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Depleting soil nutrients through frequency and timing of hay cutting on floodplain meadows for habitat restoration and nutrient neutrality

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ABSTRACT

Floodplain meadows support a high level of botanical diversity because the nutrient inputs from flood sediments are balanced by nutrient offtake via an annual hay harvest, leading to nutrient neutrality. This prevents a build-up of nitrogen (N) and phosphorus (P) and depletes excess nutrients, which mitigates eutrophication in catchment areas and prevents reductions of biodiversity through competitive exclusion.

A replicated field trial was undertaken in floodplain meadows in central England, with the aim of comparing the nutrient offtake potential throughout the growing season with a single or a double-cut system, and determining when haymaking should occur to maximise nutrient offtake and nutritional value of the hay. Additionally, farmer perspectives were gathered to investigate the practicality of implementing a second hay cut.

The results revealed that a single summer hay cut may be sufficient to balance nutrient inputs. However, a double-cut, where a second harvest replaces autumn grazing, has the potential to actively lower N and P levels, removing 8.69 g m^{-2} N and 0.80 g m^{-2} P. Maximising time between cuts in a double-cut system provides the greatest opportunity for nutrient removal.

Temperature is a key driver of plant growth. The relationship between accumulated thermal time and calendar date in central England has advanced by around two weeks between 1961–1990 and 1991–2020. Delayed hay cutting under agri-environment scheme restrictions may be increasingly detrimental to botanical diversity with advancing seasons, due to lower nutrient removal under a single-cut system, and increased competitive exclusion. Taking a first cut at the mid-summer peak in offtake potential, currently 20–30 June in central England, and a second cut in the autumn offers an opportunity to deplete excess nutrients. Whilst farmers identify practical and financial concerns that may make a second cut prohibitive in some cases, this could be overcome by, e.g., demonstrating the higher-than-expected nutritional value of hay from a second cut.

1. Introduction

Floodplain meadows are lowland grasslands which are subject to occasional flooding. Known for their nutritious fodder they are cut for hay annually. Traditionally managed floodplain meadows support a species-rich botanical assemblage of up to 40 species per square metre – compared to less than five species in intensively managed pastures. This in turn supports a diversity of invertebrate, bird, mammal and reptile species (Lawson et al., 2018; McGinlay et al., 2016; Rothero et al., 2016). This community type is threatened across Europe by land-use change and agricultural intensification (Prosser et al., 2023). Many of the remaining species-rich floodplain meadows across the European Union are protected under the Habitats Directive (Council Directive 92/43/EEC, 1992).

Across northern Europe, these meadows commonly support a meadow foxtail (*Alopecurus pratensis)* – great burnet *(Sanguisorba officinalis)* grassland community, defined by the UK National Vegetation Classification system as a mesotrophic grassland denoted MG4 (Rodwell, 1992) or European Nature Information System (EUNIS) code 6510, lowland hay meadow (European Environment Agency, 2013). This community is characteristic of moderately fertile permanent lowland meadows.

The main drivers of floristic diversity on floodplain meadows are: (1) hydrological regime (2) soil nutrients and (3) meadow management

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regime (McGinlay et al., 2016). The latter traditionally consists of a midsummer hay cut, followed either by aftermath grazing, usually by cattle (McGinlay et al., 2016, 2017) or a second cut at the end of summer (Bock et al., 2013; Ludewig et al., 2015).

In order for these species-rich meadows to persist they need to be a productive part of our modern agricultural system (Donath et al., 2004). This necessitates producing a valuable crop yield in a way that promotes the resilience of the biodiversity within the meadow, whilst also contributing to improved water quality, flood alleviation, and carbon sequestration (Lawson et al., 2018; Pavlů et al., 2021; Tallowin and Jefferson, 1999).

1.1. Nutrient management and nutrient neutrality

Nitrogen (N) and phosphorus (P) are key plant nutrients that are present in river sediments, with sources including pollution from sewage outlets and runoff from urban, industrial and agricultural land (Gowing et al., 2002; Neal et al., 2010). These nutrient-rich sediments are deposited on floodplain meadows during flood events and provide a source of natural fertility that produces a hay crop without the need for application of mineral fertilizers (Fig. 1).

Eutrophication of rivers and connected wetland systems within the floodplain is a significant concern for these fragile ecosystems (Natural England, 2022). Excess nutrients allow competitive algae and terrestrial plants to dominate, smothering slower growing species and reducing oxygen availability in aquatic systems. N and P are of particular concern in this context and mitigation schemes aim to reduce these nutrients by requiring new developments in at-risk catchments to demonstrate nutrient neutrality through mitigation schemes that will offset any inputs caused by the new development (Planning Advisory Service, 2022; Stevens et al., 2004).

With the right management regime, haymaking on floodplain meadows has the potential to act as a significant and multi-functional mitigation technique that can effectively remove nutrients at a catchment scale whilst also increasing biodiversity and forming a valuable part of a viable nature-friendly farming enterprise. This approach can contribute to the requirement for nutrient neutrality in new developments within sensitive catchments in England and Wales (Natural England, 2022; Natural Resources Wales, 2022), and nutrient management targets under the European Water Framework Directive (Tschikof et al., 2022). These species-rich plant assemblages also offer greater tolerance to drought and flooding than the species-poor communities that often replace them, so they also represent a climate resilient solution (Bobbink and Willems, 1991; French, 2017; Gowing et al., 2010; Silvertown et al., 1994).

1.2. Double-cutting for nutrient reduction

The yield and nutrient content of hay changes as the growing season progresses. In Europe it is common to manage floodplain meadows with two hay cuts each year, one at mid-summer and one in the autumn (Bock et al., 2013). However, in the UK it is now more usual to manage them with aftermath grazing in the autumn following a summer cut, rather than taking a second cut. Whilst grazing does remove some of the nutrients incorporated in livestock body mass, most of it is rapidly redeposited via animal waste. Nutrients in animal excreta take a more mobile form and may be more readily leached back into water courses than if they were still bound up in plant material (Hogg, 1981; Whitehead, 2009). Removal of a second hay crop in the autumn presents a more effective way to reduce available pools of these nutrients from the system when compared to a single summer hay cut, and has been shown to be the most effective treatment for re-establishing highly species-rich, stress-tolerant plant communities on wet meadows (Poptcheva et al., 2009). This nutrient reduction benefits, not only the biodiversity in the

