Use of atypical plant resources for cattle farming in Western Europe to drive agroecological transition

Thomas Puech, Anne Farruggia, Daphné Durant, Jean-Francois Glinec, Sandra Novak, Frédéric Signoret, Fabien Stark, Damaris Sterling

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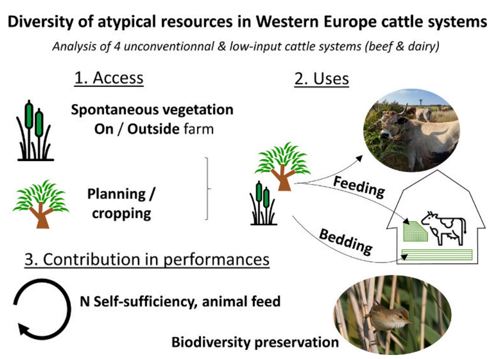
T. Puech[a,*], A. Farruggia[b], D. Durant[b], J.F. Glinec[c], S. Novak[d], F. Signoret[e], F. Stark[f], D. Sterling[a,b]

[a] UR ASTER, INRAE, 88500 Mirecourt, France
[b] UE DSLP, INRAE, 17450 Saint-Laurent-de-la-Prée, France
[c] GAEC de Trévarn, 29800 Saint-Urbain, France
[d] INRAE, FERLUS, 86600 Lusignan, France
[e] GAEC de La Barge, 85690 Notre-Dame-des-Monts, France
[f] SELMET, Institut Agro - Montpellier, Montpellier University, INRAE, CIRAD, 34060 Montpellier, France

HIGHLIGHTS

- We analyse the use of atypical resources in 4 low-input cattle farming systems in Western Europe.
- There is a wide range of atypical resources that can be used in livestock farming for animal feed and/or bedding.
- These atypical resources can make a significant contribution to the N metabolism and self-sufficiency of cattle systems.
- These resources contribute to biodiversity preservation and can help livestock farming systems adapt to global changes.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: In the efforts to optimize their production processes and yields, livestock systems overlook less productive on-farm areas and resources. Given the challenges of feed self-sufficiency, climate change mitigation and adaptation, and biodiversity conservation, it makes sense to revalue these resources to support agroecological transition in livestock systems.
OBJECTIVE: This paper introduces the concept of 'atypical resources', defined as plant resources that are part of the farm environment but are not conventionally used. The aim is to explore their nature, access, use and potential contribution to the performance of livestock systems.
METHODS: The study examines four unique and under-researched cattle farming systems (dairy or beef) using atypical resources in Western France through comprehensive analysis, and assessment of nitrogen metabolism.
RESULTS AND CONCLUSIONS: Our results show a rich diversity of atypical resources such as abandoned land, hedgerow slopes, woody leaves, ditch bottoms and marsh reeds. These resources, coming from the farms

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* Corresponding author at: UR ASTER, 662 Av. Louis BUFFET, 88500 Mirecourt, France.
E-mail address: thomas.puech@inrae.fr (T. Puech).

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themselves or their surroundings, are used for animal feed and/or bedding. The contribution of atypical resources in the nitrogen metabolism of the system ranges from almost 0 % to 12 %, while their contribution to animal feed varies for almost 0 % to 29 %. In addition, the management practices and grassland-based farming systems associated with these resources may limit N waste, preserve habitats and enhance biodiversity.
SIGNIFICANCE: This article examines an under-explored but critical issue that is essential to address the current challenges of livestock systems in Western Europe. We advocate for further research to generate knowledge and methods that harness the multiple services provided by atypical resources, thereby facilitating agroecological transition and addressing spatial management challenges.

1. Introduction

Since the second half of the 20th century, progressive specialization of agriculture in Western Europe has gradually disconnected crop and livestock farming (Billen et al., 2014). The specialized agriculture model relies heavily on the use of chemical inputs, fossil fuels and import of protein feed (Cordell and White, 2011; Pinsard, 2022). Climate change challenges agricultural systems, both in terms of mitigation (Arneth et al., 2019) and adaptation, while ensuring global food security (Barbieri et al., 2022; Benoit and Mottet, 2023; Lee et al., 2023). Some livestock systems (grass-based or crop-livestock) are widely recognized by the scientific community as relevant models for the agroecological transition (Altieri et al., 2012; Therond et al., 2017). However, these livestock systems, based on utilizing grassland and semi-natural areas, are particularly vulnerable to climate change. Eisler et al. (2014) proposed various strategies for adapting livestock systems, including the use of resources derived from the local environment of farms. This type of resources is already used for ruminant farming in various 'pastoral' regions with strong pedoclimatic constraints (Jouven et al., 2010). Conversely, these spaces, considered unsuitable in the productivist paradigm, have been either artificialized or abandoned by farmers and thus ignored by agricultural research and development. Indeed, there is little mention of these resources in specialized livestock regions across much of Western Europe, where the majority of fodder comes from temporary grasslands or dedicated annual feed crops (maize, cereals, legumes). However, the perspectives of agroecological transition of these systems (Sijpestijn et al., 2022; Tomich et al., 2011) raise the opportunity for developing pastoral practices to use resources that are part of the natural environment (trees, hedgerows, moors, marshes, etc.) of farms. Currently, this environment is generally managed independently of production systems and is perceived as unproductive (or even counterproductive) in the intensification and optimization paradigm. While much research focuses on how livestock practices can adapt to climate change, these resources and associated farming practices are generally excluded from agronomy or animal science research. Consequently, we have limited understanding of their characteristics and how farmers use them (Girard and Alavoine-Mornas, 2014).

This paper introduces the concept of 'atypical resource', which we define as the set of plant resources that are part of farms environment (including surroundings). The term 'atypical' is a relative concept, as atypicality can refer either to the nature of the resources themselves or to current practices in a given area (or a given period), which may be common to other ones.

