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REVIEW

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Grassland renovation has important consequences for C and N cycling and losses

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Abstract

Sward degradation is a serious threat to the functioning of agricultural grassland and the provision of ecosystem services. Renovation measures are frequently applied to restore degraded swards. The success is highly variable, and substantial trade-offs can be related to the process of renovation. This paper starts with a general classification of renovation measures and then investigates the processes that are directly related to renovation and lead to a change in botanical composition and affect soil functions and C and N fluxes. These processes are strongly interrelated and dependent on site, climate, and management condition as well as on the timescale. The more an existing and degraded sward is deliberately disturbed prior to a renovation measure, for example, by ploughing, the stronger will be the change in sward composition, and the stronger will be the potential yield and quality advantage. However, the risk of a release of soil organic C and N emissions to the environment will also increase. These emissions will usually decrease in time, but so will the positive effects on sward composition. This demonstrates that the renovation of swards is normally the second best solution and a proper and well-adapted grassland utilization and management should be adopted to avoid degradation in the first place.

KEYWORDS

carbon, nitrogen, reseeding, sward improvement, vegetation

1 | INTRODUCTION

Grasslands are expected to provide multiple services among which the production of energy, protein, and structural carbohydrates for feeding livestock plays a pivotal role (Isselstein & Kayser, 2014). Grassland renovation or renewal is mainly a reaction to a decline in yield and nutritive value or of other ecosystem services. This failure is usually related to changes in the botanical composition; vegetation cover is reduced, light capturing is poor and so is the photosynthesis of the vegetation; weeds may have entered and occupied a substantial area of the sward (Frame, 1992; Taube & Conijn, 2004). In general, grassland systems are rather stable compared to arable systems and they usually do not require regular maintenance efforts such as tillage and sowing. Yet, in time, sward composition and soil conditions may deteriorate through technical and weather impacts and their interaction with management (wheel traffic, poaching, drought, winter damages, flooding, slurry application, suboptimal synchronization of N input and frequency of defoliation, under- or overgrazing). The system is then degraded. The intention of renovation is to bring grasslands back to the state of productivity which they once had and ideally even improve the swards by taking advantage of progress in plant breeding and new varieties (Reheul et al., 2017). Renovation has, however, wider implications, and other ecosystem services apart from production are also affected. Most of these services are also related to grass production, such as maintenance of soil quality and reduction in erosion risks by well-rooted grass cover; ensuring high surface and groundwater quality through effective nutrient use by grass swards; and mitigating climate change through high carbon sequestration and low N_2O emissions (Soussana, Tallec, & Blanfort, 2010; Soussana et al., 2007; Wachendorf & Golinski, 2006).

Improving grasslands, mainly with the aim to improve livestock production, has always been a main part of grassland management. Fertilization, the introduction of valuable forage species, and improved grazing practices are proven measures to make grasslands more productive (Frame, 1992). Further practices include disturbing the existing sward–soil system to some degree. However, interference in a relatively stable system, which permanent grasslands usually are, has consequences not only for soil and sward structure, but also for nutrient cycling as well. An improved grassland sward might then have a higher demand for nutrients and require an adapted balance of nutrients and fertilization. On the other hand, if grasslands are not appropriately managed, degradation and destruction of the soil–plant system over time can result in decreased yields and in temporal or permanent losses of C and N (Zhang, Kang, Han, Mei, & Sakurai, 2011) and, consequently, affect the quality of the system and the environment. In the soil–plant system, cycling of C and N is most important and directly links soil quality, environmental conditions, climate, and the requirements of good grassland growth (Conant, 2010; Rumpel et al., 2015). Thus, this paper will focus on consequences of grassland renovation on the sward composition and on C and N cycling.

In the present review, we investigate the issue of grassland renovation in an agronomical framework. Renovation measures are targeted to change the grassland vegetation in a way that its functioning is improved and reaches at least a level that it had before. The extent of intervention depends on how much of the competition by the old sward needs to be decreased to ensure that (a) the desired species in the old sward get an advantage over the agronomically less valuable grass species; and (b) the newly introduced seeds will be successfully established. The degree of disturbance will then directly affect the extent of changes to the soil structure and mineralization of C and N.

The intention of the present review is to give a brief overview of renovation aims, measures, and consequences for grassland services. We will set a framework for terms and definitions around grassland renovation and continue with principle considerations about the different processes that are induced and affected by grassland renovation measures. Finally, we will discuss how vegetation, soil, and N fluxes respond to renovation under practical farming conditions. Generally, the focus of the present review is on grassland in temperate climate. Yet, the conceptual framework for renovation, the classification of measures, and the principles underlying the responses of vegetation and soil are certainly not restricted to temperate grassland alone.

2 | TERMS AND DEFINITIONS

We consider grassland renovation as a bundle of target-oriented agronomic measures to bring a grassland sward (a grassland system) back into a condition in which it can fully function and deliver the intended ecosystem services. In the first place, this is the quantity and quality of herbage, that is, the agronomic performance. As grasslands are multifunctional, renovation may also be targeted at enhancing biodiversity, groundwater protection, soil conservation, climate change mitigation, or improved cultural service.