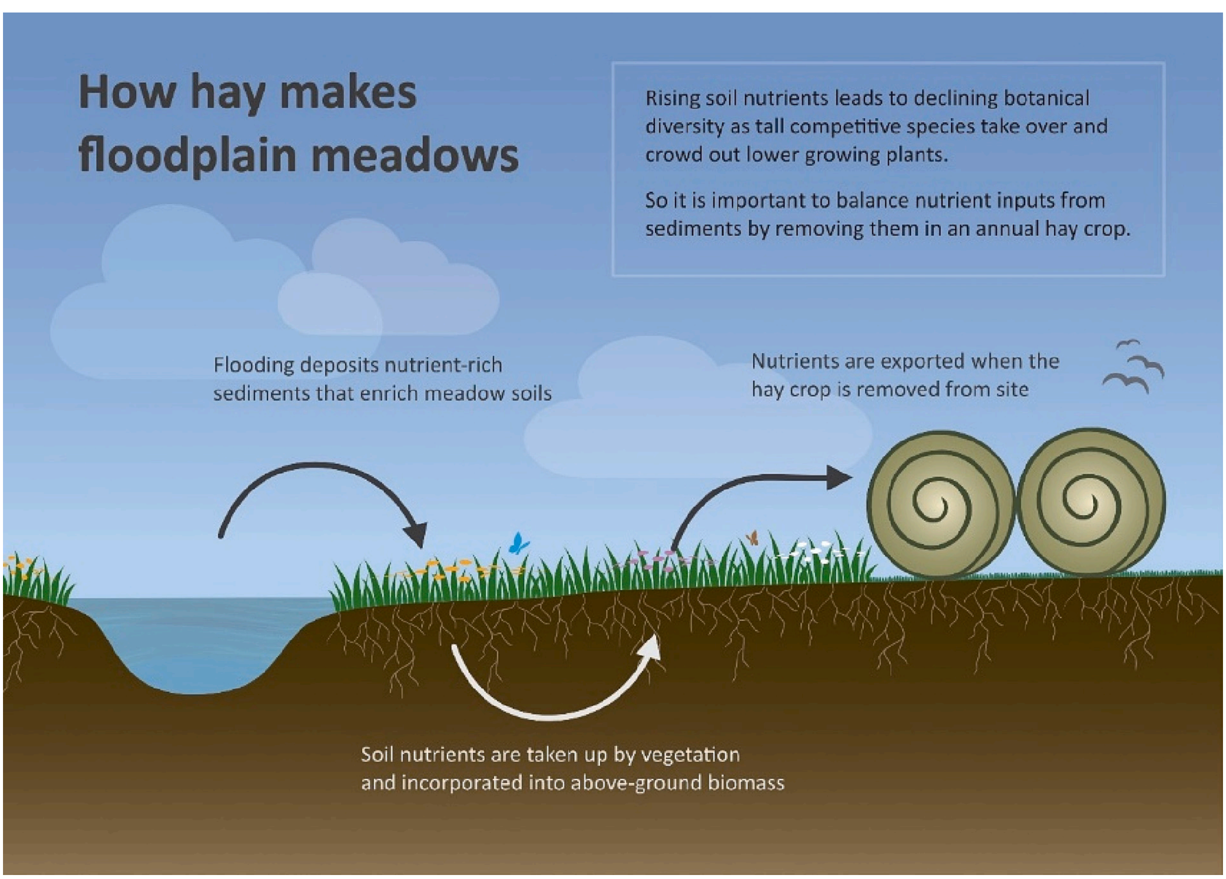

Fig. 1. The hay cycle, demonstrating the importance of nutrient removal via haymaking to promote biodiversity.

meadow itself, but potentially all the connected aquatic and terrestrial systems in the catchment.

1.3. A socio-ecological system

Floodplain meadows are socio-ecological systems that form part of agricultural landscapes across Europe. In the UK they have been in existence for a thousand years, earning specific mention in the Domesday Book of 1086 CE (Rothero et al., 2016), having been shaped by the interaction between natural processes and anthropogenic land-use (Lomba et al., 2019; McGinlay et al., 2016). They can still be a valuable part of modern nature-friendly farming systems. It is essential to understand the practical implications of management techniques to ensure a sustainable connection between conservation and agricultural goals when designing meadow management schemes.

In this study we aim to compare the nutrients removed with a single versus a double hay cut. We ask: What is the optimum time to perform haymaking so as to maximise nutrient offtake and nutritional value of the hay? To answer this question, we use a time-series dataset measuring the yield and nutritional quality of floodplain meadow hay in four sites in central England throughout the growing season from April to September. We also report perspectives of farmers on the practicalities of implementing a second hay cut. We conclude by making recommendations on the timing and frequency of hay cutting to maximise the nutritional value of hay.

2. Materials and methods

2.1. Study sites

Three long-established, floodplain-meadow sites in Buckinghamshire and Oxfordshire, UK were selected for this study. Historical data from a fourth comparable site were available from a previous study with data collected in April to July of 2010, 2011 and 2012 (Wotherspoon, 2015). See Fig. 2.

Botanical survey data recorded during June 2020 was fitted to the Modular Analysis of Vegetation Information System (MAVIS) (Centre for Ecology and Hydrology, 2020) and showed each site to support the MG4 community type, specifically the MG4b or MG4c sub-communities (Rothero et al., 2016). This is the *Alopercurus pratensis* – *Sanguisorba officianalis* community typical of European floodplain meadows.

All sites have been managed long-term through an annual hay cut and aftermath grazing by sheep or cattle. The sites are managed by a range of landowner types, including public amenity land management, a commercial agroecological enterprise and a wildlife charity.

2.2. Sample collection

A randomised block and plot design was used with one block at each meadow site. Nine plots were sampled in each block in 2020. Following a power analysis, six plots were sampled in each block in 2021. The plots were relocated each year to avoid any influence arising from the harvest

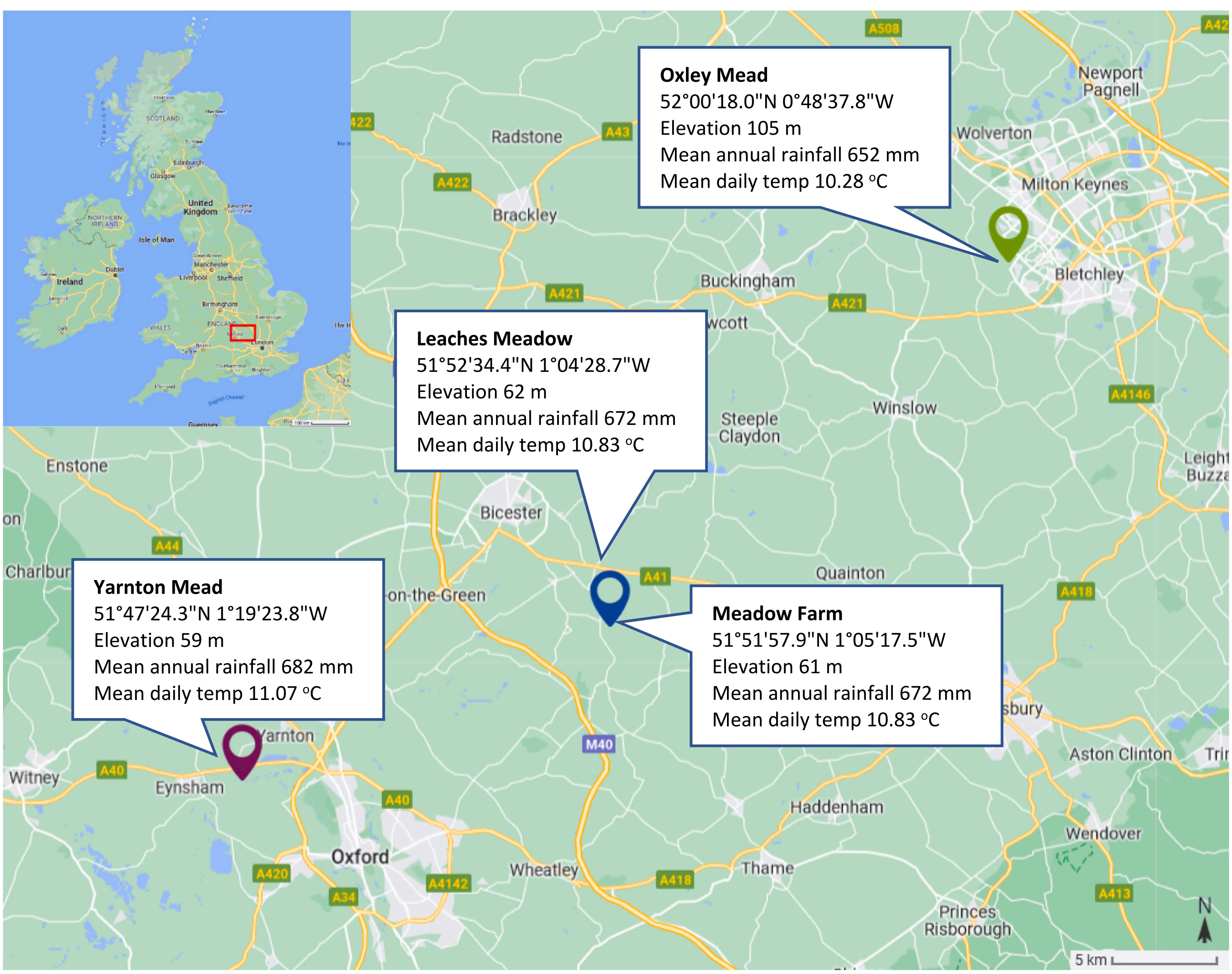

Fig. 2. Study site locations. Oxley Mead, The Parks Trust. Meadow Farm and Leaches Meadow, The Berkshire, Buckinghamshire and Oxfordshire Wildlife Trust (BBOWT). Yarnton Mead, FAI Farms Ltd. Google map data ©2022.

date in the previous year.

