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Review

Meta-analysis of the effects of undersown catch crops on nitrogen leaching loss and grain yields in the Nordic countries

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ABSTRACT

The growing of catch crops aims to prevent nutrient leaching in autumn after harvest and during the following winter, but due to competition, catch crops may also reduce yields of the main crop. We used meta-analysis to quantitatively review 35 studies conducted in Denmark, Sweden, Finland and Norway over the past four decades. These studies assessed the effect of both non-legume and legume catch crops undersown in spring cereals on nitrogen (N) leaching loss or its risk as estimated by the content of soil nitrate $N(NO_3^- - N)$ or its sum with ammonium $N(NH_4^+ - N)$ in late autumn. The meta-analysis also included the grain yield and N content of spring cereals. To identify sources of variation, we studied the effects of soil texture and management (ploughing time, the amount of N applied), as well as climatic (annual precipitation) and experimental conditions (duration of experiments, lysimeter vs. field experiments, the decade in which the experiment took place).

Compared to control groups with no catch crops, non-legume catch crops, mainly ryegrass species, reduced N leaching loss by 50% on average, and soil nitrate N or inorganic N by 35% in autumn. Italian ryegrass depleted soil N more effectively (by 60%) than did perennial ryegrass or Westerwolds ryegrass (by 25%). In contrast, legumes (white and red clovers) did not diminish the risk for N leaching. Otherwise, the effect on N leaching and its risk were consistent across the studies conducted in different countries on clay and coarse-textured mineral soils with different ploughing times, N fertilization rates (<160 kg ha^{-1}), and amounts of annual precipitation (480–1040 mm). Non-legume catch crops reduced grain yield by 3% with no changes in grain N content. In contrast, legumes and mixed catch crops increased both grain yield and grain N content by 6%.

Therefore, in spring cereal production, non-legume catch crops represent a universal and effective method for reducing N leaching across the varieties of soils and weather conditions in the Nordic countries. Moreover, the trade-off between potential grain yield loss and environmental benefits seems tolerable and can be taken into account in environmental subsidy schemes.

Contents

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1. Introduction

Eutrophication by nitrogen (N) is a major and growing water problem for the Baltic Sea and agriculture is a significant contributor to the diffuse N loads (Gustafson, 2012). The climate of the majority of Baltic Sea catchment areas is characterized by relatively mild winters and surplus winter precipitation, which make arable soils vulnerable to nitrate leaching. This especially applies to the lighter textured soils under intensive spring cereal production, which occupy 43% of arable land in Finland, about 33% in Denmark, and 25% in Sweden (Eurostat, 2015). In Finland, N loads from agriculture rose by 27% during 1985–2006 despite decreases in commercial N fertilizer use and, thus, lower N balances (Aakkula et al., 2012), resulting in average annual N leaching losses of 15 kg ha^{-1} (Vuorenmaa et al., 2002). In Sweden, annual N losses usually amount to 15–45 kg ha^{-1}, with the largest losses occurring on highly permeable sandy soils with low water-holding capacity and limited rooting depths (Stenberg et al., 1999). In Norway, cereal production generally leads to N losses of 20–43 kg ha^{-1} (Vagstad, 2001), while in Denmark, N leaching for arable farms averaged over soil types and fertility levels is, according to a simulation model, an estimated 36 kg ha^{-1} (Knudsen et al., 2006).

The primary intention for using catch crops is to take up N from the soil, and thereby reduce the soil nitrate N content vulnerable to leaching during autumn and winter (i.e., Thorup-Kristensen et al., 2003). Nitrogen uptake by commonly used ryegrass species can reach up to 30–40 kg ha^{-1} (Alvenäs and Marstorp, 1993; Thomsen and Hansen, 2014). Growing catch crops after harvesting the main crops has been identified as an even more useful strategy than reducing the application of fertilizer or no-till techniques (Hansen and Djurhuus, 1996; Constantin et al., 2010). Undersowing in the main crop in spring is particularly potential in Nordic countries, where climatic conditions after harvest of the main crops may reduce the development of a late-sown catch crop. This method maximizes the time available for catch crop growth after harvesting the main crops, thereby also avoiding tillage in early autumn, which generally stimulates N mineralization (Aronsson, 2000). Several studies reported that, in northern conditions, the use of undersown catch crops considerably reduces nitrate loss (Gustafson et al., 1998; Lemola et al., 2000) and the content of soil nitrate N before winter (Lyngstad and Breland, 1995; Lyngstad and Børresen, 1996), which is considered an indicator of N leaching risk (Breland, 1996; Känkänen et al., 1998).

