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Yields and greenhouse gas emissions of cultivation of red clover-grass leys as assessed by LCA when fertilised with organic or mineral fertilisers

Kaija Hakala [a,*], Hanna-Maija Nikunen [a,1], Taija Sinkko [b], Oiva Niemeläinen [a]

[a] MTT Agrifood Research Finland, Plant Production Research, Tietotie, Planta, 31600 Jokioinen, Finland
[b] MTT Agrifood Research Finland, Biotechnology and Food Research, Latokartanonkaari 9, 00790 Helsinki, Finland

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ABSTRACT

Red clover-grass leys incorporating three clover (*Trifolium pratense* L.) varieties and two grass species, tall fescue (*Festuca arundinacea* Schreb) and timothy (*Phleum pratense* L.), were sown in 2003 and grown for three harvest years (2004–2006). The crops were fertilised either once with organic fertiliser (cow manure applied in the sowing year) or yearly with mineral fertiliser. The yields of the harvested bomasses were measured and the greenhouse gas (GHG) emissions estimated by life cycle analysis (LCA) yearly for both fertilisation types. At the end of the experiment, the carry-over effect of the red clover-grass leys was studied with spring wheat (*Triticum aestivum* L.). Mineral fertilisation resulted in higher yields, but also about 2–3 times higher GHG emissions per unit clover-grass biomass than organic fertilisation. Grasses were favoured by mineral fertilisation, while the proportion of clover was higher and decreased less with time with organic fertilisation. Clover leys sown without grasses yielded least and produced the highest emissions per unit biomass. Tall fescue sown with clover produced more consistent yields than timothy, especially during drought stress and when the ley aged. Organic fertilisation appears the most sustainable way to produce field biomass for energy, at least when legumes are sown in the ley. After three years of clover-grass production, the biomass yield of spring wheat sown without fertiliser was about 4 t ha^{-1}, which could augment production of biomass per parcel, and would decrease the amount of GHG emissions from bioenergy production whether fertilised with organic or mineral fertilisers.

1. Introduction

The EU aims at mitigating climate change by reducing greenhouse gas (GHG) emissions. One way to reduce GHG emissions is to substitute fossil-fuel-based energy sources by those that are renewable. Thus, the EU has set an ambitious target of 20% of total EU energy consumption being based on energy generated from renewable sources by 2020 [1]. Agriculture is a major producer of GHG through animal husbandry and field cultivation [2]. A major share of the GHG emissions from field production results from the manufacture and use of industrially produced nitrogen (N) fertilisers. Emissions are caused firstly by the Haber–Bosch process, which uses natural gas or sometimes coal as a hydrogen source to reduce

Abbreviations: GHG, greenhouse gases; DM, dry matter.

* *Corresponding author*. Tel.: +358 29 531 7169.
E-mail address: kaija.hakala@mtt.fi (K. Hakala).
[1] Present address: Hanna-Maija Nikunen Co., Palotie 3 as 2, 86800 Pyhäsalmi, Finland.

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atmospheric N to ammonia. After field application, both mineral and organic fertilisers emit N_2O [3–5], which represents an important component of GHG emissions. Fertiliser factories are able to decrease emissions associated with production of N fertilisers and thereby have decreased the GHG emission values of the fertiliser [6], but nevertheless N fertilisers remain a major source of GHG emissions in agriculture. Other sources of GHG from both field bioenergy and food production are fuel consumed during field operations, production and usage of lime and plant protection chemicals, and transport of agrochemicals and farm products. Regularly ploughing and cultivating fields also promotes mineralisation of soil organic matter and thereby stimulates CO_2 emissions, especially when the soil organic matter content is high [7]. Ploughing also stimulates emissions of N_2O and leaching of nutrients [5].