A 1 m × 1 m quadrat was harvested in each plot on each harvest date. Samples were collected at four time points between June and September in 2020 and six time points between May and September in 2021 (Pavlů et al., 2021). The sampling date allocated to each quadrat was randomised using the Excel RAND() function and all three blocks were sampled within the same week. The location and elevation of plots were recorded using Leica RX1200 GPS geosystem.

A double-cut treatment was also used with quadrats cut in the third week of June being harvested again in the second week of September.

Each 1 × 1 m quadrat was cut to a height of 4 cm using hand clippers (Bosch Isio, Stuttgart). The cut material was weighed and sub-sampled in the field using a spring balance (Salter, Manchester). Sub-samples of approximately 300 g were sorted into graminoids and forbs (including legumes) prior to drying in an oven at 40 °C. Dry yield weights were recorded prior to nutritional analysis.

2.3. Nutritional analysis

Hay samples for 2020 were ground to <2 mm, then samples weighing 2 g were dry ashed in a kiln at 550 °C to remove organic matter. Two replicates, blanks and a certified standard hay sample were included in each run to estimate analytical error. The ash was then dissolved in hydrochloric acid. Analysis by Inductively Coupled Plasma Optical Emissions Spectrometry (ICP-OES) gave results for phosphorus (P) that were well above the limit of detection for this method.

Samples from 2021 were analysed by Sciantec Labs (Cawood Scientific Ltd., Winkfield, UK) via ICP-OES, providing results for P, and Near-infrared (NIR) spectroscopy, providing results for crude protein, which was converted to N using the formula N = crude protein / 6.25.

2.4. Thermal time and weather data

Throughout this study, variables are measured against accumulated thermal time rather than calendar date. Thermal time can be measured in units of accumulated Growing Degree Days (GDD) and is a method commonly used in agriculture to determine the timing of agricultural interventions that depend on crop maturity (Calvache et al., 2021; Elnesr and Alazba, 2016; R. S. Smith and Jones, 1991; Snyder et al., 1999). This can be more accurate than using calendar date, which takes no account of the prevailing weather conditions that drive growth (Lonati et al., 2009). This interannual variation in thermal time is likely to be increasingly important as seasonal progression becomes less predictable under climate change.

Accumulated thermal time was calculated from daily mean temperature data: $GDD = ((T_{max} + T_{min}) / 2) - T_{base}$, where GDD is Growing Degree Days (^{o}C.d), T_{max} is maximum temperature that day (°C), T_{min} is minimum temperature that day (°C), T_{base} is base temperature for growth (4.5 °C) (Lonati et al., 2009). Note that GDD should always be a positive number and if the calculation results in a negative, zero should be substituted (Abel et al., 2018; Ansquer et al., 2009). Daily air temperature data were obtained from local weather stations at Oxford and Woburn (Met Office Library and Archive, 2020).

Accumulated GDD can be used effectively to plan agricultural activities with a monoculture crop for which T_{base} is known (Calvache et al., 2021). A useful T_{base} figure for mixed temperate meadow assemblages is 4.5 °C (Lonati et al., 2009). A start date of 01 February has been found to be a reliable threshold in calculating thermal time for species-rich grasslands in the northern hemisphere due to the influence of lengthening photoperiod on the onset of stem elongation (Ansquer et al., 2009; Peacock, 1976). Growth is minimal before 01 Feb due to short days and low temperatures.

Soil moisture is also a significant driver of plant growth. Actual evapotranspiration (ET_a) can be used to estimate this influence (L. P. Smith, 1960). The relationship between yield and cumulative ET_a was found to be linear. To standardise actual yield data and correct for the influence of soil moisture, a standard cumulative ET_a was calculated based on a 10-year mean for the 2010–2020 period and used to scale actual yields to give an adjusted yield that is then used to calculate offtake rates to remove the short term effects of soil moisture perturbations.

To examine the changing relationship between accumulated GDD and calendar date, GDD was derived from long-term mean temperature data for Oxford using the model presented by Elnesr and Alazba (2016). The modelled GDD was compared to calendar date to quantify how the relationship between these variables has changed (Elnesr and Alazba, 2016; Met Office, 2022).

2.5. Model selection and fitting

Analysis by linear mixed-effects model (LMM) was chosen to account for both fixed and random effects, and the non-independence of hierarchical data in this longitudinal split-plot repeated measures design. The lmer() function in the lme4() package of R Studio (R Core Team, 2019) was used (R version 4.1.2). The fixed effect was accumulated thermal time (GDD). Site was a random effect, plots within each site were a nested random effect and year was a crossed random effect.

LMMs were fitted for yield, N offtake and P offtake as response variables using data spanning the full April to September growing period.

The relationship between these response variables and GDD is not linear and use of split seasonal models has been shown to offer the best fit for predicting yield and nutritive value in single species stands of *Lolium perenne* and *Bromus valdivianus* in Mexico (Calvache et al., 2021).

To determine the best point at which to split the dataset for each response variable, an inflection point in the full April to September dataset was determined for each dataset using the R package 'inflection' (R Core Team, 2019). The derived split seasonal datasets were then fitted with LMMs to examine the strength of the relationship to GDD.

2.6. Stakeholder interviews

This study has collected perspectives from those who manage species-rich floodplain meadows in the UK in a decision-making capacity, using a combination of haymaking and aftermath grazing. A pilot questionnaire and in-depth interviews aimed to: (1) understand the practicalities of making hay at different times; (2) explore the influence of hay cutting time and frequency on perceived hay value; and (3) to explore whether and how study results are likely to influence those views.

A total of 109 responses were received to a pilot stakeholder questionnaire, made available from February to April 2020. Of these, eight individuals were selected for in-depth semi-structured interviews, representing farmers operating a commercial farming system, either with or without a formal organic or regenerative system in place, as well as conservation managers not reliant on the commercial value of the meadow. This approach provided a comprehensive coverage of the positions that these groups take to the management of floodplain meadows (Adams, 2015).

Interviews were carried out between April 2021 and August 2022 via Microsoft Teams. Questions were provided to participants in advance and included preliminary fieldwork results to enable them to prepare their answers and compile any supporting documentation they felt was appropriate ahead of the interview.

3. Results

3.1. Seasonal yield and nutrient offtake

The yield and nutrient removal potential for a combined double cut in late June and mid-September is 422.4 g m^2 for dry matter yield, 8.69 g m^2 for N and 0.80 g m^2 for P (Table 1). This represents an uplift in

Table 1
Yield and nutrients removal potential of a double cut system. Yield and P offtake are based on data from 2020 and 2021. N offtake data is available for 2021 only.

