A Marginal Abatement Cost Curve for Irish Agriculture

Teagasc submission to the

National Climate Policy Development Consultation

Prepared by Teagasc's Special Working Group on Abatement Totals
(part of Teagasc's Greenhouse Gas Working Group):

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Executive Summary

Teagasc is pleased to avail of the opportunity to make a submission to the public consultation on National Climate Policy Development. This consultation has provided a platform and opportunity to collate the outcomes of Teagasc's research and knowledge transfer programmes on Greenhouse Gas (GHG) emissions, into a Marginal Abatement Cost Curve (MACC) for Irish agriculture. This MACC quantifies the current opportunities for abatement of agricultural greenhouse gases, as well as the associated costs/benefits, and may be of use for guidance in the development of policies aimed at reducing greenhouse gas emissions from the non-ETS sectors.

This submission has been prepared by Teagasc's Working Group on GHG Emissions, which integrates the extensive and diverse range of organisational expertise in research and practice associated with agricultural greenhouse gases. This current report builds upon previous submissions and reports prepared by this Working Group, which highlighted the challenges associated with a) reducing Irish agricultural GHG emissions and b) accounting for these reductions in the Irish National GHG Inventory. In addition, it identified opportunities for abatement and specific mitigation measures for agriculture in an Irish context. In this current report, Teagasc quantifies the abatement potential of these mitigation measures, as well as their associated costs/benefits. The objective of this analysis is to provide clarity on the extent of GHG abatement that can realistically be delivered through incentivisation of cost-effective agricultural mitigation measures, as well as clarity on which mitigation measures are likely to be cost-prohibitive. The result is a menu of measures ranked in order of their cost.

The analyses in this report were conducted in the context of Food Harvest 2020, an industry-led initiative that sets out a strategy for the medium-term development of the agri-food sector. This strategy specifies pathways to growth for individual sectors of the agri-food industry, and includes, *inter alia,* a target of a 50% increase in the volume of milk production, and a 20% increase of the value of beef production. Under a Food Harvest 2020 scenario, the historical downward trend in agricultural GHG emissions is projected to reverse due to the growth in economic activity in this sector. In the absence of abatement measures, by 2020 emissions are projected to increase by *c.* 7% compared to the 2010 level. This increase is not substantial in comparison to the projected rise in agricultural output, due to ongoing gains in production efficiency and reductions in the carbon-footprint (GHG emissions per unit produce) of agricultural produce. Therefore, these figures would still represent a decline in the carbon intensity of agricultural production. This reference scenario does not consider the potential for GHG emissions reductions through technical means. The value of the MACC presented in this report is that, using the Food Harvest 2020 scenario as a reference scenario, it allows us to explore the additional potential for GHG abatement in Ireland by the year 2020.

This report presents the first comprehensive MACC for Irish agriculture and is based on extensive research programmes conducted by Teagasc and national and international research partners over the last decade. It is important to note that a MACC cannot remain static, nor should it be interpreted as definitive. This is because the potential volume for GHG abatement, as well as the associated costs/benefits are likely to change over time as ongoing research programmes deliver new mitigation measures, or as socio-economic or agronomic conditions evolve. Therefore, the MACC presented in this report should be interpreted as the first outcome of an iterative process. Developments in the science of GHG abatement and in the market conditions faced by Irish agriculture will continue to shape the MACC into the future.

The analyses underpinning the MACC curve follow a dual methodology: Life Cycle Analysis (LCA) was used to assess the potential for “real” global reductions in GHG emissions associated with each potential mitigation measure adopted in Ireland. Simultaneously, the methodology of the Intergovernmental Panel on Climate Change (IPCC) was used to quantify the proportion of reductions that would be measured and recorded in the National GHG Emissions Inventory, and credited to the agricultural sector in Ireland. There are important differences in these two accounting conventions which may have implications for policy; these implications are highlighted in this report.

Using an LCA methodology, the analyses showed that the total abatement potential arising from cost-beneficial, cost-neutral and cost-effective mitigation measures (cost-effective measures being those for which the cost of implementation is lower than the projected price of international carbon credits) amounts to 2.5 Mt of carbon dioxide equivalents (CO_2eq) per annum by 2020, compared to the Food Harvest 2020 reference scenario. This potential is largely insensitive to deviations in the projected price of carbon credits. Using the IPCC methodology, the analyses showed that – if the 2.5 Mt CO_2eq reduction per annum were to be achieved – only 1.1 Mt CO_2eq per annum of this would be recorded and credited to the agricultural sector in the Irish National GHG Emission Inventory. The cultivation of biofuel / bioenergy crops has potential to account for a further reported reduction of 1.2 Mt of CO_2eq per annum by 2020, mainly associated with the displacement of fossil fuel usage. However, in the Irish National Emissions Inventory, these energy related reductions would largely be attributed to the fuel consuming sectors defined in the IPCC methodology, i.e. the transport sector and power generation sector.

Realisation of the 1.1 Mt CO_2eq (IPCC) reduction potential is projected to bring the reported agricultural emissions from Irish agriculture down to 18.90 Mt CO_2eq per annum by 2020, which would be the same level estimated by the EPA for the Kyoto first commitment period (EPA, 2012). This value corresponds to a 5.5% reduction in reported agricultural GHG emissions compared to the Food Harvest 2020 reference scenario level in 2020, or virtually no change from the reported agricultural emissions in 2010 or from the estimated emission levels in the Kyoto commitment period. Alternatively, it would represent a 4.5% reduction compared to the reported agricultural emissions in 2005 (EU Effort Sharing reference year).

It is important to note that these figures represent the total *potential* abatement that can be *realistically* achieved following *full implementation*, wherever *biophysically* possible, i.e. where the physical environment of individual farms does not technically constrain implementation. Realisation of these reductions requires a concerted effort from farmer stakeholders, advisory services, research institutes, policy stakeholders and the agri-food industry.

Most of the cost-beneficial mitigation measures that have potential to deliver the 1.1 Mt CO_2eq of reported emission reductions are measures associated with increased production efficiencies, i.e. measures that maximise output of produce per unit of farm input. Examples include: additional increases in the Economic Breeding Index, extended grazing and nitrogen efficiency. These measures are expected to simultaneously reduce greenhouse gas emissions and increase farm profitability. However, notwithstanding this, these measures will require incentivisation in order to realise their environmental and economic potential, mainly through knowledge transfer facilitated by large-scale advisory programmes. As a first step in this process, Teagasc is currently developing the Carbon Navigator to advise farmers on the most cost-effective approach to implementing these measures on individual farms.

Farm afforestation has significant potential for national abatement of GHG through carbon sequestration and through fossil fuel substitution (energy savings). The marginal abatement potential from afforestation depends on the degree to which annual planting rates can be accelerated over and above the current baseline planting rate of 8,000 ha per year, and the extent to which forest productivity per unit area can be increased. It is estimated that the total marginal abatement potential from increased afforestation ranges from 2.3 to 5.6 Mt CO_2eq, depending on planting rates and productivity. The associated marginal abatement costs range from €26.3 to €42.7 per tonne CO_2eq, which is close to the projected 2020 price of carbon credits on the international market. However, in the current National GHG Emission Inventory Reports, such abatement will be credited to the Land Use, Land Use Change and Forestry Sector, rather than the agricultural sector. Furthermore, the detailed GHG-accountancy rules for forestry are currently subject to international negotiations.

Based on the analyses in this report, any further reductions in reported agricultural GHG emissions – over and above the 1.1 Mt CO_2eq that can be delivered through cost-beneficial mitigation measures – would require either:

- The introduction of mechanisms that incentivise the cultivation of biofuel / bioenergy crops and accredits (part of) the carbon credits (up to 1.2 Mt CO_2eq) from the resultant fossil fuel displacement to the agricultural sector;
- The introduction of mechanisms that incentivise farm afforestation and that accredits (part of) the carbon credits (up to 3.5-7.0 Mt CO_2eq) from the resultant carbon offsetting to the agricultural sector;
- Financial incentivisation of measures that are currently cost-prohibitive: although this would not affect the cost-effectiveness of these measures or the overall cost of

their implementation to society, this would reduce the cost to farmers and hence incentivise implementation;

- The future introduction of further additional mitigation options, the effectiveness of which is currently the subject of ongoing research programmes.

Finally, it cannot be ruled out that adoption of mitigation measures may interact with the Food Harvest 2020 reference scenario, and change the associated agricultural activity data. In other words: many of the mitigation measures presented in the MACC are associated with either a negative or positive cost; adoption of these measures may change the economic performance of farms positively or negatively, respectively. In the case of widespread adoption, this change in farm economic circumstances would change the projections for the Food Harvest 2020 reference scenario. This potential feedback loop is not considered in the current MACC presented in this report.

Glossary and Definitions

Activity data	Data that quantify the scale of agricultural activities associated with greenhouse gases at a given moment in time. Activity data are expressed as absolute numbers (e.g. number of dairy cows, national fertiliser N usage) and typically change over time.
AD	Anaerobic Digestion
Biophysical constraint	Limitation, set by the natural environment, which is difficult or impossible to overcome. Example: "the use of bandspreading equipment for slurry spreading in spring is biophysically constrained to well-drained and moderately-drained soils, and is excluded from poorly-drained soils".
C	Carbon
Carbon-footprint	The amount of greenhouse gas emissions (CO_2, N_2O, CH_4) associated with the production of a specific type of agricultural produce, expressed as kg CO_2eq per kg produce (e.g. per kg beef, milk).
Carbon Navigator	Software advisory tool, developed by Teagasc, that identifies farm-specific management interventions that will reduce the carbon-footprint of the produce of that farm.
CH_4	Methane
CO_2	Carbon Dioxide
CO_2eq	Carbon Dioxide Equivalent
COFORD	Programme of Competitive Forest Research for Development
CSO	Central Statistics Office
DO	Domestic Offsetting
EBI	Economic Breeding Index - a single figure profit index aimed at helping farmers identify the most profitable bulls and cows for breeding dairy herd replacements. It encompasses milk production, fertility, calving performance, beef carcass, maintenance and health.

Emission coefficients	Established numbers that quantify the greenhouse gas emissions associated with activity data (see above), and that are expressed as "emissions per activity unit", e.g.: nitrous oxide emissions per kg fertiliser N applied. Generally, the values of emission coefficients do not change over time, unless more accurate/representative values are obtained by new research.
EPA	Environmental Protection Agency (Ireland)
ETS	Emissions Trading Scheme
EU	European Union
FAO	Food and Agriculture Organisation
FAPRI	Food and Agricultural Policy Research Institute
FH 2020	Food Harvest 2020
GHG	Greenhouse Gas
Ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
kt	Kiloton (1,000,000 kg)
LCA	Life Cycle Analysis
LU	Livestock Unit
LULUCF	Land Use, Land Use Change and Forestry
MACC	Marginal Abatement Cost Curve (details in Textbox 1.1, section 1.1.3)
M€	Million euro
Mt	Megaton (1,000,000,000 kg)
N	Nitrogen
N_2O	Nitrous Oxide

NFS	Teagasc National Farm Survey
Non-ETS Sectors	Sectors of the economy outside the Emissions Trading Scheme
NZ MoE	New Zealand Ministry of Environment
SEAI	Sustainable Energy Authority of Ireland
SOC	Soil Organic Carbon
t	tonne (1000 kg)
UNFCCC	United Nations Framework Convention on Climate Change

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1. Introduction

In this section the rationale for the study is set out, the Teagasc research programme in this area is summarised, the context of the study is explained and the terms of reference for the report are set out.

1.1 Rationale

Teagasc is pleased to avail of the opportunity to make a submission to the public consultation on National Climate Policy Development. This consultation has provided a platform and opportunity to collate the outcomes of Teagasc's research and knowledge transfer programmes on Greenhouse Gas (GHG) emissions, into a Marginal Abatement Cost Curve (MACC) for Irish agriculture. This MACC quantifies the current opportunities for abatement of agricultural greenhouse gases, as well as the associated costs/benefits, and has been developed for guidance in the development of policies aimed at reducing greenhouse gas emissions from the non-ETS sectors.

This submission has been prepared by Teagasc's Working Group on GHG Emissions, which integrates the extensive and diverse range of organisational expertise on agricultural greenhouse gases.

1.1.1 Teagasc programmes on abatement of agricultural GHG emissions

Teagasc operates ambitious research and knowledge transfer programmes on greenhouse gases, which focuses on developing cost-effective abatement strategies for Irish agriculture. Recently, Teagasc secured significant funding from the Department of Agriculture, Food and the Marine to coordinate the Greenhouse Gas Ireland Network research consortium, bringing together most significant research actors on GHG research in Ireland. For its Knowledge Transfer programme, Teagasc is currently developing the Carbon Navigator: a software tool for farmers and advisors, that guides cost-effective reductions of the carbon intensity of Irish produce.

Internationally, too, Teagasc is taking a leadership role: it is leading a component of the FP7 project Animal Change; it is workpackage leader and Governing Board member of the EU Joint Programme Initiative on Agriculture, Food Security and Climate Change (FACCE-JPI: www.faccejpi.com); participating in several working groups of the Global Research Alliance (www.globalresearchalliance.org) and participating in the FAO's Partnership on benchmarking the environmental performance of livestock supply chains. Through these international activities, Teagasc's research on national abatement options is firmly embedded in a global research context.

1.1.2 Previous Teagasc submissions to consultations relating to agricultural GHG emissions

This current report builds upon the knowledge and information contained in recent submissions by the Working Group to previous consultations in relation to agricultural GHG emissions, specifically:

- Submission to the proposed Climate Change Response Bill (January 2011): *Irish Agriculture, Greenhouse Gas Emissions and Climate Change: opportunities, obstacles and proposed solutions* (Appendix C) www.teagasc.ie/publications/view_publication.aspx?publicationID=61
- *Teagasc Submission to the Public Consultation on the Potential for Domestic Offsetting of Greenhouse Gas Emissions in Ireland* (November 2010) (Appendix D) www.teagasc.ie/publications/view_publication.aspx?publicationID=62
- *Briefing note: Carbon Audits for Irish Agriculture* (December 2011) (Appendix E) www.teagasc.ie/publications/view_publication.aspx?publicationID=1063

In these previous contributions, Teagasc outlined the significant challenges that are associated with efforts to further reduce GHG emissions from Irish agriculture. In summary, these challenges include:

1. Carbon efficiency in Irish agriculture is already at a high level

   The grass-based livestock production systems that form the cornerstone of Irish agriculture are already highly carbon-efficient, and are associated with a low carbon footprint for livestock produce (FAO, 2010). In fact, a recent study by the European Commission (Leip *et al.*, 2010) showed that Ireland has the lowest carbon footprint in the EU for milk, and the fifth lowest carbon footprint in the EU for beef. Given that carbon efficiency in Irish agriculture is already high, this makes further reductions in GHG emissions increasingly challenging.

