’ may differ between regions and networks, but it is interesting that 53% of Continental farms stated that they had hedgerows compared with none in the Boreal networks. Similarly, 86% and 89% of Boreal and Pannonian farms stated that they had species-rich grassland on farm compared with 35% of farms in the Alpine networks. Grass margins and buffer strips along watercourses were more common in Atlantic (28% and 39%) and Continental (26% and 31%) networks than in the Alpine (4% and 19%), Boreal (5% and 23%) and Pannonian (0% and 7%) networks.

Nutrient application closed periods, and nutrient planning were most prevalent in the Atlantic networks (65% and 66% respectively). This contrasted with the Mediterranean networks in which 13% of farms had nutrient application closed periods and 33% had a nutrient plan; and the Alpine networks in which 15% of farms had a nutrient plan (Table 2). Wetlands and managed floodplains were clearly most prevalent in the Pannonian networks (68%; compared with 4% to 27% in other networks), while fire breaks were only common in the Mediterranean networks (79%). Finally, historic/archaeological features and public walkways/access to water courses were most prevalent in the Boreal networks (56% and 36% respectively).

The results indicate that farmers across Europe have varying expectations of their PG, and will accept different levels of production performance. There are also differences in terms of the proportions of farms that have intensified or extensified in recent years and the percentage of farms with certain environmental features and planning activities. These contrasts can be attributed to biophysical, economic and socio-cultural differences between biogeographic regions and countries. Despite these differences, there are challenges such as weather and access to capital, which are common to multiple biogeographic regions.

In 2023, a second survey was carried out on 184 of the farms questioned in 2019, with a focus on what had changed in the intervening years. The re-survey questionnaire was designed to measure magnitude and direction of change within PG management and farm characteristics.

Table 2. The percentage (%) of farms which had each of the environmental features on their PG (improved and unimproved) in each region.

Feature	Alpine	Atlantic	Boreal	Continental	Mediterranean	Pannonian
Hedgerow	44.4	37.5	0.0	52.7	29.2	32.1
Tree Planting/Agroforestry	16.7	36.6	27.3	37.5	83.3	14.3
Species-rich grassland	35.2	45.5	86.4	69.6	70.8	89.3
Designated area for shelter and/or vegetation for birds	5.6	34.8	22.7	24.1	37.5	78.6
Grass margins	3.7	27.7	4.5	25.9	12.5	0.0
Invasive species control	14.8	27.7	9.1	32.1	45.8	78.6
Stocking rate control	31.5	34.8	22.7	45.5	41.7	75.0
Closed period for grazing	11.1	29.5	22.7	24.1	37.5	75.0
Closed period for nutrient application	16.7	65.2	54.5	48.2	12.5	82.1
Nutrient plan	14.8	66.1	22.7	35.7	33.3	7.1
Wetlands/Managed flood plains	3.7	17.9	27.3	13.4	4.2	67.9
Areas of natural habitat	9.3	31.3	27.3	23.2	33.3	82.1
Buffer strip along water course	18.5	39.3	22.7	31.3	20.8	7.1
Fire break	0.0	0.0	0.0	0.9	79.2	0.0
Agri-tourism	5.6	4.5	13.6	11.6	8.3	3.6
Animals managed for recreational purposes	5.6	7.1	18.2	19.6	12.5	7.1
Historic or archaeological features	1.9	20.5	54.5	7.1	37.5	0.0
Public walkway/access to watercourses	13.0	31.3	36.4	17.9	16.7	7.1
Other	0.0	7.1	9.1	0.9	4.2	0.0

Farm size was found to have increased for the majority of farms (62.6%) between 2019 and 2023. Interestingly, there was not an equivalent increase in stock, with only 10.9% of farms increasing their livestock. Increases in farm size were generally opportunistic, when neighbouring land became available. Changes in farm livestock numbers were generally for economic purposes. Grass yields varied across the biogeographic regions, as did the output per hectare reflecting the different environmental conditions. Similarly, the environmental indicators varied between biogeographic regions, with the Pannonian region having a higher proportion of farm area under a nature conservation designation than other biogeographic regions.

The mean number of grass species on farms in each biogeographic area increased between 2019 and 2023 (Table 3). Farmers who increased biodiversity of the sward attributed this to improving “Biodiversity and climate robustness”, “Resowing with a multi species mixture”, “Agri-Environment scheme (GS4)”. Those who dropped a particular species did so because it “Didn’t work well in a mix”, or “Disappeared”. This indicates that farmers are influenced to some extent by agri-environment schemes but that they also monitor sward performance to ensure that any introduced species is compatible with their farm system. Answering this question accurately requires the farmer to accurately identify the plants in the natural environment, so the increase in plant species could be a reflection of an improved understanding as well as an increase in sward diversity.

Table 3. The mean number of grass species reported by respondents in each biogeographic area in 2019 and 2023.

Grass species included: Heather, Rush, Perennial Ryegrass Italian Ryegrass , Hybrid Ryegrass, Timothy, Meadow Fescue, Red fescue, Tall fescue, Rough Meadow Grass, Common meadow grass, Creeping Bent, Cocksfoot, Red Clover, White clover, Subterranean clover, Chicory, Plantain , Lucerne , Crested dog's-tail, False oat-grass, Heath false-brome, Erect brome, Meadow foxtail, and Yellow oat-grass

Biogeographic area	2019	2023
Alpine	4.3	4.3
Atlantic	6.3	8.8
Continental	8.3	10.3
Mediterranean	3.5	5.6
Pannonian	3.6	no data
Boreal	4.5	no data

The survey findings demonstrated the differences between the farm networks in the different biogeographic regions in terms of both productivity and environmental or sustainability indicators.

3. Co-innovation farm workshops

In 2019, each farm network ran a co-innovation workshop to discuss the main local issues for PG management and the potential to test and trial new PG management options or emerging technologies by demonstration and experimentation (Figure 3). Co-innovation workshops were also an opportunity to discuss how contrasting management strategies relate to or align with developments in agricultural and environmental policies and farm support. Subsequent annual co-innovation workshops were used to discuss results from field experiments and demonstrations (Tasks 3.3 and 3.4) to ultimately decide on which management options and technologies to 'road test' (Task 3.6), thereby steering the direction of further work. In 2023, in a final set of co-innovation workshops, the invitation was extended to a wider network of farmers to enable broader knowledge exchange and to inform the practical face-to-face workshops managed by Wageningen Research in WP6.



Figure 3. Many co-innovation workshops had a farm walk element to encourage discussion.

There was a wide range of SUPER-G farm networks in terms of livestock type, biogeographic region and production system intensity (Table 1). This meant that there was also variety in the range of PG management challenges discussed in the co-innovation workshops among farmers and advisers. However, many permanent grasslands occupy land that has agro-climatic, biophysical and other limitations that restrict viable agricultural land use to grassland. The main challenges for managing and maintaining PG, therefore, often related to:

- Soils, land, climates and microclimates that have a production or versatility limitation related to stoniness, wetness, shallowness, dryness, high/low temperature, steep slopes, complex microrelief, rocky outcrops or frequency and duration of flooding.
- How to improve the productivity of the land.
- Managing sward species composition, including decisions around if and when to reseed or overseed and what species mixes to sow.
- Adapting to more extreme weather patterns, including increasing frequency and severity of droughts, waterlogged conditions and floods.
- Implementing grazing strategies to improve grass utilization and overall productivity.
- Understanding the relative cost:benefit ratio of different management interventions.
- Improving the utilisation and nutritional quality of grass.
- Length of tenancies.
- Lack of incentive to retain PG.
- Integrating production, biodiversity and landscape – some were positive about stewardship although they acknowledged that it could restrict management.

There was considerable interest in understanding more about the various ways PG can be managed to improve productivity, but also for the delivery of multiple public goods or ES. In many farm networks, food production was considered to be the most important ES, but there was also considerable interest in non-provisioning ES. Among other matters, workshop participants were interested in increasing resilience to extreme weather conditions, biodiversity, economics (cost/benefit of management interventions), the use of shelter belts, nutrient management, diverse swards, carbon storage, land use/management policy, livestock breeds and citizen priorities.