Terms like renovation, rejuvenation, reseeding, renewing, overseeding, ploughing-in, and grassland break-up, among others, have all been related to interventions in the grassland sward in order to improve the conditions in some way, mainly for production. The term "renovation" is derived from the Latin *renovare*, from *re-* "again" and *novare-* "make new," from *novus*, "new." Renovate means to make changes and repairs to (an old house, building, room, etc.; Merriam Webster dictionary online 17.01.2018) the grassland sward so that it is back in good condition and delivers the intended ecosystem service. Related terms like renew, restore, refresh, rejuvenate all mean: to make like new. We suggest to structure possible interventions in the grassland sward in two broad categories: (1) improving the sward without altering the soil structure that means to retain the old sward = (a) rejuvenation (no seed—but improving drainage, pH, nutrient balance, and weed control; avoid over- or undergrazing, reduce field tracking) and (b) oversowing that is partial reseeding with new seed that is competitive; and (2) improving the sward by new seed and disturbing the soil structure to some extent. Between these two broad categories, there are various transitions which are summarized in Table 1. Measures are grouped along a gradient of sward and soil disturbance. With increasing disturbance, the existing sward is more and more weakened and the competitive strength against the newly introduced seed is reduced. At the same time, the risk of temporal yield losses due to low establishment of introduced seed increases. Increasing sward and soil disturbance is usually also related to a higher input of energy and thus higher costs.

3 | GRASSLAND SYSTEMS AND NUTRIENT CYCLING

Permanent grassland, even when grazed, can be regarded as a relatively stable system with comparably greater amounts of organic matter, larger earthworm populations,

TABLE 1 Strategies and measures for sward renovation (adapted from Frame, 1992)

	1 Retain old sward		2 Disturb old sward	
	Rejuvenation	Partial reseeding	Surface methods	Cultivation methods
Old sward	Retained	Partially replaced	Completely replaced	Completely replaced
Destruction of old sward	None	None or partial	Chemical	Physical
Soil cultivation	None or surface	None or minimum	None or surface	Tillage/Ploughed
Herbicide	Selective	None or grass suppressants	Total sward destruction	Weed control, total sward destruction
Methods	Improved management	Oversowing/direct drilling	Oversowing/direct drilling	Cultivation methods and drilling or broadcasting
Seed	None	Reduced rates	Full rate	Full rate

→ Increasing disturbance of sward and soil
Decreasing competition from old sward
Increasing inputs and costs
Increasing risks of (temporal) yield losses

a denser network of roots resulting in higher aggregate stability, more microbial biomass, and a greater activity of various soil enzymes compared with arable fields (Whitehead, 1995). Soil conditions and nutrient cycling do not only differ between cut and grazed grassland, but are also depending on fertilizer input and botanical composition of the sward. Even changing from a grass sward to a clover pasture will affect root distributions and worm population and result in changes in soil structure and chemical transport (Williams, Scholefield, Dowd, Holden, & Deeks, 2000). Grassland renovation or transformation into arable land will disturb this system and is likely to lead to larger losses of N and C.

Nutrient cycling is at the core of assessing the sustainability of forage farming systems. A comprehensive analysis and evaluation would require the consideration of a complex range of factors on different spatial and temporal scales and would also involve analyzing the production conditions of imported feed stuffs (Taube, Gierus, Hermann, Loges, & Schönbach, 2014). Generally, amounts of nutrients that are utilized in forage systems are much greater than the rather small amounts that leave the system with products like milk and meat (Aarts, Biewinga, & van Keulen, 1992; Aarts, Habekotte, & van Keulen, 2000; Whitehead, 1995). At the farm scale, nutrient efficiency is thus depending on how well the cycling of nutrients within soil–plant–animal system is organized. Losses reduce the cost-effectiveness (profitability) of production, and as emissions from agro-ecosystems, they contribute to environmental stress—pollution of atmosphere and surface and groundwater (Wachendorf & Golinski, 2006). The extent to which losses occur is to a great deal depending on management factors.

4 | RENOVATION AND RELATED YIELDS AND C FLUXES

Fostering sequestration of organic C in soil is an important mitigation strategy to increased concentrations of carbon dioxide in the atmosphere (Soussana & Lüscher, 2007). Due to permanent vegetation cover, soil rest, and the interactions of soil biota and soil structure, grassland sites, permanent grassland in particular, can store relatively great amounts of organic C (Six et al., 2002). The annual rate of C sequestration in grassland soils is at least twice that of arable land, depending on age, management, and frequency of land or management changes (Billen, Röder, Gaiser, & Stahr, 2009; Goidts & van Wesemael, 2007; Linsler, Geisseler, Loges, Taube, & Ludwig, 2013). A foremost strategy for climate protection would thus be the preservation and creation of grassland. Up to 40% of the aboveground biomass production, which corresponds to 1–3 t C ha^{-1}, is returned annually to the soil (Vertes et al., 2007). A small part of this stock will contribute to the stable C fraction of the soil. The rate of accumulation of C in grassland soil depends on the present C and N concentration and is further influenced by variation of nutrient input, soil type, climate, and soil water budget (Ammann, Spirig, Leifeld, & Neftel, 2009; Hassink, 1994; Poeplau et al., 2011).