2. Options to reduce methane emissions are limited

   In general, Ireland's climate, biophysical environment and farm infrastructure are most suitable for ruminant livestock production, which is associated with significant emissions of methane. As a result, methane accounts for approximately half of agricultural GHG emissions. It has proven notoriously difficult to significantly reduce methane emissions from ruminants, despite significant international research efforts. In Ireland, reductions in livestock numbers had previously been suggested as an alternative pathway to reducing national methane emissions, but – given that 90% of Irish beef produce, 80% of milk and 50% of sheep/lamb produce is exported - this is likely to lead to displacement of livestock production systems to other jurisdictions. In light of the current high degree of carbon efficiency of Irish livestock systems, such efforts to reduce methane emissions could – paradoxically – result in an increase in global GHG emissions, if livestock is displaced to environments or farming systems that have a higher carbon footprint. This process is known as “carbon-leakage”.

3. Measurement of agricultural emissions and reductions

The measurement, reporting and verification of GHG emissions from the agricultural sector is highly complicated from both a scientific and administrative perspective. Unlike most other sectors, the consumption of non-renewable energy and fossil fuel (which is relatively easy to quantify) accounts for only a very small proportion (*c*. 5%) of Irish agricultural emissions. Instead, most of Ireland’s agricultural emission profile arises from methane emissions by ruminants, methane emissions from manure management, and nitrous oxide emissions from soils, fertiliser and manure. These emissions show a large degree of variation, depending on *inter alia* soil type, climate and the production intensity of agriculture. Direct measurement of these emissions requires significant instrumentation; therefore these emissions are commonly estimated from agricultural “activity data”. The natural variation in GHG emissions, and the need to utilise indirect measurement methods to establish the level of GHG emissions, makes it difficult to verify and recognise reductions in GHG emissions on individual farms, which in turn poses challenges to the incentivisation of such reductions.

4. “Counting carbon” does not always equal “cutting carbon”

The UNFCCC requires that all countries participating under the Kyoto Agreement conduct ongoing National GHG Inventories, which report GHG emissions per jurisdiction. This “country-based” approach has given rise to complications for the Irish agricultural sector, as some of the inputs used in Irish agriculture are imported from other jurisdictions and the emissions associated with the production of these imports are not accounted for in the national inventory. As a result, abatement measures that result in reduced imports – and hence in reduced GHG emissions associated with these imports – can not be accounted for in the National Inventory. In previous reports, Teagasc explained how, in some cases, this could promote the use of “perverse” abatement strategies, that appear to reduce national GHG emissions, but could inadvertently result in an increase in global GHG emissions. This is further complicated by the separate reporting of agricultural emissions and emissions / offsetting from the Land Use, Land Use Change and Forestry (LULUCF) sector. The separation of this sector from agriculture for reporting purposes means that agriculture as a sector cannot get credit for carbon offsetting by farm afforestation or land use change to bio-fuels/bio-energy. This in turn reduces opportunities for incentivisation of such activities at farm level.

1.1.3 What is new in this submission?

In its previous reports and submissions, Teagasc outlined the challenges associated with reducing GHG emissions from agriculture, and the difficulties in accounting for these reductions. In addition, Teagasc identified a number of mitigation strategies aimed at reducing the carbon footprint of Irish produce.

Since January 2011, the Teagasc Working Group on GHG emissions has developed an integrated methodology to assess the total abatement potential of each of these mitigation strategies, as well as the associated monetary costs/benefits. This has facilitated the production of a Marginal Abatement Cost Curve (MACC) for Irish agriculture, which forms the basis of this current report. A MACC visualises the abatement potential of individual mitigation strategies in ascending order, from the most cost-effective (cost-beneficial) to the least cost-effective (cost-prohibitive) strategies. This quantifies the potential costs/benefits associated with progressive reduction targets for agricultural GHG emissions. The concept and terminology of a MACC is further explained in Textbox 1.1 below. The objective of this exercise is to provide objective data and information, derived from research, and a platform for discussion for the consultation process on the development of a national climate policy.

This MACC is not the first one of its kind for Ireland. In 2009, Teagasc contributed to the report by SEAI on *"Ireland's Low-Carbon Opportunity: An analysis of the costs and benefits of reducing greenhouse gas emissions"* (Motherway & Walker, 2009). However, this took place at a time that the majority of potential abatement strategies were still subject to ongoing research; therefore that MACC included only four mitigation options, with a total abatement potential of less than 0.5 Mt CO_2eq. Similarly, Breen (2011) assessed the marginal abatement cost for a number of policy based and technical abatement measures.

In addition, the EPA report on the Domestic Offsetting Scoping Study for Ireland (O'Keeffe *et al.*, 2011) (www.epa.ie/downloads/pubs/research/climate/CCRP_6_web.pdf) listed the abatement potential and costs/benefits of six mitigation measures at EU level. However, considering the variety of farming systems and differences in the biophysical environment across EU member states, and the impact of this variation on both GHG emissions and the associated costs/benefits, the results of this study cannot necessarily be directly extrapolated to national strategies to reduce emissions from Irish agriculture.

The Scottish Agricultural College has conducted a MACC exercise for UK agriculture (Moran *et al.*, 2011), evaluating the abatement potential and costs/benefits of as many as 31 mitigation measures. Whilst there are many similarities between this UK study and this current report, both the abatement potential and the costs/benefits are specific to the farming systems operated in each country. Therefore, to the best of our knowledge, the MACC presented in this current report constitutes the first comprehensive attempt to quantify the abatement potential and associated costs/benefits for GHG emissions, specifically for Irish agriculture.

Textbox 1.1: What is a Marginal Abatement Cost Curve?

A Marginal Abatement Cost Curve (MACC) is a graph that visualises the abatement potential of GHG mitigation measures, and the relative costs associated with each of these measures. Figure 1.1 below provides a simplified, hypothetical example of a MACC.

A MACC provides two elements of information:
1. It ranks the mitigation measures from cost-beneficial (i.e., measures that not only reduce GHG emissions, but also save money in the long-term) to cost-prohibitive (i.e., measures that save GHG emissions, but are expensive in the long-term). Cost-beneficial measures have a "negative cost", and are those in Figure 1.1 below the x-axis, on the left-hand side of the graph. Cost-prohibitive measures are above the x-axis, on the right-hand side of the graph.
2. It visualises the magnitude of the abatement potential of each measure, as indicated by the width of each bar.

In addition, a MACC commonly includes an indication of the price of carbon credits on the international market. "Cost-neutral measures" are those measures that carry zero cost in the long term. Measures that cost money (above the x-axis), but cost less than the price of carbon are called "cost-effective measures", as their implementation is cheaper than the purchase of carbon credits.

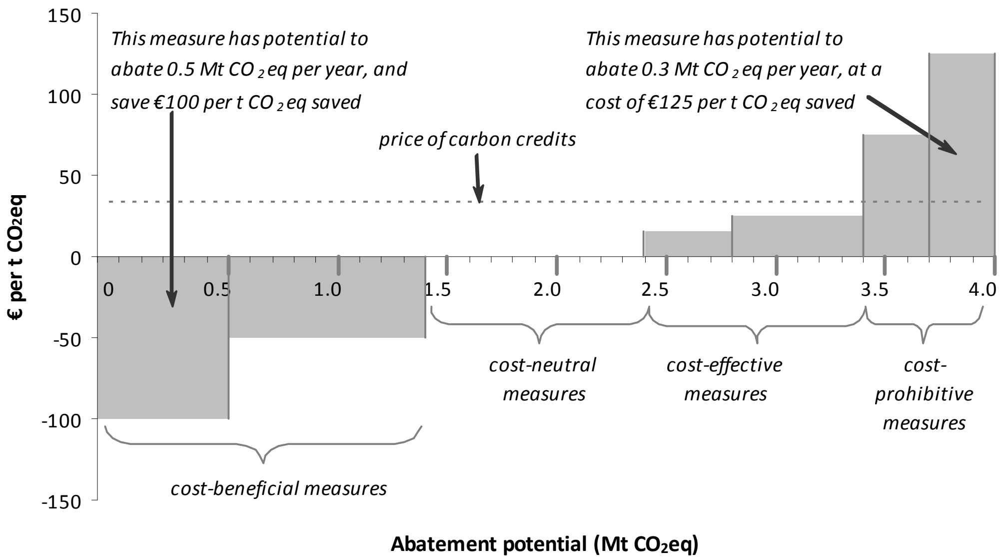

Figure 1.1: Hypothetical example and explanation of a Marginal Abatement Cost Curve (MACC)

In the hypothetical example above, cost-beneficial, cost-neutral and cost-effective measures account for an abatement potential of 1.4, 1.0 and 1.0 Mt CO_2eq, respectively, giving a total abatement potential of 3.4 Mt CO_2eq per annum. The remaining 0.6 Mt CO_2eq of abatement potential is associated with costs in excess of the price of carbon credits, and hence deemed cost-prohibitive.

1.2 Context

1.2.1 Agricultural GHG emissions (current)

Agricultural emissions have been in steady decline since 1998, with total sectoral emissions in 2010 8.3% lower than the 1990 reference levels (Duffy *et al.*, 2012). Nevertheless, in 2010 agriculture accounted for 18.7 Mt CO_2eq, or 30.5% of national emissions (EPA, 2012). Among developed nations, only New Zealand has a higher proportion of total GHG emissions associated with agriculture than Ireland (NZ-MoE, 2010). The contribution of agriculture to Irish GHG emissions is high compared to the EU average of 9%, and reflects the relative importance of Irish agriculture, which is predominantly based on export of ruminant livestock products, to the Irish economy (Breen *et al.*, 2010).

Methane (CH_4) and nitrous oxide (N_2O) make up the vast bulk of agricultural GHG emissions, due to the dominance of cattle and sheep livestock production in Irish agricultural output. Methane emissions sourced from livestock enteric fermentation is the primary source of greenhouse gases, accounting for 45% of total agricultural emissions in 2010, whilst N_2O emissions arising as a result of chemical/organic fertiliser application and animal deposition comprise a further 37% (EPA, 2012). The other major source is methane and nitrous oxide emissions associated with manure management, accounting for 13% of agricultural emissions.

Enteric and nitrogen-sourced emissions have continued on a downward trajectory since 1998. However, N_2O emissions from synthetic fertiliser application increased in 2010, following an 18% increase in fertiliser sales between 2009 and 2010 (EPA, 2012).

1.2.2 Food Harvest 2020

The MACC presented in the report was conducted against the background of national policies and strategies for the agricultural sector in Ireland, and specifically in the context of the Food Harvest 2020 strategy for the sector (www.agriculture.gov.ie/media/migration/agri-foodindustry/foodharvest2020/foodharvest2020/2020strategy/2020Foodharvest190710.pdf)

Food Harvest 2020 is an industry-led initiative that sets out a strategy for the medium-term development of the agri-food sector. It identifies the opportunities and challenges facing the sector and the actions needed to ensure that it maximises its contribution to our export-led economic recovery. The Food Harvest 2020 report develops a vision for the agri-food sector as a dynamic, consumer-focused, future-oriented industry, which avails of new opportunities in expanding international markets for high quality, safe and naturally produced products. To fully realise this vision, the report specifies the following targets to be achieved by 2020:

- Increase the value of primary output in the agriculture, fisheries and forestry sector by €1.5 billion. This represents a 33% increase compared to the 2007-2009 average;

- Increase the value added in the agri-food, fisheries and wood products sector by €3 billion. This represents a 40% increase compared to 2008;
- Achieve an export target of €12 billion for the sector. This represents a 42% increase compared to the 2007-2009 average.

In addition to these overall objectives, the report contains specific growth targets for sectors agriculture, including a 50% increase for milk volume, following the abolition of milk quota in 2015, as well as a 20% increase in the total value of beef produce.

The underlying strategy centres on acting smart, thinking green and achieving growth.

- Acting smart: knowledge, skills and ideas;
- Thinking green: verifying and capitalising on Ireland's natural advantages and resources;
- Achieving growth: innovation and scale for efficient and sustainable increases in output to deliver long-term profitability.

1.2.3 Projected GHG emissions under a Food Harvest 2020 scenario

The Food Harvest strategy gives a profoundly new role to the concept of environmental sustainability in agriculture: no longer is sustainability considered a potential impediment to the growth of the sector: instead, the low carbon-footprint of Irish produce (Leip *et al.*, 2010), and the relatively high proportion of "good status" water bodies in Ireland (European Commission, 2010) are now considered key-strengths of the competitiveness of the Irish agricultural sector and essential ingredients for realising the growth targets.

However, this vision of sustainable growth is not without challenges. A preliminary study on the environmental analysis of Food Harvest 2020 (Schulte *et al.*, 2012) reported that – in principle – there is potential for the industry to simultaneously meet the Food Harvest 2020 growth targets and environmental targets, but only if this process is carefully managed from the start.

In this context, one of the main challenges to sustainability is to achieve the growth targets while limiting GHG emissions from the agricultural sector. Using the FAPRI-Ireland model, Donnellan & Hanrahan (2012) estimated that achieving Food Harvest 2020 targets will increase projected agricultural GHG emissions (inclusive of emissions from fuel combustion) from 18.8 Mt CO_2eq in 2010 to 20.0 Mt CO_2eq per annum by 2020, a relative increase of 1.2 Mt CO_2eq, or *c.* 7%. This increase is mainly the result of the higher number of ruminants projected under a Food Harvest 2020 scenario with associated increased methane emissions, as well as a concurrent projected increase in N fertiliser use, leading to increased N_2O emissions.

It is worth noting that:

- The 7% projected increase in GHG emissions under a Food Harvest scenario is produced in the context of a projected 1/3 increase in the Gross Value Added of primary production;
- The projected total level of agricultural emissions (20.0 Mt CO_2eq per annum) is similar to emissions in the reference year of 2005, in which agricultural emissions amounted to 19.8 Mt CO_2eq per annum.

Both statistics signify progressive gains in production efficiency and a declining carbon-footprint of Irish produce. The projected future increase in efficiency is expected to be driven by changes in the composition of the national herd, with a higher ratio of dairy cows to suckler cows. Whilst the carbon footprint of the latter is allocated to beef produce only, the carbon footprint of dairy cows is allocated proportionally to both dairy and beef produce, resulting in relatively more produce per unit of GHG emissions generated.

1.3 Terms of reference

1.3.1 Objective

The objective of the study presented in this report was to assess the total GHG abatement potential and associated costs/benefits of GHG mitigation measures for agriculture, and to present these as a marginal abatement cost curve (MACC). The aim of this exercise is to provide objective information and a platform for discussion for the consultation process on the development of a national climate policy.

1.3.2 Initial selection of measures

Numerous agricultural mitigation measures for GHG abatement have been reported in the international literature (see e.g. Moran *et al.*, 2011). However, both the relative and absolute abatement potential of each of these measures, as well as their associated costs/benefits, are highly dependent on the biophysical and socio-economic environments that are specific to individual countries. In other words: it is not possible to simply copy the abatement potential, nor costs/benefits from other countries for use in Ireland. Therefore, for the MACC curve presented in this report, individual measures were selected and included for Irish agriculture on the basis of the following criteria:

- Measures must be applicable to farming systems common in Ireland;
- Scientific data, from completed research, must be available on the relative abatement potential of each measure, as well as the relative cost/benefit;
- For each measure, activity data (actual and projections) must be available to assess the total national abatement potential and associated cost/benefit.