The final part of the first co-innovation workshops focused on the PG management options or educational tools that farmers and advisers would like to trial or develop. Farmers were interested in trialing:

- Sward renewal (including slot seeding) methods to understand the impact of new grassland plant species /varieties on productivity and the delivery of public goods.
- Seed mixtures suitable for PG; in particular alternatives to the standard productive grass species (e.g. *Lolium perenne* or *Phleum pratense*) that tolerate intensive pasture, drought or upland use.
- Increasing the legume content in grassland swards.
- Measurement methods to target pasture allocation better and improve grass utilisation.
- Apps that support controlled pasture allocation and PG management.
- Use of diverse swards to improve efficiency of production and increase water infiltration.
- The use of virtual fencing for improved livestock grazing management for productivity and biodiversity.
- Improved nutrient management including using novel (e.g. organic certified) fertilisers and making better use of organic manures.
- Mechanical loosening compared with increasing plant species diversity (through overseeding) in swards as a means of increasing productivity, improving biodiversity and reducing flooding risk.
- Grazing management for productivity, biodiversity and other public goods.
- The use of specific livestock species or breeds to control weeds or invasive species.
- The establishment and management of PG blocks to support pollinators, natural predators and wildlife within arable landscapes.
- Methods for incorporating habitat support for biodiversity into PG management.

Delegates were also interested in a cost/benefit analysis of improving 'untouched' permanent pasture and the integration of trees and shelter belts into PG landscapes; and in acquiring more information and data on how much soil carbon PG can store and sequester.

Many farmers (e.g. in UK, France and Sweden) also felt that education was an important option that would be beneficial to the farm business as the citizen and consumer would then be more aware of what they were purchasing. Educating the consumer would make them aware of where their food comes from and how it relates to land types, landscapes, local rural communities and the delivery of other public goods.

The various discussions ultimately resulted in trials, demonstrations and experiments covering the following broad categories:

i) New grassland species, diverse species swards:

- Introduction of new grassland species
- Overseeding with diverse species or mixtures

ii) Precision grassland management:

- The use of plate meters and other yield estimation techniques
- Grazing management tools and the introduction of rotational grazing
- Satellite or drone technologies for yield and quality estimation
- Use of other precision technologies for grazing (e.g., in field weighing / virtual fencing / GPS collars / apps)

iii) Nutrient management:

- Quantification of nutrient balances
- Precision nutrient management, including variable rate fertiliser application
- Analysis of grassland quality (e.g., protein and dry matter)
- Better use of organic manures
- Use of slow-release fertilisers
- Modelling soil carbon (C) dynamics to increase soil C stocks

iv) Agri-environment options:

- Agroforestry, promotion of tree establishment and growth
- Grazing management and other management strategies for productivity, biodiversity and other public goods (including conserving in-field grass / deferred grazing)
- Cutting management and other management strategies for productivity, biodiversity and other public goods
- New livestock breeds for PG and/or ES
- Increasing legume cover to reduce mineral N fertiliser and decrease N₂O emissions
- Soil moisture dynamics/surface run-off volume estimation/ groundwater quality and volume estimation
- Comparing ES delivery from temporary grassland, PG-improved and PG unimproved
- Management of peri-urban PG water meadows for ES delivery
- Mechanical loosening for improved drainage and productivity
- Use of locally harvested seeds for re-vegetation

v) Education

- Producing education materials on ES delivery from PG
- Testing a citizen science approach to determining plant species diversity in grasslands

Once trials and experiments had been set up, co-innovation workshops in subsequent years focused on reporting on key findings and discussing the practical implementation of PG management options and how they may be integrated into new agri-environment schemes. Farmer and adviser delegates discussed how sustainable grassland management can improve the resilience of livestock grazing businesses by improving productivity, increasing grass utilisation, optimising livestock performance and accessing alternative income streams. Topics covered included:

- The pros and cons of integrating multi-species swards into grassland systems
- What do healthy grassland soils look like and how to manage them?
- What are the optimal grazing strategies for different grassland swards?
- How to make the most of manures
- Managing grasslands to secure agri-environment payments
- The key topics that future workshops should focus on

4. Synergies and trade-offs

Trials and experiments on commercial farms investigated the ES delivery synergies and tradeoffs associated with a wide variety of PG management options (see section 4 above). This section synthesizes the main findings from over 60 trials, demonstrations and field experiments that were co-developed and implemented with farmers. SUPER-G report D3.6 on “Synergies & Tradeoffs” provides more detailed information including 45 papers summarising findings from individual trials and field experiments.

MULTI-SPECIES SWARDS

When establishment of multi-species swards (MSS) is successful, there can be clear potential synergies between climate regulation, biodiversity, water quality, and production. However, even in low input systems, improvements in productivity are not guaranteed (e.g. when the existing sward has a good proportion of productive species such as perennial ryegrass - *Lolium perenne* - and white clover – *Trifolium repens*), and if establishment is poor, there can also be potential trade-offs with production, as weeds can be difficult to control. The persistence of some species (particularly herbs) is also challenging, although this is usually improved through rotational grazing. There are contrasting approaches to managing MSS in the different biogeographic regions and countries, which also contrast in terms of whether productivity or other ES are prioritised.

In the UK and northwestern France, multi-species swards were used that could achieve comparable dry matter yields to conventional perennial ryegrass monocultures, and comparable livestock performance (and on occasions improved livestock performance). However, in some other countries and regions, there tends to be a greater focus on improving biodiversity with the use of “conservation” mixes. While these are likely to deliver more ecosystem services, they tend to have lower dry matter yields and digestibility, which can lead to reduced livestock performance. The use of locally harvested seed can be an effective method to regenerate swards and improve biodiversity.

There is an element of risk associated with introducing MSS as the associated seed mixes are more expensive than simpler mixes and they can be difficult to establish. It usually takes a process of ‘trial and error’ before a MSS mix that is suited to local conditions can be found. Whichever seed mix is chosen, it is often the case that some of the herb species do not persist beyond a few years. Farmers should therefore be assisted in developing an understanding of the set of species in each mix that is likely to persist and can provide production benefits alongside ES delivery for many years, without the need for frequent overseeding or reseeding. The agronomy of managing MSS also needs further development. Policy makers should therefore consider supporting farmers to ‘de-risk’ the adoption of MSS. It should also be noted that these diverse swards often require a completely different management approach to traditional monocultures, and resources are needed to train farmers in the skills needed to manage these swards.

PRECISION GRASSLAND MANAGEMENT

Virtual Fencing

The adoption of virtual fencing can provide clear potential synergies between ecosystem services (ES). It is extremely useful both from a practical management perspective (improving grassland management and utilisation; and introducing a leader-follower system for cattle) and in the delivery of ES, such as protecting water courses and sensitive habitats. However, these

technologies are expensive and are not currently economically viable without some form of support. In addition, animal welfare regulations related to the use of such technologies can be a barrier to adoption. However, results from trials by SUPER-G partners have shown no negative animal welfare impacts of virtual fencing when compared to 'traditional' electric fencing.

GPS collars

GPS collars are used to monitor animal locations, but they do not control livestock movements. They can be useful to determine where and when cows are calving, and also for monitoring animal health and behaviour. While these collars are cheaper than virtual fencing, they are still expensive, and technical support is a very important element in their adoption. GPS collars do not offer the same productivity and conservation benefits as virtual fencing. However, there are no societal animal welfare concerns around GPS sensors.

Use of satellites (for grass measurement / monitoring)

The work undertaken by SUPER-G partners indicates that satellite imagery can be used to monitor grass yield and quality over large, extensive areas. However, the accuracy of such technologies is not sufficient for intensive grazing (such as dairy cow paddocks). However, technologies are always improving and there is a need for further independent research in this area.

Rising Plate Meters

This technology has been widely adopted in the UK and Ireland to monitor grass production at field and paddock level. However, there is increased interest from farmers and advisers in other biogeographic regions. For farmers new to the technology, it often requires a change in mindset to take the time to measure grassland swards each week. For other farmers, they may not have the time to carry out plate meter readings due to other commitments. Many farmers that start plate metering revert to 'eyeballing' (i.e., estimating grass cover by eye) within a few weeks or months. Rising plate meters (RPM) are best suited to monocultures. They are much less suited to diverse, multi species swards that have a different vegetation structure to pure grass or grass-clover swards, and whose composition changes throughout the year. RPM are productivity focused. However, project partners in Sweden (SLU) have found some potential use for them in conservation grazing to determine the heterogeneity and complexity of grassland sward heights and structures.

NUTRIENT MANAGEMENT

Increasing productivity of organically-managed, upland grasslands can be challenging. In experiments on traditional rig and furrow pastures in the north of England, poultry manure was more effective than cattle farmyard manure or soft rock phosphate at increasing grass yield and soil phosphorus (P) reserves. However, careful management is needed to avoid a potential trade-off with water quality. More work is needed to determine the specific circumstances in which soft rock phosphate could be effective as a phosphate fertiliser.

