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RESEARCH ARTICLE

Managing perennial biomass crop margins for biodiversity: Insights from fine-resolution soil and plant niche models

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Abstract

1. The challenge of energy production against a target of net-zero emissions has led to the growth of policies promoting the cultivation and use of perennial biomass crops by governments in the United Kingdom and globally. Many of these crops are long-lived and require low management inputs, raising questions about how the management of their field margins may influence biodiversity and whether interventions, including those funded by agri-environment schemes, could enhance biodiversity alongside the crop. In intensive, temperate agricultural systems, crop margins are widely recognised as important for supporting farmland biodiversity; however, little research has focused on how the margins of low-intensity perennial biomass crops function in this role. These margins can differ from conventional arable margins in structure, shading and management intensity, meaning that their biodiversity potential, and the management practices most likely to enhance it, remain poorly understood.
2. Our study focuses specifically on the management of margins surrounding short-rotation coppice (SRC) willow and miscanthus, aiming to identify approaches most likely to benefit plant biodiversity. We combined fine-resolution soil and plant niche models with field surveys to evaluate how different management practices may affect habitat suitability for grassland species.
3. High residual soil fertility emerged as a major constraint on establishing forb-rich grassland assemblages, including those targeted by conservation seed mixes. Model simulations indicate that reducing fertility through repeated cutting and removal of plant material can improve suitability, though gains are gradual and strongly site-dependent. Margin width also played a critical role, with narrow, shaded margins showing reduced suitability for light-demanding species, consistent with shade-driven edge-to-area effects. Field surveys revealed very low frequencies of target forb species, confirming that assisted introduction is required where species-rich outcomes are desired.

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4. *Synthesis and applications*. Together, these results highlight the need for margin-specific management guidance for perennial biomass crops and demonstrate how niche-based modelling can inform the design of effective agri-environment options.

KEYWORDS
edge-to-area effect, field margin management, perennial biomass crop margins, plant biodiversity, plant material removal, shade tolerance, soil and plant niche modelling, soil fertility

1 | INTRODUCTION

Perennial biomass crops, including woody crops and grasses, have the potential to contribute significantly to the UK's renewable energy goals and greenhouse gas emissions targets (Hodgson et al., 2024; Rowe et al., 2009). However, concerns about potential biodiversity loss and competition with food production for land continue to feature in discussions regarding the benefits of these crops (Clifton-Brown et al., 2023).

The biodiversity impact of perennial crops has been explored in previous studies (Donnison et al., 2021; Rowe et al., 2009, 2011), but most of these studies have focused on the inherent biodiversity value of the crops themselves, rather than investigating how crop management practices might enhance or diminish that value. Manning et al. (2015) proposed two primary strategies for managing perennial biomass crops that could reduce environmental impact and competition with food production, while potentially enhancing biodiversity and crop productivity by increasing ecosystem service provision. The first strategy involves managing existing perennial biomass crops to support ecosystem service provision and promote biodiversity, using well-designed agri-environment schemes and wildlife-friendly management practices (Manning et al. 2015; Whittingham, 2011). In the United Kingdom, bespoke agri-environment schemes for perennial biomass crops do not yet exist, with subsidised management options available based on generic options designed for conventional crops (Department for Environment Food & Rural Affairs, 2023a). The second strategy suggests strategically locating new bioenergy plantations with consideration of their landscape context, in order to minimise or even enhance their effects on biodiversity and ecosystem services (Manning et al. 2015).

Of the limited studies that have explored perennial biomass crop management for biodiversity, most have focused on within-crop management, primarily the rotational length of SRC willow, or unplanned variation in crop density in miscanthus (Dauber et al., 2015; Vanbeveren & Ceulemans, 2019). While these studies are valuable, the management options considered may not be widely applicable in commercial practice due to detrimental effects on crop yield or the impracticalities of implementation. In this study, we aim to identify and explore management practices that, while potentially incurring some commercial cost, are considered by industry stakeholders to be viable options for enhancing biodiversity within commercial perennial biomass crop production systems (Sylvester et al., 2022). We also examine, in the context of England, where Environmental Land Management Scheme payments could or are being extended to perennial biomass crops.

When considering management options for perennial biomass crops, it is important to recognise the unique characteristics of these crops compared to conventional systems. SRC willow and energy grasses, especially *Miscanthus* × *giganteus*, are the principal temperate perennial biomass crops (Clifton-Brown et al., 2023). The differences between SRC willow and *Miscanthus* × *giganteus* and conventional arable crops are substantial. Perennial biomass crops are managed with limited or no herbicide and fertiliser applications and have extended lifespans of up to 25 years, during which no cultivation occurs (Mehmood et al., 2017). The margins of perennial crops also have unique features: they are often largely unmanaged, other than annual cutting, and, unlike many arable crop margins, are not subject to routine cultivation or herbicide application but drift if possible (Cobb et al., 1999). Perennial biomass crop margins, particularly those planted under energy crop schemes, are often wider (up to 8 m) than those in conventional systems, and depending on orientation, shelter and shade may have taller vegetation due to the height of the associated perennial biomass crops, with miscanthus reaching 3 to 4 m and SRC willow reaching 6 to 8 m. As a result of these unique characteristics, past studies, interventions and models developed to understand and manage conventional arable crops and crop margins may not be directly applicable to perennial biomass crops.

In 2023, the Sustainable Farming Incentive (SFI), the largest agri-environmental scheme in England, was extended to include SRC willow and miscanthus for the first time, allowing landowners to apply for payment to establish flower rich grass margins. The prescribed management, however, was identical to that of conventional crop margins, making no adjustments for the differing conditions within perennial biomass crops margins (Department for Environment Food & Rural Affairs, 2023b).

We address the following research questions: (Q1) what are the likely short- and long-term outcomes of current management? and (Q2) what alternative options might be best to manage perennial biomass crops margins for biodiversity benefit? The goal, in terms of positive impacts on plant biodiversity, is assumed to be the establishment of forb species characteristic of lowland species-rich grassland based on the seed mixes prescribed within the SFI. The outcomes were assessed in terms of changes in modelled habitat suitability for injurious weeds, nectar plants, and grass and forb species that are constituents of recommended seed mixes for species-rich grassland creation. To help address our questions, we parametrise a soil and plant niche model (MultiMOVE) to be able to predict the short- and long-term effect of different management options for perennial biomass crop margins on biodiversity. We model the change in habitat suitability for a range of plant species and apply these models to surveyed locations in the margins of perennial biomass crops. The fine resolution of our modelling approach (Henrys et al., 2015) uses observed data at each location as baseline input to the models. This allows credibility in the models to be immediately gained by comparing predictions of plant habitat suitability with baseline observed species composition. We used the soil and plant niche model to explore three margin management scenarios and associated changes in conditions for plant biodiversity: (i) the creation (via sowing) of species-rich grassland in narrow versus wide crop margins where plant assemblages are likely to be influenced by reduced light levels; (ii) how a long-term regime of annual plant material removal and no fertiliser inputs on field margins could reduce soil fertility and change habitat suitability for plants; (iii) the impact of the removal of plant material via broad spectrum herbicide application. Finally, we combine scenario outcomes with the field observations to develop a management guide, indicating the likely outcomes from combined or single actions. This guide requires robust field testing, but forms a strong basis for the development of agri-environment scheme options to enhance plant biodiversity in margins of SRC willow, miscanthus and similar perennial biomass crops.