	Yield g m^2	N offtake g m^2	P offtake g m^2
Cut 1, late June	247.16	3.86	0.50
Cut 2, mid-Sept	175.25	4.83	0.30
TOTAL DOUBLE CUT	422.41	8.69	0.80
% increase for double cut compared to a single June cut	70.91	125.25	60.0

offtake compared to a single late June cut of 71 % for yield, 125 % for N and 60 % for P.

Yield, nitrogen and phosphorus offtake varied across the growing season, with differences across sites and between plant functional groups (Figs. 3–5.)

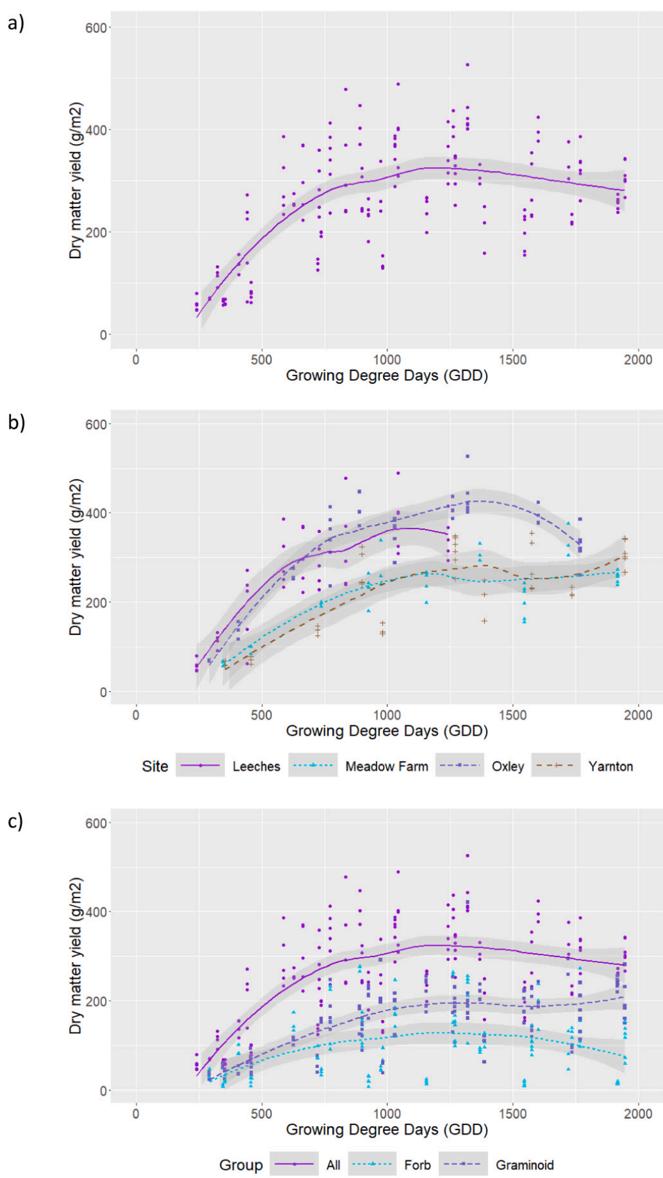

Fig. 3. Dry matter yield offtake g m^2 from 306 samples taken across four floodplain meadow sites in 2010–12 and 2020–21. A trendline is shown for a) all sites combined, b) each site separately and c) divided by functional group: graminoids versus forbs (the latter includes legumes.) The data in (c) are from 2020 and 2021 only.

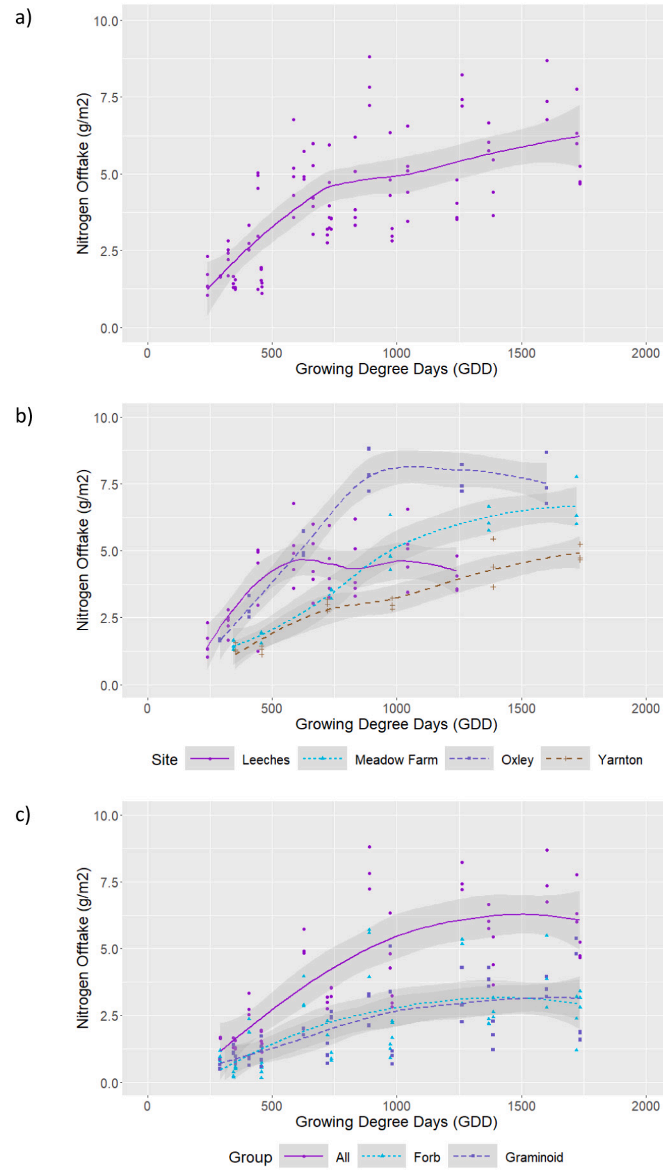

Fig. 4. Nitrogen (N) offtake g m^2 from 153 samples taken across three floodplain meadow sites in 2010 and 2021. The trendlines shown are for a) all sites, b) each site separately and c) divided by functional group: graminoids versus forbs (the latter includes legumes.) The data in c) are from 2021 only.

3.2. *Thermal time*

The relationship between accumulated GDD and calendar date has advanced by 14–15 days between the 1961–1990 and 1991–2020 means for Oxford, England (Fig. 6).

3.3. *Inflection points*

The optimal time point for harvest to maximise dry matter and nutrient removal, and the opportunity for regrowth and a second harvest, is 895 GDD for yield, 772 GDD for N and 902 for P (Table 2). The mean calendar dates for the 1991–2020 period in Oxford that corresponds to these GDD values are 30 June for yield and P, and 20 June for N. These dates will vary each year according to seasonal temperature trends. They are approximately 2 weeks earlier than during the 1961–1990 period and are likely to advance further under climate change.