While variable rate precision fertiliser technologies led to a more equal distribution of nitrogen (N) use efficiency (NUE) within fields, thus preventing local N surpluses, it did not lead to higher NUE at the field level. There was therefore no efficiency or productivity gain for farmers. Support would therefore be needed to encourage the adoption of variable rate nitrogen application and deliver the potential environmental benefits. Such technology is only really applicable to high input-high output grassland systems, and it is questionable whether true multifunctionality can be achieved in these circumstances.

Slow-release fertiliser on ski slopes had positive effects on species diversity and reduced erosion risk. However, there was a small trade-off in terms of water quality and greenhouse gas emissions. On balance it is an effective method for increasing plant species diversity and reducing erosion risk in alpine landscapes where recreational activity is concentrated.

PERMANENT GRASSLAND (PG) MANAGEMENT PRACTICES & AGRI-ENVIRONMENTAL INDICATORS

Biodiversity

Unimproved PG can be an important habitat for threatened species. Improved PG can also support valuable habitats (within fields and on field margins) and is an important carbon store. There is potential for intensive grassland to support biodiversity more effectively if farmers are sufficiently incentivised.

Specific grazing and cutting regimes may be needed to support certain threatened species and to increase insect species abundance and richness. The diversity of PG plant species can also have a positive effect on insect and other species. For example, in one study the presence of legumes and herbs and a two-cut regime (cf. a single late cut) had a positive effect on pollinator species abundance and richness.

On upland pastures, rugged breeds such as highland cattle can be used to control invasive vegetation and control fire risks. Mollasses blocks can be used to encourage cattle into certain areas to control invasive scrub vegetation and protect PG. However, these blocks need to be moved on a regular basis to avoid livestock creating patches of bare soil (i.e., reduced vegetation covers) and thereby increasing erosion risk.

Climate regulation

Permanent grassland is a critical carbon store, and a significant proportion of European grasslands have the potential to sequester additional carbon. However, many older permanent grasslands are most likely 'saturated' in soil organic carbon (SOC) with no further capacity to sequester additional carbon (C). Higher SOC stores relate to specific soil and vegetation types and tend to be found in higher rainfall areas. In one alpine study, higher SOC stocks were recorded in pastures rich in plants typical of warmer, low-altitude, species-rich environments. Another study, at a long-term site in northern England, highlighted how significant differences in lime, nutrient and manure inputs can result in only a small and, for some treatments, no change in SOC. Any differences were only observed in the top 0-7.5 cm depth soil layer, although the measurements also highlighted the importance of C in deeper soil layers (7.5-15, 15-30, 30-60 and 60-90 cm depth) as carbon stocks. Indeed, other studies have highlighted the importance of subsoil as a carbon store and the potential to sequester some additional carbon in these layers (e.g. Ward *et al.*, 2016).

Grassland renewal can result in loss of soil C in the season of renewal, but sequestration of C over the longer term may be greater due to productivity gains in the following years (i.e., net positive C sequestration). Soil carbon in permanent grasslands needs further monitoring and research, as soil C dynamics and the effects of management on soil carbon are not fully understood.

Using clover in place of fertiliser (manufactured or organic manure) reduces greenhouse gas emissions, in particular of nitrous oxide. In Switzerland, lower N₂O emissions were found where clover was used in place of livestock manures. However, there was clear evidence that grasslands need organic N inputs to retain their carbon stores and act as a carbon sink. Thus, a

trade-off between avoiding N₂O emissions but keeping soil C stocks was identified. A higher frequency of prolonged drought could mean that more permanent grasslands become a carbon source.

Widespread use of clover (or other legumes) could result in a loss of productivity on individual fields that are reliant on manufactured N fertiliser within high input-output systems. However, with improvements in grass utilisation (e.g. through better grazing management) the overall impact on meat and milk production may not be substantial. Furthermore, integration of legumes into PG production systems is usually accompanied by an increase in farm business resilience (lower input costs) and a reduction in ruminant livestock numbers (lower enteric methane emissions) could increase economic and environmental sustainability.

Mediation of water flows and erosion control

Permanent grasslands are effective in reducing the risk of run-off and erosion. However, compared with tillage crops such as maize, they can result in lower amounts of groundwater recharge (i.e., the proportion of the precipitation volume draining below 80 cm depth). Furthermore, grassland establishment can represent a short-term period of increased erosion and runoff risk, especially if soils are bare.

Subsoiling or 'sward lifting' of PG typically results in a dramatic increase in water infiltration rates and an increase in root density at depth. There are therefore potential benefits for production (extended grazing and drought resilience) and flood and erosion mitigation. However, such 'mechanical loosening' should only be carried out where there are clear signs of soil compaction as 'lifting' soils that are in good condition can do more harm than good. While 'mechanical loosening' can reduce soil organic carbon in the short-term, longer-term effects are unknown.

EDUCATION

There are many positive benefits from engaging citizens to consider and appreciate the role of permanent grasslands in delivering biodiversity and other ES. There is a need for more engagement activity and further research in this area.

The Swedish Agricultural University (SLU) have carried out valuable educational work to show children how livestock grazing affects the number and type of plant and animal species that landscapes can support. Such activities demonstrate how losing grazing would lead to habitat loss for many species. There are many opportunities to increase the amount of educational activity of this type in schools and colleges. There is also the potential to carry out similar activities with adults – looking at the impacts of management on ES delivery. The SLU initiative focused on biodiversity, but this could be extended to look at other ES (e.g., water quality, climate regulation and landscape).

5. Assessment of PG innovative management options

The SUPER-G ‘benchmarking and testing’ network included 17 experimental and demonstration platforms (Table 4) located across six biogeographic regions (Atlantic, Continental, Pannonian, Alpine, Boreal, Mediterranean), and at which the most detailed measurements of productivity and ES delivery were carried out using agri-environmental indicators developed in WP2 (Newell Price, 2020). Innovative PG management options such as the use of legumes for improving productivity and mitigating N₂O emissions and dealing with drought as a consequence of climate change; and new technology such as virtual fences in grazing systems and the use of spectral and electromagnetic sensors were tested and assessed with various criteria, from ease-of-use, improved provision of ES to profitability and technology readiness for sustainable PG management.

Results from commercial farms and the experimental platforms were aggregated and reported in detail by Rankin *et al.* (2023). Section 5 provides a synthesis of the main findings. As part of task 3.4, the most relevant PG management options, innovations, and technologies, covering four themes: i) new grassland species, diverse species swards, ii) precision grassland management, iii) nutrient management, and iv) agri-environment options, were assessed based on a set of seven criteria (Buchmann *et al.*, 2024).

The following four overarching themes were assessed: i) new grassland species, diverse species swards, ii) precision grassland management, iii) nutrient management, and iv) agri-environment options. As a next step, a set of seven criteria were used for their assessment, i.e., improved provision of studied ES, potential for provisioning multiple ES, technology readiness level, ease-of-use by farmers, useability for pastures and/or meadows, potential to improve profitability, and relevance and/or transfer beyond local context.

The following **17 management options** were assessed:

i) New grassland species, diverse species swards:

1. Introduction of new grassland species
2. Overseeding with diverse species or mixtures

ii) Precision grassland management:

3. Plate meter, other yield estimation techniques
4. Grazing management tools, rotational grazing
5. Satellite or drone technologies for yield and quality estimation
6. Use of other precision technologies for grazing (e.g., in field weighing / virtual fencing / GPS collars / apps)

iii) Nutrient management:

7. Quantification of nutrient balances
8. Precision nutrient management, variable rate fertiliser application
9. Use of slow-release fertilisers
10. Modelling soil carbon (C) dynamics to increase soil C stocks

Table 4. SUPER-G field experimental and demonstration platforms.

Ecosystem services (ES) investigated: P = food production, B = biodiversity, C = carbon sequestration and greenhouse gas (GHG) mitigation, W = water quality, F = flood control, E = erosion control. Type of agriculture: Con = conventional, Org = organic. Livestock types: S = sheep, D= dairy, B = beef, H = horses, P = pigs, G= goats.