This study aims to (i) explore the nature of several atypical plant resources in the context of livestock production in Western Europe, (ii) understand their various uses, and (iii) quantify their contribution to performances of livestock systems using a system metabolism approach based on nitrogen flows. It is based on four farming systems already using atypical resources and therefore not representative of the dominant livestock systems in Western Europe.

2. Material and methods

2.1. Description of the four studied farms

This study is based on two commercial farms and two INRAE experimental farms implementing a system experiment (Meynard et al., 2012). Two farms manage a dairy herd: Trévarn farm located in Brittany (73 ha of permanent grassland, 74 crossbred Holstein x New Zealand cows; hereafter referred to as "*Dairy 1*"), and the OasYs experimental farm ("*Dairy 2*") located in the Poitou (61 ha of temporary grassland, 30 ha of annual forage crops, 72 crossbred Holstein x Scandinavian Red x Jersey dairy cows). The other two farms are located in marshland areas of the Atlantic coast and manage a local-breed suckler herd called "Maraîchine": La Barge farm (147 ha of permanent grassland, 10 ha of alfalfa, 50 adult cows; "*Suckler 1*") and the Transi'marsh experimental farm on INRAE Saint-Laurent-de-la-Prée (100 ha of permanent grassland, 60 ha of crops, 45 adult cows; "*Suckler 2*"). Dairy 2 operates at low input levels, and the other three farms are organic (Mondière et al., 2024; Novak et al., 2022). Dairy 1 and Suckler 1 are grass-based systems and have long integrated atypical resources into their management system (Glinec, 2019). Dairy 2 and Suckler 2 are crop-livestock systems on which the introduction of atypical resources remains relatively marginal but structures the research project strategies (Durant et al., 2020, 2021; Mesbahi et al., 2022).

These farms were chosen because they use different kinds of local botanical resources, allowing us to explore a range of resources and farming practices associated. Farms are also not representative of the dominant systems, as (i) they have little if any dependence on inputs (mineral fertilizers, fodder), (ii) their production process depends on the use of atypical resources and (iii) the genetic make-up of the animals has been adapted to the specific nature of the resources used (whether dairy or suckling). We acknowledge that the relatively generic scope of this work comes not so much from the sample studied but from (i) the diversity of atypical resources, farming practices, and associated performances covered, and (ii) the issues and challenges that livestock systems face.

2.2. Combining different approaches to analyse the systems

2.2.1. Participatory observation to 'understand' how farms operate and how farmers use atypical resources

We used participant observation (Perrin, 2021) to analyse livestock practices, particularly those related to the nature and usage of atypical resources. This method of immersion in farms' daily life and interaction with the farm managers (over a one-week period per farm) enabled us to collect the elements necessary to understand their management processes and farmers' motivations. One of the main advantages of participatory observation is its ability to alternate between formal periods of inquiry (1 to 2 h per day) and informal understanding within the daily life of the farm (Perrin, 2021). Participant observation aimed to gather information on: farmers' motivation to use atypical resources, nature and use of these atypical resources, their production system to conduct a functional analysis of agricultural operations (Moulin et al., 2001) and finally, quantitative data to analyse the metabolism of each system.

2.2.2. System metabolism analysis on farm management and the role of atypical resources

We conducted a system metabolism analysis using a common conceptual model (Fig. A in Appendix 1) for each farm in 2022, in order to quantify the systems' performances and especially the role of atypical resources. All material flows are expressed in nitrogen (N) as N is widely used to analyse the metabolism of agricultural systems (Garnier et al., 2016; Stark et al., 2016; Steinmetz et al., 2021; Tedesco et al., 2017) and it is one of the main limiting factors in extensive systems such as those studied here (Barbieri et al., 2021; Morais et al., 2021).

Technical N performances were studied on the basis of metabolic analysis through Ecological Network Analysis indicators (ENA - Latham, 2006; Ulanowicz et al., 2009) and metrics conventionally used in agronomy (productivity, efficiency – Puech and Stark, 2023). Details are presented in Appendix 1. Indicators calculated give an account of:

- System activity. This metric, derived from ENA, accounts for all the N circulating in the system.
- System self-sufficiency. Self-sufficiency is calculated on the basis of an indicator of the circularity of N flows from the ENA.
- Inputs. N inputs are broken down into three categories: inputs from (i) biological processes (symbiotic fixation) and atmospheric deposits, (ii) mineral fertilization and (iii) purchases of organic matter, which in the situations studied consist almost exclusively of straw and feeds.
- Role of atypical resources. The influence of atypical resources on system functioning is assessed through two metrics: the proportion of atypical resources in the N metabolism of the systems (ARI - Atypical Resources Integration) and the proportion of atypical resources in animal feed (ARF - Atypical Resources for Feed).
- System productivity. Productivity is classically used in agronomy (Puech and Stark, 2023) to account for the production capacity of agricultural systems per agricultural area unit including atypical resources.
- Efficiency. Efficiency is calculated as metabolic N efficiency, i.e. the capacity of systems to produce in relation to system activity including flows associated with atypical resources. Metabolic efficiency is calculated as the sum of food output (milk, meat, grain) divided by system activity (Puech and Stark, 2023).
- Losses. N losses are a proxy for the environmental performance commonly used in agronomy.

3. Results

3.1. Atypical resources supply strategy

We identified three strategies (which can be combined) for characterizing atypical resources use. These strategies are based on both the nature of the atypical resources (botanical composition) and their location (within the farm or in its surrounding area).

