The carbon footprint of maize silage[1]

J M Wilkinson[ab] and P C Garnsworthy[b]
[a] *MGA Nutrition Consultant.*
[b] *School of Biological Sciences, University of Nottingham, Sutton Bonington Campus, Loughborough, Leics, LE12 5RD.*

Summary

The carbon footprint (CFP) of maize silage is 177 g CO_2e/kg dry matter (DM), comprising emissions from production of fertiliser, sprays and seed (84% of total CFP) and from machinery use (16%). Nitrogen use efficiency (N in product/N input) is typically 83% for forage maize and 25% to 35% for milk production. Enteric methane emissions account for 38% and feed production for 25% of total dairy farm CFP. UK agriculture aims to move towards net zero carbon emissions in line with government objectives. The CFP of maize silage may be reduced by i) reducing total N input; ii) soil carbon sequestration and iii) cover cropping. Nutritional options to reduce livestock CFP include i) reducing diet crude protein and fibre levels, ii) using feeds known to reduce methane production in the rumen, iii) selecting feeds with low CFP and iv) formulating diets for lowest feasible CFP.

Introduction

The most important greenhouse gas (GHG) contributing to global warming is carbon dioxide (CO_2), but the main GHG produced on farms are methane (CH_4) from enteric fermentation and manure, and nitrous oxide (N_2O) from the reduction of fertiliser and manure nitrate, together with oxidation of ammonia, in soil. These direct emissions from land and livestock, aggregated with indirect emissions embedded in production of purchased inputs, are converted to carbon dioxide equivalents (CO_2e) to derive a 'carbon footprint' (CFP) of a product at the farm gate or of a whole farm.

The UK government has legislated for an 80% reduction in carbon emissions from 1990 levels to achieve net zero emissions by 2050 (DBEIS, 2019). There is much talk about how we might achieve 'net zero carbon' or carbon neutrality, where emissions are balanced completely by green energy and carbon storage. In this brief review, components of maize silage CFP are outlined together with some mitigation measures to move maize silage production and utilisation towards a net zero carbon balance.

Emissions from crops

Emissions from crops include nitrous oxide from soils, those embedded in the manufacture of fertilisers, seeds, chemicals, electricity, equipment used in field operations, and from the silo during feed-out.

The main GHG from crop production is N_2O. However, crops make relatively efficient use of nitrogen (N) inputs compared to livestock. N use efficiency (NUE - N in product as a percentage of N input), is above 67% for most arable crops grown in the UK, with NUE of forage maize typically 83% (Wilkinson and Audsley, 2013).

Carbon dioxide, nitrous oxide and volatile organic compounds (VOC) are emitted from maize silage during feed-out. VOC such as alkenes, ethyl esters (e.g. ethyl acetate and ethyl lactate) and carbonyl compounds (aldehydes) are potent environmental pollutants because they are ozone precursors (Mitloehner et al., 2009). Elevated concentrations of VOC in maize silage reflect delayed silo sealing which is accompanied by increased yeast and ethanol levels (Brüning et al. 2018).

Emissions from livestock

Emissions from livestock include methane from enteric fermentation, nitrous oxide from manure and those embedded in the manufacture of animal feeds.

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Methane production from enteric fermentation is directly related to dry matter (DM) intake and diet neutral detergent fibre (NDF) concentration, and inversely related to concentrate DM intake. Methane production per litre of milk decreases with increasing level of milk output. Average milk yield per cow in UK is increasing by 88 kg/year and is predicted to reach 9,000 kg/cow by 2030, reducing methane emissions per kg milk by 47% compared with 2004 values (Garnsworthy, 2004). The trend of increasing annual milk yield per cow has additional environmental benefits because fewer cows are needed to maintain a given level of national milk output.

Nitrous oxide emission is directly related to nitrogen excretion in manure (or digestate) and level of artificial fertiliser input. Livestock NUE (N in product as a percentage of N intake) is relatively low compared to crops - 25 to 30% for milk production (Sinclair et al., 2014). Excess N intake by the animal is excreted in urine and faeces, some of which is lost as ammonia, and some is oxidised to nitrate in soil and subsequently reduced to N_2O. Research effort is going into improving diet formulation to reduce total level of protein and its degradation in the rumen so that total N intake can be reduced whilst at the same time maintaining microbial protein synthesis and balancing total protein and essential amino acid supply with animal requirement.

Manure is a significant source of emissions from livestock. The most effective way of mitigating manure emissions is to use it as a N source in anaerobic digestion (AD) for methane energy production. Optimisation of methane production in AD systems involves mixing other fermentable substrates with manure, such as maize silage or food waste.

In a three-year study of 415 British dairy farms, whole-farm carbon footprint averaged 1.23 (range 0.82 to 2.76) kg CO_2e/litre of milk (DairyCo, 2014). The main sources of emissions were methane from enteric emissions (38% of total), methane from manures (6%), nitrous oxide from manures and artificial fertilisers (15%), fertiliser production (7%), feed production (25%), fuel (3%), electricity (3%) and other e.g. lime, bedding (2%).

