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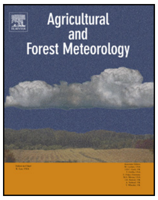

Contrasting impacts of afforestation on nitrous oxide and methane emissions

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ABSTRACT

The impacts of afforestation, with either Sitka spruce [*Picea sitchensis* (Bong.) Carr.] or European ash (*Fraxinus excelsior* L.), on nitrous oxide (N_2O) and methane (CH_4) emissions were assessed using a chronosequence (age-related) approach. Conversion of a semi-natural wet grassland on mineral gley soils to a Sitka spruce plantation drastically increased N_2O emissions, whereas the opposite trend was seen for CH_4 emissions. Annual cumulative emissions of N_2O increased from 0.12 ± 0.17 (±values indicate standard error, SE) kg ha^{-1} yr^{-1} at the grassland site to 10.12 ± 2.19 kg ha^{-1} yr^{-1} at the 16-year old forest site in this study, which constituted one of the highest recorded losses for unfertilised coniferous forests in Europe. In contrast CH_4 emissions decreased from 7.61 ± 3.49 (grassland site) to 0.49 ± 0.65 (7-year old forest) kg ha^{-1} yr^{-1}, with the 16-year old forest site acting as a small sink (−0.80 ± 0.12 kg ha^{-1} yr^{-1}). The contribution of these gases in terms of carbon dioxide (CO_2) equivalents to the total greenhouse gas (GHG) budget showed that they can reduce the global warming amelioration capacity for this type of land use change by 10 ± 2%, although the magnitude of this reduction is associated with significant uncertainty. In comparison the conversion of a managed grassland into an ash plantation on mineral brown earth soil had no clear effects on either N_2O or CH_4 emissions, with annual cumulative fluxes for N_2O of the order of 10 times lower than those from the coniferous stands. A combination of factors could have contributed to these contrasting outcomes, including differences in ecosystem productivity, soil characteristics, management practices, microbial population structure and activity, variations in root activity and vegetation composition, as well as interannual climatic variability, and this is discussed. Overall, the results indicate the difficulty in generalising the impacts of afforestation on GHG budgets in the absence of a better understanding of how tree species, as well as soil and climatic factors, interact to determine trace gas emissions.

1. Introduction

Afforestation is regarded as an effective mechanism, in addition to a reduction in anthropogenic emissions, for global warming amelioration (see Articles 3.3 and 3.4 of the Kyoto Protocol, UN, 1997; IPCC, 2007) due to the capacity of trees to sequester CO_2 from the atmosphere. However, the impact of this type of land use change on the budgets of other greenhouse gases such as N_2O and CH_4 has received much less attention, and the contribution of these gases to the total GHG budget of forest ecosystems remains unclear. N_2O is produced in the soil as a by-product or end-product of a series of microbial processes as part of the biogeochemical nitrogen (N) cycle, which is intimately linked to, and influenced by, the carbon (C) cycle (Schulze, 2000). The environmental variables that influence both cycles are numerous, and each one of them can contribute, either directly or indirectly, to N_2O emissions. Three main N_2O-producing microbial processes have been recognised to date: nitrification, denitrification and nitrate ammonification (Baggs and Philippot, 2010). In terms of N-substrate flows, nitrification acts on the substrates liberated by the decomposition and mineralisation processes, which indirectly govern rates of N_2O production (Schulze, 2000). All these processes are carried out by microbial guilds that are often very specific in their particular environmental requirements (Baggs and Philippot, 2010). Modifications in

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ecosystem properties due to afforestation, including effects on biomass production, soil aggregation and acidity, soil hydrological status, and microbial population structure and function, are likely to significantly influence N_2O and CH_4 production and emission. Regarding CH_4, both methanogenesis and methane consumption (i.e. methane oxidation) are known to occur in soils. Methanogenic microbes are responsible for CH_4 production through the breakdown of organic compounds under anoxic conditions, and at low redox potential, conditions that are usually found in very wet soils (Ponnamperuma, 1972; Smith et al., 2003). Aerobic methanotrophs, on the other hand, oxidise CH_4 to CO_2 usually under conditions where the gas can readily diffuse from the atmosphere to the soil. Some soils can act therefore as sinks for methane, others as net sources, and the direction of gas flux can be greatly influenced by the soil hydrological status that will be linked with forest growth and development. The common practice of drainage of wet soils prior to afforestation might therefore be expected to result in increased levels of CH_4 consumption.