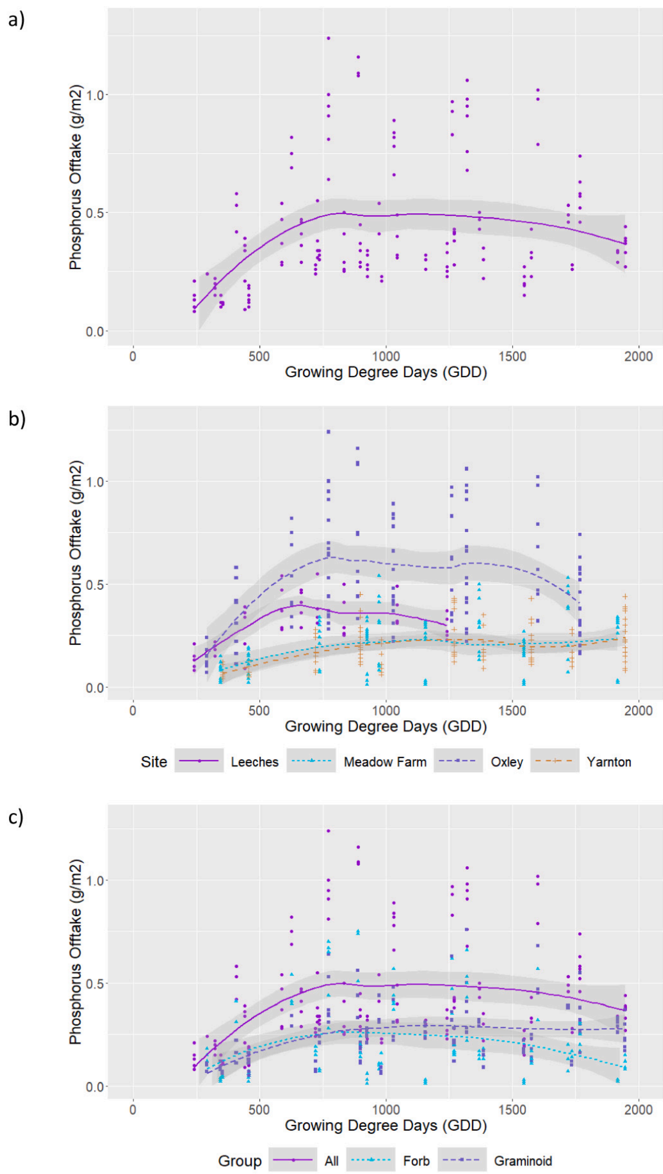

Fig. 5. Phosphorus (P) offtake g m^2 from 225 samples taken across four floodplain meadow sites in 2010, 2020 and 2021. Trendlines shown for a) all sites, b) each site separately and c) divided by functional group: graminoids versus forbs (the latter includes legumes.) The data in c) are from 2020 and 2021 only.

3.4. Thermal time effect size

The full April–September datasets were divided at the aforementioned inflection points. Linear Mixed Effects models (LMMs) were fitted to these split seasonal data to examine the effect size of accumulated GDD (Table 3).

Dry matter yield increased by 0.43 g m^2 per 1 GDD during the early season model up to 895 GDD ($p \leq 0.0001$). After this point the model was not significant, indicating no significant change in yield during the late season ($p = 0.26$).

N offtake increased by 0.006 g m^2 per 1 GDD during the early season model up to 772 GDD (p $\leq$0.0001). After this point the increase fell to 0.001 g m^2 per 1 GDD ($p = 0.03$).

P offtake increased by 0.0003 g m^2 per 1 GDD during the early season up to 901 GDD ($p = 0.004$). After this point the model was not significant, indicating no significant change in offtake during the late season ($p = 0.15$).

3.5. Farmer perspectives

Table 4 provides representative examples from the stakeholder questionnaire and interviews under the themes of practical land management, weather and climate, financial considerations and the likelihood that this research might influence their future land management decisions. These are discussed in Section 4.3.

4. Discussion

4.1. Hay cutting for nutrient reduction

Our results reveal that the potential dry matter yield from a double cut is 420 g m^{-2}, with an offtake of 8.69 g m^{-2} of N and 0.80 g m^{-2} for P (Table 1). These results represent a combined yield that is 71 % higher than a single summer cut that removes 125 % more N and 60 % more P. These findings are similar to results for dry meadows in the Park Grass Experiment, which found the combined double cut delivered 52 % more dry matter yield (1903–2018 data), 80 % more N and 78 % more P (1956–59 data) compared to the single summer cut across all treatment plots (Perryman and Ostler, 2021; Storkey et al., 2015; Warren and Johnston, 1964).

Nutrient budgets can vary significantly depending on local circumstances but, for phosphorus, inputs from sediment deposition are likely to be around 5 kg ha^{-1} yr^{-1} (Gowing et al., 2002). A single summer hay cut at 0.50 g P m^{-2} (5 kg P ha^{-1}) would balance typical inputs and the extra P removal in the second cut is actively reducing the level of this nutrient in the system. Nitrogen is more difficult to quantify as the cycle is more complex (Gowing et al., 2002; Stevens et al., 2004) but the fact that the second cut has a higher N content than the first suggests a double cut system also represents an effective way to remove this nutrient. The nutritional quality of the second cut also makes this a valuable fodder crop in sustainable pasture-fed livestock systems.

N was found to be higher in the second cut compared to the summer cut and this is consistent with the findings of Ludewig et al. (2015), who postulated that the reason for this could be: a) increased concentration due to slower growth and therefore lower yield (dilution effect); b) the slower summer regrowth resulting in a cut with a higher leaf to stem ratio, with N being more concentrated in the leaves; c) larger variability in soil moisture prompting plants under drought stress to take up osmotic component such as N-containing amino acids to lower their internal water potential and increase the uptake of water. They also found that sites with a higher ratio of grasses to forbs showed higher energy, protein and lower fibre in the second cut (Ludewig et al., 2015). This is consistent with the results of the present study, where energy and protein were higher in the second cut and the graminoid:forb ratio was also higher in the second cut across all sites. Ludewig et al. (2015) attributed this to grasses having headed prior to the first cut and the regrowth having a higher ratio of nutrient-rich leaves to more fibrous stems, whilst the herbs were more likely to be in their reproductive phase at the time of the second cut.

Many meadow plants experience a period of summer dormancy after the intense growth of early spring and summer and go on to have a second period of active growth later in the season (Fig. 7). This summer dormancy is also a time when crop quality is lower as nutrients have been expended in flowering and seed production, leaving fibrous spent flower stalks and old leaves (Tallowin and Jefferson, 1999). As such, cutting during the active growth phases in late June or early July and again in September, either side of this dormant period, results in a crop with higher nutritional content. The early cut also triggers a pulse of compensatory regrowth (Ansquer et al., 2009; Piippo et al., 2009), leading to a higher combined yield and nutrient offtake compared to a single late cut. This compensatory regrowth may result from increased net photosynthetic rate, higher growth rates, increased tillering or branching, and/or the ability to reallocate carbon stores from underground stores to shoots (Strauss and Agrawal, 1999).