2 | METHODS

2.1 | Study site selection and location

Flora and soil surveys of commercial SRC willow and miscanthus crop margins were conducted, providing data to test and parameterise the MultiMOVE model (modelling codes can be found in Barneze & Smart (2026). We did not need licences or permits to conduct the fieldwork; we did require the landowner permission which was obtained in each case either via email or verbally. Site selection was based on semi-structured interviews with industry stakeholders, who provided information on current management practices and the location of potential study sites. Prior to the semi-structured interviews, informed consent was obtained verbally and confirmed at the start of each interview. Participants were provided with participants' information sheet in advance, detailing the objectives of the interview and the data management procedures, including data sharing, handling and storage. The interview scope covered current practices and attitudes towards biodiversity management. The question used to inform this paper was: *How are you currently managing your crop margins?* The interview process highlighted a diverse range of current margin management, including but not limited to interventions to establish flower-rich grassy margins through sowing of approved seed mixes. This included seeded mixes prescribed under SFI and comparable mixes under the related but more targeted Countryside Stewardship scheme, both schemes being part of the UK government's umbrella Environmental Land Management Scheme. Site selection was designed to provide the best coverage possible, within the project constraints, of the diverse range of current margin management. In total, 19 margins were selected for sampling, over six farms; three farms with miscanthus in Somerset and three farms with SRC willow in Cumbria in the United Kingdom. The selected margins covered three management options applied either singly or in combination: standard minimal management (cut and material left on site), plant diversity management (sown or unsown), weed control (herbicide, rotavation or none) and plant material management (cut and removed or cut and left); sowing and herbicide applications were converted into modelling parameters and compared with standard minimal management (Table 1). Rotavating was excluded as the practice, which was being trialled by an industry-leading landowner, was found to promote the growth of injurious weed species, an outcome

TABLE 1 Detailed information from each of the locations used for soil and vegetation survey.

Farm	Region	Crop	Margin	Seed mix	Management	Transects
1	South-west England	Miscanthus	Sown	Biodiversity mix—GS4	Cut and left	4
1	South-west England	Miscanthus	Unsown	—	Cut and left	1
1	South-west England	Miscanthus	Unsown	—	Cut and removed	1
2	South-west England	Miscanthus	Unsown	—	Cut and left	5
3	South-west England	Miscanthus	Sown	CIPM2	Cut and left	1
3	South-west England	Miscanthus	Unsown	—	Cut and left	1
4	North-west England	SRC willow	Unsown	—	Herbicide	2
5	North-west England	SRC willow	Sown	Croquet	Cut and left	2
5	North-west England	SRC willow	Unsown	—	Cut and left	1
6	North-west England	SRC willow	Unsown	—	Rotavated	1

Abbreviations: Biodiversity mix—GS4, combines grasses, deep-rooting herbs and legumes; CIPM2, Flower-rich grass margin mixture; Croquet, grass seed mix; SRC willow, short rotation coppice willow.

unwanted by landowners. The practice was therefore deemed an unviable option for future use.

2.2 | Plant and soil survey and sampling

Plant and soil surveys were conducted in 2023. At each of the selected margins, a transect was laid out in a representative area along each margin. The transects were 25 m long and positioned 2.5 m perpendicular distance from the edge of the cropped area. Five 1 × 1 m quadrats were placed along each 25 m transect at 0, 6, 12, 18 and 24 m. Margin width from the crop edge to the boundary edge was also measured.

For the vegetation sampling, within each quadrat, all vascular plants were identified to species level and percentage cover was estimated by eye for each species, plus bare ground, litter and total bryophyte to give a total of at least 100%. Where species' canopies overlapped, percentage cover was potentially higher than 100%.

For soil sampling, three intact soil samples (diameter = 5 cm, depth = 15 cm) were collected from each transect once the vegetation surveys had been completed. Samples were taken from quadrats 1, 3 and 5. Prior to sampling, any vegetation was cut to the soil surface using a knife or scissors. On return to the laboratory, soil samples were frozen and stored at −20°C until analysis. Before soil analysis, samples were defrosted, sieved to 2 mm to remove stones and roots, and 5 g subsamples were taken for pH analysis. The remaining soil was oven dried overnight at 105°C, with soil weight recorded pre and post-drying to calculate soil moisture. A sub-sample (~1 mg) was then ball milled before analysis for soil CN ratio using a Vario EL Cube elemental analyser.

2.3 | Species ecological niche modelling

We used the MultiMOVE R package (Henrys et al., 2015) to predict changes in habitat suitability for most common and many rare higher and lower plants recorded in British habitats. This package has been used in a range of different studies and ecosystems (De Vries et al., 2010; Smart et al., 2019; West et al., 2023). The model uses a small ensemble of five statistical methods (GLM, GAM, MARS, Neural Network and Random Forest models) to model the realised niche of individual plant species. The model requires seven inputs to each model for each species: three mean Ellenberg indicator values that equate with pH, soil moisture and fertility, cover-weighed vegetation height and three climate variables (minimum January and maximum July temperature, and total annual precipitation).

In this study, 'habitat suitability' refers specifically to the modelled favourability of ecological conditions as predicted by the MultiMOVE model for each species at each quadrat location. MultiMOVE was built by combining the environmental inputs (Ellenberg N, R and F values, canopy height/light environment and climate variables) to generate species-specific ecological response surfaces (Henrys et al., 2015; Smart et al., 2019). These are then used in predictive mode to estimate how closely local conditions match the modelled realised niche of each species. Habitat suitability therefore represents a predicted likelihood that environmental conditions at a given location fall within more or less favourable niche space. Because we do not explicitly model dispersal or establishment, 'habitat suitability' expresses how suitable conditions would be for the species if it could overcome these population-filters and establish within each location.

To be able to predict changes in habitat suitability from changes in measured soil conditions, we built statistical models of the relationship between the measured soil variables (% C, % N and soil pH) and the mean Ellenberg values calculated from the plant species composition within the transects. This resulted in transfer functions that could be used to convert measured soil variables across all transects, or theoretical margins based on future management scenarios, into the required Ellenberg scores used as MultiMOVE inputs. The transfer functions were generated using neural network models. This method was selected because of the need to optimise accuracy based on a small set of predictors with strong prior ecological justification for their inclusion. Model construction was achieved using the neural network R package (Venables & Ripley, 2002; West et al., 2023).

The cover-weighted canopy height expresses the successional stage of the vegetation (Henrys et al., 2015; Smart et al., 2010) and is calculated as follows: across the $i = 1$ to n species in each sample (Equation 1):

$$\text{Cover weighted canopy height} = \sum_{i=1}^{n} \frac{(\text{vegetative canopy height} \times \text{cover})}{\sum_{i=1}^{n} (\text{cover})} \quad (1)$$

The species % cover was recorded in each plot while average canopy height data were obtained from published sources (Hill et al., 2004; Stace, 1997).