Site	Pedo-climatic region	Country	Lead organ.	Management option(s)	Measurements	ES studied	Type of agriculture	Livestock type
Centre for Sustainable Recultivation (ICSR) Vremščica	Alpine / Mediterranean 800 - 1,000 m a.s.l.	SI	UL	Grazing management. Monitoring sensitivity of grass and livestock to drought. Trialling the use of virtual fences for grazing management.	Grass yield and quality, botanical, species composition, use of innovative sensors, cameras and virtual fencing	P, B, C, W, E	Org. / low input	D, S, H, P
Santa Clotilde	Mediterranean	ES	UCO	Grazing management, fertilisation	Grass yield and quality, water balance and quality, soil quality, animal behaviour (telemetry)	P, B, C	Org / Low input con / High input con	B, P
MITANET	Continental / Alpine	IT	UNITO	Mowing/Grazing management, irrigation, fertilisation	Grass yield and quality, botanical biodiversity, nutrient balances and components, C sequestration and GHG emissions, quality of livestock products	P, B, C, W	Low input con / High input con	D, B

Site	Pedo-climatic region	Country	Lead organ.	Management option(s)	Measurements	ES studied	Type of agriculture	Livestock type
Cows and Opportunities in combination with KTC De Marke	Atlantic	NL	WR	Sustainable nutrient use, testing ANCA (annual nutrient cycling assessment) and a new farm water use assessment tool	Sustainable farming with low losses and relative high input (focus on nutrient use efficiency) 16 farms	P, C, W	Con / High input, high efficiency	D
Ossekampen Grassland Experiment	Atlantic	NL	WR	Long term (60 years) fertilisation and utilisation (cutting vs grazing) experiment	Species composition, soil fertility, DM production ; changes in time and interactions	P, B, C	Con	S
Ecology of Dutch grassland species	Atlantic	NL	WR	Relations between soil fertility, fertilisation, water management, utilisation and species composition of permanent grasslands before intensification started	Extensive survey of Dutch grasslands between 1940 -1960	P, B	Data base	D, S
Chamau	Alpine region (at 400 m a.s.l.)	CH	ETH Zurich	Intensive meadow	GHG flux measurements, grass yield and quality. Experiment to test for N ₂ O mitigation strategies	P, B, C	Con	S, D

Site	Pedo-climatic region	Country	Lead organ.	Management option(s)	Measurements	ES studied	Type of agriculture	Livestock type
Früebüel	Alpine region (at 1000 m a.s.l.)	CH	ETH Zurich	Medium intensive meadow	Grass yield and quality, GHG flux measurements, sward productivity	P, B, C	Con	S, D
Alp Weissenstein	Alpine region (2000 m a.s.l.)	CH	ETH Zurich	Extensive pasture	Grass yield and quality, GHG flux measurements.	P, B, C	Con	S, D
Rellehausen	Atlantic / Continental	DE	UGOE	Cattle grazing experiment three intensities of continuous stocking and permanent grassland under cutting/simulated grazing.	Cattle grazing experiment established 2002 (FORBIOBEN project): botanical and animal biodiversity, grass yield and quality, livestock productivity, soil fertility and quality, animal behaviour/telemetry, remote sensing	P, B, C	Con / low input Con / high input	S, B
La Blanche Maison	Atlantic West	FR	LBM	Rational pasture system applied to dairy cows, beef cattle, calves and heifers. Testing methods for the renovation of degraded grasslands.	Monitoring of cost and products, carbon storage, water quality, nutrient cycling, biodiversity, soil quality	P, B, C	Con	D

Site	Pedo-climatic region	Country	Lead organ.	Management option(s)	Measurements	ES studied	Type of agriculture	Livestock type
Cockle Park (including the Palace Leas hay meadow plots)	Atlantic	UK (England)	UNEW	Grassland management (e.g., sward plant species diversity, compaction alleviation, timing of mowing / grazing, fertiliser rate)	Grass yield and quality, pollinators, soil macro-invertebrates (e.g., earthworms), water infiltration, C-sequestration	P, B, F, C	Low input con / High input con	D, B
Hillsborough Precision Grazing Platform	Atlantic	UK (Northern Ireland)	AFBI	150-hectare integrated precision grazing platform (including cutting and grazing) for dairy, beef and sheep production, Evaluating methods for sustainable production of milk and meat from grassland and the role of precision technology in managing soil, nutrients, plants and animals	High frequency data collection for: grass yield and quality animal grazing behaviour and location, animal performance from pasture, nutrient transfer, GHG emissions and botanical biodiversity	P, B, C, W	Con	D, B, S
Skierniewice near Warsaw	Continental (Lowland)	PL	UWA	Long term fertilisation trials, crop rotation and nitrogen balance	Botanical composition, soil nutrient status and Quality, C-sequestration	P, B, C	Con / field experiment	D, B
The educational research centre	Continental (470 m a.s.l.)	SI	UL	Mowing / grazing management for suckler cows with calves or	Grass yield and quality, botanical species composition, livestock	P, B, C, W, E	Con / filed experiment	B

Site	Pedo-climatic region	Country	Lead organ.	Management option(s)	Measurements	ES studied	Type of agriculture	Livestock type
(PRC) Logatec				heifers. Nutrient management (application of organic manure or mineral fertiliser), Monitoring of grassland sensitivity to drought (heat stress of both grass and livestock)	productivity, soil nutrient status and quality. Animal health and welfare (with use of sensors cameras and drones)			
Forage Research Station, Moravian Uplands	Continental / Pannonian	CZ	MENDU	Grazing management, fertilisation, species mixes, over-seeding methods	Grass yield and quality, water balance and flows	P, W, F, E	Con & Org	D, B
Durmitor	Alpine region (1,300 – 1,700 m a.s.l.)	ME	UOM	Extensive pasture	Livestock productivity, forage quality, forage yield and DM production, soil nutrient status and quality	P, B, C	Low input Con	S, B

iv) Agri-environment options:

11. Agroforestry, promotion of tree establishment and growth
12. Grazing management and other management strategies for productivity, biodiversity and other public goods
13. Cutting management and other management strategies for productivity, biodiversity and other public goods
14. New livestock breeds for PG and/or ES
15. Increasing legume cover to reduce mineral N fertiliser and decrease N₂O emissions
16. Mechanical loosening for improved drainage and productivity
17. Use of locally harvested seeds for re-vegetation

The following set of **seven criteria** and assessment levels were used by WP3 contributors:

1. Improved provision of studied ES (yes, no)
2. Potential for provisioning of multiple ES (yes, no)
3. Technology readiness level (TRL 7 — System prototype demonstration in an operational environment, 8 — System complete and qualified, 9 — Actual system proven in an operational environment)
4. Ease-of-use by farmers (low, medium, high)
5. Useability for pastures and/or meadows (pasture, meadow, both PG types)
6. Potential to improve profitability (low, medium, high)
7. Relevance/transfer ability beyond local context (yes, no)

All 17 management options were assessed based on the seven criteria (Table 5).

All options were ranked as being relevant for transfer to other regions, and most of them were seen as applicable to both pastures and meadows. Many options improved the delivery of multiple ecosystem services. However, some options only improved the ecosystem service under study. For example, using plate meters or other yield estimation techniques, such as drones and satellites, were limited to yield estimates, and did not provide further advantages. Technology readiness levels for all options were typically ranked high (TRL 8, i.e., system complete and qualified; TRL 9, i.e., actual system proven in an operational environment), but techniques linked exclusively to drones and satellites or modelling were ranked lower (TRL7, i.e., system prototype demonstration in an operational environment). This was reflected in the assessment that most of the options were easy to use by the farmers, except drone and satellite technologies or modelling. In addition, precision nutrient management, variable rate fertiliser application and precision grazing management were rated lower, highlighting the need for knowledge transfer from science to practice. The potential to improve profitability was rated medium to high for about 70% of all options. About 40% of the options were considered highly profitable (including use of plate meters, grazing management tools, rotational grazing, quantification of nutrient balances, precision grazing, and the use of legumes). Three options (modelling, agroforestry, and use of locally collected seeds) were considered to have low potential to improve profitability. This suggests there is a need to improve knowledge exchange, demonstration activities and technical and financial support for these options in order to increase adoption by farmers.

The ratings are synthesised in Table 6 and show differences in the assessment of the different management interventions. Options within the theme new grassland species / diverse species swards as well as agri-environment options were rated the most promising, i.e., (i) introduction of new grassland species; and (ii) overseeding with diverse species or mixtures. Other options that had the highest rating were (iii) increasing legume cover to reduce mineral N fertiliser and decrease N₂O emissions; (iv) mechanical loosening for improved drainage; (v) productivity and quantification of nutrient balances; and (vi) use of other precision technologies for grazing (e.g., in field weighing / virtual fencing / GPS collars / apps). Other promising options included (i) agroforestry, promotion of tree establishment and growth; (ii) grazing management tools/rotational grazing; and (iii) grazing or cutting management and other management strategies for productivity, biodiversity and other public goods.

Table 6. Identification of the most promising permanent grassland management options. The following colour coding was used: dark green represents the most promising options, followed by light green and yellow. The least promising options and technologies are in orange.