On this basis, most of the measures included in the MACC are those described in Teagasc's previous submission to the proposed Climate Change Response Bill (Schulte & Lanigan, 2011; Appendix C):

1. Accelerated gains in the genetic merit of cows (as measured by the Economic Breeding Index)
2. Higher daily weight gain in beef cattle
3. Extended grazing season
4. Manure management
5. Other gains in nitrogen efficiency (incl. use of clover)
6. Use of nitrification inhibitors
7. Minimum tillage techniques
8. Use of cover crops
9. Bio-fuel/bioenergy crops
10. Anaerobic digestion of pig slurry

This is not an exhaustive list and there are other mitigation measures that may have potential to reduce GHG emissions from Irish agriculture. However, most of these other measures are subject to ongoing research. Pending the outcome of these studies, these measures were excluded from this first iteration of the MACC presented in this report, but could be included in future iterations. Examples of measures excluded from consideration for this first iteration of the MACC for Irish agriculture are:

- Substitution of calcium ammonium nitrate fertiliser with urea;
- Use of urease inhibitors and next-generation nitrification inhibitors;
- Anaerobic digestion of grass and/or cattle slurry;
- Enhanced carbon-sequestration in grassland;
- Additional programmes for the prevention and control of animal diseases.

These measures are discussed in further detail in Section 3.3.

In addition, there is significant potential for offsetting of agricultural GHG emissions by farm forestry; this is discussed in further detail in Section 3.4.

1.3.3 Selection of methodologies

In its previous submission to the proposed Climate Change Response Bill (Schulte & Lanigan, 2011; Appendix C), Teagasc demonstrated the importance of the choice of methodologies in quantifying and assessing the abatement potential of individual mitigation measures for agriculture, and it contrasted the use of Life Cycle Analysis (LCA) to the methodologies developed by the IPCC for the purpose of the reporting of National Emissions Inventories to the UNFCCC, hereafter referred to as the "IPCC methodology" (IPCC, 2006). In summary, the LCA methodology accounts for all GHG emissions associated with the production of agricultural produce. For agriculture, this includes upstream emissions arising from the production of imported agricultural inputs such as nitrogenous fertiliser and feed, even if the emissions associated with the production of these imported products were generated in other jurisdictions. By contrast, the IPCC methodology accounts only for GHG emissions generated within the reporting country, based on agricultural activity data and agreed emission coefficients.

For our current MACC, we use and contrast both the LCA and the IPCC methodology. While the LCA methodology demonstrates the “real” abatement potential of individual mitigation measures in terms of their potential to reduce global GHG emissions, the IPCC methodology quantifies the portion of these reductions that can be accounted for in the National Emission Inventory.

1.3.4 Limitations

This report presents the first iteration of a Teagasc MACC for Irish agriculture. Like any other study, it has limitations to its methodology that need to be acknowledged in the interpretation of its outcomes. The main limitations relate to:

1. Fluidity of data

   By definition, the figures used the development of any MACC are subject to ongoing revision and improvement; as a result, any MACC – once published – has a “limited shelf life”. Such revisions include:
   - Updates and revisions to agricultural activity data (historical and projected data), such as livestock numbers, fertiliser usage;
   - Modifications to emission coefficients associated with agricultural activities: these emission coefficients are updated periodically as new research becomes available and internationally accepted and inventories are then refined;
   - Other changes in LCA / IPCC inventory methodologies.

   Therefore, the figures used in this report are the most recent and most accurate figures available to Teagasc at the time of publication (April 2012). We have endeavoured to ensure maximum coherence with the published methodology used in the National Emission Inventories, produced by the EPA.

2. Harmonisation of methodologies and initial assumptions

   The MACC is the outcome of a large, long-term programme of multi-disciplinary research that spans soil science, animal science, crop and grassland science, environmental science and economics. In this respect, it is based on numerous individual research projects and scientific publications. As each of these projects were completed at different times and in different disciplines, one of the main challenges in producing the MACC was to harmonise the initial assumptions, associated with each individual mitigation measure, to the maximum extent possible, so that any double counting or failure to account for emissions abatement was avoided.

3. Limitations to data availability
The vast majority of figures used for the development of the MACC were taken from scientific publications, as this was a pre-condition for inclusion of individual measures (see 1.3.2). However, in some cases, the availability of data was limited. This was specifically the case in assessing the realistic extent and applicability of individual measures to various agricultural enterprises in the period to 2020. In a small number of cases, the study relied on consensus expert knowledge. Where this had to be relied on, this has been clearly indicated in the description of the methodologies of the individual measures (Appendix B).

The proper interpretation of the MACC presented in this report should pay cognisance to these limitations, as they constrain the level of confidence in the exact quantitative figures of the MACC. However, in the context of the overall objective of this report, we have a high degree of confidence in:

- The relative ranking of the individual mitigation measures included in this report;
- The order of magnitude of their abatement potential;
- The order of magnitude of their associated cost/benefit, and hence their classification as cost-beneficial, cost-neutral, cost-effective or cost-prohibitive.

2. Harmonised methodology

In this section the methodology that was used and the constraints and other necessary assumptions required to develop the MACC scenarios are set out.

2.1 Scenario development

Previously, a scenario analysis by Donnellan & Hanrahan (2012) quantified the projected impact of realising the targets in the Food Harvest 2020 strategy on agricultural GHG emissions, by contrasting a baseline scenario with a "Food Harvest 2020" scenario. In the current study, the Food Harvest 2020 growth scenario, as detailed in Donnellan & Hanrahan (2012) was adopted as the reference scenario for the level of agricultural activity data in 2020. The projections of agricultural GHG emission produced by Donnellan & Hanrahan (2012) specifically excluded any mitigation that might be achieved through the adoption of abatement technologies. Building on this work, the potential emissions reductions identified in the MACC are relative to this reference scenario and the associated emissions levels, as indicated by the arrow in Figure 2.1. The detailed activity data of the reference scenario are specified in Appendix A. Obviously, none of the scenarios can take account of unforeseen major future events such as a major outbreak of animal disease or major and unforeseen changes to the global economic outlook.

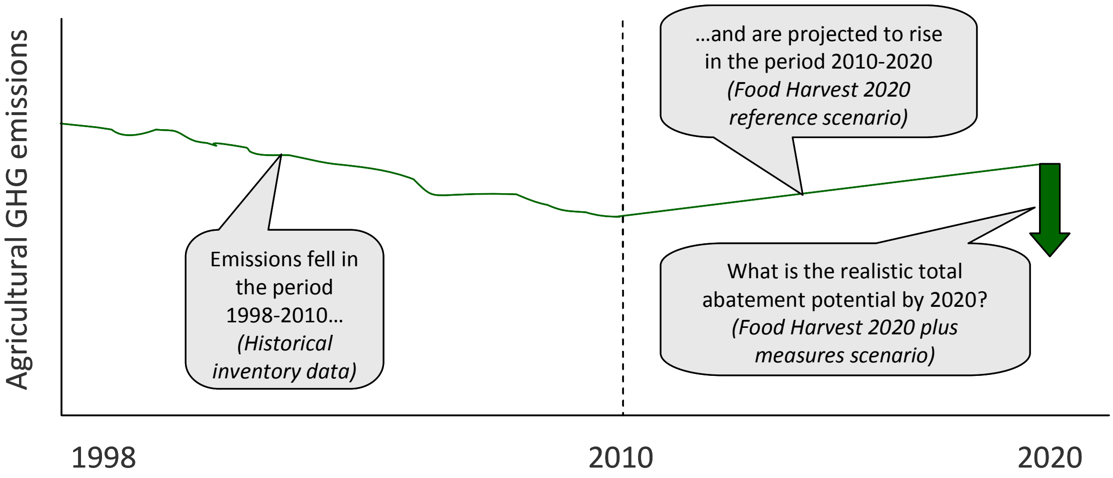

Figure 2.1: Stylised illustration of the scenarios assessed in this report. The Food Harvest 2020 plus measures scenario assesses the realistic GHG abatement potential by 2020 (green arrow) in the context of the projected emissions under the Food Harvest 2020 reference scenario. Note: graph is for illustration purposes only and is not based on specific data.

We subsequently employed two methodologies to derive the total marginal abatement potential for Irish agriculture, relative to the Food Harvest 2020 reference scenario:

1. Methodology 1: quantifies the marginal abatement potential of individual mitigation measures using an LCA methodology, hereafter referred to as the LCA Methodology.
2. Methodology 2: quantifies the marginal abatement potential of individual mitigation measures using the IPCC methodology, hereafter referred to as the IPCC Methodology.

2.2 Interactions between mitigation measures

It is important to note that many of the individual mitigation measures operate at farm systems level, impacting on multiple aspects of farm management. As a result, individual measures may interact, and either reduce or increase the abatement potential of other mitigation measures. This means that any suite of abatement measures may not be strictly additive. For example: the implementation of the measure “manure management” will impact on the generic measure “increased nitrogen efficiency”, as more efficient utilisation of nitrogen in animal manure will increase overall efficiency of fertiliser nitrogen use. Similarly, the measure “increasing the length of the grazing season” will reduce the volume of manure deposited during housing, and therefore impact on the abatement potential for the measure “manure management”.

To the maximum extent possible, the methodologies for calculation of the abatement potential of individual measures have accounted for these technical interactions, avoiding “double counting” of abatement potentials. Where relevant, this is explicitly stated in the methodology of the individual measures (Appendix B).

However, by default the current MACC scenarios do not account for land use interactions between some of the measures. This is of particular relevance (though not exclusively) to biomass / bioenergy crops and afforestation that takes place on land which was previously in agricultural use. For example, an expansion of the area of bioenergy (mainly Miscanthus) crops is assumed and likely to take place on land currently under grassland utilised by livestock. The projected expansion of bioenergy crops does not assume a decline in livestock numbers; instead, it is assumed that livestock (and associated fertiliser applications) will be concentrated elsewhere. Although this assumption is highly generic, it is consistent with the assumption that all dimensions of Food Harvest 2020 are achieved simultaneously. Furthermore, it is in line with the initial environmental assessment of Food Harvest 2020 by Schulte *et al.* (2012), which suggest that – in principle – land resources in Ireland allow for Food Harvest 2020 targets and environmental targets to be met simultaneously. Even in cases where livestock is displaced by e.g. forestry, the abatement potential resulting from this displacement is small in comparison to the abatement potential arising from the carbon sequestration from the afforestation itself (Phillips, 2007).

Accounting for land use interactions formally and quantitatively requires spatial analysis and land use models, which are currently being developed by Teagasc. To a large extent, land use potential is determined by soil type. Teagasc (in collaboration with Cranfield University and University College Dublin, and with significant co-funding from STRIVE, administered by the EPA) is currently finalising the Irish Soil Information system, and will produce *inter alia* a 1:250,000 scale next-generation soil map by 2014. These developments will facilitate the inclusion of land use interactions in future iterations of the MACC.

Finally, it cannot be ruled out that adoption of mitigation measures may interact with the Food Harvest 2020 reference scenario, and change the associated agricultural activity data. In other words: many of the mitigation measures presented in the MACC are associated with either a negative or positive cost; adoption of these measures may change the economic performance of farms positively or negatively, respectively. In the case of widespread adoption, this change in farm economic circumstances would change the projections for the Food Harvest 2020 reference scenario. This potential feedback loop is not considered in the current MACC presented in this report.

2.3 Scenario constraints

To facilitate harmonisation of methodologies to compute the abatement potential of individual measures, the constraints set out in Textbox 2.1 were applied throughout this study. As a result, the abatement potential of each of the measures in the current MACC represents the maximum abatement potential of each measure, following full implementation where not technically constrained by the biophysical environment. Similarly, the associated costs/benefits represent the maximum costs/benefits, limited solely by biophysical constraints. Additional costs associated with the incentivisation and/or implementation of measures have been excluded from the analyses, as their magnitude is likely to depend on the details of climate policy arising from the current consultation process.

Textbox 2.1: Key constraints underlying the analysis

System boundaries
For the LCA scenario, the system boundaries included GHG emissions associated with the production of agricultural produce, up to the farm gate, including emissions associated with the production of imports into the country, such as imported fertiliser and feed. Subsequent emissions “from the farm gate to the plate”, such as emissions associated with processing and distribution of farm produce, were not included in this scenario. These latter emissions are considered to be emissions associated with sectors such as food processing and transport. For the IPCC scenario, the system boundaries included national GHG emissions associated with the production of agriculture produce, but only those emissions emitted within national boundaries. This scenario excluded emissions associated with the production of imported farm inputs such as imported feed and fertiliser, (but including imported energy such as diesel used on farms) and also excludes emissions associated with processing and transportation of farm produce, in line with IPCC methodology.

Biophysical constraints
Application of some of the mitigation measures may be constrained by the biophysical environment. For example, within the measure “manure management”, soil type can limit the application of low-emissions spreading technology such as trailing shoe and bandspreader technology. Such biophysical constraints have been accounted for, and explicitly stated in Appendix B, wherever applicable.

Practice adoption constraints
Realisation of the abatement potential of individual measures will to a large extent be dependent on the level of practice adoption by individual farmers. The rate of adoption of new farm practices and technologies by farmers is difficult to project. It does not depend solely on long-term economic benefits to farmers, but may be constrained by other practical considerations, which are difficult to quantify. These other factors include farmers’ ability to understand the benefit of the technology, the value and credence farmers place in information, associated with the technology, from specific information sources and farmers’ attitude to risk taking in the form of technology adoption. Experience has shown that farmers with stronger levels of risk aversion are likely to be slower or less likely to adopt technologies, even if it can be demonstrated that the technology has an economic benefit. For an extensive literature review on factors influencing technology adoption, see Prokopy *et al*. (2008). Furthermore, the rate of adoption of the mitigation measures evaluated in this report is likely to be influenced by the details of the National Climate Policy arising from the current consultation process. For this reason, constraints on practice adoption were not considered in the MACC scenarios.

2.4 Harmonised assumptions and projections

A number of variables and projections are used throughout multiple measures. Their values have been harmonised to ensure coherence throughout the scenarios, and are listed in Appendix A. These generic assumptions and projections include:

- Agricultural activity data
  Projections on agricultural activity data for the Food Harvest 2020 reference scenario were based on the FAPRI-Ireland model (Donnellan and Hanrahan, 2012) and are consistent with those used by the EPA.

- Price of N fertiliser
  The projected price of N fertiliser in 2020 was €1.113 per kg N, based on the base price in 2010 (average price of N amongst all fertilisers containing nitrogenous compounds) and the Price Index projected by the FAPRI-Ireland model (Figure 2.2).

- Price of Oil
  Similarly, the projected price of motor fuel in 2020 was €0.98 per litre, based on projections of the fuel price index in the FAPRI-Ireland model (Figure 2.2).

- Price of carbon
  The price of international carbon credits was assumed to be €33 per tonne CO_2eq, adopted from the Energy Forecasts for Ireland to 2020 (2011 Report) by the Sustainable Energy Authority of Ireland (Clancy & Scheer, 2011).