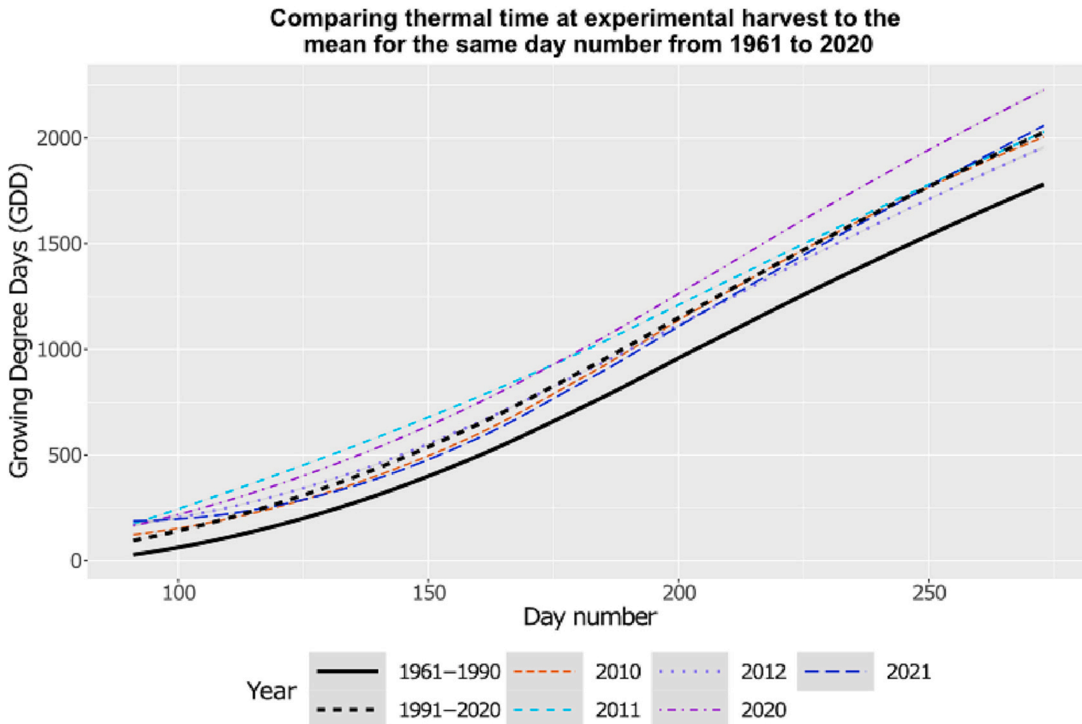

Fig. 6. The relationship between day number and GDD has advanced by 14–15 days between the 1961–1990 and 1991–2020 periods. Temperature data are for Oxford, England (Met Office, 2022; Met Office Library and Archive, 2020).

Table 2
Inflection points measured in Growing Degree Days (GDD) in April to September datasets used to split into seasonal models and define optimum harvest times for yield and nutrient removal. Temperature data for mean calendar dates are for Oxford, England (Met Office, 2022; Met Office Library and Archive, 2020).

	Yield	Nitrogen (N) offtake, g m^2	Phosphorus (P) offtake, g m^2
Inflection point	895	772	902
Mean calendar date 1991–2020	30 June	20 June	30 June
Mean calendar date 1961–1990	14 July	04 July	15 July
Change in mean date of inflection point between 1961 and 2020	Advanced by 15 days	Advanced by 14 days	Advanced by 15 days

The offtake potential for N and P from a single cut rises steeply until around mid-summer and then remains relatively constant through the rest of the growing season (Figs. 3–5). Maximising the time between cuts provides the longest window for regrowth, facilitating greater yield and nutrient removal. Therefore, taking a first cut at the mid-summer inflection point in offtake potential at 772–902 GDD (currently around 20–30 June) and a second cut in the autumn offers an improved opportunity for annual nutrient removal.

A common alternative to a second cut is one cut in the summer with aftermath grazing in the autumn. Whilst we did not assess the nutrient offtake via grazing, one can expect that while some of the nutrients consumed by grazing livestock will be incorporated into body mass and removed from the system, most of it is redeposited via animal waste (Garnett et al., 2017; Gregg et al., 2021; Tälle et al., 2015). Excreted nutrients take a more mobile form and may be more readily leached back into water courses than if they were still bound up in plant material, therefore offering little contribution towards nutrient reduction targets (Hogg, 1981; Whitehead, 2009). Further study to quantify the relative effects of aftermath grazing versus a second cut on nutrient removal would be useful in assessing the potential for a change in

Table 3
Linear Mixed Effects Models (LMMs) of the relationship between Growing Degree Days and response variables. Split seasonal models are defined by inflection points in the full-season data.

Response variable	Model	r^2	*p*-Value	Assimilated estimated variance for random effects
Yield (g m^2)	GDD: 239–895 Yield g m^2 = −52.56 + (0.43 × GDD) Obs: 129, Sites: 4, Plots: 32, Years: 4	0.73	< 0.001	Site: 2501 Plot: 267 Year: 28 Residual: 3782
	GDD: 896–1946 Yield (g m^2) = 288.31 + (0.02 × GDD) Obs: 177, Sites: 4, Plots: 50, Years: 3	0.72	0.26	Site: 4446 Plot: 2054 Year: 2604 Residual: 3082
Nitrogen (N) offtake (g m^2)	GDD: 239 to 772 N g m^2 = −0.340 + (0.006 × GDD) Obs: 57, Sites: 4	0.68	< 0.001	Site: 31 Residual: 32
	GDD: 773 to 1736 N g m^2 = 4.151 + (0.001 × GDD) Obs: 42, Sites: 4	0.71	0.03	Site: 99 Residual: 32
Phosphorus (P) offtake (g m^2)	GDD: 239 to 901 P g m^2 = 0.28 + (0.0003 × GDD) Obs: 83, Sites: 4, Years: 3	0.67	0.004	Site: 0.08 Residual: 0.03
	GDD: 902 to 1946 P g m^2 = 0.58 + (−0.0001 × GDD) Obs: 87, Sites: 4, Years: 3	0.53	0.15	Site: 0.05 Residual: 0.03

Table 4
Perspectives from floodplain meadow farmers on the practicalities of taking a double hay cut. Includes comments from eight in-depth interviews conducted via Microsoft Teams, all of whom were given advance access to preliminary study results to inform their views.