	Innovative management options and new technologies	Most promising
	<i>i) new grassland species / diverse species swards:</i>	
1	• Introduction of new grassland species	Dark Green
2	• Overseeding with diverse species or mixtures	Dark Green
	<i>ii) precision grassland management:</i>	
3	• Platometer, other yield estimation techniques	Yellow
4	• Grazing management tools, rotational grazing	Light Green
5	• Satellite or drone technologies for yield and quality estimation	Orange
6	• Use of other precision technologies for grazing (e.g., in field weighing / virtual fencing / GPS collars / apps)	Dark Green
	<i>iii) nutrient management:</i>	
7	• Quantification of nutrient balances	Dark Green
8	• Precision nutrient management, variable rate fertiliser application	Light Green
9	• Use of slow-release fertilisers	Yellow
10	• Modeling soil carbon (C) dynamics to increase soil C stocks	Orange
	<i>iv) agri-environment options:</i>	
11	• Agroforestry, promotion of tree establishment and growth	Light Green
12	• Grazing management and other management strategies for productivity, biodiversity and other public goods	Light Green
13	• Cutting management and other management strategies for productivity, biodiversity and other public goods	Light Green
14	• New livestock breeds for PG / ES	Yellow
15	• Increasing legume cover to reduce mineral N fertiliser and decrease N ₂ O emissions	Dark Green
16	• Mechanical loosening for improved drainage and productivity	Dark Green
17	• Use of locally harvested seeds for re-vegetation	Light Green

Options within the themes precision grassland management and nutrient management generally had lower ratings, in particular plate metering; other yield estimation techniques; use of slow-release fertilisers; new livestock breeds for PG / ES; satellite or drone technologies for yield and quality estimation; and modelling soil carbon (C) dynamics to increase soil C stocks. This suggests that increased uptake of some options will require further proof of concept, clear

cost-benefit analyses, and both technical and financial support to farmers before being adopted. In addition, factors such as political boundary conditions, socio-economics and the risk attitude of farmers can limit the adoption of scientifically proven, reliable management techniques (Hofmann et al., 2022). When agri-environmental policies support certain management options, or when innovators successfully implement new technologies and are successful, their adoption is likely to be higher (see also outcomes of WP4). When risks for farmers increase, e.g., losing yields due to climatic extreme events, more diverse swards are already and are likely to become more attractive. Understanding the barriers to adoption can be just as important as collecting and providing new scientific evidence for existing knowledge gaps.

CONCLUSIONS

Based on the seven criteria, a wide range of innovative PG management options were assessed, and a clear picture emerged. Options within the theme new grassland species / diverse species swards as well as agri-environment options were rated the most promising, while options within the themes precision grassland management and nutrient management generally had lower and less consistent ratings. This suggests that increased uptake of some options will require further proof of concept, clear cost-benefit analyses, and both technical and financial support to farmers before being adopted. There is a need for policymakers in different areas (agriculture, environment, economy) to develop increased incentives towards sustainable grassland use, e.g., through the implementation of national policies such as Common Agricultural Policy (CAP) Strategic Plans, considering the systems approach necessary to increase provisioning of ES from PG across Europe. Researchers need to complement such activities with co-designed research, as well as open and FAIR data sharing. All these aspects are prerequisites to increase adoption of innovative, sustainable management options and tools in the future.

6. Modelling selected indicators for ES from farm data on PG characteristics and management

Monitoring and measuring changes in agri-environmental indicators at field and farm scales provides invaluable information on how different management productions impact the sustainability of production. However, investigating relationships between farm characteristics and indicators can provide additional insight into the relationships between production, abiotic and biotic factors or metrics and overall environmental impact. In SUPER-G task 3.5, Conijn (2024) used farm data from the task 3.1 2019 survey of 352 farms to investigate correlations between various farm characteristics and permanent grassland (PG) management variables on specialised dairy farms in Europe. The correlations were assessed through linear regression and their equations were combined in a synthesis model, with PG rental charge and farm size (in hectares of Utilised Agricultural Area - UAA) as external inputs. The model illustrates how variables are connected and how they determine a number of farm characteristics, PG management and (through the use of agri-environmental indicators) the delivery of ecosystem service (ES).

There were significant positive correlations between typical PG rental charge (euros/ha) and annual milk income (euros/ha; Figure 4); and milk production (kg/ha). The latter was also positively correlated with stocking rate (dairy cows/ha UAA), milk production per cow, purchased feed (t/ha), PG grass production (t/ha) and manufactured N fertiliser application rate (kg N/ha).

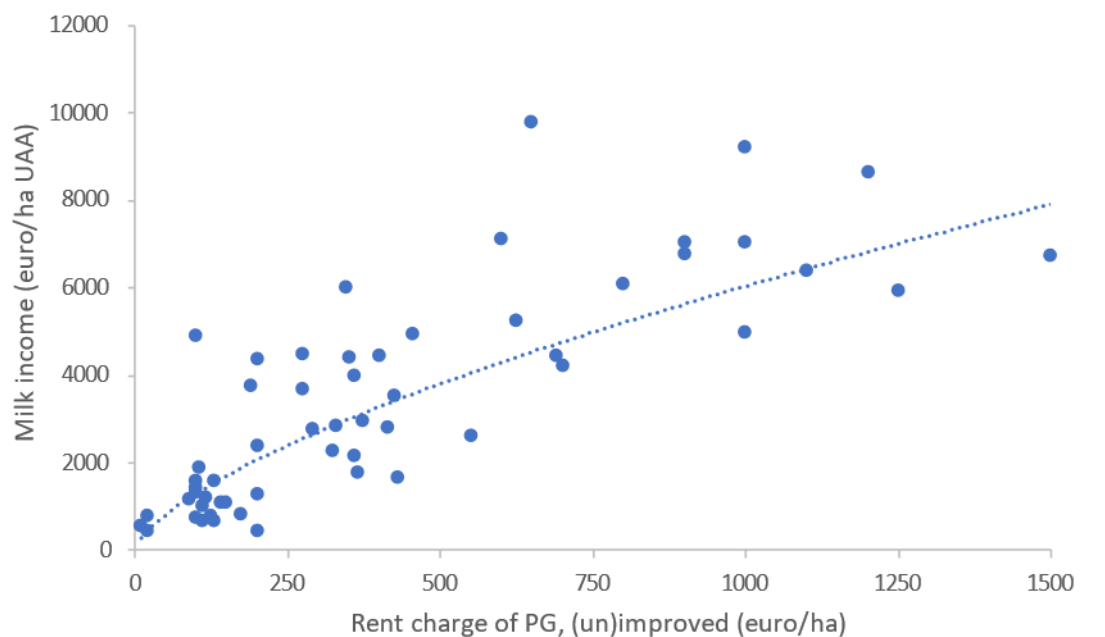


Figure 5. Correlation between annual milk income (y) and typical rent charge (x) on specialised dairy farms from the 2019 survey.

Regression equation ($R^2 = 0.68$; $n=56$):

$$y = 61.3 * (x)^{0.665} \tag{1}$$

PG grass yield (t dry matter (DM)/ha/yr) and milk production (kg/ha/yr) explained 47% of the variation in manufactured N fertiliser rate (kg N/ha/yr), while at farm level, PG grass production (t DM/farm/yr) and purchased feed (t fresh weight/farm/yr) explained 84% of the variation in milk production (kg/farm/yr). Manufactured N fertiliser rate was negatively correlated with the number of plant species on improved PG, with an average decline of 2.1 plant species per 100 kg N fertiliser applied (Figure 6); a result that is comparable to that of Francksen *et al.*, (2022) who in an analysis of controlled experiments with different N rates found an average decline of 1.5 species per 100 kg N/ha applied.