- CO_2eq emissions for N fertiliser manufacturing
  The carbon emissions associated with the manufacturing of nitrogenous fertilisers were used for the LCA methodology only. The literature lists a wide range of values for these emissions, based on N product and manufacturing processes. We assumed that gains in N efficiency will translate into reductions in CAN and Urea application rates, and that the application rates of compound fertiliser N will remain unaffected. The generic values of N manufacturing CO_2eq emissions for the current MACC are based on the review by Wood & Cowie (2004), who reported average values of 6.87 and 4.02 kg CO_2eq per kg fertiliser N for CAN and urea, respectively. For grassland applications, we subsequently assumed that the ratio between CAN and urea application will remain unchanged by 2020 at a ratio of 71:29 (Lalor *et al*., 2010), resulting in average N fertiliser manufacturing emissions of 6.05 kg CO_2eq per kg fertiliser N. For tillage crops, in which use of urea is rare, we assumed CAN N fertiliser manufacturing emissions of 6.87 kg CO_2eq per kg fertiliser N.

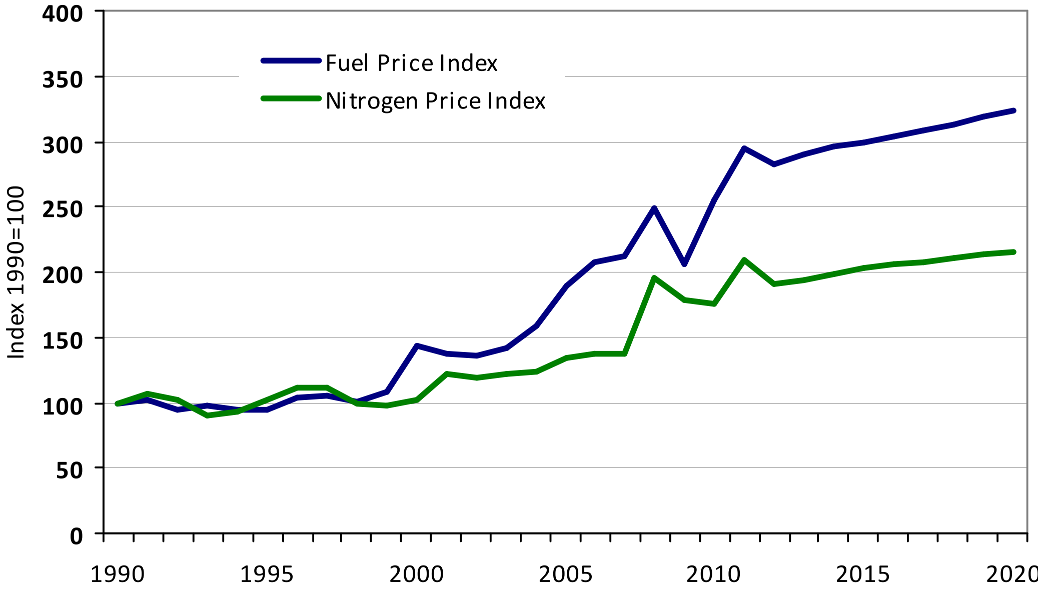

Figure 2.2: Price Index Projections for Fuel and Fertiliser Nitrogen.Note: data from 1990-2011 is actual historic data; data from 2012 onwards are projections (Sources: CSO and FAPRI-Ireland)

3. Results and Discussion

In this section the actual MACC derived from the analysis is presented, reflecting both the LCA and IPCC methodologies.

3.1 Marginal Abatement Cost Curves

3.1.1 LCA methodology

The MACC for Irish agriculture, based on LCA analysis, is presented in Figure 3.1. The main features of this MACC are:

- Total abatement potential:
  The total maximum biophysical abatement potential of the mitigation measures included in this analysis amounted to *c.* 3.4 Mt CO_2eq. Of this potential, *c*. 2.5 Mt CO_2eq was accounted for by measures that were either cost-beneficial or cost-neutral in the long term. A further 0.3 Mt CO_2eq was accounted for by two measures (cover crops and sugar beet cultivation for bioethanol) with a marginal abatement cost in excess of, but within the uncertainty range of the projected 2020 international market price of carbon credits. Together, these cost-efficient measures represent a potential reduction in GHG emissions by *c*. 2.8 Mt CO_2eq. Finally, *c.* 0.6 Mt CO_2eq was accounted for by measures considered to be cost-prohibitive, with a marginal abatement cost well in excess of the international price of carbon. These figures and categorisations are largely insensitive to potential deviations in the projected price of carbon credits, as only 0.3 Mt CO_2eq is accounted for by measures associated with a cost within the margin of error of this price projection.

- Ranking of measures:
  The measures in Figure 3.1 are colour-coded by the nature of their intervention: for green measures, the abatement potential results from generic gains in production efficiency, resulting in reduced inputs per unit of farm produce. Yellow measures are those that involve land use change, mainly to biofuel/bioenergy crops, while blue measures are those that require technical interventions, commonly associated with the purchase of new equipment and/or farm inputs.
  In this light, the ranking of measures is striking: most of the “green measures” are cost-beneficial, since gains in efficiency do not only result in a reduced carbon-footprint, but also in a lower input:output ratio, representing reduced costs to individual farms. The yellow measures (with the exception of ethanol from sugar beet) are either cost-neutral or marginally cost-beneficial, while the blue measures range from cost-beneficial (minimum tillage techniques) to cost-prohibitive (nitrification inhibitors).

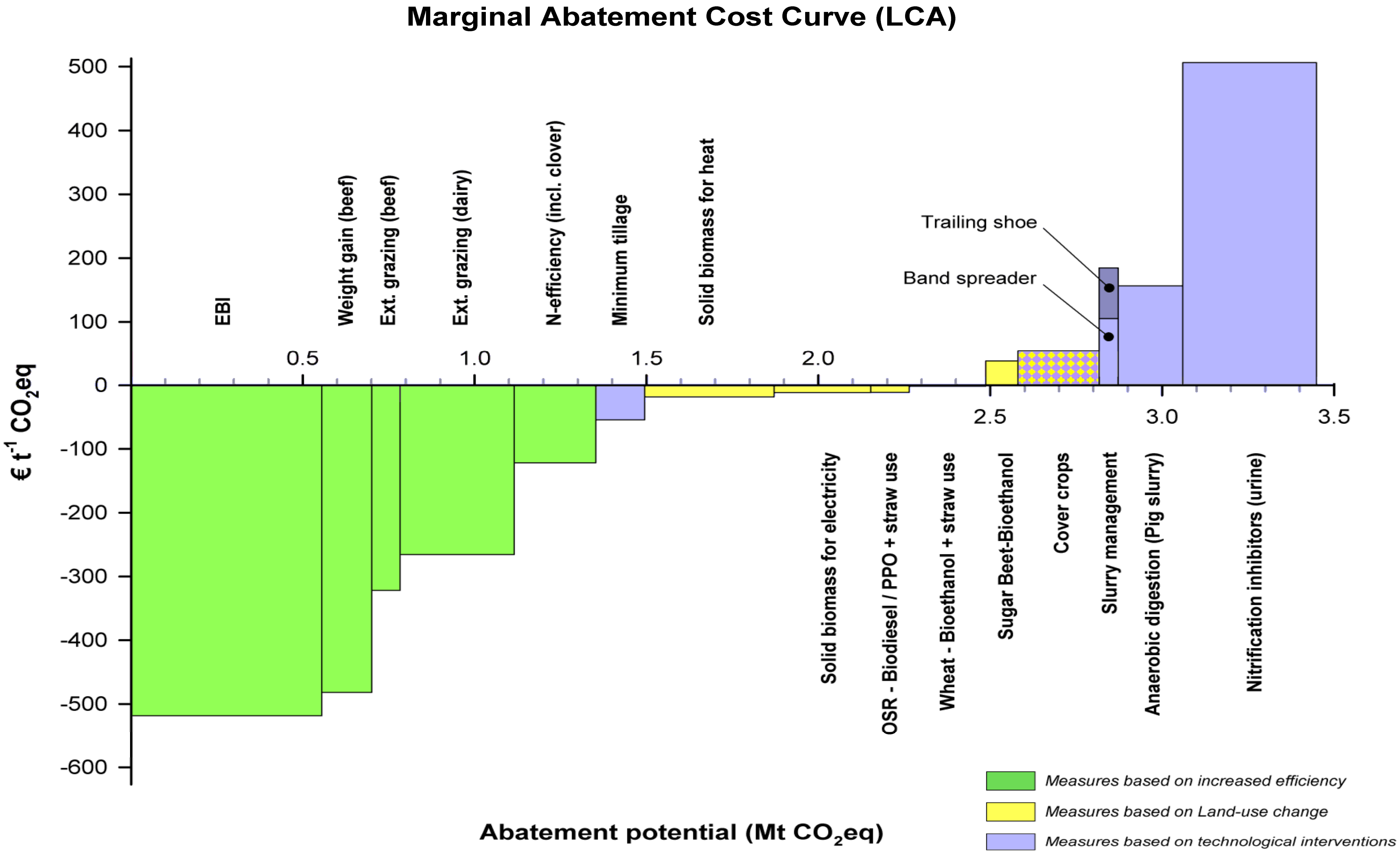

Figure 3.1: Marginal Abatement Cost Curve for Irish Agriculture, using LCA analysis. Colours indicate measures based on efficiency (green), land use change (yellow) and technological interventions (blue).

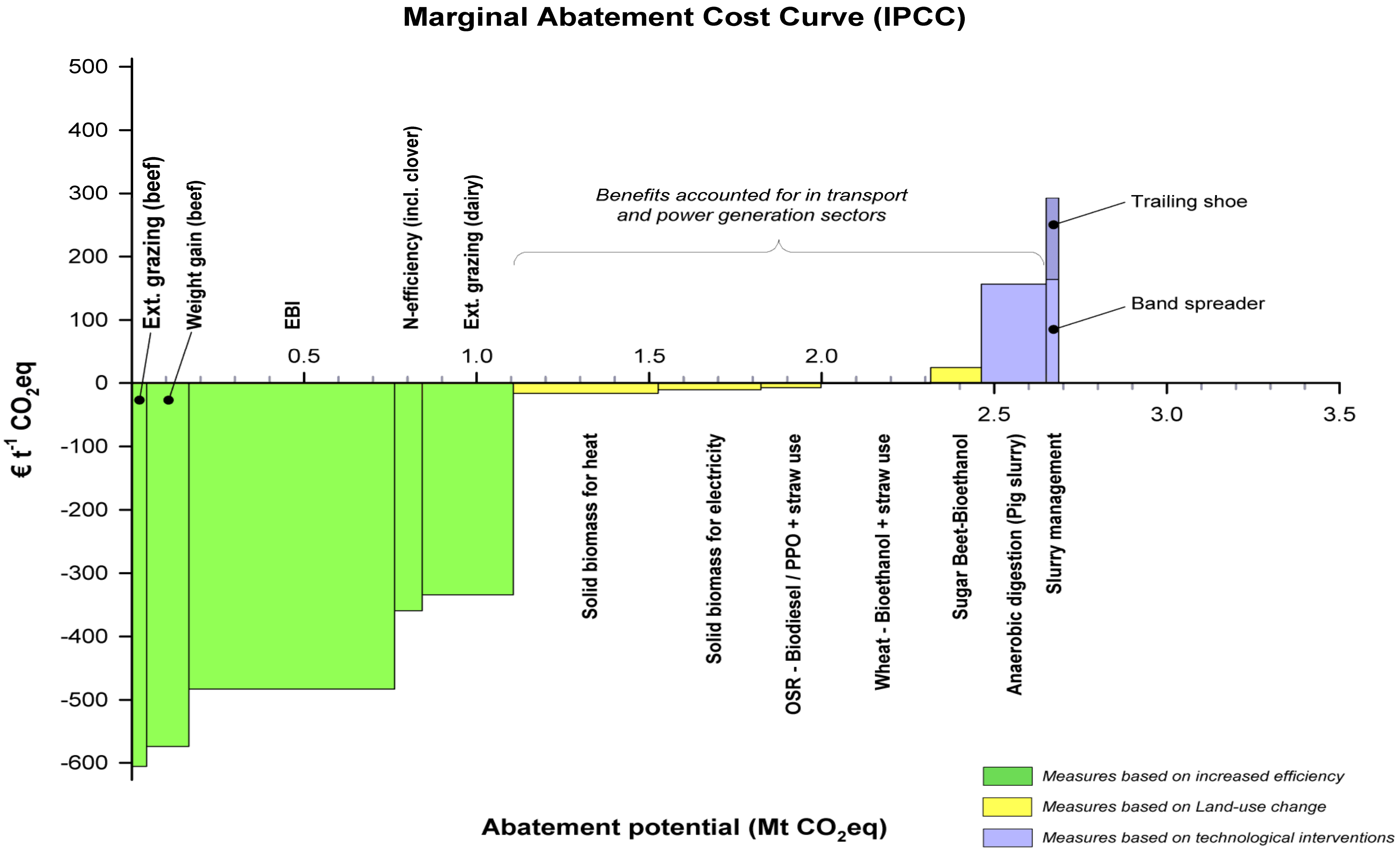

Figure 3.2: Marginal Abatement Cost Curve for Irish Agriculture, using IPCC analysis. Colours indicate measures based on efficiency (green), land use change (yellow) and technological interventions (blue).

3.1.2 IPCC methodology

The MACC for Irish agriculture, based on IPCC analysis, is presented in Figure 3.2. The main features of this MACC are:

- Total abatement potential
  The total maximum biophysical abatement potential of the mitigation measures, using the IPCC methodology amounted to just under *c.* 2.7 Mt CO_2eq. This represents the share of the total abatement potential that can be accounted for in the National Emissions Inventory. However, due to the sector definitions delineated by the IPCC, less than half (*c*. 1.1 Mt CO_2eq) of this accountable abatement potential will be attributed to the agricultural sector. The abatement potential of biofuel/bioenergy measures (including anaerobic digestion of pig slurry) will be attributed to the transport and power generation sectors, instead. This is explained by the fact that the abatement potential of biofuel/bioenergy crops is largely the result of the associated displacement of fossil fuel imports, rather than reductions in direct GHG emissions. Almost all of the 1.1 Mt CO_2eq abatement potential that can be attributed to the agricultural sector consists of measures relating to improved production efficiency ("green" measures").

- Ranking of measures:
  The ranking of measures using the IPCC differs from the ranking that emerged from the LCA methodology: EBI moved down to the third most cost-effective measure. In addition, using the IPCC methodology the apparent marginal cost of slurry management increase by more than 50% compared to using the LCA methodology, making it appear more expensive than the anaerobic digestion of pig slurry. The reason for this change is that the IPCC accounts for only part of the reductions in carbon emissions associated with a change in manure management, but accounts for all costs at the same time. This results in a higher cost per unit emission reduction, accounted for in the IPCC methodology.