Renewable transport fuels, such as alcohol, could be manufactured from wheat (*Triticum aestivum* L.) grain, for example. However, field production also produces GHG emissions. Therefore, the EU has set strict directives for the volume of emissions allowed in biofuel production in order to encourage sustainable production in comparison with fossil fuel production [8]. In an earlier work we calculated the GHG emissions in connection with first generation biofuel production from wheat, barley (*Hordeum vulgare* L.), rapeseed (*Brassica rapa* L. or *Brassica napus* L.) and sugar beet (*Beta vulgaris* L. *var. altissima*) in Finnish conditions [4]. We established that cultivation of grain, rapeseed or sugar beet in Finnish conditions fail to reach the emission limits set in the Renewable Energy Directive of the EU [8]. The main obstacle is that when higher yields are registered, also the N fertiliser use increases to support the higher yield, thereby nullifying the benefit of the increased yield [4]. Liming soils and corresponding emissions are not included as default values for the emission calculations for cereals in the Renewable Energy Directive of the EU [8], but were taken into account in our calculations, as liming is necessary under Finnish conditions and can result in substantial CO_2 emissions. While liquid biofuel production from first generation sources, such as wheat or barley grain, for Finnish conditions, has been shown not to reduce GHG emissions compared with fossil fuels, second generation biofuels produced from grasses such as reed canary grass (*Phalaris arundinacea* L.), for example, could be more sustainable [2]. Promising results were recorded when grasses were used as raw material for biogas production [9]. A high yielding grass species could produce 30 MWh ha^{-1} y^{-1} of methane-based energy [10].

According to some estimates, development of mineral N fertilisers supported the lives of a third of the world's population in the 20th century and N fertilisers are indirectly responsible for feeding half of the current global population [11]. Also into the future, mineral fertilisers will remain important in meeting the world's food needs. However, using legumes to fix atmospheric N for food, fodder and bioenergy, and efficiently circulating manure from animal husbandry, could help to decrease GHG emissions from agriculture and society on general [3,12]. While legumes used as an N source could be environmentally friendly regarding GHG emissions, they are not an absolute solution to N losses to atmosphere or nutrient leaching [5,12–14].

The amount of nitrogen fixed by legumes in a ley, or when grown as green manure, can be considerable, up to 200 kg ha^{-1} y^{-1} for red clover (*Trifolium pratense* L.) [15], and 360 kg ha^{-1} y^{-1} for a red clover-perennial ryegrass ley [16]. The amount of N fixed depends on the species and proportion of both legume and the companion grass, the age of the ley, soil type and the climatic conditions during growth [13,15–22]. When sown for forage in a mixture with grasses, legumes can support grass growth under ideal conditions [19], although the transfer of N between grasses and legumes during ley growth is seldom enough to stimulate optimal yields [16,18]. On the other hand, legumes may improve soil quality and fertility in many ways, e.g. through adding carbon and organic N in the soil, thus promoting growth of the following crops [12]. However, when a ley is actively harvested for forage, the after-effect for the next crop may sometimes be small, only about 10–20 kg ha^{-1}, especially when the legume-grass balance is not ideal [16,17,23].

In the present field study we tested the biomass production potential and GHG emissions of cultivation of different combinations of grass and red clover fertilised with either mineral or organic fertiliser. Our aim was to find out which combinations would produce the highest biomasses with the lowest GHG emissions caused by cultivation, what would be the optimal production time of a grass ley in the combinations and what the effect of the clover-grass growth would be on soil nutrients during the experiment and after the experiment has ended (the carry-over effect for the next crop). Red clover was chosen as the legume species, as it has been found superior in biomass production and N fixation/acquisition in northern conditions [16,24]. Three red clover varieties were used: an old Finnish diploid variety 'Jokioinen', a tetraploid and very winter hardy Swedish variety 'Betty' and a highly productive (in good conditions) Estonian tetraploid variety 'Ilte' [25]. Two companion grasses to grow with each of the red clover varieties were chosen on the basis of their yield and competitive qualities: a moderate competitor timothy (*Phleum pratense* var. Tuure) [26,27] and a less commonly used grass tall fescue (*Festuca arundinacea*, var. Retu), which has good regrowth capacity, good drought resistance and good winter hardiness [28,29]. We expected to get higher and more persistent clover yields with organic fertiliser with lower and less readily soluble nutrient levels, and higher total yields with mineral fertiliser with higher nutrient content and easier solubility [18]. As the grass leys in Finland gradually lose their productivity [18], we expected to see a general optimal growing time relative to GHG emissions, but also differences in persistence attributable to different cultivation methods and grass-clover-mixtures [17,18]. The final objective was to find out what would be the most sustainable way to produce biomass for bioenergy, in this case especially from the viewpoint of GHG emissions of cultivation per unit biomass and bioenergy produced.

2. Materials and methods

2.1. Arrangement of experiment

The experiment was arranged in a split-strip-plot design with four replicates. The main plots were two grass species, their