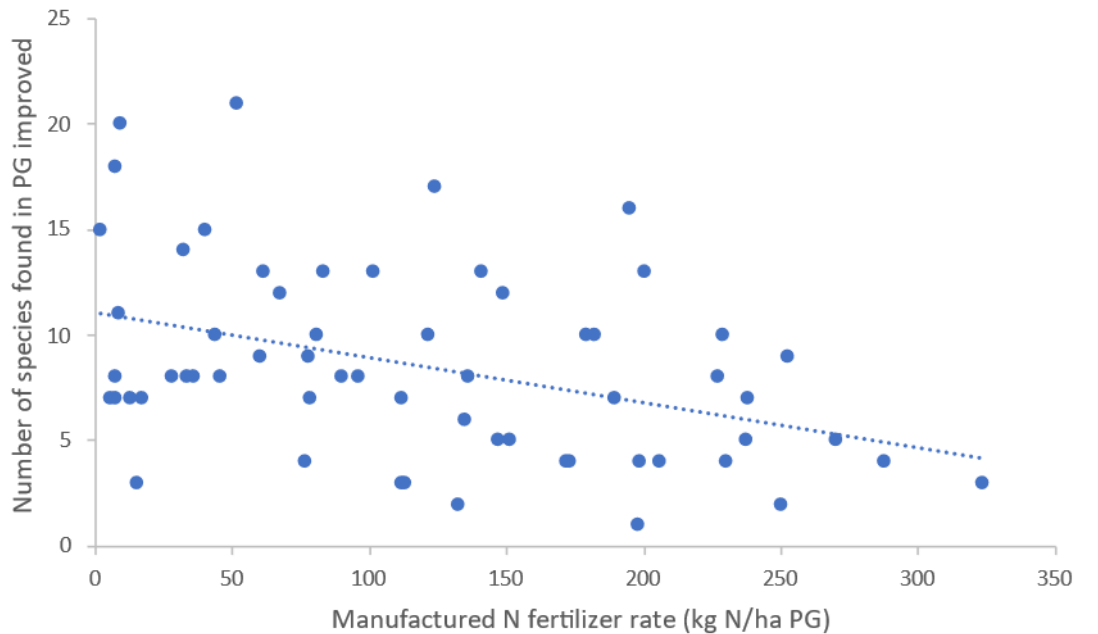


Figure 6. Correlation between number of plant species found in PG improved (y) and the annual application of manufactured N fertiliser on PG improved (x) on specialised dairy farms from the 2019 survey.

Regression equation ($R^2 = 0.16$; $n=61$):

$$y = -0.0214 * x + 11.1 \quad (12)$$

The main activity of a specialised dairy farm is the conversion of feed into milk, with varying proportions of home-grown grass and imported feed. At a given level of milk production, the required feed can either be produced at the farm or can be imported from outside the farm. Related to this, another interesting finding was that the ratio between the amount (kg/yr) of purchased feed per farm and PG grass production (kg DM/yr) per farm (viz. imported feed divided by PG grass; kg/kg) was reasonably correlated with milk production intensity per ha (Figure 7). This correlation illustrates that for higher milk production per ha, generally more feed is imported relative to the on-farm PG grass dry matter production, which could be explained by the limitations of producing grass per ha and the higher total feed requirement when more milk is produced per ha.

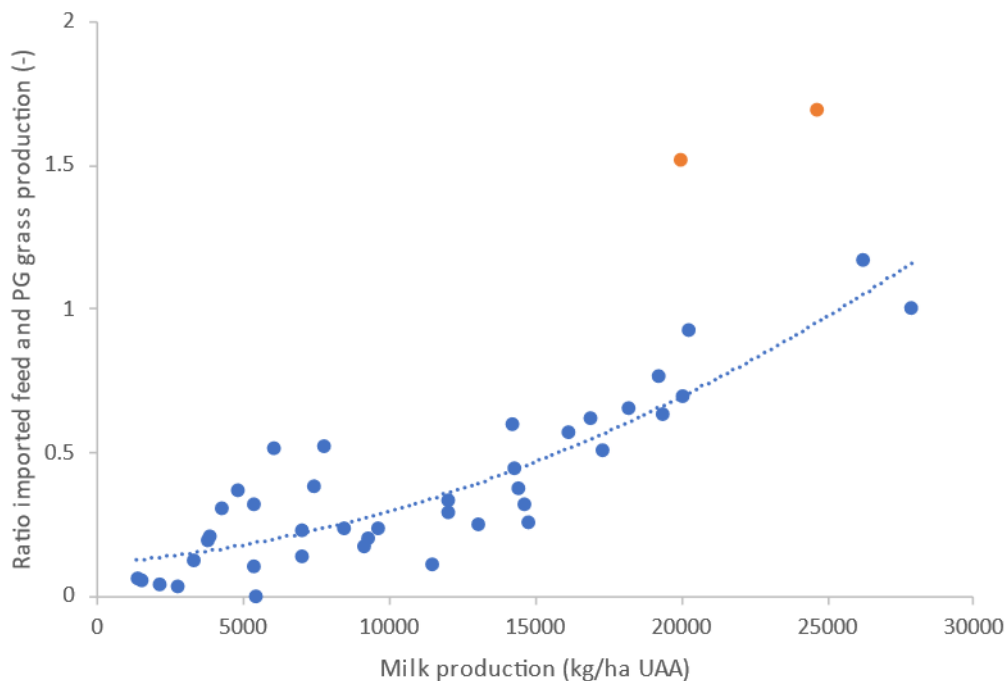


Figure 7. Correlation between the ratio (y) of imported feed per farm and grass produced from PG per farm and annual milk production per ha (x) on specialised dairy farms from the 2019 survey.

Regression equation ($R^2 = 0.78$; $n=40$, excluding the two orange data points):

$$y = 1.35 \cdot 10^{-9} \cdot x^2 + 0.153$$

The equations derived from the various correlations were combined in a synthesis model with PG rental charge (euros/ha) and farm size (ha of UAA) as external inputs. The resulting synthesis model illustrates how variables are connected and how they determine a number of farm characteristics and aspects of PG management. It was also used to calculate indicators of ecosystem service (ES) delivery and demonstrates the dependency of milk production intensity (per ha) on the ‘typical rent charge of PG in the area’ via correlations with milk income, dairy cow stocking rate and milk production per cow.

The model correlations highlighted how milk production was dependent on a combination of imported (purchased) feed and on-farm grass production from PG. These two feed sources are partly exchangeable, but purchased feed was clearly more important relative to on-farm PG grass production in terms of its influence on milk production per ha. While forage efficiency (kg milk per kg feed) showed a positive relation with milk production intensity, this was not the case for fertiliser efficiency (kg grass DM from PG per kg manufactured N applied – at the farm level) for most of the specialised dairy farms.

For biodiversity, more grass (i.e. dry matter production) from PG on the farm correlated with more manufactured N fertiliser use, which had a negative effect on PG plant species diversity. For climate regulation, the principal indicator was the ruminants stocking rate and this was shown to be a function of PG rental charge (Figure 8).

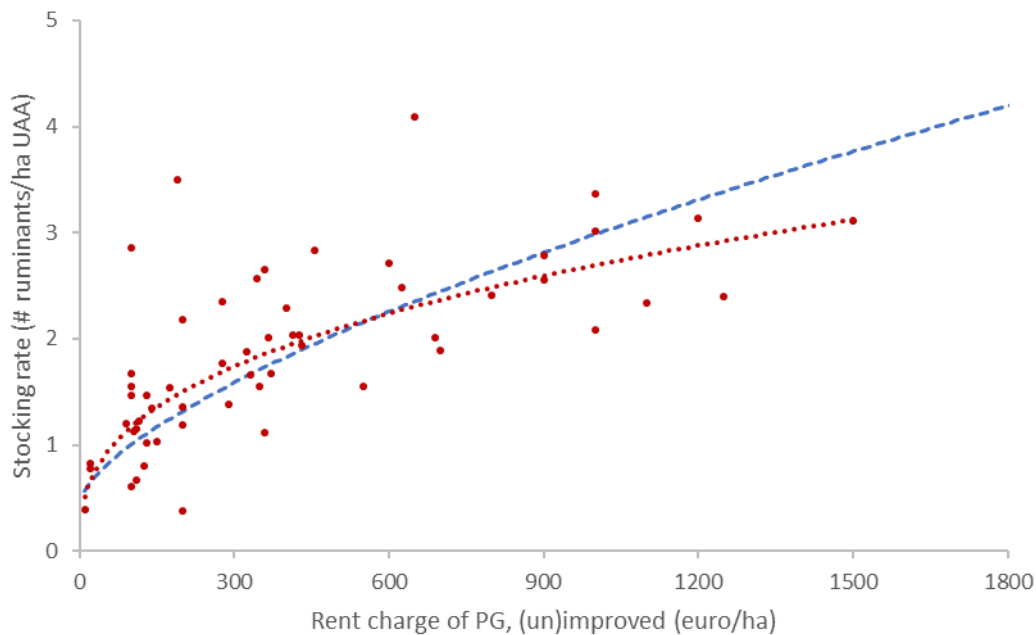


Figure 8. Stocking rate of total ruminants (in LU) as a function of PG rent charge. Red dots are data points from the survey. The red dotted line results from a linear regression applied directly to the data and the blue dotted line was calculated by multiplying the calculated stocking rate of milking cows by the average ratio of total ruminants (in LU) relative to milking cows (i.e., 1.437).