- The first strategy employed by farmers is to use spontaneous vegetation present on their farm. These areas can be specifically managed (fenced off) to be used at specific periods. This strategy enables Suckler 1, and to a lesser extent Suckler 2, to take the most of the diversity of vegetations spontaneously growing in wetlands. These include hygrophilic meadows, characterized by prolonged immersion from winter to late spring, their more elevated ditch edges, which contain different vegetations depending on whether they are exposed to brackish water (e.g. *Agrostis stolonifera, Glyceria fluitans*) or fresh water (e.g. *Phragmites australis, Phalaris arundinacea*), and ditch bottoms featuring vegetations that is only accessible in summer or dry periods (e.g. *Ludwigia peploides, Atriplex halimus*). At Dairy 1, the vegetation of the hedgerow slopes is fully integrated into the grazing strategy. These hedgerow slopes are either protected to be exploited at a more ecologically-suitable season for plant growth, or grazed by animals according to the farmers' needs. They are maintained by manual clearing each year to preserve their ecological and forage functions. Finally, tree leaves (hedges, groves, or intra-plot agroforestry trees) constitute forage resources for the animals at Suckler 1, Dairy 1, and Dairy 2 farms.
- The second strategy is to use atypical resources located outside the farm, in its surrounding area. These resources are not exploited or have even been left abandoned by other actors. For example, cattle graze the edges of roads or along ditches or hedges (Suckler 1). Farmers mow unused reedbeds (Suckler 2) or low-productive natural meadows neglected by their neighbours (Dairy 1). These wet and sloping meadows of the Breton bocage are marginalized by dominant agricultural systems, because their strong natural constraints (slope, hydromorphy) make them difficult to artificialize.
- The third strategy is to crop atypical resources, as a voluntary, coherent and planned action. Woody fodder species constitute atypical resources for animals in Dairy 2, alongside temporary grasslands and dedicated annual fodder crops. Dairy 2 has planted a variety of woody plants (Novak et al., 2016, 2020), totalling 70 species of trees, shrubs, or vines, that are mainly woody plants for forage, pruned as pollards, coppiced, or pleached for direct grazing by animals.

3.2. Strategies for using atypical resources

Livestock farmers use these resources to provide a low-cost animal feed in time when 'conventional' resources are no longer available particularly during droughts, and/or for mulch in buildings, while preserving the habitats that support biodiversity on their farm or in their area. Three categories have been identified:

- The first strategy involves integrating atypical resources into grazing schedule to optimize forage availability throughout the grazing season. Farmers describe this grazing practice as the most economical, as it reduces mechanization costs.

This strategy is particularly well implemented at Suckler 1 (Fig. 1). In spring, animals graze only the highest permanent mesophilous meadows (non-flooded), while 11 ha of them and the elevated edges of hygrophilous meadow plots are fenced off to defer grazing until mid-summer. Towards the end of spring, 40 ha of unfenced hygrophilous meadows are grazed. In summer, the green and palatable vegetation of dry ditches, ditch edges and plots edges make up 10 % of the ration, while the flowering-stage grass on deferred areas that were fenced off from grazing in spring provides the remaining 90 %. In autumn, the animals graze the regrowth of all the meadows, while the ditches re-fill with water. This rigorous strategy of rotation grazing is organized using mobile fences. At Dairy 2, the strategy is to graze the woody plants in the agroforestry system in summer or early autumn, when there is no more

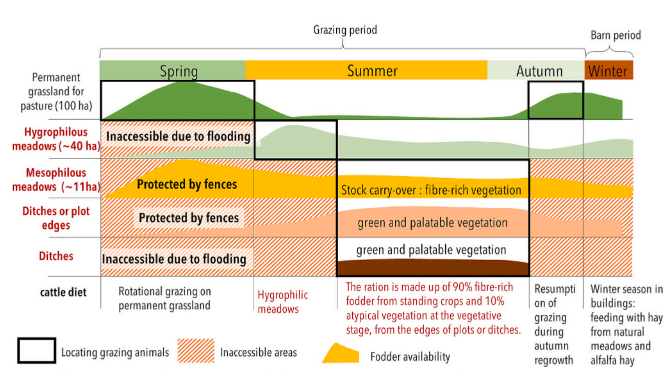

Fig. 1. Feeding sequences at Suckler 1 according to type of resources, availability, accessibility and localization.

grass in the pastures. Trees and shrubs, arranged in hedges or lines within the plots, are protected by electric fencing which is removed for grazing. Cows graze for a few half-days to limit damage to the trees, and often at night to take advantage of milder temperatures. The leaves of the woody plants then provide a grazing resource additional to annual summer grazing crops.

- The second strategy is to use atypical resources mainly during the winter season. At Dairy 1, atypical hay (from abandoned grasslands) is distributed during winter to dry cows when they have lower physiological needs (Fig. 2). Feed trough waste, which represents about ¼ of the volume of this feed, is reused to mulch the cubicles. This is the only source of biomass used for bedding.

- The third strategy is to use atypical resources for animal bedding. At Suckler 2, farmers mow reedbeds approximately 10 to 20 km from the farm in September. These reed bales are distributed in November–December, fulfilling about ¼ of the farm's bedding requirements. Farmers prefer to spread the reed before the autumn calving season, because reed produces slightly more dust when mulched. Analyses have shown that reed manure has the same properties as cereal straw-based manure (Durant et al., 2020).