Grassland soils can store more C and N than arable land, but emissions are not necessarily smaller. In practice, there is indeed a great variability in emissions from grasslands soils, both with regard to the type of emissions (CO_2, N_2O, CH_4) and the effect of site conditions and grassland management (Soussana et al., 2007).

Two aspects of C fluxes will be considered in this chapter, one is herbage yield and the other is soil organic C content. The major agronomic aim of renovation is to sustain and even improve herbage production—this includes fixing C from the atmosphere into production of biomass. In conjunction with studies on the vegetation response to grassland renovation, extensive research has been undertaken on the yield response to renovation (e.g., Hopkins, Gilbey, Dibb, Bowling, & Murray, 1990; Hopkins et al., 1985; Keating & O'Kiely, 2000; Schils et al., 2002; Shalloo, Creighton, & O'Donovan, 2011; Velthof et al., 2010). As for the vegetation response, the immediate yield response is strongly dependent on the amount of sward and soil disturbance prior to resowing. The higher the degree of disturbance and, thus, the stronger the vegetation change, the higher is the potential yield benefit of renovation. This is illustrated in Figure 1, which is a schematic representation based on a range of experiments throughout Central and Western Europe. Within the first two years after renovation, the yield advantage of the renovated compared to the untreated permanent (control) sward may amount up to 30%. However, there are also experiments showing either no yield effect or even a short-term yield depression after renovation (Biegemann, Loges, Poyda, & Taube, 2014; Hopkins, Murray, Bowling, Rook, & Johnson, 1995; Schmeer, 2012; Velthof et al., 2010), the latter being due to production losses in the year of sward disturbance and resowing (see also Figures 2 and 7). Irrespective of the short-term effect, to our knowledge there are no data available that give evidence for a long-lasting (>3 years) yield benefit of resown swards in temperate climate. However, the benefits for herbage quality may last longer than the positive effect on herbage yield (Hopkins et al., 1990; Schils et al., 2002). The role of plant breeding is another aspect. In a review on production potentials of grassland and forage crops in Belgium and the Netherlands, Reheul et al. (2017) report that the genetic gain in dry matter production of grasses and clover is rather small (0.3%–0.5%) and that even this small progress is hardly ever realized in practice (see also Annicchiarico, Barett, Brummer, Julier, & Marshall, 2014; Chaves, De Vliegher, Van Waes, Carlier, & Marynissen, 2009; Laidig, Piepho, Drobek, & Meyer, 2014). As an alternative, Reheul et al. (2017) and Wachendorf and Golinski (2006) stress the importance of good agronomic practices in forage farming, a good agreement between N supply and utilization (grazing intensity, cutting frequency), use of harvesting machinery, soil conditions, and drainage.

The potential benefit of oversowing without disturbing the existing grass sward is shown in Figure 2. There was no yield drop in the sowing year, and yield was slightly superior to the control sward in the medium term. Whether such agronomic advantage does occur or not is strongly dependent on the successful establishment of seed from the introduced forage species. This, in turn, is largely affected by the availability of light and sufficient soil moisture content (Haugland & Froud-Williams, 2001). Success of sowing is only to a small degree depending on technological aspects; a prerequisite is a high and well-controlled seed quality and advanced seeding techniques to ensure good germination rates. Competition, however, in the early establishing phase can lead to a substantial decrease in the proportion of sown grass species (Haugland & Tawfiq, 2001; King, 1971; Sangakkara & Roberts, 1986), especially under adverse soil conditions and the presence of strong competitors in the old sward (Milimonka & Richter, 2001). As a result, management measures that affect

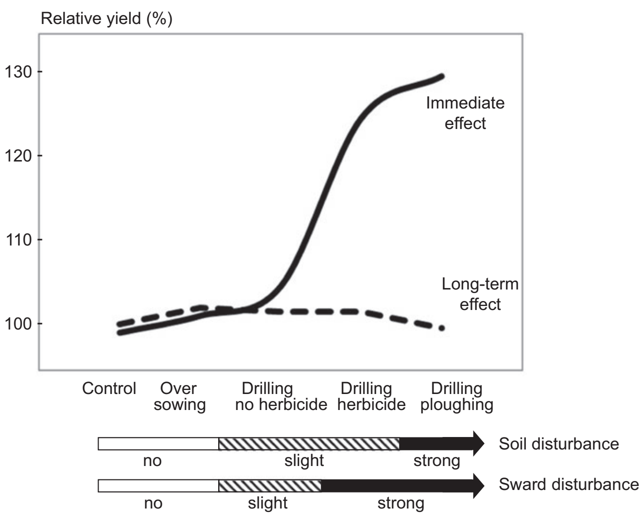

FIGURE 1 The effect of a range of grassland renovation measures with an increasing soil and grass sward disturbance prior to sowing on the immediate (first two years after renovation, continuous line) and the long-term (thereafter, dashed line) herbage yield of temperate grasslands (schematic representation)