The age-dependent impact of afforestation on GHG emissions can be assessed by monitoring fluxes from forest chronosequences, where a direct comparison can be made between emissions from forest stands of different ages and adjacent unforested areas that represent the conditions prior to the change in land use. Whilst there is evidence that the afforestation of grasslands on organic soils could trigger an increase in production/emission of N_2O, together with a reduction in CH_4 emissions (Martikainen et al., 1993, 1995; Nykänen et al., 1998; Ball et al., 2007), other studies report a decrease in N_2O emissions (e.g. Merino et al., 2004; Mishurov and Kiely, 2010), especially when fertilised grasslands are converted into unfertilised forest stands. In some cases no net change was found (Mäkiranta et al., 2007; Maljanen et al., 2012). Differences in land use history and management practices, tree species/vegetation composition, soil chemical and physical properties, C/N substrate availability and/or differences in microbial population structure could all contribute to these different outcomes, making any generalisation difficult. Evaluation of the impact of tree-age on non-CO_2 GHG emissions has seldom been addressed (i.e. Ball et al., 2007; Peichl et al., 2009). The assessment of any increase in non-CO_2 GHG emissions associated with afforestation are particularly important as they have the potential to reduce or even negate the global warming ameliorating capacity of afforestation-mediated increases in carbon sequestration. More research is therefore required to improve country-wide estimates of the potential global warming amelioration capacity of tree plantations. For many countries, including Ireland, any major GHG mitigation benefits associated with afforestation are primarily associated with coniferous plantations, particularly *Picea sitchensis*, which comprise over 52% of the total area covered by trees, but other deciduous forest stands, including species such as *Fraxinus excelsior* (3.1% of total area covered by trees; Forest Service, 2007), can be significant and are likely to become more important in the future with a general shift away from coniferous plantations. This investigation therefore assessed the impact of coniferous and deciduous afforestation (utilising a tree age-related approach) on non-CO_2 trace gas emissions, together with an evaluation of how changes in a number of environmental/soil factors (e.g. soil moisture, substrate availability, pH and tree performance) may have impacted the trace gas fluxes.

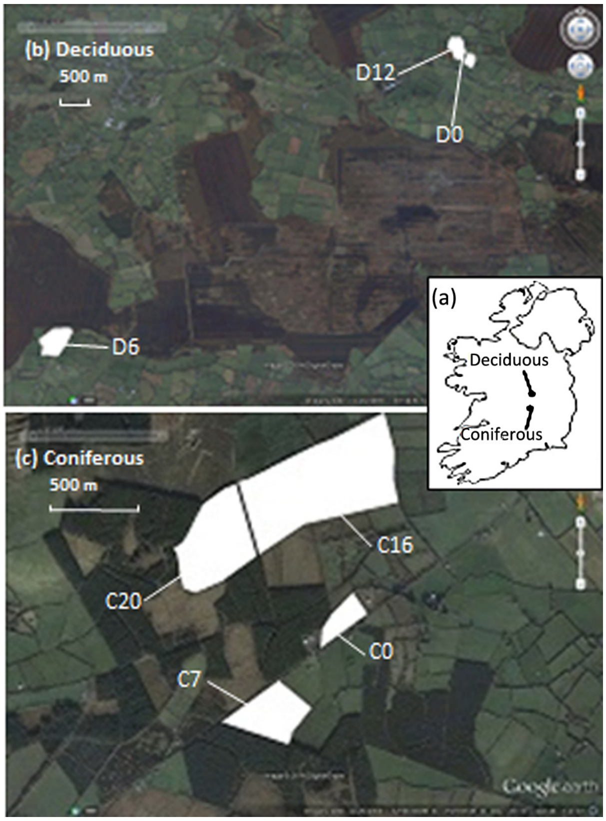

Fig. 1. Map of Ireland showing the location of the study sites in the Irish Midlands (a); the deciduous chronosequence (b) comprising three subsites D0 (grassland), D6 (6 year old) and D12 (12 year old), and the coniferous chronosequence (c) comprising four subsites C0 (grassland), C7 (7 year old), C16 (16 year old) and C20 (20 year old). Note that different scales have been used for panels b and c. Images taken from Google Earth.

2. Materials and methods

2.1. The chronosequences

Measurements were made at a coniferous and a deciduous chronosequence in the Irish Midlands, each one comprising adjacent subsites representing different temporal stages in the growth of *P. sitchensis* and *F. excelsior* first generation plantations (Fig. 1). The individual sites used in each chronosequence were located within a 5–10 km radius. The coniferous chronosequence (Fig. 1c), located in County Laois (52°57′N, 7°15′W; 260 m a.s.l.), consisted of four sites identified in this study as C0, C7, C16 and C20: a semi-natural, unimproved grassland similar to the site prior to afforestation (i.e. time zero of the chronosequence; C0) and three forested sites of increasing tree age (7, 16 and 20-year old; C7, C16 and C20, respectively). The densities of planting for the forested sites were 2533, 2350 and 1316 trees ha^{-1} for the C7, C16 and C20 sites, respectively. The deciduous chronosequence (Fig. 1b), located in County Offaly (53°18′N, 7°12′W; 73 m a.s.l.) consisted of three sites identified as D0, D6, and D12: a fertilised grassland (D0) and two forested sites of increasing tree age (6 and 12-year old; D6 and D12, respectively). The densities of planting were 3000 and 3533 trees ha^{-1} for the D6 and D12 sites, respectively. The two chronosequences differed in relation to soil type and characteristics, management practices and vegetation cover of the associated grassland (Table 1), but the regions investigated were assumed to have similar levels of N-deposition (see De Kluizenaar and Farrell, 2000) and climate given their close proximity. The coniferous sites were located on a wet mineral gley soil with a high clay content (Saiz et al., 2006), in an area considered as marginal agricultural land (Conry, 1987); none of the sites were fertilised and drainage had been carried out through the installation of surface drains prior to tree establishment. The original *Juncus effusus*-dominated grassland (C0) was previously used for rough grazing. The deciduous sites, located in a region of medium to well drained brown earth soils that could support a variety of land uses (Hammond