3.3. *Atypical resources play a highly variable role in the N performance of the farms*

The metabolic analysis shows a gradient of system activity (total amount of N supporting system activity by circulating) correlated with the stocking density of these systems (Table 1 and Appendix 2): Suckler 1 presents the lowest level of activity while the Dairy 2 system has the highest. Suckler 2 and Dairy 1 have intermediate stocking densities and levels of activity. The low activity of beef systems (Suckler 2 and Suckler 1) is largely explained by the pedo-climatic constraints of marsh areas (resulting in low productivity of permanent grasslands – 2.3 to 2.5 t DM.ha^{-1} in 2022) and the lower physiological needs of these systems that do not produce milk, particularly in terms of N. The grasslands of the two dairy systems are more productive (5.6 t DM.ha^{-1} for permanent grasslands at Dairy 1, 5.1 t DM.ha^{-1} for temporary grasslands at Dairy 2). Even atypical grasslands at Dairy 1, including wet ones are more productive, mainly due to rainfall during summer (3 t DM.ha^{-1}). More than 2/3 of system N self-sufficiency (from 66 to 81 %; Table 1) comes from crop/grasslands–livestock integration (i.e. internal flows). In all farms, N inputs are mainly provided by symbiotic fixation and atmospheric deposits (which provide 99 % of N inputs at Suckler 1 and Dairy 1). Permanent meadows (including low-productive natural grasslands at Dairy 1) are poor in legumes, providing 20 (Suckler 1, Suckler 2) to 30 kg N.ha^{-1}.yr^{-1} (Dairy 1) by symbiotic fixation. Dairy 2 temporary meadows can contain more than 50 % clover and provide nearly 80 % of total N inputs (approx. 130 kg N.ha^{-1}.yr^{-1}). Purchases of straw for bedding account for 14 % of inputs at Suckler 2, while straw and

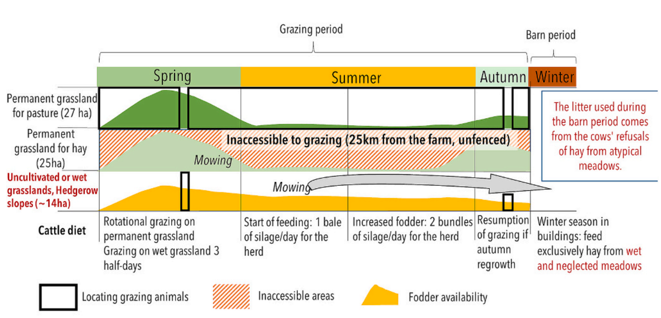

Fig. 2. Feeding sequences at Dairy 1 according to type of resources, availability, accessibility and localization.

Table 1
Indicators of N metabolism of the four farms in 2022.

Indicators	Cattle farms		Dairy farms	
	Suckler 1	*Suckler 2*	*Dairy 1*	*Dairy 2*
System activity (total system N flows) (kgN.ha^{-1})	111	181	251	534
Self-sufficiency (internal N cycling rate) (%)	71	72	81	66
N inputs from fixation + atmospheric depositions (kg N.ha^{-1} and % of total N inputs)	30 (99 %)	30 (86 %)	44 (99 %)	141 (87 %)
N inputs from purchases of conventional straw and concentrates (kg N.ha^{-1} and % of total N inputs)	0.4 (1 %)	4.9 (14 %)	0.6 (1 %)	14.4 (9 %)
N input from mineral fertilization (kg N.ha^{-1} and % of total N inputs)	0 (0 %)	0 (0 %)	0 (0 %)	6.9 (4 %)
Proportion of atypical resources in the N metabolism of the system (ARI) (%)	12	3	5	≈ 0
Proportion of atypical resources in animal feed (ARF) (%)	29	≈ 0	11	≈ 0
System N net productivity (kg N.ha^{-1})	3.0	3.8	14.7	39.5
N metabolic efficiency (%)	2.7	2.1	5.8	7.4
N losses (kg N.ha^{-1})	11.7	25.1	17.5	55.7
Metabolic N losses (%)	11 %	14 %	7 %	10 %

concentrates together represent 9 % of inputs at Dairy 2.

Atypical resources play a medium role (less than 5 %) in the total metabolism of the farms (ARI – Table 1), except at Suckler 1 where atypical resources account for 12 % of total system activity (Table 1). Atypical resources account for a significant proportion of the annual animal N intake (ARF – Table 1) at Suckler 1 and at Dairy 1: respectively 29 %, mainly for summer grazing (hygrophilous and mesophilous meadows and ditches), and 11 %, for grazing and winter fodder (wet meadows). At Dairy 2 and Suckler 2, the use of these resources for animal feed through grazed woody plants or grazed reeds was negligible until 2022. It is also interesting to note that these atypical resources cover respectively 37 % and 80 % of litter requirements at Suckler 2 (reedbeds) and Dairy 1 farms (refusals of hay from abandoned grasslands).

There is no causal relationship between the intensity of atypical resources use and performances metrics (system productivity and efficiency). Differences in performance can be mainly explained by production orientations. Studied dairy systems are more productive per unit area than suckler ones (Table 1). In terms of net metabolic productivity, dairy systems remain also 2 to 3 times more productive than suckler ones.

Concerning N losses, they were higher at Dairy 2 and Suckler 2 systems than at the two others. These differences are mainly due to the presence of arable lands, where leaching losses are estimated at 38 and 34 kg N.ha^{-1} respectively, compared with an average of 7.5 kg N.ha^{-1} on permanent grasslands (Anglade thesis (2015)). Finally, in terms of metabolic efficiency (losses related to system activity), Suckler 2 is the least efficient.

4. Discussion

4.1. *Methodological challenges to assess farming systems using atypical resources*