Theme	Comment
Practical land management	"My concern with the second cut in September is the ground may be starting to get a little bit wet, so getting the large equipment on that's needed for cutting hay may actually be damaging."
	"[For a second cut] you want it to be at least 8 inches long. Once it's down to like 4 or 3 inches, you're not going to actually be able to physically rake it up and bale it. So there's a minimum sward height to make it work from mechanical point of view. There's a 50 % hit rate of being able to do a second cut. But we've always made that into silage."
	"I do get pretty good aftermath grazing. I haven't quantified it in terms of how much regrowth I get, but I don't think I would ever have enough to make a second hay cut. It would have to be a silage cut because it would be very short and it wouldn't have seeded again. So it would be tricky to make hay on, I think. I would be anxious about trying to make hay in September, especially with rather leafy stuff where you need a lot of heat to dry it."
	"Generally from doing one cut I get sufficient forage that I need for feeding over the winter, and I would then tend to need it more for aftermath grazing to keep the cattle out for a longer period of time during the autumn. So rather than making two cuts of hay and leaving myself short of grazing ground, I tend to graze it. Otherwise I end up bringing the cattle inside earlier when I've run out of grazing and then feeding them in the buildings, which is more expensive than having them out grazing in the field."
	"As the owner of less than 1 ha of land with old (narrow) gates, availability of contractors with suitable equipment (i.e. small enough to get into field) can be a problem. Also, modern tractors and equipment are so heavy it causes serious compaction of our very solid clay soil. Even minor ruts persist for years in permanent grassland."
Weather and climate	"I think with climate bringing longer growing spells and earlier spring we will need to adapt and pull hay cutting forward a bit. But obviously we need the data to back that up to make sure it doesn't adversely impact the habitat and species we're managing for."
	"What gives a little bit more flexibility now is, if we have a smaller weather window, making round bales with the netting, so we can leave them there. So if we were able to get it cut and baled, but not necessarily picked up and put in the barn, it doesn't matter. We can leave them out there and they can get rained on. With square bales, you got to get them undercover or else the rain gets down in between the sections and it rots inside and out. So the time pressures are not as tricky around the weather if we're doing rounds."
Financial	"The problem with [double cutting] is you've got double the cost. So it's a lower yield on the second cut, so I guess it would just have to be an analysis of whether the cost would make it worth it because you still got to get the mowers out, the tedders out the balers out there. So the mowers and the tedders are on a per hectare basis, so it doesn't matter how much yield you're getting, the cost is the same. And then the balers are on a per bale basis. So the baling cost would be in line but the mowing and tedding cost would be expensive if we're only getting a low yield. I think it's enough to make me interested but it feels like it might need to be higher yielding on that second cut in order to justify the cost because we have to bring contractors in to do it. And also the price of hay at the time. So you know, if demand is really strong in the price is really good, it would be worthwhile."
Research influence	"Yes, we might think of using a double cut in a situation where we were unable to bring on livestock for an aftermath graze, so as to ensure that the condition of the meadow wasn't impacted by this change in management."
	"Not likely, simply because there is a wealth of free grazing/hay available here so I don't need the extra yield. But the nutrient removal aspect has been used to good effect elsewhere to promote botanical diversity so may do it for that reason. Good to know it's a tool in the toolbox and what the implications are. More data is useful in informing applications for derogations etc. so always want to know more."
	"I don't think the extra work of a double cut would ever be justified by the marginal increase in yield. And anyway, we need grazing in autumn more than we need extra hay."
	"We've never used double cutting but I would be interested to explore it for a couple of reasons. For one, it's difficult access to graze those meadows and also because there is a value in the hay. We've got customers, so more hay could be a good thing and it might allow us to out winter more animals elsewhere on the farm. So I would be interested in exploring it, but I think we wouldn't want to do it every year."
	"And just practically speaking, that 15th July date is just hard to fit in with other hay cutting on the rest of the farm. And there'd be a bit more quality and a bit more yield, and if it's lifting more of the nutrients off, which is what the whole idea is, then that seems like it's win-win. That's great! It's just such an arbitrary thing to just set a date when every year is so different."
	"I think that the double cutting date would be useful in some circumstances. If what we can do promotes as much biodiversity in the pasture as possible, which then supports as many types of insects and pollinators or ground nesting birds or whatever, that for me is much more important than getting a few extra bales of hay or getting an extra percent protein in my hay."
	"I did think that the protein content would drop off more than that. The increase in biodiversity and what we can do to enhance that is something that we're very passionate about and is one of our major considerations. So if it was showing that cutting earlier actually helped that then that's certainly something that I would be willing to consider, providing I haven't got nesting birds in those fields, or can go round them or whatever."
	"Definitely. The protein graph surprised me. I wouldn't have expected it to be so flat after mid-summer. I personally would have imagined the protein to drop right through the year. What we've talked about here will put me in a position to ask the landowner next year to apply for a dispensation so we can cut earlier and look at doing two cuts. I think going forward, if we're going to have more hot summers and longer periods of no rain, then we have to change the way we manage these meadows."
Ground nesting birds	"We carry out regular bird transects, so we would pick up whether we got curlew or lapwing nests on the ground. If you come too early, then even though the young may have hatched and maybe on their feet and walking around, actually exposing them to the hazards of foxes and wider predation can have a huge negative impact on species such as that."
	"That's the thing about this broad-brush approach. Why don't we figure out where the birds are and not cut just that field, but cut all the other fields? Otherwise we have a whole farm not being cut until later because there *might* be one nest somewhere within 300 acres."
	"For the first time this year we've actually had nesting curlew down on the river. We've got a couple of chicks fledged there and we've had a local team supporting. Where we found the nest site, we electric fenced it off and they found a couple of successful chicks and they've been down there and caught the chicks yesterday, ringing them to monitor them. So that's really good to see. We're gonna be cutting one of the fields this weekend, and the curlew project team are gonna come down there and try and find the chicks before I go through it with a mower to try and move them on and make sure they're not in the field when it's cut. I think they said they're gonna come back every time, like when we turn the grass they'll come back and make sure that the chicks aren't in the grass there or move them on."

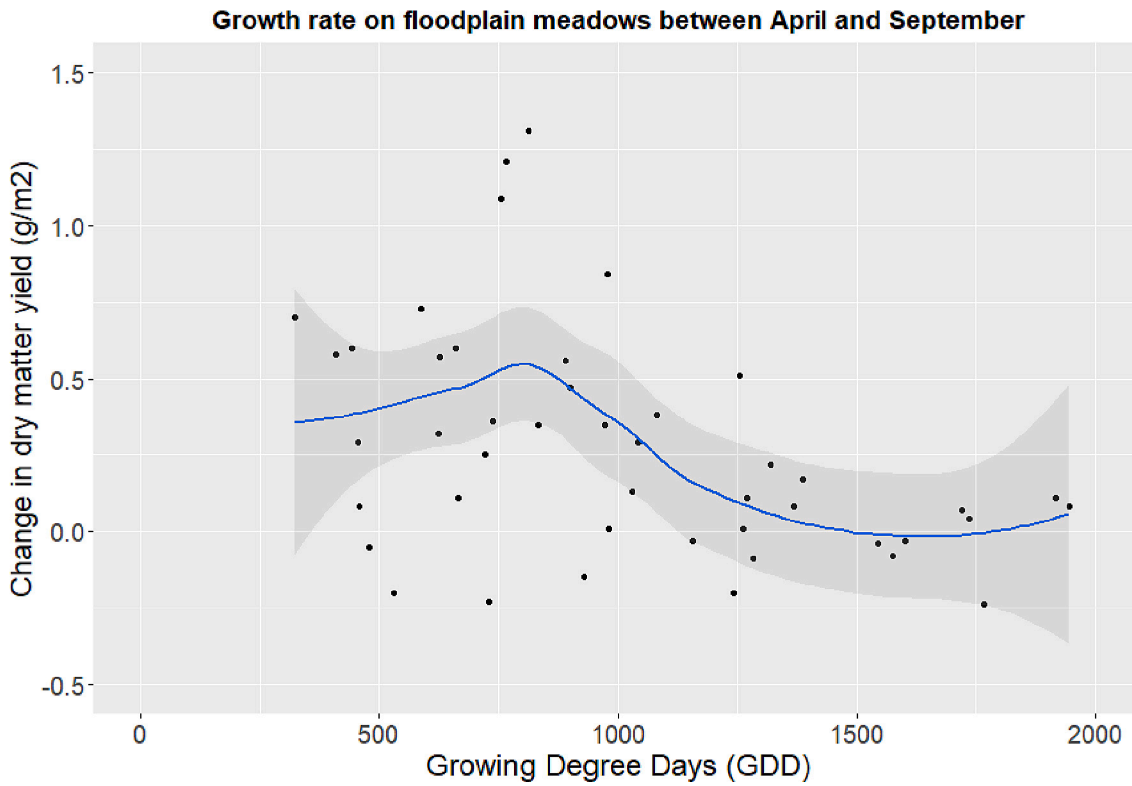

Fig. 7. Growth rate on study sites in 2010–12 and 2020–21 showing the active growth phases of early summer and early autumn, separated by late summer dormancy.

management to influence nutrient cycling at a catchment scale.

4.2. Hay cutting and biodiversity

The high botanical diversity found on floodplain meadows has arisen from the annual practice of cutting hay around mid-summer that has been common across Europe's floodplains for a thousand years (McGinlay et al., 2016, 2017). This botanical diversity is fundamental to providing habitat, nectar and food plants for the wide range of invertebrate, bird and other wild species that depend on these meadows. Agricultural intensification over the last century has seen most of this diversity lost to cultivation and nutrient enrichment under intensive agricultural management, or changes in land use away from agriculture altogether (Gowing et al., 2002).

Plant available phosphorus (P) is a key factor determining botanical diversity in semi-natural mesotrophic grasslands (Gilbert et al., 2009). Low P availability is associated with species-rich meadows, whilst high P availability is associated with species-poor communities (Zelnik and Čarni, 2013). Nitrogen (N) is also inversely correlated with species-richness, favouring grasses through competitive exclusion (Silvertown et al., 2006).