The correlations derived from the data are spatial i.e. explaining part of the variation among farms at different locations in Europe, and may not necessarily represent causal relations between variables. Causal relations are necessary to predict how farms will change e.g. if their production costs decline or their revenues increase. Nevertheless, the model can be used to gain some insight into the general nature of the interlinkages between external drivers, farm structure, PG management and some related ES on specialised dairy farms in Europe.

The correlations are logical and combine economic considerations with limitations due to natural constraints in PG grass productivity (per ha) and milk productivity (per cow). Higher costs need higher revenues and therefore higher income from milk on specialised dairy farms. Higher milk income directly links with higher milk production, while this milk production can be obtained both via higher dairy cow stocking rates and higher milk production per cow. Producing milk requires feed and the two investigated sources were purchased feed and grass from PG. So, milk production is positively correlated with purchased feed and PG produced grass. More grass from PG generally needs greater nitrogen supply to produce the grass, which partly translates into higher manufactured N fertiliser rates. Finally, higher N fertiliser rates generally correspond with fewer plant species in the sward and thus correlate with lower plant species diversity.

The analysis also shows how different aspects of the farm business are correlated. A farmer can buy feed or produce feed (grass and forage crops grown on farm), and these are in part exchangeable. Buying (more) feed and relying less on farm-produced feed may require less manufactured N fertiliser input to the farm, which may 'allow' greater plant species diversity on the PG of the farm. However, this combination of higher feed purchase and lower fertiliser application is not likely according to the correlations, and purchasing more feed seems not the

best option for supporting biodiversity at a national or global scale (Chaudhary & Kastner, 2016; Jaureguiberry et al., 2022). However, overall impacts depend on the consequences of the purchased feed in the location where it was produced (Chaudhary & Kastner, 2016). Such external impacts of purchased livestock feed need to be included for a comprehensive analysis, but this was outside the scope of this project.

In the synthesis model, PG rental charge acts as a driving variable that determines the outcomes, such as milk production intensity per ha, amount of purchased feed per ha, PG productivity and PG plant species diversity. To provide more 'space' for ES other than food production, either the costs need to decrease or additional revenues, besides the income from selling milk, need to be found. These could come from adding value to the milk by producing products (e.g. yoghurt, cheese or ice cream) with a higher margin; by diversification of the farm business (e.g. via additional income from tourism); or by payments for specific ES other than food production.

Interestingly, forage efficiency (kg milk per kg feed) but not fertiliser efficiency (kg grass DM per kg manufactured N fertiliser applied - at the farm level), was found to correlate positively with milk production per hectare. Generally, farms with higher milk production per ha also had higher forage efficiencies, thus using less feed, imported and PG grass, per kg milk. This could be related to a number of causes, such as the nutritive value of the feed (higher quality in farms with higher milk production levels) or the genetic variety of the milking cow (higher feed conversion by milking cows in farms with higher milk production levels), although these could not be analysed using the survey data. However, greater forage efficiency does not necessarily result in greater sustainability or lower environmental impact, as indicated by Jevons paradox (Polimeni et al., 2009), which suggests that if milk production is unconstrained the opposite may be true.

In the case of manufactured N fertiliser efficiency, a number of low productivity dairy farms had very high efficiency values, related to relatively (very) low manufactured N fertiliser application rates. This indicates a situation where other N sources are important, such as high clover cover in the PG sward and the efficient use of organic manures. Low manufactured N fertiliser use for producing milk has environmental advantages (e.g. lower GHG emissions and higher plant species diversity), but if correlated with low productivity levels, it also has the disadvantage of using more land per kg milk, or producing less milk overall. This illustrates a trade-off between delivering multifunctionality from grasslands (Schils et al., 2022) and meeting the demand for meat and milk along with the environmental costs or externalities associated with this. For a comprehensive analysis of food (specifically meat and milk) production versus environmental impact (or multifunctionality), total land use should be taken into account, which includes the land that was used for the production of purchased feed.

7. Road testing

Innovations identified at co-innovation workshops and tested on commercial farms and experimental platforms were 'road tested' on other commercial farms across six biogeographic regions. The focus was on investigating the practical implementation of PG management options and the opportunity to discuss experiences with other farmers through facilitated, per-to-peer learning. These farms also functioned as demonstration farms, with at least one open (demonstration) day organised on each farm.

The following PG management options and innovative practices were tested or demonstrated on commercial farms within the 23 SUPER-G farm networks:

- Integrating legumes (e.g. white clover) into grass dominated PG swards
- Investigating various timings through the summer for the establishment of multi-species swards.
- Introducing rotational grazing systems to improve productivity, grass utilisation and the delivery of other ES (e.g. pollination)
- Demonstrating and validating the use of canopy sensing to monitor grass growth and quality
- Using a variety of seed mixes including deep-rooting herbs and legumes to investigate the potential to increase productivity in low- to medium-intensity systems and tolerate drought and/or waterlogged conditions
- Testing virtual fencing for more flexible grazing management
- The use of GPS collars to monitor livestock grazing locations and behaviour
- Managing permanent grasslands within agri-environment schemes for biodiversity
- Combining robotic and mobile milking with grazing
- Providing enhanced pollination from permanent grasslands within arable landscapes

It was clear from the road-testing activities that for many farmers, understanding the costs and practicalities of implementing new management options and how they relate to agri-environment payments for specific actions was vital to their decision making. Demonstration days enable discussion and the creation of new social norms, which with a sufficient level of technical and financial support relative to the specific measure to be adopted, can result in widespread uptake.

8. Discussion and conclusions

The SUPER-G project has used the following definition of permanent grassland (PG): “any land dominated by grasses or herbaceous forage that can be grazed/mown and has not been included in the crop rotation of a holding for five years or more”. This definition was prevalent in the early 2000s (e.g. EU, 2004) and has been adapted in subsequent years by the European Commission to include consideration of a limited percentage of shrub and tree cover on land dominated by grasses, legumes and herbs. In most cases, the principal use of land that meets these definitions is for grazing by livestock, cutting for livestock forage or a combination of the two. New grassland-based business opportunities are being developed such as the extraction of protein concentrates or production of paper from grass, but the main economic activity currently relates to the production of meat, milk, wool and related products.

The above uses of PG in many circumstances relate to or result from the limitations of the land in terms of its versatility (i.e. ability to grow a range of crops), capability (which crops it is possible to grow economically) and productivity (yield potential relative to energy and material input). Rearing livestock on PG allows food production from land that in many cases is limited to growing plant material (i.e. grasses) that cannot be consumed by humans. This concerns a significant proportion of the utilised agricultural area in Europe (c. 30%), which is limited by a combination of soil, climate and geography that makes the land too steep or remote, or the soils and climate too stony, cold, wet, dry or hot to grow arable or horticultural crops commercially. These limitations therefore present challenges to those managing the land alongside socio-economic challenges such as the length of tenancies and the cost base of production, including land rental charges (Klopčič et al., 2020).

Farmers have adapted to the challenges of managing PG-dominated farming systems and have developed approaches and farming practices that have responded to societal demands. In the second half of the 20th century, this involved a move towards increasing reliance on manufactured fertilisers to drive production on many farms with higher production potential (i.e. with a good to very good growth class, mainly in the Atlantic region; e.g. Green, 1990). On farms with lower production potential, modern practices such as fertiliser use and earlier cutting have been introduced on the better land while more ‘traditional’ practices have been retained on unimproved PG (Hejcman et al., 2013). In any case, the number of farming practices that can be adapted on PG is limited by the fact that cultivation on such land is often challenging (Table 7).

The SUPER-G co-innovation workshops were an opportunity for farmers and advisers to discuss new ways of managing PG (Klopčič et al., 2020). A variety of approaches were proposed, and the majority of farmers focused on their need to better understand how to use the basic materials and methods at their disposal to improve PG management. Farming practices such as liming, nutrient management, manure management, overseeding, grazing and cutting generally received more interest than new technologies such as remote sensing and virtual fencing. Nevertheless, a number of opportunities were identified for further investigation through trials, demonstrations and experiments.

In general terms, on unimproved PG (i.e. land with greatest limitations and lower capability), the main opportunities for improving productivity and the delivery of a range of ES related to grazing strategies and the use of livestock breeds adapted to the conditions.