Feed carbon footprint

The carbon footprint (CFP) of livestock feeds includes emissions released during crop production, storage, transport and processing. Also, for feeds other than forages, CFP includes allowances for land use (changes in management) allocated on the basis of long-term equilibrium and land-use change (e.g. deforestation) allocated on a global basis, so as not to penalise unduly an individual crop or land that has been in cultivation for many years. The CFP calculation also allows for imported and home-grown commodities according to the balance of trade and countries of origin. For by-products such as soya bean and rapeseed meal, CFP components are allocated to primary and secondary products on the basis of relative economic value.

Forage feeds have relatively low CFP compared to cereal grains by-products and compound feed (Table 1), with maize silage having a substantially lower CFP than grazed grass or grass silage, mainly due to lower fertiliser input and reduced machine use. 84% of total maize silage CFP is associated with inputs e.g. fertiliser, seed, sprays and 16% with machinery use in cultivation and harvest.

Table 1. *Carbon footprint of some forages, raw material feeds and dairy compound* (Wilkinson and Garnsworthy, 2016; Feedprint, 2020; Global Feed Lifecycle Assessment Institute, 2020).

	Carbon footprint (g CO_2 e/kg DM)
Forages	
Maize silage	177
Whole-crop wheat silage	325
Grass silage	382
Grazed grass	398
Cereal grains	
Barley	469
Wheat	493

Oilseed meals	
Rapeseed meal	563
Soya bean meal	4099
By-products	
Moist distillers' grains	45
Breakfast cereal	140
Wheatfeed	310
Sugar beet pulp	517
Wheat dried distillers' grains with solubles	971
Minerals	1188
Protected fat	3260
Compound feed	
Standard dairy compound	944

Carbon footprints of processed feeds of relatively high economic value (e.g. protected fat, dairy compound feed) are higher than CFP of by-products of lower economic value e.g. breakfast cereal (Table 1). Components of dairy compound CFP, excluding land use change, are: cultivation inputs (42% of total CFP), machine use (10%), processing (19%), feed mill (12%), additives (5%) and transport (10%, Feedprint, 2020).

Towards net zero carbon for maize silage

Reduced N input

A review of options to reduce GHG from crops highlighted reducing total N input as a potential management strategy because reductions in N were reflected in relatively small decreases in crop yield, which were more than compensated by greater reductions in N_2O emissions and by reduced primary energy use in fertiliser manufacture. In the case of forage maize, a 20% reduction in total N was associated with a 4% yield reduction but a 10% reduction in CFP (Wilkinson and Audsley, 2013). Reductions in N input may be possible without reducing crop yield if maize follows a legume crop (Ma et al., 2012) or if a cover crop is grown (see below).

Soil carbon sequestration

How much carbon is sequestered in soil under maize? In a French field-scale trial comprising the first four years of maize monoculture after C3 crops, with all above-ground vegetative parts removed, soil organic carbon (SOC, sampled to 35 cm depth) increased linearly at a rate of 570 kg C/ha per year (Balesdent and Balabane, 1996). Accumulation of SOC was attributed to high production and relatively slow biodegradation of maize root material.

At a crop yield of 12 t DM/ha, the CFP of maize silage (from Table 1) is 2124 kg CO_2e/ha (578 kg C/ha). Therefore, to achieve carbon neutrality, 578 kg C/ha must be sequestered annually in soil. At first sight the level of SOC sequestration recorded by Balesdent and Balaban (1996) in the first four years of maize cultivation might indicate that forage maize could be a carbon neutral crop. But this rate of SOC accumulation was probably higher than would occur with maize grown for longer periods, or in rotation with other crops. In a 15-year Canadian trial involving maize grown for silage either continuously or in a four-year rotation (maize-barley-barley-wheat), maize-derived SOC (to 30 cm depth) increased on average by 300 kg C/ha per annum for continuous maize and 117 kg C/ha per annum for rotational maize (Bolinder et al., 1999).

A large proportion of topsoil carbon from forage maize residues (stubble and roots) may be lost to the atmosphere as carbon dioxide through rapid biodegradation. However, in soils under maize, SOC can accumulate below the plough layer to 70 cm depth (maximum sampling depth, Gregorich et al., 2001), which is less likely to be lost to the atmosphere than material in the uppermost layers of soil.

Interestingly, Laamrani et al (2020) found over a 20-year period that a no-till continuous maize regime had higher total carbon in topsoil (0 to 15 cm) than maize in rotation with soya beans and winter wheat and concluded that no-till and had a positive effect on accumulation of carbon in topsoil. In a US study of no-till forage maize grown for bioenergy, Follett et al. (2012) recorded an increase in SOC, albeit in a relatively impoverished soil, of 25t C/ha over a 9-year period, a rate of 2,778 kg C/ha per year. Significantly, over 50% of the increase in SOC was between 30 and 150 cm soil depth (maximum sampling depth). The authors stressed the importance of taking deep soil samples when assessing carbon sequestration in soils under maize crops.