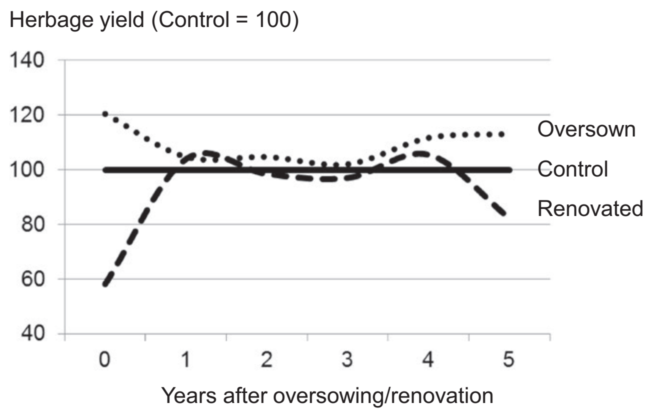

FIGURE 2 Medium-term effect of grassland improvement measures on the herbage yield, control = no sward treatment (continuous line), oversown= oversowing without sward disturbance (dotted line), renovated = complete mechanical sward disturbance plus resowing (dashed line), after Elsäßer, Rothenhäusler, & Wurth (2015)

competition for light like the cutting regime become comparatively important (Opitz von Boberfeld, 1986).

Renovating a grass sward is accompanied by changes in soil organic C. Soil mineralization is greatly affected by any disturbances of soil structure, for example, magnitude and frequency of tillage—the more the permanent sward is destroyed prior to reseeding, the higher is the short-term mineralization of organic C.

Ploughing is an example for a massive destruction of the existing soil structure and root system and, depending on water conditions and rainfall, can lead to increased gaseous losses in form of CO_2, N_2O, and leaching of NO_3 (MacDonald, Rochette et al., 2011; Velthof et al., 2010). Measures that disturb the soil structure and the soil–plant system less usually lead to fewer emissions as well. The nutrient turnover processes that have been accelerated by disturbance can be slowed down and their effect mitigated by ensuring a fast establishment of a good sward that will immobilize N and C by building up yield, sward, and root systems and soil structure. This makes grassland renovation, even in its extreme form of ploughing and reseeding, different from the transformation to arable land where the soil will be regularly disturbed by tillage, and large quantities of C and N will inevitably be lost over a long period of time that can actually last decades (Davies, Smith, & Vinten, 2001; Springob, 2004). Immediate large N leaching losses and emissions of C and other greenhouse gases are almost unavoidable when grassland is turned to arable cropping (Curtin, Fraser, & Beare, 2015; Kayser, Seidel, Müller, & Isselstein, 2008; MacDonald, Chantigny et al., 2011; Poeplau et al., 2011; Velthof et al., 2010).

Apart from the level of disturbance, the amount of mineralization of organic carbon is also dependent on the soil type and aggregate structure, the hydrology of the soil, and the age of the old sward (Bimüller, Kreyling, Kölbl, von Lützow, & Kögel-Knabner, 2016; Jarvis, Stockdale, Shepherd, & Powlson, 1996; Vertes et al., 2007). Carolan and Fornara (2015) conducted a study at a chronosequence of 45 permanent grassland sites across Northern Ireland with a well-documented history of single reseeding events over the last 50 years. Their results suggest that management-induced effects on key soil physical properties may have significantly greater implications for C sequestration in permanent grassland soils than infrequent reseeding events even when related to soil disturbance. After a renovation event with ploughing-up of grassland and immediate resowing, Necpalova et al. (2014) found a considerable decrease in soil organic C (20% reduction) within a few months (Figure 3). Even after 25 years of grassland utilization following renovation, the soil organic C did not fully recover. Other recent experiments on sandy soils did not confirm the findings of Necpalova et al. (2014). In experiments by Linsler et al. (2013) turning an existing sward by ploughing and reseeding it with a grass mixture did not lead to a reduction in soil organic C in the topsoil layer compared to an untreated control sward. These findings demonstrate the need to consider the wider environmental conditions of a grass sward when evaluating the potential C losses to the atmosphere after the renovation of grasslands.

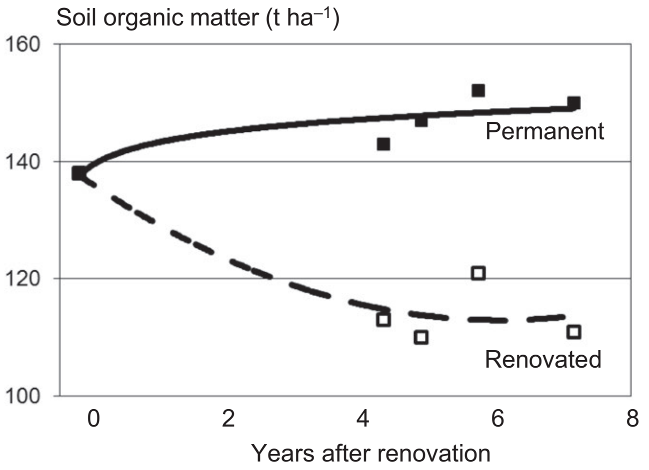

FIGURE 3 Soil organic carbon (0–30 cm) under permanent and renovated grassland during seven years following renovation. The site was intensively managed permanent grassland with average herbage yields of 14 t DM per year. For renovation, the paddock was ploughed and reseeded with a perennial ryegrass white clover mixture. Differences between treatments were significant at $p = 0.05$ (after Necpalova et al., 2014)