3.1.3 Differences between the LCA and IPCC methodologies

Figures 3.1 and 3.2 demonstrate the marked differences between the MACC curves resulting from the application of the LCA methodology and the IPCC methodology. In summary: while the LCA MACC shows that the total abatement potential of cost-beneficial and cost-neutral mitigation measures for agriculture amounts to *c*. 2.5 Mt CO_2eq, the IPCC MACC shows that only 1.1 Mt CO_2eq of this potential can be accounted for and attributed to agriculture in the Irish National GHG Emissions Inventory. These differences between the two MACC curves can be explained by the following three reasons:

1. Some measures are not yet included in the IPCC based National Inventory
   Measures can only be included in the IPCC-based National Inventory when sufficient scientific data is available to quantify and verify their effectiveness. This applies to

most technical (“blue”) measures, such as slurry application technology, nitrification inhibitors and cover crops. In principle, pending the outcomes of further research, such measures could be included in future iterations of the National Inventory.

2. The abatement achieved by some measures is attributed to sectors other than agriculture in the IPCC based Inventory
   The effectiveness of some measures – mainly those relating to biofuel/bioenergy production – can be accounted for in the IPCC-based National Inventory, but is attributed to sectors other than agriculture, such as the transport and power generation sectors. This also applies to farm-forestry (see Section 3.4). In principle, there are potential mechanisms to ensure that the agricultural sector is credited with (part of) the abatement potential of these measures; see Teagasc (2010) (Appendix D) for details.

3. Some measures lead to GHG reductions outside Ireland
   Some of the measures, mainly those that result in reduced imports of feed and nitrogenous fertilisers, result in reductions in GHG emissions outside Ireland. While such reductions reduce the carbon-footprint of agricultural produce, and are included in the LCA MACC, they can not be accounted for in the IPCC inventory for Ireland as the reduction will be captured in the inventory of the country where the feed or fertiliser would have originated. This is the case for measures relating to e.g. improved N efficiency, slurry management, minimum tillage and cover crops.

These differences in GHG measurement have far-reaching implications for strategies aimed at realising the full abatement potential of agricultural mitigation measures. It may prove difficult to incentivise mitigation measures where the mitigation achieved cannot be accounted for or accredited to the agricultural sector. Secondly, these differences may lead to “perverse” mitigation practices, i.e. measures that result in a reduction in national GHG emissions as accounted for in the Inventory, but an increase in global GHG emissions, as captured by the LCA analysis. Examples include the application of minimum tillage and cover crops: while these measures result in reduced GHG emissions based on the LCA methodology, they result in *increased* emissions as accounted for in the National Inventory. The reason for this is that changes in carbon sequestration may be counted in an LCA methodology, as minimum tillage reduces soil organic carbon (SOC) loss relative to conventional ploughing. However, Ireland has not opted to ratify Article 3.4 of the Kyoto Protocol and thus does not elect to report C stock change associated with land management. Therefore SOC changes were not counted in the IPCC methodology, but increased N_2O emissions from N input from residues associated with minimum tillage were included, resulting in an apparent negative abatement potential using the IPCC methodology.

3.2 Abatement potential for agriculture

3.2.1 Abatement totals

The implications of the analyses and MACC presented in this report can be summarised as follows: the total maximum biophysical abatement potential of cost-beneficial and cost-neutral GHG mitigation measures for agriculture is currently estimated to amount to 2.5 Mt CO_2eq. Realisation of this abatement potential is estimated to translate into a 1.1 Mt CO_2eq reduction in reported agricultural emissions in the Irish National GHG Emissions Inventory, compared to the projected emissions under the Food Harvest 2020 reference scenario.

The measures that deliver the 1.1 Mt CO_2eq reduction potential that can be accounted for, are those measures that relate to improvements in efficiency (“green measures”). These measures are cost-beneficial, as higher production efficiency leads to reduced farm inputs, hence reducing direct costs and GHG emissions simultaneously. However, this does not imply that this potential will be realised without incentivisation (see Section 3.2.2 below).

Measures relating to biofuel/bioenergy production (“yellow measures”) have potential to contribute a further 1.4 Mt CO_2eq to reductions in the national reported emissions. However, these reductions will be attributed to the transport and power generation sectors. Most of these measures involve land use change and are marginally cost-beneficial or cost neutral, and further incentivisation may be required for their abatement potential to be realised (see Section 3.2.2 below).

Most of the remaining measures, largely those associated with technical interventions (“blue measures”), are either cost-prohibitive or cannot (yet) be accounted for in the Inventory.

This means that reduction targets for agriculture over and above 1.1 Mt Mt CO_2eq (compared to the Food Harvest 2020 scenario) by 2020 will require either:

1. measures that are currently cost-prohibitive, i.e. with associated costs in excess of the cost of purchasing carbon credits, or:
2. measures that are currently accounted for by the LULUCF sector, e.g. farm afforestation (see Section 3.4 below).

Note that these figures represent the abatement potential that have been scientifically proven to be cost-effective using research available up to 2012. In future, further mitigation measures may be added to this list. These measures are currently subject to national and international research, and are briefly described in section 3.4.

3.2.2 Incentivisation

The figures presented above represent the abatement potential that can realistically be achieved, taking account of biophysical limitations. However, it is important to note that the adoption of measures requires incentivisation. In other words: if no incentive is present, this abatement potential will not be realised. It could be argued that if no incentivisation was required for a measure to be implemented, then “it would have been implemented already”. However, different measures may require different types and/or intensities of incentivisation.

Incentivisation of cost-beneficial measures

Most of the cost-beneficial measures relate to increased resources use efficiency (“green measures”); their implementation should result in monetary savings in the long term. However, most of the green measures require intensive farm management (including nutrient management, grassland management and animal husbandry), and therefore require a concerted programme of knowledge transfer and advisory services. Teagasc is currently developing the Carbon Navigator (due to be launched in July 2012) to aid individual farmers in customising and implementing these “green measures”. In addition, there are a number of food processor-led initiatives aimed at implementing these measures. At the same time, Bord Bia and Teagasc have developed and implemented a carbon calculator for beef production, which can be used to record and account for ongoing reductions in GHG emissions from individual farms.

Incentivisation of cost-neutral measures

Most of the cost-neutral measures are those that involve land use change, and specifically the planting of biofuel/bioenergy crops (“yellow measures”). Whilst these measures would not be associated with net costs to farmers, their implementation would not result in monetary savings in the long term, either. A major obstacle to incentivisation of these measures is that the GHG emissions associated with biofuel/bioenergy crops (through displacement of fossil fuel inputs) are currently attributed to the transport and power generation sectors. In previous reports and submissions, Teagasc discussed how a Domestic Offsetting scheme could provide a mechanism to overcome this obstacle, by attributing (part of) the associated reductions in GHG emissions to the agricultural sector and providing further financial incentivisation for the uptake of these measures; for details see Textbox 3.1, Schulte & Lanigan (2011) (Appendix C) and Teagasc (2010) (Appendix D).

Incentivisation of cost-effective measures

Only one of the measures included in the MACC curve, i.e. the cultivation of sugar beet for ethanol production, carried an associated cost close to the price of carbon, namely €24.39 per t CO_2eq (IPCC methodology) or €38.39 per t CO_2eq (LCA methodology). In practice, this means that implementation of this measure would be associated with a cost to farmers; therefore it is unlikely that its abatement potential will be realised through market-forces alone. At the same time, as the cost of this measure is below the price of carbon credits, financial incentivisation of this measure could theoretically constitute a marginal cost saving to society as a whole – compared to the costs of the hypothetical purchase of carbon credits. This is complicated by the fact that the abatement potential of this measure – similar to that of other biofuel and bioenergy crops (see above) – will largely be attributed to the transport and power generation sectors.

Textbox 3.1: Domestic Offsetting for agriculture: pros and cons

What is Domestic Offsetting?

A Domestic Offsetting (DO) scheme is a potential national scheme to facilitate trading of carbon emissions with sectors that fall outside the Emissions Trading Scheme (ETS), such as the agricultural sector, transport and the residential sector. The main purpose of a DO is to financially incentivise effective abatement measures within the non-ETS sectors. Currently – in absence of a DO scheme – there is no mechanism to financially reward the carbon-offsetting potential of individual projects or initiatives within the non-ETS sectors (including agriculture), but in 2011 the EPA published a scoping study on the potential for a DO scheme for Ireland (O'Keeffe *et al.*, 2011). Teagasc made a submission to the public consultation on this scoping study, which is included in Appendix D of this report.

Potential benefits

The main potential benefit of a DO scheme is that it could provide a direct financial incentive for individual farmers to proactively seek to reduce greenhouse gas emissions, for example through the cultivation of biofuel / bioenergy crops or the installation of anaerobic digestion (AD) plants. Under current conditions, GHG emissions from agriculture are quantified and reported only on a sectoral basis, over which individual farmers have limited to no control; as a result individual farmers cannot be remunerated, nor given nominal credit, for potential sectoral reductions in GHG emissions. This is an obstacle to the incentivisation of cost-neutral and cost-effective abatement measures in agriculture.

Potential drawbacks

The main potential drawback of a DO scheme for Irish agriculture is that – depending on the nature of the DO scheme – it may be associated with prohibitive transaction costs. Transaction costs are associated with the measurement, verification and reporting of the carbon-offsetting potential of specific abatement measures on individual farms. These costs are expected to vary significantly by farm enterprise type. For example: the transaction costs associated with establishing the carbon-offsetting potential of biofuel / bioenergy crops, AD plants and farm afforestation will be relatively low. By contrast, the transaction costs associated with the accurate measurement or estimation of the carbon-offsetting potential abatement measures on livestock farms will be prohibitively high, due to the variety and complexity of livestock production systems, dependency on soil type and other context-specific parameters.

Summary

In its submission to the EPA scoping study on Domestic Offsetting, Teagasc recommended that - if a DO scheme is implemented - it is targeted towards enterprises and interventions that are associated with a high potential for carbon offsetting and low transaction costs, i.e. primarily the cultivation of bio-energy crops and biofuel crops, farm afforestation and AD plants. Furthermore, transaction costs can be reduced by use of partial rather than full Life Cycle Analyses, i.e. by quantifying the change, rather than the full scale of emissions associated with individual farms.

For further details see Appendices D and E of this report.

Incentivisation of cost-prohibitive measures

Most of the cost-prohibitive measures are those associated with the introduction of technological solutions, such as low-emission slurry spreading equipment, plants for the anaerobic digestion of pig slurry or the introduction of nitrogen inhibitors. Incentivisation of these measures is likely to require a reduction of the associated costs to farmers, for example a reduction in the capital investment costs. It is important to note that this reduction in costs to farmers does not equate to a reduction in the cost to society – since measures such as grants would have to be funded from taxation.

3.2.3 Wider environmental considerations

It is important that the incentivisation and implementation of measures aimed at reducing GHG emissions from agriculture takes account of other agri-environmental considerations, including ammonia emissions, water quality, bio-diversity and soil quality. In some cases, GHG mitigation measures may have synergistic impacts on other environmental variables, e.g.: more efficient use of N fertiliser will not only reduce associated N_2O and CO_2 emissions, but also reduce farm N surplus and hence the risk of N loss in the form of ammonia or nitrate. However, some GHG mitigation measures may inadvertently represent an increased risk to other environmental variables, e.g.: the inappropriate application of extended grazing may increase risk of soil compaction, with associated risks to water quality and nitrous oxide emissions. Such risks are highly farm, soil and context specific and depend to a large degree on farm management aspects, which is subject to ongoing research in Teagasc. Table 3.1 outlines the *indicative* interactions between GHG abatement measures and other environmental variables. Further details are specified in Appendix B.

Table 3.1: Indicative potential impact of each of the GHG abatement measures on environmental variables. Note: ✓ *indicates reduced environmental risk,* **X** *indicates potential for increased risk.*

Measure	greenhouse gases (LCA)			other environmental variables			
	methane	*nitrous oxide*	*carbon dioxide*	*ammonia*	*water quality*	*herbicide use*	*soil quality*
EBI	✓	✓	✓				
Live Weight Gain	✓	✓	✓				
Ext grazing	✓	✓ or **X** ?	✓	✓	**X**		**X**
Manure management		✓ or **X** ?	✓	✓			**X**
Nitrification inhibitors		✓			✓		
N-efficiency		✓	✓	✓	✓		
Min till		**X**	✓		✓	**X**	✓
Cover crops		✓	✓		✓	**X**	
Bio-energy crops		✓	✓		✓		
Biofuel crops		✓	✓				
Sugar beet for ethanol		✓	✓		**X**		**X**
AD (pig slurry)	✓		✓		✓		

3.3 Other potential abatement measures

The scientific literature contains many other potential GHG mitigation measures, which were not included in this first iteration of the MACC for Irish agriculture, presented in this report, for reasons outlined in Section 1.3.2. Examples of relevance to Irish agriculture include: pasture sequestration, anaerobic digestion of biomass, substitution of CAN fertiliser with urea, use of urease inhibitors and next-generation nitrification inhibitors, programmes for the prevention and control of animal diseases, the development of methane vaccines, identification of methane inhibitors and selection of low emitting ruminants. Teagasc pro-actively participates in ongoing international research programmes on most of these potential measures. We expect that - upon completion of these programmes - many of these measures will be included in future iterations of the MACC for Irish agriculture. In this section, we discuss some of these measures in more detail.

3.3.1 Pasture sequestration

Under the terms of Article 3.4 of the Kyoto Protocol, countries can elect to report the impact of land management activities on carbon stocks. One of these elective activities is pasture sequestration. Currently, there are few countries that have elected to report this activity. This is due to the fact that whilst baseline SOC levels and the gross level of sequestration can be readily measured and compared to other land-use categories, the additional effect of management changes is much more difficult to quantify (Schultze *et al.*, 2010).
This is due to the fact that the input rates of organic C into most soil systems is very small (< 1 t C ha^{-1} yr^{-1}) compared to the background SOC levels (typically 80 - 140 t C ha^{-1}). Whereas the quantity and quality of input of carbon via litter fall and plant residues after harvest might be directly measurable, inputs via roots and rhizo-deposition are more difficult to assess. The fundamental mechanisms involved are not yet fully understood and there is still no proper quantification of the release of organic and inorganic C compounds from roots or the assessment of seasonal dynamics. This low rate of change also requires that management practices are in place for a minimum of ten years before any statistically significant shift in SOC is detectable (Smith *et al.*, 2005). Teagasc is currently actively participating in national and European research efforts to quantify and model the impact of management on sequestration. However, there is currently not enough validated research on management effects to include pasture C-sequestration in the MACC.

3.3.2 Anaerobic digestion of biomass

Anaerobic digestion of biomass produced from Irish grassland would produce biogas (55% methane) that could be used directly for heat and electricity generation, or the biogas could be upgraded to the same standard as natural gas (biomethane – 97% methane), injected into the natural gas grid and subsequently used for a range of commercial purposes (Smyth *et al.*, 2011). The initial studies of Smyth *et al.* (2009), Smyth *et al.* (2010) and Korres *et al.* (2010) indicate that grass biogas/biomethane is a viable solution to meeting Ireland's biofuel (40% renewable energy, 12% renewable heat and 10% renewable transport fuels by 2020) and greenhouse gas reduction (20% reduction relative to 2005 by 2020) targets in terms of technology, energy balance, GHG savings and policy constraints. The key to competitiveness for biogas/biomethane is the renewable energy targets which place it in competition not with cheap natural gas but with other renewables (Smyth *et al.*, 2010).