However, a disadvantage of undersowing catch crops is competition with the main crops for nutrients, soil moisture and light, resulting in a few-percent loss of grain yield (Jensen, 1991; Andersen and Olsen, 1993; Breland, 1996; Lyngstad and Børresen, 1996; Karlsson-Strese et al., 1998; Känkänen et al., 2001, 2003) or a statistically non-significant reduction of yield (Wallgren and Lindén, 1994; Ohlander et al., 1996).

Previous meta-analyses summarized catch crop studies conducted mainly in the USA and Canada with corn or sorghum as the main crops (Miguez and Bollero, 2005; Tonitto et al., 2006) and in the European Mediterranean basin and the American Midwest with different main crops, including cereals and vegetables (Quemada et al., 2013). Although studies have explored the environmental effects of catch crops in cereal production in the Nordic countries during the past 40 years, none has yet carried out a meta-analysis.

The present study aimed to summarize Nordic experiments on the effects of catch crops undersown in spring cereals on N leaching loss or its risk, soil $NO_3^- - N$ or inorganic N ($NO_3^- - N + NH_4^+ - N$) in late autumn. The meta-analysis also included both the grain yield of the main crops and their quality. We further examined the effectiveness of catch crop species and whether different soil texture groups, the ploughing time (autumn/spring), or the soil depth modified this effect. We also tested whether the effect differed between the studies with different durations of experiments, local precipitation amounts, N fertilization used, or between lysimeter and field studies. Finally, we examined whether the results differed between the countries or over the decades.

2. Materials and methods

2.1. The database

The database consisted of 35 studies published between years 1988 and 2014 in peer-reviewed scientific journals (30 articles), in seminar proceedings (3 articles), in newspapers (1 article), and one unpublished study (Appendix A and Reference list marked with asterisks). Altogether 14 studies were conducted in Denmark, 11 in Sweden, 7 in Finland, and 3 in Norway. We found the articles by searching for key-words ("catch crops" or "cover crops" AND "soil nitrate N" or "soil $NO_3^- - N$ " or "soil inorganic N" or "soil mineral N" or "nitrogen leaching" or "nitrate leaching" AND Denmark; Sweden; Finland or Norway) in the Web of Science Database; we also found the journal articles in the reference lists of previously published articles.

To be included in the database, a study had to meet the following criteria:

1. The study was carried out in Denmark, Sweden, Finland or Norway.
2. The main crops were spring wheat, spring barley, and oats.
3. Catch crops were undersown in spring.
4. The study had an appropriate control group (i.e., one with no catch crop).
5. The study assessed the effects of undersown catch crops on total N leaching, nitrate N leaching, soil nitrate N or inorganic N, grain yield, or grain N content.
6. Responses to catch crops were recorded as either original data for each experimental year or as means of treatments (i.e., with undersown catch crops) and controls (i.e., with no catch crops) for the duration of the experiment with standard deviations and sample sizes (number of years).

A total of 26 studies were excluded from our database since means for each experimental year or means and SD at the end of an experiment were unreported. An experiment was defined as a continuous sequence of consecutive years in a given field; the duration of the experiments that met these criteria varied from two to seven years, with a mean of three years.

The catch crops were four non-legume species (Italian ryegrass (*Lolium multiflorum* Lam.), perennial ryegrass (*Lolium perenne* L.), Westerwolds ryegrass (*L. multiflorum* Lam. var *westerwoldicum*) and rapeseed (*Brassica napus* L.)) and two legume species (white clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.)).

The soils were clay and coarse-textured mineral soils with pH 5.5–7.5. Manure or inorganic fertilizer was applied at rates of