Table 7. PG management options

Management practice	Options
Use	Haymaking; silage; grazing; pollination; honey; edible plants; bioenergy-biofuel; none
Cuttings/grazings per year	1; 2; 3; 4-5; >5
Exploitation seasons	Winter; summer; autumn + spring; spring + summer + autumn; all year round
Grazing species	Cattle; sheep; goats; horses; deer; buffalo; reindeer; pigs; poultry; wild herbivores; mixed; none
Grazing pressure	Low (<0.3 LU/ha/y); medium (0.3-1.2 LU/ha/y); high (1.3-2 LU/ha/y); very high (>2 LU/ha/y); none
Grazing practice	Continuous extensive (free roaming); rotational; continuous intensive; shepherded; none
Grazing interval	Short (<21 days); medium (21-35 days); long (> 35 days)
Frequency of livestock movement	Every day; every 2-5 days; every 5-14 days; > every 14 days; not moved
Overseeding	Regular (every 3-4 years); periodical (every 4-8 years); occasional (about every 8-12 years); rare; none
Lime use	Yes; no
Fertiliser type	Manufactured fertiliser; livestock slurry; farmyard manure; poultry manure; other organic manures
Fertiliser frequency	Occasional; regular (once a year); frequent (more than once a year); none
Manure spreading	Surface broadcast, trailing hose; trailing shoe; injected
Irrigation type	Sprinkler; flooding; fertigation
Irrigation frequency	Occasional (droughts); regular; none
Harrowing	Occasional; regular (every year); none

There is potential for grazing strategies to be supported by the use of virtual fencing and GPS collars, but these currently require technical and financial support to be viable on most commercial farms (Rankin et al., 2023). To be justified economically and environmentally, new technologies either need to reduce overall costs or increase production without increasing externalities (i.e. overall environmental impact). New technologies that increase costs therefore need to result in higher grass yields or improved livestock health and productivity, resulting in greater meat or milk production per livestock unit. However, if the technology results in greater provision of ES, they need to be supported by agri-environmental payments, as well as technical advice to encourage and enable uptake.

On improved PG (i.e. land that is either cultivable or at least has good production potential and has been improved through the use of lime, reseeded, manufactured fertilisers and/or organic manures), the same opportunities are available alongside various cutting strategies (to improve grass quality, optimise grass growth and support pollinators); reseeded or overseeded to introduce legumes and herbs; improved nutrient management; better use of organic manures; use of platimeters to monitor grass growth; and integration of trees (i.e. silvopasture). To achieve multifunctionality (i.e., the provision of multiple ES), the carrying capacity and natural productive potential of the land need to be factored into management strategies. Greater attention to breeds (that thrive on PG), sward botanical composition, and grazing and cutting strategies; and less reliance on inputs can help optimise production and reduce environmental impacts.

Finally, it is important to consider the factors that have driven innovation in the past and that may have led to increased meat and milk production at the expense of sustainability. The requirement to innovate and increase both production and productivity has been driven by land rental charge, fluctuations in commodity prices and input cost increases. Data from specialist dairy farms indicated how production levels related to PG rental charge, manufactured fertiliser application rates and the proportion of purchased feed in the diet of high genetic merit dairy cows (Conijn, 2024). A high cost base and an embedded growth obligation has to some extent driven the need to increase milk production, fertiliser use and the proportion of purchased feed in dairy cow diets, resulting in increasing overall environmental impacts or externalities. Yet grazed grass is still the cheapest form of ruminant livestock feed, and with a focus on breeds that can optimise milk and meat output from grass; sward composition that can not only fix nitrogen from the atmosphere but also has greater tolerance of drought and waterlogged conditions; and reduced reliance on manufactured fertiliser to lower the cost base, a more resilient system that delivers multifunctionality can be achieved. This may require technical and financial support from government, but it would allow PG to perform an enabling role within the agri-food system to not only help feed 742 million people in Europe (449 million in the European Union), but help engender a food system capable of feeding a growing global population of over 8 billion people.

PG managed and used to deliver multifunctionality can provide meat, milk and other grass-derived products; pollinators (to support arable and horticultural crop production); natural predators (to reduce the need for pesticides); and habitats (to support biodiversity, including many valued and threatened species). It also has an important role to play in regulating water flows; protecting soils from erosion; providing clean water; and conserving vital carbon stores. In addition, some PG can sequester additional carbon, although rates are slow, some grasslands are already carbon-saturated, C sequestration is easily reversible and total amounts are limited.

9. References

Buchmann N., Bufe C., Hejduk S., Hiron M., Janicka M., Oenema J., Rankin J., Vanwalleghem T., Klopčič M., Newell Price P. (2024). SUPER-G, Deliverable report 3.7 on Assessment of innovative permanent grassland management options. EC Project Number 774124-2, 19 pages.

Chaudhary, A. and Kastner, T. (2016). Land use biodiversity impacts embodied in international food trade. *Global Environmental Change* 38, 195-204, ISSN 0959-3780, <https://doi.org/10.1016/j.gloenvcha.2016.03.013>

Conijn S. (2024). Modelling selected ecosystem service indicators from farm and permanent grassland management data. Deliverable 3.8 of the SUPER-G project.

EU (2004). Commission Regulation (EC) No 796/2004 of 21 April 2004 laying down detailed rules for the implementation of cross-compliance, modulation and the integrated administration and control system provided for in of Council Regulation (EC) No 1782/2003 establishing common rules for direct support schemes under the common agricultural policy and establishing certain support schemes for farmers.

European Communities (2000). Farm Structure historical results- surveys from 1966/67 to 1997. Final version October 2000. Luxembourg Office for Official Publications of the European Communities. Downloaded 7 May 2021.

<https://ec.europa.eu/eurostat/documents/3217494/5625659/KS-27-00-742-EN.PDF/9e30d9ac-56d9-4e5a-86cf-2dc5474cd6d8>

Eurostat (2017). Permanent grassland: number of farms and areas by agricultural size of farm (UAA) and size of permanent grassland area. Online data code EF_POGRASS. Accessed on 18 February 2021.

https://ec.europa.eu/eurostat/databrowser/view/EF_POGRASS/default/table?lang=en

Eurostat (2023) Agri-environmental indicator – cropping patterns:

https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_cropping_patterns

Francksen R.M., Turnbull S., Rhymer C.M., Hiron M., Bufe C., Klaus V.H., Newell Price, J.P., Stewart G. and Whittingham, M.J. (2022). The Effects of Nitrogen Fertilisation on Plant Species Richness in European Permanent Grasslands: A Systematic Review and Meta-Analysis. *Agronomy* 12, 2928. <https://doi.org/10.3390/agronomy12122928>

Green B.H. (1990). Agricultural intensification and the loss of habitat, species and amenity in British grasslands: a review of historical change and assessment of future prospects†. *Grass and Forage Science* 45, 365-372.

Hejzman M., Hejzmanová P., Pavlů V., Beneš J. (2013). Origin and history of grasslands in Central Europe – a review. *Grass and Forage Science* 68, 345-363.

Hofmann B., Ingold K., Stamm C., Ammann P., Eggen R.I.L., Finger R., Fuhrmann S., Lienert J., Mark J., McCallum C., Probst-Hensch N., Reber U., Tamm L., Wiget M., Winkler M.S., Zachmann

L. and Hoffmann S. (2022). Barriers to evidence use for sustainability: Insights from pesticide policy and practice. *Ambio* 52, 425–439

Jaureguiberry, P. *et al.* (2022). The direct drivers of recent global anthropogenic biodiversity loss. *Science Advances* 8 (45). <https://www.science.org/doi/10.1126/sciadv.abm9982>

Klopčič M., Lively F., Buchmann N., Tonn B., Cvirn M., Sacco D. ... and Newell Price, P. (2020). Report on co-innovation farm workshops to identify existing and innovative approaches and technologies for testing. Deliverable 3.4 of the SUPER-G project.

Mulvenna C., Smooth K., Lively F., Rankin J. and Newell Price, J.P. (2021). Overview of data, key gaps, and trends in PG management in the different biogeographic regions. Deliverable 3.2 of the SUPER-G project.

Newell Price J.P. (2020). Quantifying ecosystem services on permanent grassland - A short list of agri-environmental indicators. Deliverable 2.2b of the SUPER-G project.

R Core Team, (2020). R: A Language and Environment for Statistical Computing, R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>

Rankin J., Brown S. and Newell-Price P. (2023). SUPER-G, Deliverable report 3.6 on Synergies & Trade-offs. EC Project Number 774124-2, 321 pages.

Schils R.L.M., Bufe C., Rhymer C.M., Francksen R.M., Klaus V.H., Abdalla M., ... and Newell Price J.P. (2022). Permanent grasslands in Europe: Land use change and intensification decrease their multifunctionality. *Agriculture, Ecosystems & Environment* 330, 107891.

Ward S.E., Smart S.M., Quirk H., Tallowin J.R., Mortimer S.R., Shiel R.S., Wilby A., Bardgett R.D. (2016). Legacy effects of grassland management on soil carbon to depth. *Glob. Chang. Biol.* 22, 2929–2938.