Our results suggest benefits of a second cut in autumn to maximise nutrient offtake, but it is unclear how such a change in cutting regime would affect biodiversity. A meta-analysis of studies on European grasslands (Tälle et al., 2018) showed that cutting more frequently was important to maintain botanical diversity in productive grasslands (like floodplain meadows) in order to reduce nutrients and manage access to light within the sward (Hautier et al., 2009). Whilst botanical diversity may be favoured by more frequent mowing, a change in mowing frequency may result in a change in botanical composition with some species being favoured by mowing over grazing or vice versa (Schaich and Barthelmes, 2012). It is possible that this change in species composition may affect yield or nutrient content, but this was not evident in this short-term study, and the authors are not aware of any research investigating this for floodplain meadows in the UK so this represents a knowledge gap that would be useful to address.

Studies have revealed that there is no significant effect on plant species richness from the timing between cuts (Humbert et al., 2012). *Re*-flowering or delayed flowering of species between cuts in a double-cut system can provide a valuable source of late-summer nectar for pollinators (Johansen et al., 2019; Piippo et al., 2009; Strauss and Agrawal, 1999). A meta-analysis of studies in Europe has shown that mowing more frequently than once per year was most beneficial for nature conservation on productive semi-natural grasslands in Europe, whilst low-intensity grazing had the most negative effect (Tälle et al., 2015, 2016, 2018). This is most likely due to the increased removal of soil nutrients through mowing promoting species richness.

Agri-environment schemes introduced since the 1980s have restricted haymaking until mid-July, based on the likely fledging date of ground-nesting birds (McGinlay et al., 2016). Fig. 6 shows that this mid-July date may have been suitable for managing botanical diversity through nutrient removal in the 1961–1990 period but that this relationship to thermal time has since advanced by around two weeks. Bock et al. (2013) found that the typical time of hay cutting in Germany had advanced in response to advancing seasons until agrienvironment schemes introduced in the 1980s prevented this trend. Even before the delayed hay cutting dates were introduced, the advance in typical hay cutting date of approximately 1 day per decade did not keep pace with advancing phenology of meadow foxtail (*Alopercurus pratensis),* a key species in floodplain meadows (Bock et al., 2013). Temperature is one of the primary drivers of plant growth (Calvache et al., 2021; Lonati et al., 2009) and this delay in hay cutting beyond mid-summer may now be proving detrimental to botanical diversity on these meadows (Gilbert et al., 2009; Poptcheva et al., 2009; Silvertown et al., 2006; Zelnik and Čarni, 2013. This disconnect between dated restrictions and plant phenology is only likely to increase under climate change.

In the Netherlands, pollinator abundance and diversity has been found to be higher in hay meadows managed for floristic diversity than in those managed for birds, so management aimed at increasing botanical diversity needs to be a priority to support trophic relationships from the bottom up (Tanis et al., 2020). However, farmers interviewed as part of this study have demonstrated that success in the conservation of ground nesting birds can be achieved through working with local bird groups to find and protect birds where they are nesting, rather than risk degradation of the whole meadow system through untargeted delays in cutting (Table 4).

4.3. Practical considerations

There are many practical considerations for farmers when making meadow-management decisions. Table 4 provides relevant themed comments from stakeholder interviews and the key messages are:

- Aside from date restrictions in agri-environment schemes, weather is the biggest factor governing the timing of haymaking. A dry weather window of 3–4 days is required for hay to be cut, turned, dried and baled. Suitable weather is increasingly difficult to predict under climate change and taking a double cut requires doing this twice in the same year.
- Sward length may be a limiting factor for a second cut. Respondents reported that a sward height of at least 8 in. (20 cm) is needed to enable effective baling. Shorter crops may have to be ensiled rather than dried for hay, bringing with it the associated use of plastic bale-wrap and the need to transport the extra weight of a wet crop.
- The financial cost of a second, smaller harvest may be prohibitive. Costs for cutting and turning may be on a per-hectare basis, so are the same regardless of yield, whilst baling may be per-bale and so remains proportionate to the yield. There may need to be financial incentive beyond the value of the hay itself to make double cutting attractive to a commercial farm enterprise.
- Fit with other farm activities can be problematic if attempting to make hay at varying times when contractors may have moved on to other crops.
- Many remaining floodplain meadows are small and fragmented. Physical access by large modern machinery may be difficult and contractors may not be interested in attending small sites when there is high demand from other crops on larger and/or easier sites.
- Many respondents stated that autumn grazing space to outwinter animals successfully was more valuable to them than a second, smaller hay crop.
- The protein content of late-season hay was surprising to most respondents, with the common assumption being that protein content would fall continuously after mid-summer, making late hay fit only for bedding. The better-than-expected feed value of the double cut, along with the opportunity to promote biodiversity was attractive to them, many of whom are passionate about improving the nature value of their farm.

Many of these practical and financial concerns may make a second cut prohibitive but could be overcome by demonstrating the higher-than-expected nutritional value of this hay (a subject being investigated by the authors) and by ensuring the public services in the form of improved water quality, nutrient management, biodiversity conservation and carbon storage are adequately compensated for in agrienvironment schemes. Ultimately, land managers need greater flexibility to balance the natural cycles in these dynamic systems to achieve the best results for both nature and their farm enterprise. Fixed calendar dates do not allow them to respond to interannual variations in local conditions.

5. Conclusions

Haymaking on floodplain meadows is an opportunity to more than offset typical nutrient inputs from river catchments.

To maximise the effectiveness of this natural nutrient pump, it is essential to work with the changing seasonal rhythms of plant phenology. The current reliance on dated restrictions for haymaking may be increasingly detrimental to botanical diversity as the relationship between temperature and date continues to advance under climate change. Thermal time is a more relevant metric than calendar date for predicting plant phenology and has advanced by around 2 weeks since the 1961–1990 period.

At the current time, the optimum haymaking period for nutrient removal is likely to be around 20–30 June in central England, corresponding to 772 GDD for N and 902 GDD for P. This will continue to advance under climate change and vary between years and this needs to be allowed for in agrienvironment schemes prescriptions to accommodate use of a double-cut system for nutrient reduction.

Whilst further research is needed to examine the effect of aftermath grazing versus a second hay cut on botanical diversity and long-term nutrient removal in floodplain meadows, using both techniques as the situation demands to manage these dynamic systems is likely to give rise to the best results.

There are many practical considerations that farmers need to balance when making meadow-management decisions, including weather, physical constraints, availability of equipment and staff, fit with other farm activities and the financial implications of each intervention. Many farmers are highly motivated by biodiversity conservation gains and would prioritise this where possible within their system. Appropriate recompense via agri-environment schemes should be made available for these public services that provide a win-win for biodiversity conservation and farming.

Floodplain meadows are a dynamic system with many site-specific considerations and interannual variation. Both accurate information and flexibility are needed to enable land managers to work with natural processes to achieve the best outcomes for nature and their farm enterprise. Agri-environment scheme prescriptions need to facilitate this responsive management approach.

CRediT authorship contribution statement

Vicky Bowskill is a PhD researcher and David Gowing and Shonil Bhagwat are her supervisors. Vicky Bowskill: Methodology, investigation, formal analysis, data curation, writing – original draft, visualisation, project administration Shonil Bhagwat: Conceptualization, validation, writing – review and editing, supervision, funding acquisition (social science components) David Gowing: Conceptualization, validation, writing – review and editing, supervision, funding acquisition (natural science components).

Declaration of competing interest

The authors declare that they have no known conflict of interest.

Data availability

The data which supports this publication is part of ongoing PhD research and will be made available via the Environmental Information Data Centre (EIDC) at the conclusion of that project.

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