5 | VEGETATION RESPONSE TO RENOVATION

Degradation as well as improvement of grasslands is closely related to the vegetation cover, that is, the plant species identity, composition, and development (Tilman, Wedin, & Knops, 1996). Thus, renovation aims at modifying the vegetation cover: reducing bare soil, increasing desired, valuable species, and decreasing weeds and less valuable species (Butkuviene, 2009; Taube & Conijn, 2004). A sward renovation should then sustain or improve yields and the herbage feeding value. Better yields and feeding values increase herbage intake by ruminants and herbage use efficiency (Golinski & Kozlowski, 2000). This would also accelerate the C and N cycling in the soil–plant-ruminant system and, depending on the grassland management, potentially improve nutrient use efficiency and reduce the risk of nutrient emissions (Biegemann et al., 2014; Seidel, Kayser, Müller, & Isselstein, 2009; Terlikowski & Barszczewski, 2015; Velthof et al., 2010).

After renovation, the vegetation of the new sward will undergo changes, a process that is highly variable. There are several examples in the literature of both success and failure depending on the particular site, vegetation composition, and management conditions (e.g., Milimonka & Jänicke, 2003; Müller & Hrabe, 2008; Pierre, Deleau, & Osson, 2013). The extent of the immediate change in vegetation after renovation depends on the amount of sward and topsoil disturbance prior to resowing. Figure 4 demonstrates that the yield share of *Lolium perenne*, a highly preferred species in intensively managed temperate grassland, is hardly affected by oversowing within the first year when neither the sward nor the soils are treated. On the other hand, after a complete disturbance of the sward *Lolium perenne* is dominating the vegetation while the not sown weed species *Poa trivialis* is strongly suppressed (Opitz von Boberfeld & Scherhag, 1980). There is some uncertainty whether oversowing without sward and soil disturbance will have a lasting effect on sward quality; various experiments leave some doubt regarding the efficiency of oversowing (Lemasson, Pierre, & Osson, 2008). However, there is also a chance that oversowing done repeatedly over the years may lead to the desired vegetation change in the longer term.

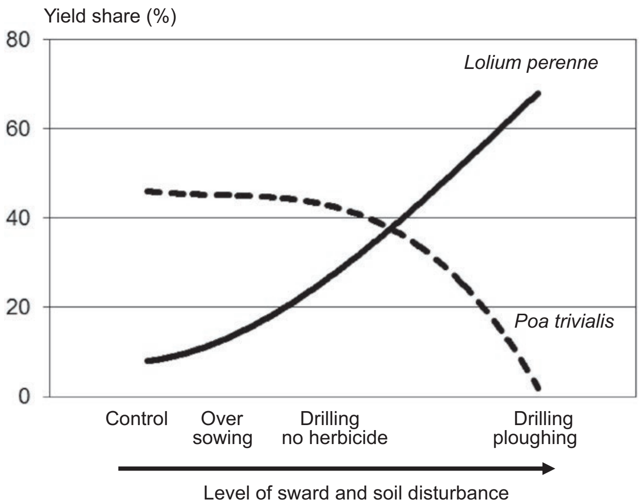

FIGURE 4 Example of short-term vegetation response: The effect of various renovation measures on the yield share of the highly valuable forage grass species *Lolium perenne* and the less valuable (secondary) grass species *Poa trivialis* in the year after renovation (after Opitz von Boberfeld & Scherhag, 1980)

There is no guarantee that a strong immediate response in sward composition to renovation will last. There has been extensive experimentation throughout Europe during the second half of the last century investigating the long-term effects of renovation. It has been shown that depending on the seed mixture and the way and intensity of grassland management, the vegetation composition may develop highly dynamical for some years and then eventually reverts to a stage where it had been before renovation (Hoogerkamp, 1984; Klapp, 1943; Müller, 1989). Figure 5 shows an example for this. The sown and highly competitive grasses *Lolium perenne* and *Dactylis glomerata* dominated the resown swards for up to 7 years and were then replaced by a vegetation with species and varieties that had not been sown (Brünner, 1967). Only when the swards were grazed, in contrast to cutting, the sown species managed to survive in the sward for longer. From an agronomic point of view, such a dynamic vegetation development is not intended—weed species may rapidly invade and deteriorate the sward status, which would then require another renovation. The challenge of renovation is to anticipate the site and management conditions that are likely to cause adverse dynamic vegetation changes and to compose the seed