Cover crops

The Maize Growers Association has put sustained effort into assessing the potential of cover crops, either undersown or sown after maize, to reduce post-harvest soil erosion (see reviews by Oestergaard, 2015; Stephens, 2017 and Myhill and Tucker, 2020). A further benefit of cover crops is that they can retain up to 70 kg N/ha that might otherwise be leached as nitrate into water courses or emitted to the atmosphere as N_2O during winter months, potentially allowing a reduction in fertiliser or manure N input in the following spring.

The extent to which an increase in SOC might occur depends on type of cover crop (C:N ratio), season of sowing (spring v autumn), length of growing period and crop yield. Crops with a relatively low C:N ratio (<20:1) such as legumes, are degraded in soil more rapidly than crops with a high C:N ratio (e.g. rye) and are less likely to have longer-term effects on SOC. There is little information on the potential to increase SOC of deeper-rooting (>40 cm depth) cover crops (e.g. lucerne), but they are unlikely to have significant potential unless grown for at least one full season (see review by White et al., 2016).

Nutritional options

Research is underway to find diet ingredients to reduce methanogenesis in the rumen (CIEL, 2020). Many feed additives, such as ionophores, saponins, tannins and algae, reduce methane production *in vitro*, but effects on methane emissions by animals are often small or short-lived. The rumen microbial population is very adaptable and will often adjust to overcome methane inhibitors (Beauchemin et al., 2008). The best strategy to reduce methane is to formulate diets that improve performance and contain ingredients known to lower methane emissions. Examples include increasing concentrates and reducing forage, increasing starch and reducing fibre, adding fat to the diet, improving grazing management, and replacing grass silage with maize silage (Beauchemin et al., 2008). Clearly, some strategies have implications for rumen health and milk composition, so should be implemented with caution.

Lower protein diets result in lower N excretion, which is beneficial for reducing both nitrate pollution and N_2O emissions. Reducing dietary crude protein concentration to 15% of total DM generally reduces feed intake, but does not reduce milk production if rumen fermentable energy is increased and amino acid profile of rumen bypass protein is maintained (Sinclair et al., 2014). Maize silage is an excellent component of lower protein diets due to its low protein and high starch contents. Broderick (2003) showed that increasing the ratio of dietary starch to fibre has a greater beneficial effect on milk protein yield and NUE than altering dietary protein content.

Diets for high-yielding dairy cows usually require supplementation with rumen-protected protein sources. Soya bean meal has been widely used in the past, but there are environmental, social and economic pressures to reduce the use of soya in ruminant diets. Indeed, some supermarkets have told milk suppliers to reduce or eliminate soya from dairy diets. The main reason for the popularity of soya bean meal is its high concentration of protein, a high proportion of which is bypass protein. Studies have shown, however, that alternative proteins can replace soya bean meal. Dried distillers' grains with solubles can be used at up to 20% dietary inclusion without affecting performance (Garnsworthy et al., 2021a). A new protected rapeseed product (NovaPro, Yelo, 2021) is available with a bypass protein content similar to that of soya bean meal. Research demonstrated that not only can NovaPro replace soya bean meal, but it can also enhance milk yield due to its better amino acid balance (Garnsworthy et al., 2021b).

Formulating diets for dairy cows to meet requirements for metabolisable energy and metabolisable protein for 40 kg milk/day revealed that diets based on maize silage generally had higher NUE than diets based on grazed grass or grass silage, which reflected better balance of rumen-degradable protein supply with animal requirement (Wilkinson and Garnsworthy, 2016).

Using CFP values in Table 1, a conventional (base) diet was formulated that met nutritional requirements for 40 kg milk/day and also a diet with lowest feasible CFP, in which grass silage was substituted by a higher level of maize silage and cereal grains were replaced with by-product feeds of lower CFP (Table 2). The CFP of the lowest feasible diet was 62% lower than that of the base diet. Whether or not the low CFP diet would be economically more attractive than the base diet would depend on the relative prices of raw materials; at current prices (January 2021), the low CFP diet was 6% cheaper than the base diet.

Table 2. *Base diet and lowest feasible diet carbon footprint (CFP). Milk yield 40 kg/day*.

	Base diet	**Lowest feasible diet CFP**
Raw materials (kg DM/day)		
Maize silage	11.87	14.53
Grass silage	3.95	-
Barley	3.44	-
Moist distillers' grains	-	3.72
Breakfast cereal	-	3.81
Soya bean meal	1.00	-
Rapeseed meal	1.85	1.69
Bypass fat	0.35	-
Minerals	0.15	0.15
Diet CFP (g CO_2e/kg milk)	292	110

Conclusions

1. The carbon footprint of maize silage is lower than that of other forage crops.
2. Methane and feed production account for around two thirds of total dairy farm carbon footprint.
3. Maize can contribute to soil carbon sequestration, especially under no-till management.
4. Diets can be formulated to reduce carbon footprint by using maize silage supplemented with by-product feeds.

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