The results of metabolic analysis of the four farms studied were consistent with recent studies on crop–livestock systems in temperate regions, especially in terms of the N metabolic indicators based on Ecological Network Analysis (TT, TST or ICR; Laurant et al., 2023; Puech and Stark, 2023; Steinmetz et al., 2021). However, this work highlights the need for further development of methodological indicators to assess farming systems for sustainability and agroecology transition. Indeed, the dominant farming systems are driven by productivity, which is assessed per unit of production, such as utilized area or number of animals (Van Der Werf et al., 2020). From this point of view, the two systems that use the most atypical resources are also the least productive per unit area (in relation to the type of production) and well below the productivity of the dominant systems in Western Europe. However, they are most efficient systems in terms of closing cycles with the lowest losses in relation to their activity. The challenge today is thus no longer to look at the absolute quantity of goods produced, but at the relative quantity produced compared to the amount of resources mobilized or exchanged to produce it. This notion of productive efficiency is becoming central to understanding the performance of agricultural systems (Benoit and Mottet, 2023; Nguyen-Ba et al., 2023; Van Der Werf et al., 2020) in terms of resource conservation. Our results suggest that the use of atypical resources is a factor in low environmental nitrogen losses at farm level. The atypical resources studied are roughages that are poor substitutes for conventional and high productive resources (cereals, maize) with high levels of input and environmental impact (e.g. Beaudoin et al., 2016 for groundwater quality). However, the use of these atypical resources is part of a systemic approach to agroecological transition (particularly with regard to the use of grassland in ruminant systems) that promotes a reduction in inputs, but also a maximization of the use of natural resources and a search for circularity in the use of resources (for example the use of by-products) to reduce inputs required for production (Dumont et al., 2013; Van Zanten et al., 2019) and a diversification of farming systems (Reckling et al., 2023), for which assessment methods and metrics are to be rethought (Magne et al., 2024).

4.2. Atypical resources provide a diversity of ecosystem services

This notion of productive efficiency is all the more interesting given that agricultural systems include areas that deliver ecosystem services that are not limited only to supply services. In the example of the woody resources of Dairy 2, the trees provide not only fodder as seen through the prism of feed values. Some tree leaves may have an antioxidant and micronutrient composition that could potentially play a beneficial role in animal health (Maxin et al., 2024). Trees provide also shade for animal welfare during hot summer periods and may improve soil fertility through in-soil nutrient uptake (Koutika et al., 2022) and store carbon (Zellweger et al., 2022). Abandoned natural-valley meadows in Brittany (Dairy 1) or reedbeds in marshes (Suckler 1 and Suckler 2) also play an important role in carbon sequestration (Whitaker et al., 2015), while also shaping landscapes and providing environmental services simply by offering native habitats for many animal and plant species. At Suckler 1, atypical vegetations and their environments provide habitats for a unique and sometimes endangered fauna. These wet grasslands host breeding waders like the black-tailed godwit (*Limosa limosa*) or the common redshank (*Tringa totanus*), while reedbeds constitute specific habitats for the common reed warbler (*Acrocephalus scirpaceus*). Voluntary farmers can receive economic input by subscribing specific Agri-environment-climate measures called "AECM biodiversity" which involve payment for farming practices (delayed mowing/cattle grazing on grasslands) that are known to support the conservation of breeding waders. At Dairy 1, the vegetation of the hedgerow slopes represents nearly 50 % of the plant biodiversity of the farm (Glinec, 2016) and host rare species such as the aquatic ragwort (*Jacobaea aquatica*), or the white-toothed shrew (*Crocidura leucodon*). Preserving these resources in the landscape helps to maintain wild biodiversity, provided that farming practices respect their biological cycle to ensure renewal. This is the case, for example, with reeds used as an atypical fodder, as reeds struggle to tolerate frequent mowing (Hawke and José, 1996) or repeated spring grazing. Like many plant species with high 'standing stock' potential, reeds need time to build up the reserves that will be available later in the season. The challenge is therefore to adopt management practices adapted to the biological cycle of both the reeds and reed-associated wildlife. Finally, these resources work well in extensive farming systems with robust and low production levels cows. Farmers can ensure their animals are environment-adaptable by choosing breeds that can thrive on coarse and less nutritious atypical forages. Suckler 1 and Suckler 2 chose to raise a rustic local breed (Maraîchine). Dairy 1 and Dairy 2 opted to crossbreed a purely dairy breed (Holstein) with breeds that are well adapted to grazing and have good reproductive ability (Scandinavian Red) and are also particularly tolerant to heat stress (Jersey). However, using atypical resources also requires planning to accommodate a learning period for both animals and farmers (Meuret and Provenza, 2015).

4.3. Scaling up the use of atypical resources calls into question territorial management

Beyond the four case studies, the scaling up of atypical resources use raises questions about (i) the nature of atypical resources, (ii) the territorial management and (iii) the knowledge to be produced to support agroecological transitions. In this article, we defined atypical resources in relation to their context. The term 'atypical' is dated and located. Its subjectivity may be questioned, as it is defined in contrast to resources commonly used in agriculture and on which research and development organizations produce knowledge regarding their nature, technical practices and performances in agronomy or animal science. This qualifier could have different applications and modalities in other contexts.

A recent report from the French Ministry of Agriculture points out that 20.000 ha of agricultural area is abandoned each year (*"unused agricultural land or put to any agricultural, environmental, energy or hunting use"* - Baduel et al., 2023) probably due to access issues, natural constraints, or the decline of livestock farming. Some of these areas could likely be a source of atypical resources similar to the 'abandoned meadows' at Dairy 1 farm. The potential value of these areas for livestock systems could well (re)emerge given the Intergovernmental Panel on Climate Change outlook for Western Europe (Lee et al., 2023), which projects a marked prevalence of summer droughts in the coming decades. Atypical resources (on or off-farm) may also confer the system a degree of adaptation to climate change: these areas can serve as 'zones of flexibility' by partially offsetting the shortage of regular fodder or straw, and also as self-sufficiency drivers.

This work therefore calls for atypical plant resources to be managed collectively at a regional scale in order to produce resources sustainably while preserving the essential role of these spaces in the preservation of endemic wild biodiversity, which often entail heritage preservation challenges (Zhao et al., 2024). However, while the availability of some resources seems limited in space and time (e.g. reedbeds in marshlands, abandoned wetland meadows), others resources, such as the agroforestry resources developed at Dairy 2, could experience larger-scale development. These resources may be adapted to a wide diversity of agricultural systems and provide a pathway enabling agricultural systems to adapt to the challenges of agroecological transition (Altieri et al., 2012; Gliessman, 2004) and climate change (Lee et al., 2023). However, the inertia of development due to the biology of these resources, the lack of current knowledge about their benefits (both for livestock systems and ecosystems) call for these resources to be put on the political, scientific, and agricultural agendas in order to bring about change in agrifood systems (Conti et al., 2021).