The climate data (mean min January temperature, mean maximum July temperature and total annual rainfall) were extracted from HadUK/CHESS data using the XY coordinates for the site locations (Table 2).

2.3.1 | Modelling changes in soil conditions to achieve species-rich grassland

Conversion of improved grassland, the dominant initial crop margin habitat, to unimproved species-rich grassland requires reduced fertility and for target species to establish. The latter depends on available seed sources and availability of microsites for regeneration. While cutting and the introduction of seed was a feature of some field margins in the surveyed sample, the removal of cuttings was rare yet is critical if nutrient levels are to be lowered and to ensure that gaps in the sward are not smothered by cut vegetation. The impacts of plant material removal with zero fertiliser application were modelled to explore whether expected reductions in fertility would increase habitat suitability for desirable plant species over the long term bearing in mind the high residual fertility associated with former management as intensive arable or grassland.

TABLE 2 Average annual rainfall, mean minimum January temperature, mean maximum July temperature for each site extracted from HadUK/CHESS and mean soil parameters ± standard deviation required for MultiMOVE.

Crop	Farm	Location	Hectad	Precipitation (mm year^{-1})	Min temp in January (°C)	Max temp in July (°C)	Mean soil %C	Mean soil %N	Mean soil pH
Miscanthus									
	1	South-west England	ST22	981.986	2.392	21.806	2.40 (0.90)	0.22 (0.08)	5.95 (0.37)
	2	South-west England	ST12	1141.76	2.619	20.907	3.34 (0.57)	0.35 (0.06)	5.77 (0.15)
	3	South-west England	ST03	798.696	2.304	22.296	3.28 (1.12)	0.30 (0.10)	6.24 (0.39)
SRC willow									
	4	North-west England	NY52	962.703	0.858	20.511	1.55 (0.59)	0.13 (0.06)	6.4 (0.39)
	5	North-west England	NY34	882.276	0.881	20.661	2.22 (0.75)	0.18 (0.06)	7.14 (0.52)
	6	North-west England	NY12	875.077	1.464	20.120	3.27 (0.07)	0.32 (0.01)	5.59 (0.25)

Abbreviation: SRC willow, short rotation coppice willow.

Modelling fertility change, due to plant material removal, required assembling non-linear equations for the rate of change in key soil variables over time. The soil variables were % C, % N and soil pH since these are the inputs to the neural network models that translate soil variables into mean Ellenberg indices for input into MultiMOVE. There was not sufficient data from the survey sites to provide this information, therefore, literature was searched for long-term experiments, observations and modelling studies from which rates of change could be extracted. Three key data sources were used: Resch et al. (2021) which provided data on the impacts of hay cutting over 22 years on % C and soil pH, De Deyn et al. (2011) which provided data on the impact of hay cut in combination with or without seed addition on % C and % N, and Countryside Survey (a national monitoring programme of the countryside for Great Britain) which provided data on % C and soil pH (Table 3). Rates of change were used to parameterise simple asymptotic models as follows (Equation 2):

$$y = a - ((a - b).e(-c.x)) \quad (2)$$

where x = time in years, a = maximum value associated with the target vegetation type, b = intercept and therefore the value of the soil variable at baseline, and c = rate of change in y as x changes.

Starting values for soil were based on observed survey data from the crop margins, while the value for the target vegetation type was defined from a database of reference soil measurements for British plant communities (Critchley et al., 2002). Mean values of soil % C, % N and soil pH were extracted for samples located in vegetation referable to the MG5 lowland unimproved neutral grassland community (Rodwell et al., 1992). The model form ensures that all variables tend to plateau over time, reflecting observed long-term equilibration between inputs and outputs resulting from management (Poulton et al., 2018).

2.3.2 | Assessment of modelled change in plant species composition

We assembled predictions of change in habitat suitability over time for species routinely included in the GS4 neutral grassland creation seed mixes (Table 1). While constituents vary slightly between seed mixes, the species chosen encompassed the principal forbs and grasses that would be expected to be present and persist in a successfully established unimproved neutral grassland in lowland Britain.

In addition, we extracted modelled change in habitat suitability for injurious weeds (Maskell et al., 2020), foodplants for butterfly larvae (Smart et al., 2000) and nectar-producing forbs (Baude et al., 2016).

2.4 | Modelling management scenarios

The modelled baseline represents the observed environmental and climatic conditions in 2023. We then defined scenarios of change in

TABLE 3 Details of the data sources used to build models of change in soil conditions in response to long-term species-rich grassland restoration.

Study n°	Source study	Length of experiment or observation period (years)	Intervention	Soil variables for which rate of change over time was extracted
1	Resch et al. (2021)	22	Hay cut	% C, soil pH
2	De Deyn et al. (2011)	16	Hay cut (±seed addition)	% C, % N
3	Countryside Survey	9	Not known but assumed to be extensification under agri-environment options	% C, soil pH

TABLE 4 List of scenarios and the parameter change on MultiMOVE model for crop margins management.

Scenarios	Details	MultiMOVE parameter change
Standard minimal management	Sites are just cut (cut at about 30 cm) each year to keep them from getting too tall or shrubs from establishing. All material is left on site.	Vegetation height set at baseline observed values since all were under perennial grass vegetation.
Plant material removal	With zero fertiliser application.	Reduce soil fertility.
Crop margin width	Margin with standard minimal management but different width, varying from 2 to 8 m. Narrow margins will be heavily shaded by perennial biomass crops and field boundaries (especially if these are hedges).	Effect of shade on narrow margins applied by setting vegetation height to 2 to 3 m throughout the time period.
Sowing crop margins	Margins are sown with grass and flower mix seeds.	Soil variables (% C, % N, soil pH) change over time according to the trajectories modelled using four observed time series.

the model inputs (soil conditions and vegetation height) representing the impact of management change in miscanthus and SRC willow plantations over the 25 years life span of these crops (in 5-year intervals). The interventions can be found in Table 4. Scenarios were explored individually and in combination with plant material removal, as past studies suggest this action is likely critical in lowering soil fertility and sufficiently opening the sward to allow the establishment of the desired species-rich grassland contained within the SFI seed mixes (Natural England, 2010).

Values of each soil variable were then converted using the transfer functions into the change in mean Ellenberg indices between each time step that should be added or subtracted from the baseline values. The resulting set of baseline and 5-yearly values of each mean Ellenberg index gave the input data required to solve MultiMOVE at each time step. Adding in local climate data and vegetation height completed the inputs required to drive change in habitat suitability for plant species at each location over time.

The cover-weighted vegetation canopy height input to MultiMOVE was set throughout the time period at the observed baseline value or increased to a range of between 2 and 3 m to simulate shading in narrow field margins.