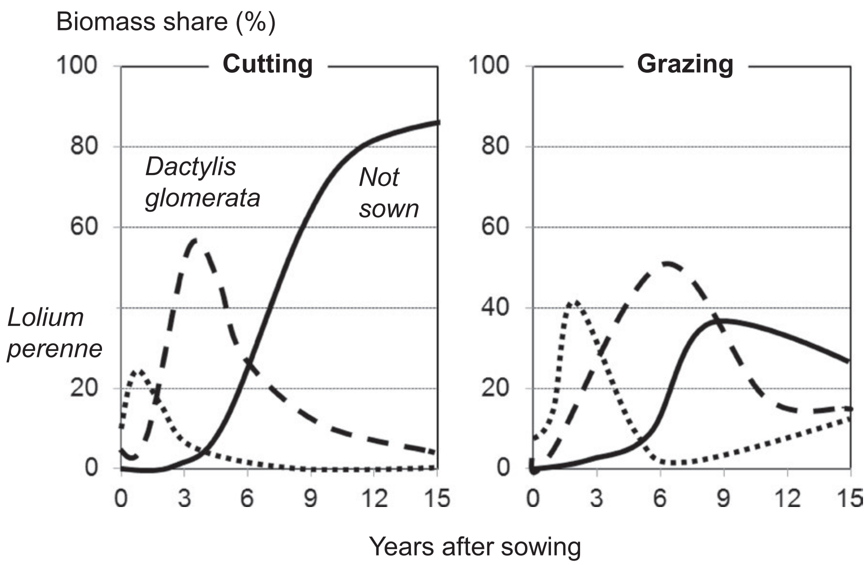

FIGURE 5 Example of a long-term vegetation response: the effect of grazing management of a resown grass sward on the yield share of the sown species *Lolium perenne* (dotted line), *Dactylis glomerata* (dashed line), and on the bulk of not sown species invaded (continuous line), after Brünner (1967)

mixtures accordingly followed by a management that is well adapted to the site and sward.

6 | EFFECT OF RENOVATION ON ROOT C-POOL

Roots are the main sink for belowground C (Domanski, Kuzyakov, Siniakina, & Stahr, 2001) and a source for soil organic matter. The majority of roots under permanent grassland swards are located near the surface, which is the zone of the highest microbial activity (Deinum, 1985). Large amounts of fine root biomass in this shallow layer and favorable conditions for mineralization foster the turnover of roots, which forms an important part in the nutrient cycling of grassland systems (Stewart & Frank, 2008). The effects of grassland renovation measures on root turnover depend on sward condition and renovation technique. Ploughing-up will disturb the more or less equilibrated system of root formation and decay. An initially higher availability of oxygen after soil disturbance will enhance the decay of the structural tissue dominated root C-pool which before had a slow turnover (Dietzel, Liebman, & Archontoulis, 2017). At the same time, parts of the topsoil with their characteristically large amounts of roots are buried into greater soil depths (up to 25–30 cm) and this might lead to a certain decrease in microbiological C-respiration as a consequence of reduced microbiota activity and lower aeration. These processes can help to explain the fact that a shallow but intensive sward deterioration by a rotary cultivator can lead to a similar N-mineralization than ploughing (Creighton, Kennedy, Hennessy, & O'Donovan, 2016).

After resowing, the formation of new roots from grasses and legumes will take some time. At first, embryonal roots will develop from the seeds and these do not have the potential to take up and thus immobilize as much C as roots of an old sward; this is also because of the limited tiller density in newly sown grass swards. However, rooting depths of embryonal grass roots exceed those of the following adventive roots (Müller, 1989). Generally, deep rooting can markedly contribute to building up a root C-pool as root turnover is reduced in greater soil depths (Oram et al., 2017). At the onset of tillering of the newly sown grasses, the root systems will change to adventive rooting. From that time onward, root biomass formation and thus C sequestration will mainly depend on tiller density. However, in periods of a high increase in tiller number the root development is hampered by a time lag effect: During this time, assimilate-C is preferably allocated to the tiller buds and not to the roots (Matthew, Mackay, & Robin, 2016). Two or three years after sowing, root biomass will have reached the status before renovation; any further increase is mainly due to the nonliving root fraction (Müller, 1989).

Compared to an old and unproductive sward, the newly sown grass and legume cultivars with their high growing potential can markedly contribute to the enhancement of the root C-pool (Marshall, Collins, Humphreys, & Scullion, 2016). According to Jungers et al. (2017), C-pools in roots have a greater effect on net greenhouse gas (GHG) mitigation than soil organic C (SOC) in the short term. Changes over time in root characteristics may alter patterns in long-term C storage (Figure 6). It can be concluded that grassland renovations can lead, at least in the short term, to a reduction in soil organic C with related CO_2 losses, but also offer a chance to increase the root C-pool. Reijneveld, van Wensem, and Oenema (2009) observed an increase in soil organic matter under grassland over twenty years when intensive renovation measures were combined with the successful introduction of vigorous grass varieties. The improvement of renovation measures should consider these challenging aspects for the future.