5. Conclusion

This study presents a diversity of atypical resources identified through four unique and non-representative cattle farming systems in Western France. This diversity is expressed both in terms of nature, origin and the use made of these resources. Atypical resources can represent a significant share of the N metabolism of a farm, especially for animal feed to periods of lack of available resources. There is no obvious causal link between the use of atypical resources and classical agronomic performance (productivity, efficiency) in the systems studied, insofar as they are only part of coherent systems aimed at exploiting the complementarities between crops and livestock. Integrating atypical resources is part of systemic transition to agroecology with multiple expected benefits (biodiversity, N waste, climate change adaptation and mitigation). Metabolic approach helps to quantify the role that atypical resources can play, but needs to be complemented by other approaches to objectify all the services provided by these resources (animal health, biodiversity conservation, contribution to the beauty of the landscapes). Given the challenges tied to agroecological and climatic transitions, this work raises issues around (i) territorial management in the event of an extension of use of atypical resources, and (ii) the nature of the knowledge we need to gain to properly support their use.

CRediT authorship contribution statement

T. Puech: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Formal analysis, Data curation, Conceptualization. **A. Farruggia:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **D. Durant:** Writing – review & editing, Writing – original draft, Project administration, Funding acquisition. **J.F. Glinec:** Writing – review & editing, Writing – original draft, Investigation. **S. Novak:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Funding acquisition. **F. Signoret:** Writing – review & editing, Writing – original draft, Investigation. **F. Stark:** Writing – review & editing, Writing – original draft. **D. Sterling:** Writing – review & editing, Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation.

Declaration of competing interest

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2025.104329.

Data availability

Data will be made available on request.

References

Altieri, M.A., Funes-Monzote, F.R., Petersen, P., 2012. Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron. Sustain. Dev. 32, 1–13. https://doi.org/10.1007/s13593-011-0065-6.

Anglade, J., 2015. Agriculture biologique et qualité des ressources en eau dans le bassin de la Seine: caractérisation des pratiques et applications territorialisées. Université Pierre et Marie Curie, Paris.

Arneth, A., Denton, F., Agus, F., Elbehri, A., Erb, K., Osman Elasha, B., Rahimi, M., Rounsevell, M., Spence, A., Valentini, R., 2019. Framing and Context. In: Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems. IPCC.

Baduel, V., Hubert, C., Lejeune, H., 2023. Stratégies d'usage des terres en France dans l'objectif d'assurer la souveraineté alimentaire et de préserver la biodiversité (Rapport No. 22107). CGAER report 22107, Paris.

Barbieri, P., Pellerin, S., Seufert, V., Smith, L., Ramankutty, N., Nesme, T., 2021. Global option space for organic agriculture is delimited by nitrogen availability. Nat. Food 2, 363–372. https://doi.org/10.1038/s43016-021-00276-y.

Barbieri, P., Dumont, B., Benoit, M., Nesme, T., 2022. Opinion paper: livestock is at the heart of interacting levers to reduce feed-food competition in agroecological food systems. Animal 16, 100436. https://doi.org/10.1016/j.animal.2021.100436.

Beaudoin, N., Gallois, N., Viennot, P., Le Bas, C., Puech, T., Schott, C., Buis, S., Mary, B., 2016. Evaluation of a spatialized agronomic model in predicting yield and N leaching at the scale of the seine-Normandie Basin. Environ. Sci. Pollut. Res. https://doi.org/10.1007/s11356-016-7478-3.

Benoit, M., Mottet, A., 2023. Energy scarcity and rising cost: towards a paradigm shift for livestock. Agric. Syst. 205, 103585. https://doi.org/10.1016/j.agsy.2022.103585.

Billen, G., Lassaletta, L., Garnier, J., 2014. A biogeochemical view of the global agro-food system: nitrogen flows associated with protein production, consumption and trade. Glob. Food Secur. 3, 209–219. https://doi.org/10.1016/j.gfs.2014.08.003.

Conti, C., Zanello, G., Hall, A., 2021. Why are Agri-food systems resistant to new directions of change? A systematic review. Glob. Food Secur. 31, 100576. https://doi.org/10.1016/j.gfs.2021.100576.

Cordell, D., White, S., 2011. Peak phosphorus: clarifying the key issues of a vigorous debate about long-term phosphorus security. Sustainability 3, 2027–2049. https://doi.org/10.3390/su3102027.

Dumont, B., Fortun-Lamothe, L., Jouven, M., Thomas, M., Tichit, M., 2013. Prospects from agroecological and industral ecology for animal production in the 21st century. Animal 7, 1028–1043. https://doi.org/10.1017/S1751731112002418.

Durant, D., Farruggia, A., Tricheur, A., 2020. Utilization of common reed (Phragmites australis) as bedding for housed suckler cows: practical and economic aspects for farmers. Resources 9, 140. https://doi.org/10.3390/resources9120140.

Durant, D., Farruggia, A., Tricheur, A., 2021. Le roseau commun (*Phragmites australis*): un capital naturel utilisé en litière pour le logement des vaches allaitantes. Biotechnol. Agron. Soc. Environ. 223–235. https://doi.org/10.25518/1780-4507.19164.

Eisler, M.C., Lee, M.R.F., Tarlton, J.F., Martin, G.B., Beddington, J., Dungait, J.A.J., Greathead, H., Liu, J., Mathew, S., Miller, H., Misselbrook, T., Murray, P., Vinod, V. K., Van Saun, R., Winter, M., 2014. Agriculture: steps to sustainable livestock. Nature 507, 32–34. https://doi.org/10.1038/507032a.