When modelling change in plant diversity within the SRC willow, we required predictions of change in soil conditions as a result of incorporation of organic matter from the crop. Available miscanthus and SRC willow studies could not provide the required information regarding how % C, % N and soil pH change over the long term, due to limitations in study duration and high levels of between-site variability. To approximate these effects, we used soil transition models of the effect of woodland planting and succession on arable and improved grasslands applied previously when exploring the effects of agri-environment options (Harrison et al., 2023). We did not carry out any model exploration of management options within miscanthus.

3 | RESULTS

Across all the survey sites, minimally managed crop margins were dominated by competitive grass species with injurious weeds present at all sites. Species diversity under the different management options was highly variable across the sites providing a diverse baseline for the modelling activities. Nectar plants already present and most common on each site included *Taraxacum agg.*, *Cerastium fontanum*, *Trifolium pratense*, *Trifolium repens*, *Ranunculus repens*, *R. acris*, *Achillea millefolium* and *Leucanthemum vulgare*. Butterfly larval foodplants common on the sites included *Cirsium* spp., *Urtica dioica*, common grass species and most of the nectar plants above.

3.1 | Baseline model performance

To evaluate the performance of the MultiMOVE model in predicting outcomes, we used the area under the curve (AUC) as a primary metric to compare predicted probabilities and observed outcomes.

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The AUC is a robust measure that captures the trade-off between sensitivity and specificity across various decision thresholds, providing an aggregate indicator of model performance.

Using the *proc* package in R, we calculated the AUC for the MultiMOVE model, which yielded a value of 0.8472 (~85%). This indicates a strong predictive ability, as AUC values closer to 1.0 represent better discrimination between positive and negative outcomes (Figure S1). To assess model calibration, predicted probabilities were binned (e.g. in 0.1 intervals), and the proportion of quadrats with observed species presence was calculated within each bin. These proportions were plotted as a red line over the histogram to illustrate how well predicted probabilities correspond to actual outcomes (example of predictive performance for individual species is shown in Figure 1). This figure shows the number of absences and presences for each of the five most frequent species alongside the modelled curve, while the rank of 27 top species in terms of habitat suitability in the baseline is shown in Figure S2.

3.2 | Trajectories of change in soil variables

Evidence from the three data sources indicated positive effects of the extensifying management on all three soil variables but with varying rates of change over time (Figure 2). As noted by De Deyn et al. (2011), the introduction of seed (*Trifolium pratense*) in their experiment had positive plant–soil feedback on soil carbon concentration; hence, rates of change in % C and % N were greater in this treatment. Because seed has been deliberately introduced at some of the perennial biomass crop margin locations, we can usefully apply the parameters from the De Deyn et al. (2011) experiment, with or without seed introduction, to the perennial biomass crop margins to determine whether establishment of introduced species, particularly legumes, might enhance the rate of accumulation of carbon and have a positive impact on modelled habitat suitability for the target grassland species. Note that the GS4 seed mixes introduced into some of the sites comprise at least one of the legumes *Vicia sepium*, *Lotus corniculatus* or *T. pratense*.

The De Deyn et al. (2011) experiment was the only one from which we could extract changes in % N. In that study, % N increased over time. In the two studies with available data, soil pH was also found to increase (Figure 2).

These trajectories of change were translated into rates of change in mean Ellenberg values for N and R (Equation 2) and then used to adjust baseline observed data from each site over the 25-year period, thereby changing habitat suitability for the target plant species groups. Because we have at most four sources of data on how soils change in response to the plant material cutting and no fertiliser intervention within crop margins, these four separate models were used to generate four separate predictions of plant species. Hence, the legend in each graph refers to a modelled change in habitat suitability driven by the rates of soil change found in each study and data source. Between them, these data sources convey the uncertainty

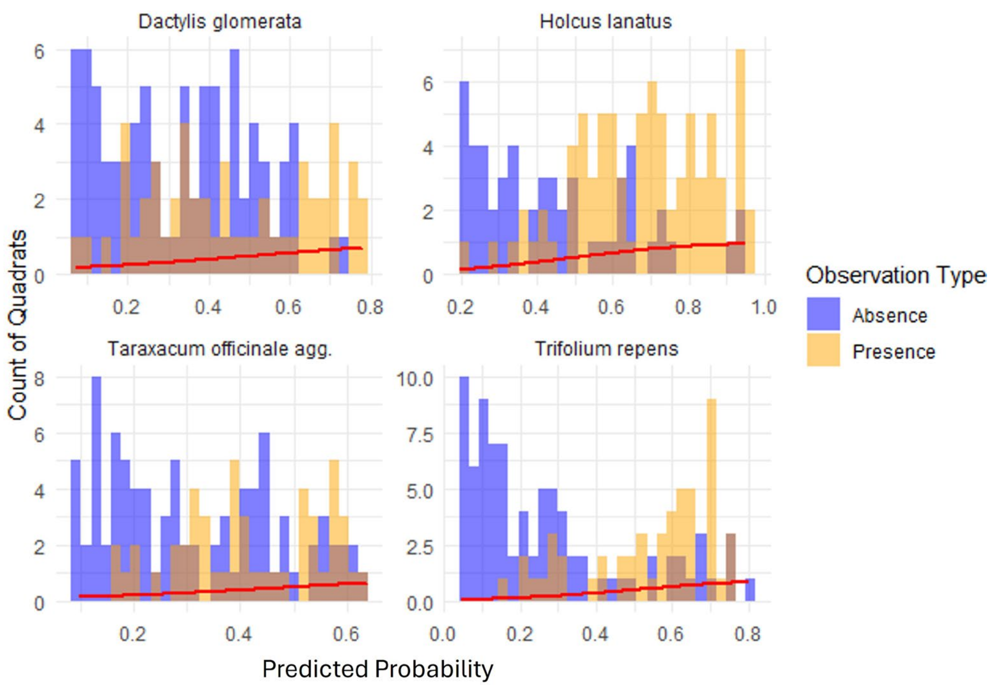

FIGURE 1 Relationship between predicted probability of species presence and observed quadrat counts for the top four most common species. Each panel shows the number of quadrats grouped into predicted probability bins, with bars coloured by observed absence (blue bars) and presence (orange bars). The red line the empirical probability of presence within each bin, calculated as the proportion of quadrats where the species was observed. This line is plotted on the same x-axis and reflects model calibration, indicating how well predicted probabilities align with observed outcomes. Predicted probabilities range from 0 (unlikely presence) to 1 (highly likely presence). y-axis scales vary by species; the maximum quadrat count per bin is indicated for each panel.