Both O'Keeffe *et al.* (2012) and Singh et al (2010) have considered the options of centralised or on-farm anaerobic digesters for grass, and Smyth *et al.* (2011) have indicated that criteria determining the suitability of a location in Ireland for biomethane production include agricultural land use, grassland farming systems prevailing, grass yield, availability of co-substrates (e.g. livestock slurry), and the opportunities for successfully using heat or accessing distribution and transmission grids for electricity or biomethane. Furthermore, Singh *et al.* (2010) have calculated that, under one set of assumptions, a total of 183 centralised anaerobic digestion facilities utilising 5.3 million tonnes grass and 3.9 million tonnes slurry per year could readily be accommodated. However, Smyth *et al.* (2011) propose that smaller digestion facilities (minimum of 100 m^3 per hour of raw biogas) would be more suitable, at least in the early stages until the technology and expertise develops sufficiently in Ireland.

Korres et al. (2010) have calculated that with improved digester design, the purchase of green electricity, using vehicles optimised for biomethane and accounting for carbon sequestration under permanent grassland, a reduction in greenhouse gas emissions of up to 75% relative to fossil diesel could be achieved.

Further research is required to reliably and comprehensively estimate the opportunities for and the realistically feasible scale of anaerobic digestion from grassland biomass in Ireland, under a range of scenario options. This research should encompass alternative national and regional expansions and contractions in current livestock enterprises, the implications of utilizing biogas versus biomethane, and how these and other factors impact on greenhouse gas abatement. A new research initiative between Teagasc, University College Cork (Environmental Research Institute) and MTT Finland will contribute to this process.

3.3.3 Substitution of calcium ammonium nitrate fertiliser with urea

The substitution of calcium ammonium nitrate with urea should lead to a reduction in N_2O, both in terms of reduced soil emissions and reduced manufacturing emissions. Comparisons of N_2O emissions upon applications of equivalent N-rates of both ammonium nitrate and urea on pasture or tillage systems have shown that emissions are *c.* 50% lower under urea application (Burton *et al.*, 2009; Venterea *et al.*, 2010). This is due to the fact that upon field application, urea must be ammonified to ammonium before N_2O emissions associated with nitrification to nitrate and subsequent de-nitrification can occur. This allows a longer time period for crop uptake. In addition, emissions associated with the manufacture of urea are lower than those for CAN. This is due to the fact that whilst emissions from urea production are dominated by CO_2 emitted during ammonia synthesis, CAN emissions also have substantial N_2O emissions associated with nitric acid production (Wood & Cowie, 2004). In fact, urea manufacture emissions range from 1.8 – 4.1 kg CO_2-eq kg^{-1} N, whilst CAN manufacture ranges from 6.1 – 8.4 kg CO_2-eq kg^{-1} N (Wood & Cowie, 2004).

The major drawback of substituting urea for CAN is that application would probably be limited to spring and autumn, as approximately 17-47% of N can be lost via volatilization under warm dry conditions (Watson, 2000). This not only reduces the fertiliser efficiency to the farmer but results in higher ammonia emissions, which in turn can result in eutrophication and higher indirect N_2O emissions from N deposition. As a result, any urea usage during summer months will have to be in conjunction with urease inhibitors, which will be the subject of a Teagasc research programme planned for 2012-2015.

3.3.4 Use of urease inhibitors and next-generation nitrification inhibitors

In order to exploit urea as a mitigation strategy, ammonia loss during warm weather conditions must be minimised. Urease inhibitors such as N-(n-butyl) thiophosphoric triamide (NBPT, commercially sold as Agrotaine), when coated on the surface of urea granules, have been demonstrated to substantially reduce volatilization, resulting in yields comparable with CAN application (Watson *et al.*, 1996).

Other novel compounds, including plant-extracted tri-terpenoid compounds, have been shown to have both urease and nitrification inhibitory properties at a fraction of the cost of dicyandiamide (DCD) (Malla *et al*., 2005). However, their effectiveness may be variable and as yet little field validation had taken place. Some forage crops (e.g. *Brachiaria* grasses) have been shown to have the ability to regulate nitrification in soils by releasing inhibitors into the soil from their roots. This biological mechanism has evolved to minimise N losses associated with nitrification, thus improving N-recovery and N-use efficiency. Genetic exploitation of biological nitrification inhibition has potential, through manipulating this natural phenomenon (e.g. *Brachiaria* grasses) and transferring these mechanisms into field crops (e.g., rice, wheat, maize and soybean) and other forages.

3.3.5 Animal disease prevention and control

Increasing the disease free status of Irish dairy and beef herds will reduce the emissions intensity of product sold. For example: elevated levels of mastitis in a dairy herd affect milk yield, culling levels, mortality, treatment costs and milk solids concentration (Geary *et al.*, 2012), while the bovine viral diarrhoea virus (BVD) is associated with suppressed immunity and consequently scouring, infertility, abortions and lower levels of animal production (live weight and milk production) (Gunn *et al*., 2005). Therefore, improvements in the herd health status of the national Irish dairy and beef herd will result in increased productivity and ultimately reduced emissions per unit of product as a result of increased output and/or less wastage. At national level, this will translate in a reduction in agricultural GHG for a given level of agricultural production. The expectation is that this potential reduction in GHG emissions will be associated with increased profitability. For example, a study commissioned by Animal Health Ireland (AHI) on BVD has shown that BVD potentially costs the industry over €120 million annually (Stott *et al.*, 2012), while estimates of farm level costs arising from mastitis range from 2.5 and to 3.0 cent per litre of milk produced (Geary *et al.*, 2012). Both of these diseases are part of national initiatives in Ireland (BVD eradication programme and Cell Check, respectively) which are being led by AHI. These two initiatives, in addition to future disease control/eradication programmes, are likely to be included in future iterations of the MACC for Irish agriculture, when more detailed information is available on their overall extent and impact.

3.4 Abatement potential from farm afforestation

3.4.1 Offsetting potential

Forestry offers significant potential for abatement through carbon sequestration and through fossil fuel substitution. To assess the total abatement potential of farm afforestation, as well as the associated costs/benefits, we utilised projections of carbon dioxide sequestration by Kyoto forests to 2030, based on *CARBWARE,* the national forest carbon reporting system developed by COFORD (Hendrick and Black, 2009). We use projections of energy savings from forestry biomass from figures prepared for COFORD by Phillips (2007), which assumes savings of 0.073 Mt CO_2 per 1000 ha. In the analysis we assume that no abatement arises from the change in land use from agriculture to forestry, in line with the overall scenario constraints, in which the agricultural targets for Food Harvest 2020 are achieved, irrespective of the rate of forestry planting (and loss of agricultural land). In essence, the analysis assumes that if the land area available for agriculture decreases this leads to an intensification of agricultural production on the remaining agricultural land base. As a result, the actual abatement potential per hectare of forestry may be understated in this analysis. The additional abatement potential arising from the potential land use change depends on the agricultural activity that forestry would displace; for example, the level of displacement of a hectare of land used for intensive ruminant production differs from the level of displacement of a hectare of land used for crop production. Philips estimates that on average an additional 0.16 Mt CO_2eq per 1000 ha of abatement could be achieved through the displacement of agricultural activity by forestry.

We evaluated two scenarios:

1. The first scenario (Normal production) uses projected sequestration of carbon dioxide by forests to 2030, calculated by CARBWARE (Hendrick and Black, 2009), referred to as CARBWARE I. This is based on the current species mix and range of yield classes of Irish forests associated with the Forest Service Afforestation Grant and Premium Scheme.
2. The second scenario (High production) examines the effect of increased production per unit area, by increasing the yield class of Sitka spruce crops from yield class 16 to 22, as calculated by CARBWARE (K. Black, pers. comm.). The latter is the average

yield class predicted to be obtainable on almost 2 M ha of marginal agricultural land (Farrelly *et al.*, 2011). For other species, calculations were kept the same as in the Normal production scenario.

For the two scenarios we calculated the abatement cost per tonne of CO_2eq for afforestation over and above an assumed baseline level of 8,000 ha per annum (the average planting rate for 2008 - 2010). The analysis also includes the increase in grants and premium payments that would be payable to forest owners for any afforestation over and above 8,000 ha per annum. We project three different planting rates to 2020, a continuation of the baseline level of planting (8,000 ha per annum), a medium planting rate (16,000 ha per annum) and a high planting rate (20,000 ha per annum).

Table 3.2: Marginal abatement cost of afforestation under three planting scenarios and two productivity levels. Source: CARBEWARE (Hendrick & Black, 2009) and authors' calculations.

Scenario			Normal Production		High Production	
Planting rate	ha yr^{-1}	*Baseline* 8,000	*Medium* 16,000	*High* 20,000	*Medium* 16,000	*High* 20,000
Total sequestered carbon	Mt CO_2	5.3	7.0	8.2	7.7	9.5
Increase over baseline		-	1.7	2.9	2.4	4.2
Energy savings (fossil fuel displacement)	Mt CO_2	0.6	1.2	1.5	1.6	1.9
Increase over baseline	Mt CO_2	-	0.6	0.9	1.0	1.4
Total sequestration & energy savings	Mt CO_2	5.9	8.2	9.7	9.3	11.4
Increase over baseline	Mt CO_2	-	2.3	3.8	3.4	5.6
Total premium payments	M€	69.4	138.9	173.6	138.9	173.6
Increase over baseline	M€	-	69.4	104.2	69.4	104.2
Total grant payments	M€	28.0	56.0	70.0	56.0	70.0
Increase over baseline	M€	-	28.0	42.0	28.0	42.0
Marginal abatement cost	€ t^{-1} CO_2eq		42.7	38.7	28.9	26.3

Table 3.2 shows that, relative to the baseline planting rate (8,000 ha per year), the total potential additional carbon sequestration and energy savings under the Normal production scenario ranges from 2.3 Mt CO_2eq under the medium planting rate to 3.8 Mt CO_2eq under the high planting rate, with associated abatement costs of €42.7 and €38.7 per t of CO_2eq, respectively. Under the High production scenario, the total potential additional carbon

sequestration and energy savings are projected by to range from 3.4 Mt CO_2eq for the medium planting rate to 5.6 Mt CO_2eq for the high planting rate, with associated abatement costs of €28.9 and €26.3 per t of CO_2eq, respectively.

It is important to note that the marginal abatement costs for forestry are highly sensitive to the degree to which planting rates can be accelerated, and yield classes can be increased. The marginal abatement costs for the High production scenario are below the projected price of carbon-credits, used in this report, indicating the potential of productive forests in offsetting GHG emissions. By contrast, the marginal abatement costs for the Normal production scenario are above the projected price of carbon-credits. However, these costs are still below the level of the cost-prohibitive measures identified in the agricultural MACC. Finally, the effects of forest management operations such as thinning may further increase the GHG offsetting potential of afforestation in future (Black, pers. comm.).

3.4.2 Accounting for LULUCF under the EU Climate and Energy Package

The Land Use, Land Use Change and Forestry Sector can currently report C sinks under Article 3.3 of the Kyoto Protocol. Under the terms of the Article, increased C sequestration in forestry planted post-1990 can be used to offset national greenhouse emissions. However, under the EU 2020 Climate and Energy Package, this offsetting of GHG emissions, using C sinks, was not included. This was due to the fact that the level of uncertainty associated with measurements of C sequestration were considered to be high and also that there were protracted negotiations at international level with regards to changes in accounting methodology. However, at the Durban Climate Change Conference in 2011, new accountancy rules were agreed with respect to reporting forest management emissions and accounting for sequestration in wood products (Decisions CMP.7). Allied to this, the IPCC recommended the merging of LULUCF with agriculture in the last set of Good Practice Guidelines (IPCC 2006). This brings closer the inclusion of C sequestration into the 2020 GHG abatement targets. However, it is currently not clear whether CO_2 removals will count towards the current national targets under the EU Effort-Sharing Agreement, or whether these removals will be additional to those targets. Whilst there is no decision on this, the speculation is that the removal capacity will be added onto national targets (essentially raising the target for countries with a large sink capacity).

4. Conclusions and implications

This section summarises the main outcomes of the MACC analyses presented in this report. It explores the magnitude of emission reductions that can be realistically achieved by the agricultural sector by 2020, as well as opportunities for further abatement or offsetting of agricultural emissions in Ireland which could be considered for inclusion in future iterations of the MACC curve once appropriate research is available.

4.1 Reducing agricultural GHG emissions: what can realistically be achieved by 2020?

The abatement potential of the measures presented in the MACC curve in this report should be considered in the context of the total annual greenhouse gas emissions attributed to the agricultural sector in Ireland. Figure 4.1 shows the total agricultural emissions for 2005 and 2010 and demonstrates that these have fallen significantly during this time period. It also shows the projected total emissions for 2020 under the Food Harvest 2020 reference scenario and under a scenario where all cost-beneficial and cost-neutral measures are fully implemented. Under the reference scenario, reported emissions are projected to increase by 1.2 Mt CO_2eq compared to 2010 levels. This increase is not substantial in the context of the projected increase in agricultural production, specifically milk volumes, and represents a decoupling of productivity and reported greenhouse gas emissions, driven by higher production efficiencies and a restructuring of the national herd (for details see Schulte & Lanigan, 2011; Appendix C). As such, the realisation of this decoupling will be a significant achievement in its own right.

Figure 4.1 also shows that full implementation of the cost-beneficial and cost-neutral measures identified in this report has the potential to reduce total reported agricultural emissions to 18.9 Mt CO_2eq per annum. Even though this report has demonstrated that these reported reductions (IPCC methodology) would only represent part of the real concurrent reductions (as measured by the LCA methodology), this figure would represent no increase in GHG emissions compared to the Kyoto commitment period, in the presence of a projected 1/3 increase in the contribution of primary agriculture to the Irish Economy (Donnellan & Hanrahan, 2012) over the Food Harvest reference period (2007-2009).