Garnier, J., Anglade, J., Benoit, M., Billen, G., Puech, T., Ramarson, A., Passy, P., Silvestre, M., Lassaletta, L., Trommenschlager, J.-M., Schott, C., Tallec, G., 2016. Reconnecting crop and cattle farming to reduce nitrogen losses to river water of an intensive agricultural catchment (seine basin, France): past, present and future. Environ. Sci. Pol. 63, 76–90. https://doi.org/10.1016/j.envsci.2016.04.019.

Girard, S., Alavoine-Mornas, F., 2014. La Trame Verte à l'épreuve du terrain: pratiques et représentations des agriculteurs. Sci. Eaux Territoir. 64–69.

Gliessman, S.R., 2004. Agroecology and agroecosystems. In: Rickerl, D., Francis, C.A. (Eds.), *Agroecosystems Analysis*. Agronomy Monographs. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, WI, USA, pp. 19–29. https://doi.org/10.2134/agronmonogr43.c2.

Glinec, J.-F., 2016. Etude de la flore d'une exploitation laitière du fond de la rade de Brest. ERICA, Conservato. Botan. Nation. Brest 30, 77–86.

Glinec, J.-F., 2019. De la botanique à la multifonctionnalité : témoignage sur l'évolution d'une ferme qui a intégré les aspects sociaux et écologiques. Fourrages 237, 41–46.

Hawke, C., José, P., 1996. Reedbed Management for Commercial and Wildlife Interests. Royal Society for the Protection of Birds, Sandy.

Jouven, M., Lapeyronie, P., Moulin, C.-H., Bocquier, F., 2010. Rangeland utilization in Mediterranean farming systems. Animal 4, 1746–1757. https://doi.org/10.1017/S1751731110000996.

Koutika, L.-S., Marron, N., Cardinael, R., 2022. The contribution of agroforestry systems to improving soil carbon sequestration. In: Rumpel, C. (Ed.), Burleigh Dodds Series in Agricultural Science. Burleigh Dodds Science Publishing, pp. 589–616. https://doi.org/10.19103/AS.2022.0106.19.

Latham, L.G., 2006. Network flow analysis algorithms. Ecol. Model. 192, 586–600. https://doi.org/10.1016/j.ecolmodel.2005.07.029.

Laurant, D., Stark, F., Le Page, C., Rousselou, E., Bazile, D., 2023. Linking organizational and technical dimensions to design integrated collective farms: a case study in Camargue, France. Agron. Sustain. Dev. 43, 48. https://doi.org/10.1007/s13593-023-00899-4.

Lee, H., Calvin, C., Dasgupta, D., Krinner, G., Mukherji, A., Thorne, P., Trisos, C., Romero, J., Aldunce, P., Blanco, G., Diongue-Niang, A., Dodman, D., Garschagen, M., Geden, O., Hayward, B., Jones, C., Jotzo, F., Krug, T., Lasco, R., Lee, J., Masson-Delmotte, V., Meinshausen, M., Mintenbeck, K., Mokssit, A., Otto, F., Pathak, M., Pirani, A., Poloczanska, E., Pörtner, H., Revi, A., Roberts, D., Roy, J., Ruane, A., Ske, J., Shukla, P., Slade, R., Slangen, A., Sokona, Y., Sörensson, A., Tignor, M., van Vuuren, D., Wei, Y., Winkler, H., Zhai, P., Zommers, Z., 2023. Synthesis Report of the IPCC Sixth Assessment Report. IPCC.

Magne, M.-A., Alaphilippe, A., Bérard, A., Cournut, S., Dumont, B., Gosme, M., Hedde, M., Morel, K., Mugnier, S., Parnaudeau, V., Nozières-Petit, M.-O., Paut, R., Puech, T., Robert, C., Ryschawy, J., Sabatier, R., Stark, F., Vialatte, A., Martin, G., 2024. Applying assessment methods to diversified farming systems: simple adjustment or complete overhaul? Agric. Syst. 217, 103945. https://doi.org/10.1016/j.agsy.2024.103945.

Maxin, G., Graulet, B., Novak, S., Mesbahi, G., Signoret, F., Glinec, J.-F., Laurent, E., Drusch, S., Farruggia, A., Durant, D., 2024. Potential health value of alternative plant resources explored as feed for ruminants. Grassland Sci. Eur. 29, 126–128.