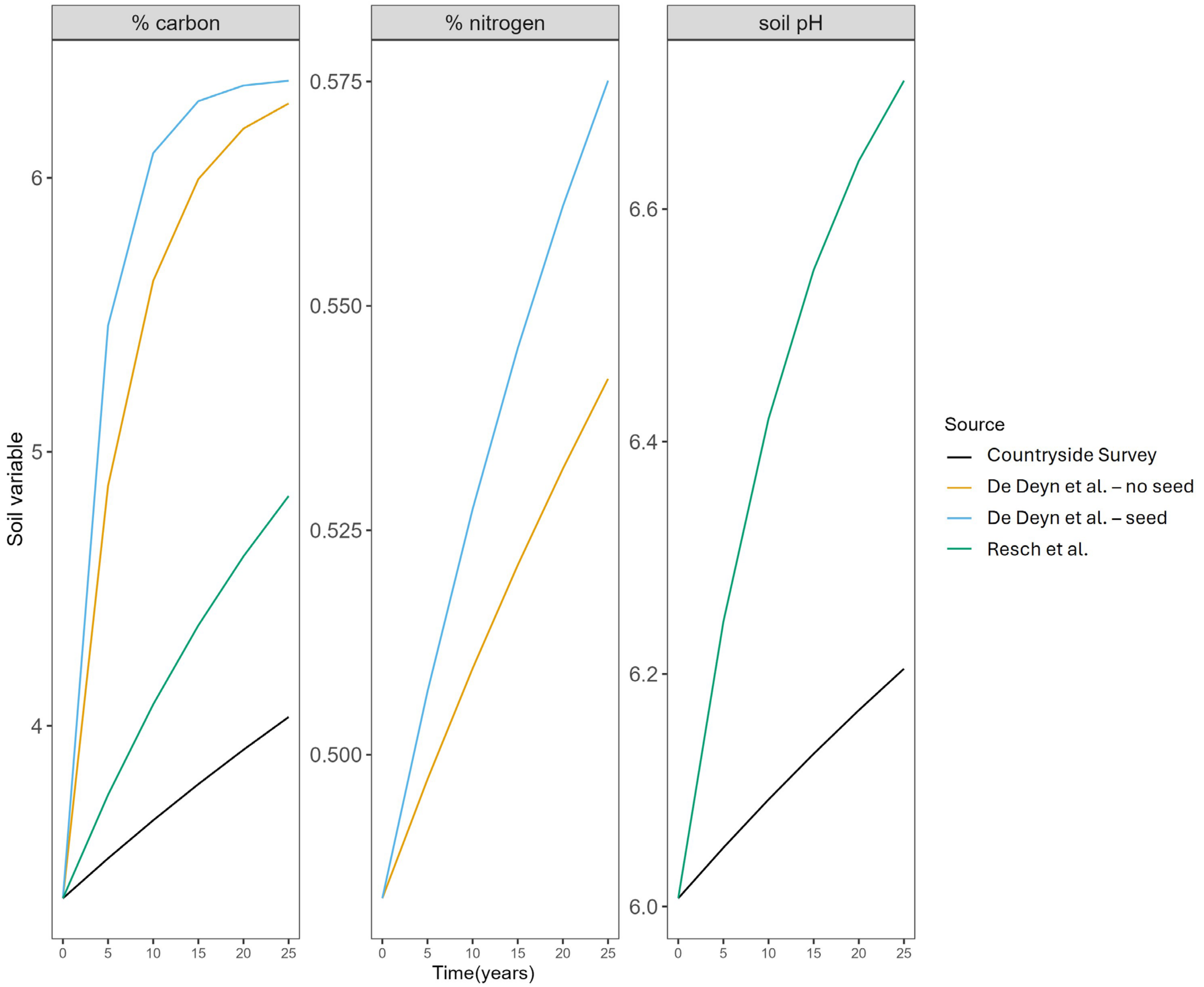

FIGURE 2 Predicted change in soil variables based on solving the non-linear models where each was parameterised using rates of soil change from each of the study sources in Table 3 above. Countryside Survey refers to extensification under agri-environment options. De Deyn et al.—no seed and De Deyn et al.—seed refer to model results based on plant material removal without and with the addition of legumes. Resch et al. refers to plant material removal treatment.

expected in how soil conditions change as plant material removal is applied over the long term in order to restore species-rich grassland.

3.3 | Predictions of change in plant biodiversity over perennial biomass crop lifetime

3.3.1 | No management other than cutting

In interpreting these outputs, it is important to note that 'habitat suitability' reflects the predicted favourability of conditions for the species to occur and persist. It is not a prediction of abundance or cover.

Only in the cutting scenario were injurious weeds expected to decline in habitat suitability over time. In the majority of scenarios, they were predicted to increase in the first 5 years and stabilise or decline thereafter (Figure S3). *Rumex obtusifolius* and *Cirsium arvense* had the highest mean habitat suitability consistent with their high frequency in the survey data; however, the wide standard deviations indicate how variable the habitat suitability predictions were across the quadrats and sites.

Grass species included in the introduced seed mix composition were predicted to increase or decrease slightly between baseline and year 5 and then remain largely stable over time (Figure S4). Again, the two species with the highest predicted habitat suitability, *Dactylis glomerata* and *Lolium perenne*, were the most common in the surveyed margins and indicate more fertile conditions relative to the grasses *Festuca rubra*, *Alopecurus pratensis* and *Poa pratensis* that, while still wide-ranging in their preferences, have ecological optima in slightly less-fertile conditions.

Forb species included in the seed mixes were predicted to see small increases or stability in habitat suitability (Figures S5 and S6). However, relative to those seed mix grasses that were most likely to find conditions suitable in the margins, most forbs had lower average habitat suitability values, with *Leucanthemum vulgare*, *Achillea millefolium* and *Trifolium pratense* predicted to be the most suitable in descending order, followed by *Centaurea nigra* and *Lotus corniculatus* (compare the y-axis in Figure S4 with those in Figures S5 and S6). The predicted richness of nectar-yielding forbs and butterfly-larval foodplants over time was uncertain. In three of the four soil change scenarios, richness of nectar plants was forecast to increase above the baseline by at most one species per 2×2 m unit area (Figure S7). In two of the four scenarios of soil change, butterfly–larval foodplants were expected to increase in richness and then decline slowly (Figure S8).

3.3.2 | Impact of plant material removal in habitat suitability

Most of the common nectar plants were predicted to be positively impacted by the plant material removal regime in unshaded margins with *Taraxacum*, a relatively high nectar yielding species, predicted to increase at all sites where it occurred. *Cerastium fontanum* was also predicted to increase at farms n° 1, 2 and 6, as was the meadow indicator *Lotus corniculatus* at farm n° 6. The relatively high-yielding nectar plants *Trifolium pratense* and *Leucanthemum vulgare* had high habitat suitability at all sites and should also benefit from assisted dispersal in the cut margins. Being a taller species, *L. vulgare* was also expected to thrive in the more shaded margins.

3.3.3 | Modelling vegetation development in the narrow, shaded margins

Here we assume that all margins are narrow enough to be significantly shaded by the adjacent crop. We simulate this by increasing canopy height values input to MultiMOVE to 2 to 3 m but apply the same soil change trajectories as above in response to expected plant material removal. Injurious weeds and most of the seed mix species are predicted to find conditions less suitable over time with an abrupt decline between baseline and year 5 (Figure 3). The nectar plants *Taraxacum*, *Cerastium fontanum*, *Lotus corniculatus*, *Trifolium pratense* and *Achillea millefolium* are all predicted to do less well in shaded margins. *Leucanthemum vulgare*, a species capable of persisting in tall grassland and scrub, saw the smallest decline in habitat suitability with greater shade (Figure 3c), while *Vicia sepium*, a more shade-tolerant forb of woodland edges and rides and taller grassland, was expected to find shaded conditions somewhat more favourable (Figure 3d). Other more shade-tolerant and taller species were also predicted to do well with increasing shade, including *Urtica dioica*, *Rubus fruticosus* agg. and the common, grazing intolerant grass *Arrhenatherum elatius*.