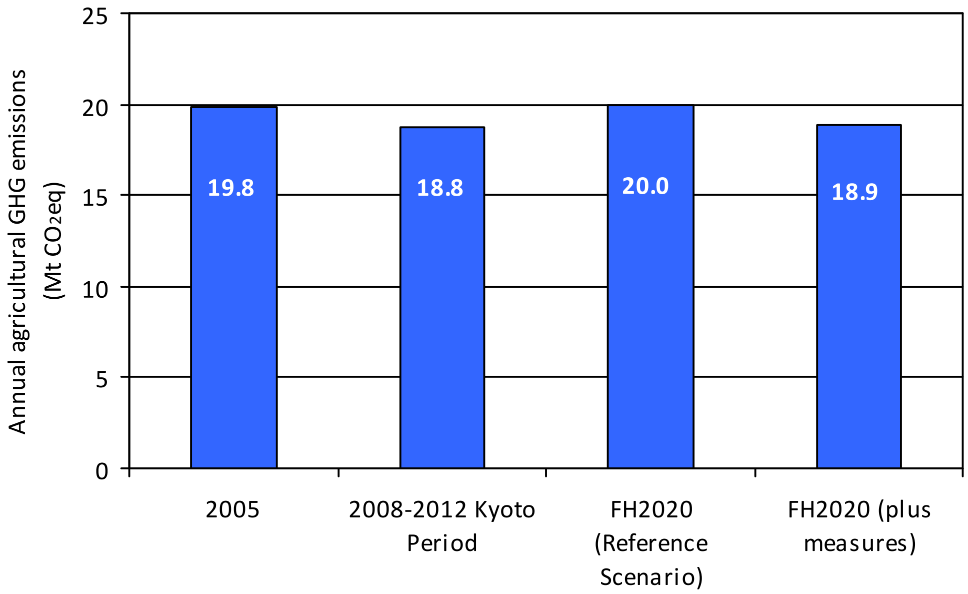

Figure 4.1: Historic agricultural GHG emissions for the EU reference year 2005 and for the Kyoto commitment period 2008-2012, following IPCC methodology, and projected GHG emissions for the Food Harvest reference scenario and the "Food Harvest plus measures" scenario, using IPCC methodology. Source: EPA (2012), FAPRI Ireland Model (2012) and authors' calculations.

Table 4.1 shows that the projected emissions under the "Food Harvest 2020 plus measures" scenario corresponds to a 5.5% reduction compared to the level in 2020 arising in the Food Harvest 2020 reference scenario (which excludes abatement measures), almost no change compared to the reported agricultural emissions for the Kyoto commitment period (2008-2012), or a 4.5% reduction compared to the reported agricultural emissions in 2005 (EU reference year).

Table 4.1: potential change in GHG emissions under the "Food Harvest 2020 plus measures" scenario, compared to the EU effort sharing reference year (2005), 2010 (most recent GHG inventory value), Kyoto period (2008-12), and to the Food Harvest 2020 reference scenario, using IPCC methodology. Source: EPA (2012), FAPRI Ireland Model (2012) and authors' calculations.

Reference year / scenario	Potential change in emissions (under FH 2020 plus measures scenario)	
	Absolute (Mt CO_2eq p.a.)	*Relative (%)*
2005	- 0.9	- 4.5 %
2010	+0.2	+ 1.1 %
2008-2012 (Kyoto commitment period)	+0.1	+0.5%
2020 (FH 2020 reference scenario)	- 1.1	- 5.5 %

It is important to note that the abatement figures for each mitigation measure in this report represent:

- the total *potential* abatement
- that can be *realistically* achieved
- following *full implementation*
- wherever *biophysically* possible.

Therefore, the potential reduction in reported agricultural GHG emissions anticipated in this report will only materialise following maximum incentivisation and full uptake of each of the cost-beneficial measures, facilitated by comprehensive, large-scale advisory programmes. This requires a concerted effort from farmer stakeholders, advisory services, research institutes, policy stakeholders and the agri-food industry.

4.2 Future pathways towards further GHG reductions

Based on the analyses in this report, any further reductions in reported agricultural GHG emissions from Irish agriculture would require either:

- The introduction of mechanisms (for example: a Domestic Offsetting scheme – see Textbox 3.1) that incentivises the cultivation of biofuel / bioenergy crops and accredits (part of) the abatement potential (up to 1.2 Mt CO_2eq) from the resultant fossil fuel displacement to the agricultural sector (Section 3.2.2);

- The introduction of mechanisms (for example: a Domestic Offsetting scheme – see Textbox 3.1) that incentivises farm afforestation and that accredits (part of) the abatement potential (up to 3.5-7.0 Mt CO_2eq) from the resultant carbon offsetting to the agricultural sector (Section 3.4);

- Incentivisation of measures that are currently cost-prohibitive measures, for example through grant-aiding of the required capital investments and / or the provision of a REFIT tariff equivalent to those available in other jurisdictions (Section 3.2.2). The cost of such incentivisation schemes should be evaluated against the costs of buying equivalent carbon credits on the international carbon market;

- The future introduction of further additional mitigation measures, the effectiveness of which is currently the subject of ongoing research programmes (Section 3.3). Examples of these include grassland sequestration (Section 3.3.1), anaerobic digestion of biomass (Section 3.3.2), substitution of calcium ammonium nitrate fertiliser with urea (Section 3.3.3) use of urease inhibitors and next-generation nitrification inhibitors (Section 3.3.4) and further programmes for animal disease prevention and control (Section 3.3.5).

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Appendix A:

Historical agricultural activity data for 1990, 2000, 2005 and 2010 and projections for 2015 and 2020 based on the achievement of the Food Harvest 2020 targets

Appendix A

Description	Units	1990	2000	2010	2015	2020
Housing (storage) Period						
Total Cattle	000 head	5,969.10	6,557.70	6,231.68	5,574.18	5,843.86
Dairy Cows	000 head	1,341.60	1173.8	1,022.4	1,031.55	1,293.33
All Other Cattle	000 head	4,627.50	5,383.90	5,209.27	4,542.63	4,550.53
Other Cows	000 head	659.20	1166.8	1,134.9	1,086.05	1,032.64
Dairy Heifers	000 head	172.30	210.4	195.2	233.50	271.23
Other Heifers	000 head	100.00	125.2	153.7	144.58	143.39
Cattle < 1 yrs	000 head	1,436.20	1,648.90	1,793.95	1,543.1	1,553.6
Cattle < 1 yrs - male	000 head	775.30	892.2	857.87	807.0	812.6
Cattle < 1 yrs - female	000 head	660.90	756.7	936.08	736.1	741.1
Cattle 1 - 2 yrs	000 head	1,311.70	1,446.40	1,447.84	1,149.8	1,157.6
Cattle 1 - 2 yrs - male	000 head	813.80	904.8	803.7	694.4	699.2
Cattle 1 - 2 yrs - female	000 head	497.90	541.6	644.1	455.4	458.5
Cattle > 2 yrs	000 head	922.60	738.70	434.87	338.4	340.7
Cattle > 2 yrs - male	000 head	638.70	491.1	275.3	216.0	217.5
Cattle > 2 yrs - female	000 head	283.90	247.6	159.6	122.4	123.2
Bulls	000 head	25.50	47.5	48.8	47.20	51.27
Total Sheep	000 head	8,020.98	7,957.34	4,694.62	5,104.79	5,076.65
Ewes Lowland	000 head	2,396.60	2,814.25	1,782.86	2,035.27	2,070.32
Ewes Upland	000 head	1,960.85	1,206.11	445.72	505.02	515.84
Rams	000 head	116.85	110.65	66.86	76.21	77.58
Other Sheep>1	000 head	298.38	204.74	98.35	122.45	129.67
Lambs	000 head	3,248.30	3,621.60	1,733.54	2,365.83	2,283.24
Pigs	000 head	1,212.10	1,718.65	1,500.40	1,730.50	2,114.53
Gilts in Pig	000 head	21.10	21.25	19.30	20.48	20.53
Gilts not yet Served	000 head	12.10	17.85	14.70	17.64	17.68
Sows in Pig	000 head	83.45	109.65	91.90	91.18	91.39
Other Sows for Breeding	000 head	21.00	23.85	28.80	28.85	28.92
Boars	000 head	6.25	4.00	1.55	1.84	1.85
Pigs 20 Kg +	000 head	749.20	1037.90	953.40	1,062.64	1,340.18
Pigs Under 20 Kg	000 head	319.00	504.15	399.70	435.46	534.44
Poultry	000 head	11,412.83	15,320.50	16,248.17	15,322.43	17,158.09
Layer	000 head	1,868.25	1,572.00	1,995.00	1,881.33	2,106.72
Broiler	000 head	8,035.13	12,426.10	13,840.00	13,051.46	14,615.05
Turkey	000 head	1,509.45	1,322.41	413.17	389.63	436.31
Horses	000 head	61.60	69.90	98.10	98.10	98.10
Mules	000 head	8.30	5.00	8.80	8.80	8.80
Goats	000 head	17.40	8.10	10.10	10.10	10.10
Fertiliser	kg of N	379,311	407,598	362,395	345,104	359,786

Source: CSO and FAPRI Ireland Model (2012)

Appendix A

Description	Units	1990	2000	2010	2015	2020
Pasture Period						
Total Cattle	000 head	6,816.10	7,037.50	6,606.62	6,281.81	6,585.74
Dairy Cows	000 head	1,359.70	1,177.50	1,092.50	1,037.73	1,315.95
All Other Cattle	000 head	5,456.40	5,860.00	5,514.12	5,244.09	5,269.79
Other Cows	000 head	731.30	1,187.00	1,136.69	1,116.69	1,061.77
Dairy Heifers	000 head	158.60	206.50	233.73	245.75	285.47
Other Heifers	000 head	68.60	125.10	163.17	164.46	163.11
Cattle < 1 yrs	000 head	1,716.10	1,751.90	1,761.25	1,676.10	1,693.66
Cattle < 1 yrs - male	000 head	903.20	919.40	826.66	816.33	824.88
Cattle < 1 yrs - female	000 head	812.90	832.50	934.59	859.77	868.78
Cattle 1 - 2 yrs	000 head	1,663.10	1,517.10	1,407.48	1,302.36	1,316.00
Cattle 1 - 2 yrs - male	000 head	985.80	912.40	760.26	725.42	733.02
Cattle 1 - 2 yrs - female	000 head	677.30	604.70	647.22	576.93	582.98
Cattle > 2 yrs	000 head	1,092.60	1,016.30	759.76	678.06	685.16
Cattle > 2 yrs - male	000 head	826.40	721.60	506.17	485.06	490.14
Cattle > 2 yrs - female	000 head	266.20	294.70	253.60	193.00	195.02
Bulls	000 head	26.10	56.10	52.04	60.66	64.61
Total Sheep	000 head	8,020.98	7,957.34	4,694.62	5,104.79	5,076.65
Lowland Ewes	000 head	2,396.60	2,814.25	1,782.86	2,035.27	2,070.32
Upland Ewes	000 head	1,960.85	1,206.11	445.72	505.02	515.84
Rams	000 head	116.85	110.65	66.86	76.21	77.58
Other Sheep>1	000 head	298.38	204.74	98.35	122.45	129.67
Lambs	000 head	3,248.30	3,621.60	1,733.54	2,365.83	2,283.24
Pigs	000 head	1,212.10	1,718.65	1,500.40	1,730.50	2,114.53
Gilts in Pig	000 head	21.10	21.25	19.30	20.48	20.53
Gilts not yet Served	000 head	12.10	17.85	14.70	17.64	17.68
Sows in Pig	000 head	83.45	109.65	91.90	91.18	91.39
Other Sows for Breeding	000 head	21.00	23.85	28.80	28.85	28.92
Boars	000 head	6.25	4.00	1.55	1.84	1.85
Pigs 20 Kg +	000 head	749.20	1037.90	953.40	1,062.64	1,340.18
Pigs Under 20 Kg	000 head	319.00	504.15	399.70	435.46	534.44
Poultry	000 head	11,412.83	15,320.50	16,248.17	15,322.43	17,158.09
Layer	000 head	1,868.25	1,572.00	1,995.00	1,881.33	2,106.72
Broiler	000 head	8,035.13	12,426.10	13,840.00	13,051.46	14,615.05
Turkey	000 head	1,509.45	1,322.41	413.17	389.63	436.31
Horses	000 head	61.60	69.90	98.10	98.10	98.10
Mules	000 head	8.30	5.00	8.80	8.80	8.80
Goats	000 head	17.40	8.10	10.10	10.10	10.10
Fertiliser(kgs N)	kg of N	379,311	407,598	362,395	345,104	359,786

Source: CSO and FAPRI Ireland Model (2012)

Appendix A

Description	Units	1990	2000	2010	2015	2020
Crops						
Pulses	tonnes	15,000	7,700	18,600	18,600	18,600
Potatoes	tonnes	605,000	454,800	420,000	334,651	313,829
Sugarbeet	tonnes	1,480,000	1,829,000	0	0	0
Barley	tonnes	1,223,000	1,309,900	1,223,000	1,183,270	1,067,009
Oats	tonnes	144,000	126,600	148,000	161,404	153,697
Wheat	tonnes	598,000	737,400	669,000	824,051	840,433
Pasture (ha)	ha	2,277,809	2,218,100	2,092,400	2,093,145	2,115,679
Hay (ha)	ha	420,397	242,600	222,596	222,327	222,759
Silage (ha)	ha	815,724	1,074,700	1,014,049	1,012,823	1,014,791
Rough Grazing (ha)	ha	626,454	506,500	441,200	441,200	441,200

Source: CSO and FAPRI Ireland Model (2012)

Appendix B:

Detailed methodologies for the computation of the marginal cost-abatement potential of individual measures

Appendix B

Appendix B

Measure:	**Improving genetic merit**
Gas(es) involved	CH_4, N_2O, CO_2
Enterprises involved	Dairy

Brief explanation of abatement mechanism:

The abatement measure “improving genetic merit” is based on the paper of O’Brien *et al.* (2011). The data used in the study was from the work of Horan *et al.* (2004, 2005) and McCarthy *et al.* (2007). In short, GHG emissions from 3 strains of Holstein-Friesian cows differing in genetic merit (measured using the economic breeding index (EBI)) were compared. The results of these field studies were included in the Moorepark Dairy System Model (Shalloo *et al.*, 2004), which is used to operate a GHG model (O’Brien *et al.* 2011).

The GHG model results showed that increasing genetic merit via EBI reduced GHG emissions per unit of product by 2% for every 10 euro increase in EBI. This was because higher EBI cows had better fertility, which reduced emissions from non-milk producing animals and improved herd lifetime milk performance relative to lower EBI cows. Higher EBI cows improved a number of traits of economic importance simultaneously e.g. fertility, health and millk performance, whereas cows of lower genetic merit only improved single traits such as milk production. The EBI was established in 2001 and, based on the outcomes of this study, it is anticipated that increasing EBI will reduce emissions through:

- Improving fertility, which reduces calving intervals and replacement rates, thus reducing enteric CH_4 emissions per unit of product;
- Increasing milk yield per unit of grazed grass and improving milk composition. This increases the efficiency of production, which decreases emissions (Martin *et al.*, 2010);
- Earlier calving , increasing the proportion of grazed grass in the diet and reducing culling and replacement rates;
- Improved survival and health, reducing deaths and disease incidences, which increases efficiency and reduces emissions.