7 | RENOVATION AND EMISSION RISKS

When grassland is renovated, the sink and source balance of nutrients, in particular C and N, will be altered. Sward improvement without destruction can have favorable effects not

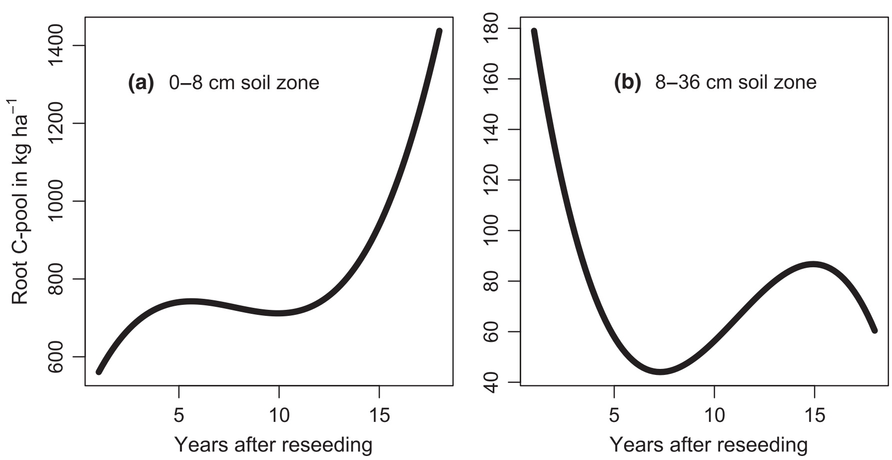

FIGURE 6 Long-term development of root C-pool in different soil depths after grassland ploughing and reseeding on a Haplic Luvisol (*Lolium perenne*-dominated swards, autumn cored, data from Müller, 1989)

only on yield and nutrient uptake by the sward, but also on C and N accumulation in the soil as well.

We have to distinguish between immediate emission risks after renovation and long-term risks (Figure 7). Both increase with the degree of soil disturbance and interact with management and soil conditions. Frequency of renovation will play a role, too: Each renovation event will trigger of immediate emission risks and destabilize the system by interacting with longer term effects. However, there is still a lack of systematic research on the topic. Nutrient emissions occur as gaseous losses and leaching (MacDonald, Chantigny et al., 2011). Emissions of CO_2 are related to soil mineralization (Willems et al., 2011), and N_2O mainly to enhanced N turnover and fertilization (Merbold et al., 2014) with the additional risk of indirect N_2O emissions that are related to larger NO_3 leaching losses (Davies et al., 2001; Krol et al., 2016; MacDonald, Rochette et al., 2011). Only techniques with no or minimal destruction of the old sward seem to be positive where emissions are concerned. Velthof et al. (2010) found that renovation increased N_2O emissions by a factor of 1.8–3.0 relative to the reference grassland. However, it has also been reported that a nondestructive renovation measure that combines killing of the sward by herbicide and direct seeding can lead to enhanced mineralization and related gaseous losses (MacDonald, Chantigny et al., 2011; MacDonald, Rochette et al., 2011; Velthof et al., 2010). In contrast, recent investigations by Buchen et al. (2017) found no significant differences in N_2O emissions after renovation by sward killing combined with direct seeding and sward killing combined with ploughing. However, on an organic soil N_2O losses were somewhat larger after ploughing than after chemical sward destruction; in all cases, N_2O emissions were much reduced in the second year after renovation. Renovation measures had no effect on biomass yield when compared with the productive intact sward. Reinsch, Loges, Kluß, and Taube (2018) compared grassland renovation by ploughing and reseeding in autumn or spring on a Eutric Luvisol in northern Germany. They found that freeze–thaw cycles were the major driver of increased N_2O emissions of 21 kg N_2O ha^{-1} $year^{-1}$ after renovation in autumn while emissions following grassland ploughing and reseeding in spring were much smaller (up to 3.9 kg N_2O ha^{-1}) and mainly driven by high soil mineral N concentrations. Despite the presence of a higher proportion of sown cultivars of productive grass species, the total biomass yield of renovated swards did not exceed those of intact grass-clover swards in the first production year (Reinsch et al., 2018). Studies measuring the NO_3 leaching losses by suction cups or using lysimeters determined N losses of 35–72 kg N ha^{-1} over the first winter following grassland renovation (Seidel et al., 2009; Shepherd, Hatch, Jarvis, & Bhogal, 2001). From investigations on sandy soils in northern Germany, Seidel, Müller, Kayser, and Isselstein (2007), Seidel et al. (2009) report that type of fertilizer as well as the level of N fertilization before renovation had no significant effect on soil mineral N in autumn and N leaching during the winter following grassland renewal in spring. When grassland was renewed in late summer/autumn, this resulted in larger NO_3-N leaching losses during the first winter (36–64 kg N ha^{-1}) compared to a renewal in spring (1–7 kg N ha^{-1}). The effect leveled out in the second winter (Figure 8). It can be concluded that losses of N via leaching and N_2O emissions after renovation can probably not be avoided, but that renovation in spring instead of autumn in combination with proper tillage and timing of fertilizer application can minimize N losses (Seidel et al., 2007, 2009; Velthof et al., 2010). With a rational intensification of fertilizer application, it is possible to lengthen the productive life of the sward and to plough less frequently (Loiseau, El Habchi, de Montard, & Triboi, 1992). There is also a site effect on losses of N_2O and NO_3 after renovation. While on sandy soils NO_3 leaching is a major pathway for losses, N_2O emissions and N_2 denitrification become more pronounced on heavier or organic soils (Buchen et al., 2017; Necpalova, Casey, & Humphreys, 2013). On a poorly drained clay loam soil in Ireland, Necpalova et al. (2013) found that soil N losses after renovation were high due to increased net mineralization (>3 t N ha^{-1}), while the proportion lost via N leaching and N_2O emissions was unsubstantial (27 kg N ha^{-1} $year^{-1}$). This was likely a result of soil properties and the anoxic status of the soil, which likely promoted complete denitrification. Zajac, Spychalski, and Golinski (2010) observed increased NO_3 concentrations in an organic soil, not only after using mechanical methods of renovation (rototiller, plough), but also after killing the sward with a total herbicide and direct drilling.