Shading is predicted to enhance nectar-plant richness by just over one species per 2×2 m unit area while butterfly–larval foodplant richness declines by the same amount (Figure 4b vs. 4a). The increased shade, however, drives species-compositional turnover so that different species are favoured in the shaded margins than those that are expected to do well in unshaded margins.

4 | DISCUSSION

4.1 | Magnitude of modelled change in response to management

We explored three main scenarios of management intervention: plant material removal with zero inputs in margins that were either narrow and shaded or unshaded, and the response of plant diversity under these conditions. Across all scenarios, the short-term outcomes of current management were characterised by rapid, but modest changes in soil conditions and corresponding shifts in habitat suitability. Predicted changes in habitat suitability were greatest between baseline and year 5, reflecting the faster early-stage response of soils to altered management before trajectories plateau.

Under current practice (annual cutting without fertility reduction), our modelling indicates that margins remain dominated by competitive grasses and injurious weeds, with limited improvement in suitability for target forb species. This aligns with field observations. Thus, short-term outcomes of current management include increased suitability for weeds and only small gains for nectar plants or seed-mix grasses, while long-term outcomes show little improvement in conditions required for species-rich grassland establishment.

The shaded condition of narrow margins acts as a strong driver of change in habitat suitability. We predict less favourable conditions for shade-intolerant, shorter grassland species and a positive response from taller, shade-tolerant species. Most indicators of semi to unimproved species-rich grasslands, including those in SFI seed mixes, were expected to decline under greater shade. In wider margins, different species are filtered by the patchwork of conditions from unshaded margins through to the dense crop which can increase total site-level diversity (Boinot & Alignier, 2023; Poinas et al., 2023). However, discussions with biomass industry leaders and field experience indicate that, with the removal of the biomass planting grant, which required wide margins (Department for Energy Security & Net Zero, 2025), growers are increasingly minimising margin width to maximise crop yield, especially in miscanthus, where machinery access is less limiting. This trend towards narrower margins is concerning as well-established miscanthus fields have a notably low weed cover within the crop (Dauber et al., 2015), meaning that margins play a disproportionately important role in maintaining biodiversity.

Field survey results highlighted that most observed species were common plants of fertile agro-ecosystems. This supports the rationale for introducing species via seed mixes; however, our results also highlight that current management alone is insufficient to support the long-term persistence of these species. Few sites are currently undertaking actions to reduce fertility. Our modelling suggests that without such interventions, the establishment

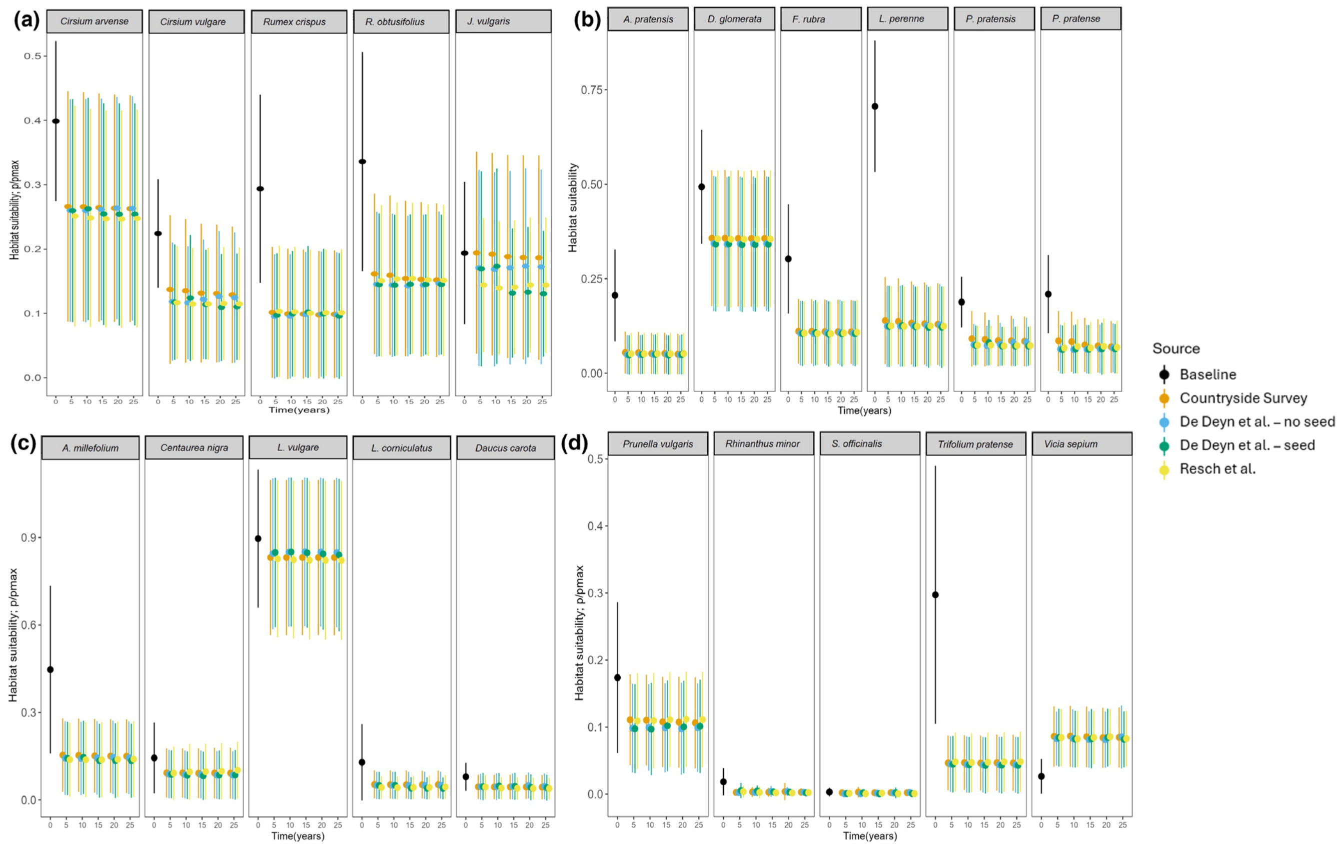

FIGURE 3 Habitat suitability for (a) injurious weeds, (b) seed-mixes grass, (c) seed-mixes forbs and (d) seed-mixes forbs in narrow shaded margins. Mean (±1 SD). The baseline is the observed values. Countryside Survey refers to extensification under agri-environment options, De Deyn et al.—no seed and De Deyn et al.—seed refer to model results based on plant material removal without and with the addition of legumes, Resch et al. refers to plant material removal treatment.