Mesbahi, G., Jawahir, A., Berthet, M., Ginane, C., Delagarde, R., Chargelègue, F., Novak, S., 2022. Rethinking grasslands in 3D: feeding preferences of dairy cows between temperate fodder trees. Grassland Sci. Eur. 27, 436–438.
Meuret, M., Provenza, F., 2015. When art and science meet: integrating knowledge of French herders with science of foraging behavior. Rangel. Ecol. Manag. 68, 1–17. https://doi.org/10.1016/j.rama.2014.12.007.
Meynard, J.M., Dedieu, B., Bos, A.P., 2012. Re-design and co-design of farming systems. An overview of methods and practices. In: Darnhofer, I., Gibbon, D., Dedieu, B. (Eds.), Farming Systems Research into the 21st Century: The New Dynamic. Springer, pp. 407–432.
Mondière, A., Corson, M.S., Auberger, J., Durant, D., Foray, S., Glinec, J.-F., Green, P., Novak, S., Signoret, F., Van Der Werf, H.M.G., 2024. Trade-offs between higher productivity and lower environmental impacts for biodiversity-friendly and conventional cattle-oriented systems. Agric. Syst. 213, 103798. https://doi.org/10.1016/j.agsy.2023.103798.
Morais, T.G., Teixeira, R.F.M., Lauk, C., Theurl, M.C., Winiwarter, W., Mayer, A., Kaufmann, L., Haberl, H., Domingos, T., Erb, K.-H., 2021. Agroecological measures and circular economy strategies to ensure sufficient nitrogen for sustainable farming. Glob. Environ. Chang. 69, 102313. https://doi.org/10.1016/j.gloenvcha.2021.102313.
Moulin, C., Girard, N., Dedieu, B., 2001. L'apport de l'analyse fonctionnelle des systèmes d'alimentation. Fourrages 167, 337–363.
Nguyen-Ba, H., Veysset, P., Ferlay, A., 2023. A new concept for agro-ecological efficiency at different scales of ruminant production systems. In: Book of Abstracts of the 74th Annual Meeting of the European Federation of Animal Science. EAAP – 74th Annual Meeting, Lyon, France, p. 159.
Novak, S., Liagre, F., Emile, J.C., 2016. Integrating agroforestry into an innovative mixed crop-dairy system. In: 3rd European Agroforestry Conference, Montpellier, France, pp. 396–398. https://euraf.isa.utl.pt/files/pub/docs/silvopastoralism_3_novak.pdf.
Novak, S., Chargelègue, F., Chargelègue, J., Audebert, G., Liagre, F., Fichet, S., 2020. Premiers retours d'expérience sur les dispositifs agroforestiers intégrés dans le système laitier expérimental OasYs. Fourrages 242, 71–78 https://hal.inrae.fr/hal-03147342.
Novak, S., Guyard, R., Chargelegue, F., Audebert, G., Foray, S., 2022. Nitrogen use efficiency and carbon footprint of an agroecological dairy system based on diversified resources. Grassland Sci. Europe 27, 683–685. https://hal.science/hal-03689465v1/document.
Perrin, A., 2021. Caractérisation des facteurs de la résilience des exploitations bovines et ovines laitières biologiques françaises. PhD thesis. INP Toulouse, Toulouse.
Pinsard, C., 2022. Assessing the Resilience of European Farming Systems to Consequences of Global Peak Oil Using a Dynamic Nitrogen Flow Model (PhD thesis). Univérsité Paris-Saclay, Paris.
Puech, T., Stark, F., 2023. Diversification of an integrated crop-livestock system: Agroecological and food production assessment at farm scale. Agric. Ecosyst. Environ. 344, 108300. https://doi.org/10.1016/j.agee.2022.108300.
Reckling, M., Watson, C.A., Whitbread, A., Helming, K., 2023. Diversification for sustainable and resilient agricultural landscape systems. Agron. Sustain. Dev. 43, 44. https://doi.org/10.1007/s13593-023-00898-5.
Sijpestijn, G.F., Wezel, A., Chriki, S., 2022. Can agroecology help in meeting our 2050 protein requirements? Livest. Sci., 104822 https://doi.org/10.1016/j.livsci.2022.104822.
Stark, F., Fanchone, A., Semjen, I., Moulin, C.-H., Archimède, H., 2016. Crop-livestock integration, from single practice to global functioning in the tropics: case studies in Guadeloupe. Eur. J. Agron. 80, 9–20. https://doi.org/10.1016/j.eja.2016.06.004.
Steinmetz, L., Veysset, P., Benoit, M., Dumont, B., 2021. Ecological network analysis to link interactions between system components and performances in multispecies livestock farms. Agron. Sustain. Dev. 41, 42. https://doi.org/10.1007/s13593-021-00696-x.
Tedesco, C., Petit, C., Billen, G., Garnier, J., Personne, E., 2017. Potential for recoupling production and consumption in peri-urban territories: the case-study of the Saclay plateau near Paris, France. Food Policy 69, 35–45. https://doi.org/10.1016/j.foodpol.2017.03.006.
Therond, O., Duru, M., Roger-Estrade, J., Richard, G., 2017. A new analytical framework of farming system and agriculture model diversities. A review. Agron. Sustain. Dev. 37, 21. https://doi.org/10.1007/s13593-017-0429-7.
Tomich, T.P., Brodt, S., Ferris, H., Galt, R., Horwath, W.R., Kebreab, E., Leveau, J.H.J., Liptzin, D., Lubell, M., Merel, P., Michelmore, R., Rosenstock, T., Scow, K., Six, J., Williams, N., Yang, L., 2011. Agroecology: a review from a global-change perspective. Annu. Rev. Environ. Resour. 36, 193–222. https://doi.org/10.1146/annurev-environ-012110-121302.
Ulanowicz, R.E., Goerner, S.J., Lietaer, B., Gomez, R., 2009. Quantifying sustainability: resilience, efficiency and the return of information theory. Ecol. Complex. 6, 27–36. https://doi.org/10.1016/j.ecocom.2008.10.005.
Van Der Werf, H.M.G., Knudsen, M.T., Cederberg, C., 2020. Towards better representation of organic agriculture in life cycle assessment. Nat. Sustain. 3, 419–425. https://doi.org/10.1038/s41893-020-0489-6.
Van Zanten, H.H.E., Van Ittersum, M.K., De Boer, I.J.M., 2019. The role of farm animals in a circular food system. Glob. Food Sec. 21, 18–22. https://doi.org/10.1016/j.gfs.2019.06.003.
Whitaker, K., Rogers, K., Saintilan, N., Mazumder, D., Wen, L., Morrison, R.J., 2015. Vegetation persistence and carbon storage: implications for environmental water management for Phragmites australis. Water Resour. Res. 51, 5284–5300. https://doi.org/10.1002/2014WR016253.
Zellweger, F., Flack-Prain, S., Footring, J., Wilebore, B., Willis, K.J., 2022. Carbon storage and sequestration rates of trees inside and outside forests in Great Britain. Environ. Res. Lett. 17, 074004. https://doi.org/10.1088/1748-9326/ac74d5.
Zhao, J., Yu, L., Newbold, T., Shen, X., Liu, X., Hua, F., Kanniah, K., Ma, K., 2024. Biodiversity responses to agricultural practices in cropland and natural habitats. Sci. Total Environ. 922, 171296. https://doi.org/10.1016/j.scitotenv.2024.171296.