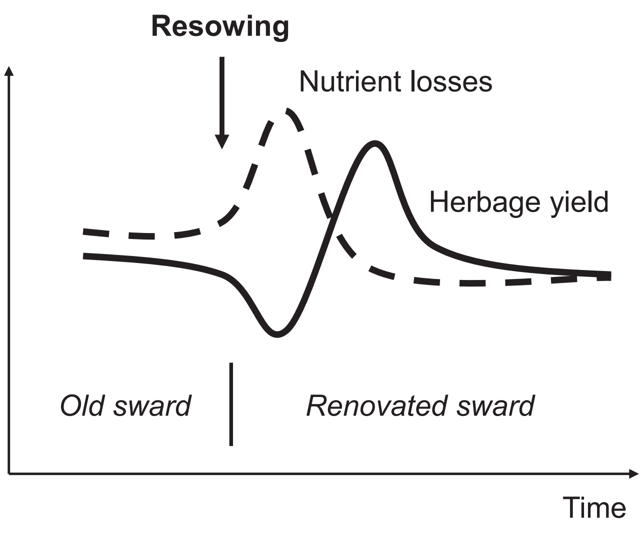

FIGURE 7 Schematic representation of the effect of resowing on the dynamics of herbage yield (continuous line) and related nutrient losses (dashed line) with time (after Hatch & Hopkins, 2007; Taube & Conijn, 2004)

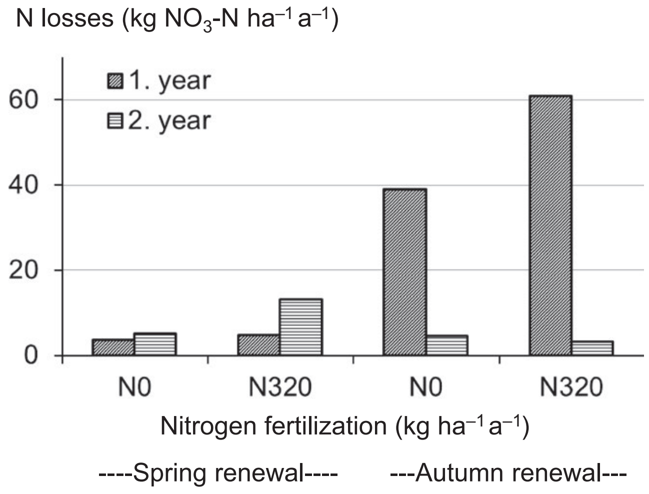

FIGURE 8 Nitrate leaching losses in the first and second year after renovation (complete grass sward disturbance by a rotary cultivator followed by reseeding) on a sandy soil after either spring or autumn renewal and no or 320 kg N fertilization annually to the previous crop, average of two experiments. The factor time of renovation and N fertilization are significant in the first year following renovation ($p < 0.05$) (after Seidel et al., 2009)

8 | CONCLUSIONS—RENOVATION AND MANAGEMENT

Grassland renovation is advised when grass swards are degraded and no longer provide the functions and services that are expected from them. It was shown that the consequences of grassland renovation are highly variable and may differ among the different services. A major reason for this is the variation of the degree of sward disturbance before sowing the new sward. Therefore, it was necessary to develop a clear classification of renovation measures. A closer look at the agronomic consequences showed that the amount of benefits in terms of higher yield and better herbage quality may vary greatly, depending on the particular environmental conditions as well as on the applied renovation techniques. The issue is becoming even more complicated when several services are considered at the same time. Trade-offs have been shown to occur when grass swards are renovated, in particular among agronomic and environmental services. An improved insight into the processes induced by renovation measures and their interactions with the site and climatic conditions is needed to be able to better balance potential benefits and potential risks of renovation measures and to adopt an appropriate grassland management. Modeling approaches for a defined set of situations could support the existing knowledge by providing data for prediction as a basis for evaluation and decision support in practice. As a rule, gentle measures of renovation that do not rely on sward and soil destruction, such as oversowing, pose little risks for renovation failure and environmental pollution. It seems promising to further develop such methods and make them more effective. Above all, renovation is likely to fail in the medium and longer term if the reasons that had contributed to grassland degradation such as overstocking, poor grazing management, imbalance of nutrient supply, cutting frequency and timing, and technical aspects of harvesting are not properly addressed after the renovation. For practical farming, managing permanent grasslands in a way that the services are sustained over time should always be given priority in order to reduce the necessity of grassland renovation.

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CONFLICT OF INTEREST

None declared.

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