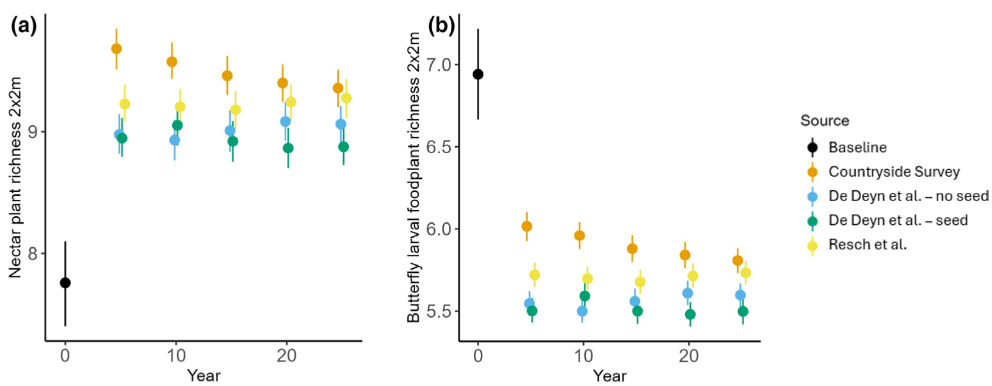

FIGURE 4 Predicted (a) nectar plant richness and (b) butterfly larval foodplant richness in narrow, shaded margins. Mean (± bootstrapped 95% CI). The baseline is the observed values. Countryside survey refers to extensification under agri-environment options, De Deyn et al.—no seed and De Deyn et al.—seed refer to model results based on plant material removal without and with the addition of legumes, Resch et al. refers to plant material treatment.

of forb-rich assemblages remains unlikely. Where plant material removal is employed, habitat suitability for many seed mix forbs was predicted to increase slightly in unshaded margins. This suggests that fertility reduction is worthwhile, but expectations should remain modest, particularly in high-fertility sites. Variation in modelled habitat suitability between and within sites suggests that targeting, using vegetation indices or soil sampling, could identify margins most likely to respond positively. In sites with high residual fertility, it may be more effective to consider alternative bespoke seed mixes, either alone or combined with routine herbicides use or tillage to maintain persistence (Fabšičová et al., 2024).

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Where plant material removal is employed, changes in habitat suitability for favourable species also increase suitability for many perennial grasses and injurious weeds. This suggests that vigilance and additional management are required to reduce their vigour and maintain the persistence of grassland forbs. Management that decreases fertility in already high-fertile and species-poor systems can increase weed growth because these opportunists exploit the increased availability of gaps, essentially a vacant regeneration niche, when perennial grasses are reduced in vigour (Doring et al., 2017).

There was no evidence that the positive plant–soil feedback from seed introduction (De Deyn et al., 2011) would substantially elevate habitat suitability in these systems, likely because most sites began with high fertility associated with previous intensive management.

A distinction between margins around tall perennial bioenergy crops and those in conventional arable or grassland systems lies in their disturbance regimes and level of shading. Margins adjacent to annual arable crops are typically exposed to regular disturbance through tillage, machinery turning on headlands, or targeted weed control. These actions periodically reset vegetation, reduce shading and create opportunities for colonisation by desirable species.

Margins around tall perennial crops such as miscanthus or SRC willow often experience very limited disturbance once the crop is established. These systems are intentionally managed as low-input, low-maintenance enterprises, with limited or no management required post establishment except for harvest operations, which typically occur annually or every 3 years depending on the crop. Combined with practical constraints of assessing margins: restricted access beside tall stands, inefficiency of transporting equipment solely to treat small areas and risk of damaging the crop margins commonly remain undisturbed for many years, allowing persistent shading, slow turnover of vegetation and long-term dominance of competitive or injurious weeds.

In contrast to margins adjacent to conventional crops, they are generally more accessible, and crop management is more intense. Consequently, they experience a greater frequency of disturbance, or at least a greater potential for disturbance through tillage, machinery turning on headlands or targeted weed control. In addition, where proactive margin management is required, additional disturbance can be readily implemented. These actions can periodically reset vegetation, reduce shading and create opportunities for colonisation by desirable species.

Thus, while issues such as high soil fertility, injurious weeds and slow establishment of desirable species are shared across farmland margins, the combination of shading and lack of disturbance is characteristic of bioenergy systems. This distinction is important for policy makers because it suggests that without explicit support or requirements from agri-environment schemes, management interventions are less likely to occur.

4.2 | Other management options

A significant barrier to establishment of species-rich grassland assemblages is the high residual fertility associated with persistent perennial grasses. Soil inversion (Glen et al., 2017; Milligan et al., 2017) offers a novel option for creating lower-fertility substrates more suitable for target species, though it must be implemented without compromising crop operations. Here, shallow excavation is used to invert surface soil horizons, burying but often not completely eradicating surface vegetation and exposing colonisable substrate less rich in N and P, and so more suitable for the persistence of target species suited to lower fertility. Our modelling shows that many seed mix grasses have higher habitat suitability than the seed mix forbs, even after 25 years of plant material removal. A benefit of soil inversion is that it can be done infrequently relative to annual plant material removal, but it would need to be done in a way that did not compromise crop management activity. The type of plant assemblages initiated would require native seed mix addition but might develop to be quite different to species-rich grassland, requiring an adjustment in the target vegetation type sought.

Bringing together the survey and modelling work with expert opinion, we synthesised findings into management pathways (Figure 5). These management pathways presented in Figure 5 require verification but provide a high-level summary of the key decisions and likely outcomes related to perennial biomass crop management with regard to biodiversity. Fertility levels are a key factor. These pathways emphasise that alternative management options combining fertility reduction, assisted introduction of forb species and retention or creation of wider margins offer the greater biodiversity benefits.

Margins with low fertility or reduced fertility can be managed towards semi-natural grasslands, while high-fertility sites may be better suited to resource-rich margins with regular sowing. In both cases, the absence of management actions results in reduced biodiversity value, particularly in high-fertility sites where unmanaged margins become dominated by a few competitive grasses.

5 | CONCLUSIONS

We found that under current practice (annual cutting with no fertility reduction), margins remain dominated by competitive grasses and injurious weeds, with very limited establishment of target forb species, as shown in the survey data. Model projections indicate that in the short-term, habitat suitability for injurious weeds increases or remains high, while suitability for most forb-rich grassland species remains low. Over the long term, soil fertility declines only marginally, meaning that habitat suitability for target grassland forbs changes little and species-rich assemblages are unlikely to establish without intervention. Narrow, shaded margins further reduce suitability for light-demanding species, reinforcing the limited biodiversity value of current management.

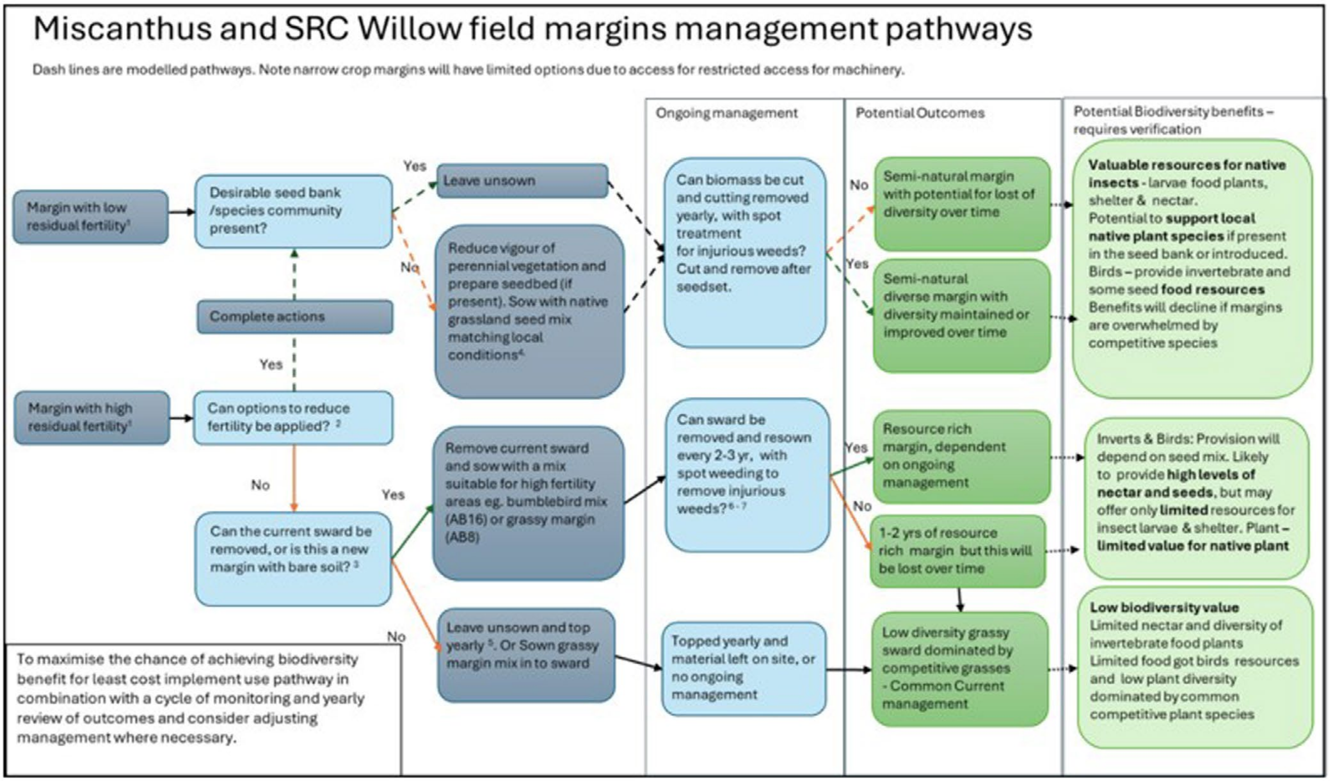

FIGURE 5 Management pathways for miscanthus and SRC willow crop margins. (1) Can be assessed based on knowledge of past fertiliser application and presence of high nutrient indicator species for example a good guide to improved, highly fertile conditions are where nutrient-loving grasses and forbs such as perennial ryegrass, cocksfoot, creeping bent, creeping buttercup and white clover occupy over 25% cover accompanied by few other forb species. (2) Options to reduce fertility may include repeated cutting and removal of plant material, with or without the use of catch crops, soil inversion to expose lower fertility soil horizons and bury existing perennial vegetation. Note these options may not effectively reduce fertility in sites with seasonal flooding. (3) Herbicide or disking can be used to remove the current sward. This action is required to provide a suitable condition for desirable species to establish. (4) Herbicide or disking can be used to remove the current sward or harrowing and sowing in the hemi-parasite yellow rattle to debilitate perennial grass cover. (5) In new margins with bare soil sowing of a mixed grass and forb community is advised to provide year-round soil cover, especially important where margins will be subject to vehicle traffic during harvesting. (6) In sites subject to regular flooding (due to flood tolerance, perennial biomass crops maybe selectively planted in flood prone fields), the benefits of resowing will need to be balanced against the risk of soil erosion and compaction associated with sward removal. The method used and timing should be carefully considered to limit risks; we suggest exploring bespoke management options for these margins (see future work). (7) With regular resowing required, this option will have ongoing costs, but benefits will only be maintained through continual active management.

The most effective interventions combine fertility reduction, wider margins and assisted introduction of forb species. Repeated cutting and removal of plant material improve habitat suitability for many nectar plants and several seed-mix forbs, although gains are gradual and strongly site-dependent. Wider, unshaded margins provide the most favourable conditions for establishing species-rich grassland assemblages, whereas narrow shaded margins favour tall, shade-tolerant species and reduce suitability for most target forbs. Additional options such as soil inversion may be appropriate in high-fertility sites where conventional restoration is unlikely to succeed.

Effective biodiversity enhancement around perennial biomass crops requires moving beyond minimal management. The most promising pathway combines targeted fertility reduction, retention or creation of wider margins, and active introduction of forb species. While restoration of species-rich grasslands may be slow and site-dependent, these interventions offer a viable route to improving plant diversity and supporting long-term biodiversity goals in perennial biomass crop landscapes.

AUTHOR CONTRIBUTIONS

Simon M. Smart: Writing—review and editing, writing—original draft, visualisation, validation, methodology, investigation, formal analysis and data curation. **Arlete S. Barneze:** Writing—review and editing, writing—original draft, visualisation, validation, methodology, investigation, formal analysis and data curation. **Ellen Lamborn:** Writing—review and editing, writing—original draft, visualisation, validation, project administration, methodology, investigation, formal analysis and data curation. **Naomi Jones:** Writing—review and editing, visualisation, validation, methodology, funding acquisition, investigation, formal analysis and data curation. **Rebecca L. Rowe:** Writing—review and editing, writing—original draft, methodology, investigation, data curation, project administration, funding acquisition and supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

MultiMOVE modelling code used can be found in https://doi.org/10.5281/zenodo.22044099 (Barneze & Smart, 2026).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Figure S1. Smoothed relationship between predicted probabilities and observed outcomes, illustrating how well the model's predictions align with actual presence/absence in the baseline scenario using MultiMOVE model.

Figure S2. Rank of the 27 top species in terms of predicted habitat suitability in the baseline using MultiMOVE model.

Figure S3. Predicted habitat suitability for injurious weeds in unshaded crop margins based on the four potential trajectories of change in soil parameters.

Figure S4. Habitat suitability for seed mix grasses in unshaded crop margins.

Figure S5. Habitat suitability for seed mix forbs in unshaded crop margins.

Figure S6. Habitat suitability for seed mix forbs in unshaded crop margins.

Figure S7. Predicted Nectar plant richness in unshaded crop margins.

Figure S8. Predicted Butterfly larval foodplant richness in unshaded crop margins.

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