Biophysical constraints accounted for	N/A	
Interactions with other abatement measures accounted for	There is potential to increase EBI by €65 per cow (Teagasc, 2011). It was assumed (expert assessment) that half of this increase (€32.5 per cow) is likely to occur under the reference Food Harvest 2020 scenario, regardless of GHG abatement initiatives. Therefore, only the remaining half (€32.5 per cow) was included as marginal abatement potential.	
Other potential environmental implications	Positive: None	Negative: None

Methodology

Mean economic breeding index	Current	75	€ cow^{-1}	Teagasc, 2011
	Food Harvest 2020	108	€ cow^{-1}	Expert assessment
	Target	140	€ cow^{-1}	Teagasc, 2011
Relative costs		-€0.0011	€ l^{-1}	McCarthy *et al.* (2007)
Abatement potential (LCA global)		0.555	Mt CO_2eq	
Abatement potential (IPCC)		0.596	Mt CO_2eq	
Cost		-€288.0	M€	

Appendix B

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Appendix B

Measure:	Average daily gain for suckler beef production systems
Gas(es) involved	CH_4, N_2O, CO_2
Enterprises involved	Beef

Brief explanation of abatement mechanism:

The measure “average daily gain” quantifies the impact of improving average daily gain over the lifetime of beef cattle from suckler beef production systems on the GHG emissions. Improvements in liveweight gain for Irish beef production systems were found by Casey and Holden (2006) and Foley *et al*. (2011) to be an important mitigation strategy. For example, beef production systems based on the use of finishing bulls, compared to steers, reduced emissions by 6% and 5% kg^{-1} beef, respectively. Improved lifetime daily gain has also been shown to be a key driver of profitability for suckler beef production systems (Crosson & McGee, 2011). The impact of improved average lifetime daily gain for beef production systems is to “dilute” the GHG emission association with production. No changes in feed efficiency were assumed.

The analysis was conducted by evaluating scenarios of beef cattle production systems with different levels of lifetime average daily gain in the Grange Beef Systems Model (Crosson *et al*., 2006; Crosson, 2008). This model facilitated the economic evaluation of lifetime average daily gain. Moreover, this model generated the outputs necessary to quantify GHG emissions (e.g. animal profile, feed budgets, manure management strategy). These outputs were applied in a beef systems GHG emissions model (BEEFGEM; Foley *et al*., 2011). This GHG model quantifies on-farm and total GHG emissions from beef cattle production systems using either LCA or IPCC methodologies. Thus, GHG emissions profiles were generated for beef cattle production systems differing in lifetime average daily gain, facilitating the calculation of the impact of this performance parameter on GHG emissions.

Improved average lifetime daily gain

→ Absolute GHG emissions related to enteric fermentation, feed provision and manure management increase since the quantities of feed consumed and manure produced are greater.

→ GHG emissions per unit of beef produced are reduced since the greater quantities of beef produced more than offset the increase in GHG emissions.

Biophysical constraints accounted for	Level of technology transfer on livestock farms is historically poor.	
Interactions with other abatement measures accounted for	It is assumed that increased lifetime average daily gain is genetically driven (albeit with no change in feed efficiency); thus, management and feeding practices do not change.	
Other potential environmental implications	Positive: None	Negative: None

Methodology

Increased lifetime average daily gain	Current	0.68	Kg day^{-1}	Teagasc, 2011
	FH2020	0.68	Kg day^{-1}	
	Target	0.75	Kg day^{-1}	Teagasc, 2011
Relative costs		-€0.004	€ kg^{-1} carcass g^{-1}	Crosson *et al*. (2006)
Abatement potential (LCA global)		0.146	Mt CO_2eq	

Abatement potential (IPCC)	0.122	Mt CO_2eq
Cost	-€70.2	M€

References:

Casey, J. W. and Holden, N.M., 2006. Quantification of GHG emissions from sucker-beef production in Ireland. Agricultural Systems 90, 79-98.

Crosson, P., 2008. The impact of cow genotype on the profitability of grassland-based suckler beef production in Ireland. Proceedings of the 22nd Annual Meeting of the European Grassland Federation, Uppsala, Sweden, 9-12 June 2008, p.771

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Appendix B

Measure:	**Extended grazing season (dairy)**
Gas(es) involved	CH_4, N_2O, CO_2
Enterprises involved	Dairy

Brief explanation of abatement mechanism:

The abatement measure “extended grazing season” is based on the paper of Lovett *et al.* (2008). The data used in the paper of Lovett *et al.* (2008) is from two studies; one study was carried out in Curtins farm in Fermoy in North Cork and the second study was carried out on Kilmaley in West Clare, both attached to Moorepark Research Centre. Data was collected over the period 1998 to 2000 on both sites. The two sites have contrasting soil types and climatic conditions with Kilmaley receiving an average annual rainfall of 1,600 mm with an impermeable soil (infiltration rate of 0.5 mm hr^{-1}) while Moorepark had an average annual rainfall of 1,000 with a highly permeable soil (10mm hr^{-1}). Both systems were optimised resulting in Moorepark having a grazing season length of 250 days per year with the corresponding Kilmaley figure of 149 days per year.

The results from the study were included in the Moorepark Dairy Systems Model (Shalloo *et al.*, 2004a) and were then fed into the GHG emission model (O’Brien *et al*., 2011). The analysis showed that for every one day increase in the grazing season, the IPCC and LCA emissions reduced on average by 0.14% and 0.17% per unit of milk. This measure interacts with the measure “manure management”, since reducing the period manure is stored while cows are grazing will reduce CH_4 emissions in addition to the emissions reduction that occurs by extending the grazing season.

Storage period

→ Increasing the grazing season reduces volume of manure present to emit CH_4 and N_2O during storage and the quantity of N available to emit direct and indirect N_2O from the application of manure to land. The strategy also reduces effluent from grass silage and NH_3 emissions from housing and manure storage. Reducing the storage period reduces the pool of total ammoniacal N available for spreading manure.

Feed quality

→ Increasing the proportion of grazed grass in the feed budget and reducing the proportion of grass silage in the diet improves feed digestibility and quality. Improving the digestibility and quality of feed consumed reduces methane emissions because of improvements in animal productivity as well as reductions in the proportion of dietary energy lost as methane (Martin *et al.*, 2010). This latter point may result from a reduction in the fibre content of the sward (i.e., an increased proportion of leaf at the expense of stem and dead material in the high quality sward) causing an increased proportion of propionate in rumen volatile fatty acids. Propionate acts as a sink for hydrogen and therefore reduces the amount available for methane synthesis. It is widely accepted that pasture is a higher quality feed than grass silage and therefore the above effect is compounded, leading to a reduction in emissions through extending the grazing season.

Fuel

→ CO_2 emissions are reduced due to the animals being outdoors for a longer period. Thus, less energy is required for feeding activities, manure management and the harvesting of silage.

Biophysical constraints accounted for	Soil drainage: Increasing the grazing season is limited on poorly-drained soils, which account for *c.* 33% of soils in Ireland.

Interactions with other abatement measures accounted for	Manure management: Manure management reduces both the volume and the storage period of manure. These reduced storage period and volumes will lead to reduced CH_4 emissions from manure storage; this is accounted for in this measure. The reduced volumes will also lead to a smaller abatement potential for the measure "manure management"; this has been accounted for in the latter measure.	
Other potential environmental implications	Positive: - Reduction in ammonia emissions from housing and manure storage - Reduction in pool of total ammoniacal N available for spreading to land	Negative: - Later grazing in autumn: higher risk of compaction and associated N_2O emissions and nitrate leaching

Methodology

mean grazing period length	Current	227	Days	Teagasc, 2011
	Food Harvest 2020	227	Days	
	Target	248	Days	Expert assessment
Relative costs		-€3.24	€ cow^{-1}	Shalloo *et al*. (2004b)
Abatement potential (LCA global)		0.332	Mt CO_2eq	
Abatement potential (IPCC)		0.264	Mt CO_2eq	
Cost		-€88.2	M€	

References:

Lovett, D.K., Shalloo, L., Dillon, P. and O'Mara, F.P., 2008. Greenhouse gas emissions from pastoral based dairying systems: The effect of uncertainty and management change under two contrasting production systems. Livestock Science 116, 260-274.

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Appendix B

Measure:	**Extended grazing (suckler beef)**
Gas(es) involved	CH_4, N_2O, CO_2
Enterprises involved	Beef

Brief explanation of abatement mechanism:

The measure “grazing season length” quantifies the impact of changing grazing season length on the GHG emissions from suckler beef production systems. The transition towards longer grazing seasons is recommended from an economic perspective since it results in lower costs of production (lower slurry handling costs and lower relative feed costs; Crosson *et al*., 2009a, b). Animal performance benefits are not considered because compensatory growth for later turned out cattle is assumed to offset temporary performance gains for earlier turned out cattle (Kyne *et al*., 2001).

The analysis was conducted by evaluating scenarios of beef cattle production systems with different grazing season lengths in the Grange Beef Systems Model (Crosson et al., 2006; Crosson, 2008). This model facilitated the economic evaluation of grazing season length. Moreover, this model generated the outputs necessary to quantify GHG emissions (e.g. animal profile, feed budgets, manure management strategy). These outputs were applied in a beef systems GHG emissions model (BEEFGEM; Foley *et al*., 2011). This GHG model quantifies on-farm and total GHG emissions from beef cattle production systems using either LCA or IPCC methodologies. Thus, GHG emissions profiles were generated for beef cattle production systems with different grazing season lengths facilitating the calculation of the impact of this parameter on GHG emissions.

Extended grazing
→ Reduced slurry CH_4 and N_2O emissions from storage since quantities stored will be lower.
→ Higher pasture, paddock and range emissions from direct deposition since during grazing will be greater.
→ Lower enteric fermentation emissions since the digestibility of grazed forages is greater than that of conserved forages and thus, the emission factor used is lower.
→ Fuel emissions are lower as a result of reduced forage harvesting and feeding out requirements.

Biophysical constraints accounted for	Soil drainage: turning out earlier or housing later in the year is physically constrained on poorly-drained soils (Lalor & Schulte, 2008). Poorly-drained soils account for *c.* 33% of soils in Ireland.	
Interactions with other abatement measures accounted for	Manure management: Manure management reduces both the volume and the storage period of manure. These reduced storage period and volumes will lead to reduced CH_4 emissions from manure storage; this is accounted for in this measure. The reduced volumes will also lead to a smaller abatement potential for the measure “manure management”; this has been accounted for in the latter measure.	
Other potential environmental implications	Positive: - reduction in ammonia emissions (Dowling *et al.*, in press) - Animal welfare benefits	Negative: - Later grazing in autumn: higher risk of compaction and associated N_2O emissions and nitrate leaching

Appendix B

Methodology				
Extending the grazing season	Current	224	days	Teagasc (2011)
	FH2020	224	days	
	Target	238	days	Teagasc (2011)
Relative costs		-€0.008	€ kg^{-1} carcass per day	Crosson *et al.* (2006)
Abatement potential (LCA global)		0.08	Mt CO$_2$eq	
Abatement potential (IPCC)		0.04	Mt CO$_2$eq	
Cost		-€26.5	M€	

References:

Crosson, P., 2008. The impact of cow genotype on the profitability of grassland-based suckler beef production in Ireland. Proceedings of the 22nd Annual Meeting of the European Grassland Federation, Uppsala, Sweden, 9-12 June 2008, p.771

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www.teagasc.ie/publications/2011/767/Roadmap_SucklerBeef.pdf

Appendix B

Measure:	**Manure management**
Gas(es) involved	N_2O, CO_2
Enterprises involved	Dairy, beef

Brief explanation of abatement mechanism:

The measure “manure management” comprises a number of related farm management actions that will reduce the GHG emissions associated with manure. These include: a continued transition from summer application to spring application of manure and use of low-emission application methods. This measure interacts with the measure “extended grazing”, since an extension of the grazing season will reduce the amount of manure stored, and hence the activity data to which the measure “manure management” applies.

Spring application

→ reduced NH_3 emissions following landspreading due to weather conditions favouring reduction in NH_3 losses, and therefore reduces the N_2O emissions associated with redeposition.

→ reduced NH_3 losses also increases the fertiliser replacement value of slurry, and therefore reduces the total fertiliser N inputs and reduces associated N_2O emissions from soil and CO_2 emissions from fertiliser manufacture.

Bandspreader or trailing shoe application methods

→ reduced NH_3 losses also increases the fertiliser replacement value of slurry, and therefore reduces the total fertiliser N inputs and reduces associated N_2O emissions from soil and CO_2 emissions from fertiliser manufacture.

Extended grazing and reduced slurry volume being produced

→ reduced volume of slurry present to emit N_2O (from direct emissions following application plus indirect emissions associated with NH_3 losses following landspreading). Slurry volume would increase by 6% due to cattle numbers increasing, but decrease by 15% due to extended grazing. Overall, this equates to a reduction of 10% in slurry volume.

Biophysical constraints accounted for	Soil drainage: spring application is physically constrained on poorly-drained soils (Lalor & Schulte, 2008). Poorly-drained soils account for *c.* 33% of soils in Ireland.	
Interactions with other abatement measures accounted for	Extended grazing: extending the grazing season will result in reduced volumes of slurry. This will lead to a reduction in CH_4 emissions from storage. In addition, a reduction in total slurry volumes will reduce the absolute quantity of abatement potential associated with slurry management.	
Other potential environmental implications	Positive: - reduction in ammonia emissions (Dowling *et al.*, in press)	Negative: - Higher risk of soil compaction and associated N_2O emissions

Methodology

Scenario 1: Increased spring application and use of bandspreader				Reference
Spring application	Current	52	%	(Hennessy *et al.*, 2011)
	FH2020	52	%	
	Target	67	%	Biophysical constraint (see above)
Use of	Current	3	%	(Hennessy *et al.*, 2011)

bandspreader / Trailing shoe	FH2020	3	%	
	Target	50	%	Economics restrict adoption to contractors. (Approximately 50% of slurry) (Hennessy *et al.*, 2011)
slurry volume	Current	20.7	million m^3 slurry	(Hennessy *et al.*, 2011)
	FH2020	21.9	million m^3 slurry	Appendix A
	FH2020 (including effect of extended grazing)	18.7	million m^3 slurry	Interaction with grazing season length (see above)
Relative costs		€0.63	€ m^{-3}	(Lalor, 2012)
Abatement potential (LCA global)		0.056	Mt CO_2eq	
Abatement potential (IPCC)		0.036	Mt CO_2eq	
Cost		€5.9	M€	
Scenario 2: Trailing shoe adoption instead of bandspreader				Reference
Relative costs		€1.28	€ m^{-3}	(Lalor, 2012)
Abatement potential (LCA global)		0.065	Mt CO_2eq	
Abatement potential (IPCC)		0.041	Mt CO_2eq	
Cost		€12.0	M€	

References:

Dowling, C., Hyde, B., Carton, O., Curran, T. and Lanigan, G.J., in press. The effects of timing and alternative land-spreading techniques on ammonia emissions from cattle slurry. Atmospheric Environment.

Hennessy, T., Buckley, C., Cushion, M., Kinsella, A. and Moran, B., 2011. National Farm Survey of Manure Application and Storage Practices on Irish Farms. Agricultural Economics and Farm Surveys Dept., Teagasc. 41 pp.

Lalor, S., 2012. Costs of adoption of low ammonia emission slurry application methods on grassland in Ireland. In: Reis, S., Sutton, M.A. and Howard C. (Eds.) Costs of ammonia abatement and the climate co-benefits. Springer Publishers (in preparation).

Lalor, S.T.J. and Schulte. R.P.O., 2008. Low-ammonia-emission application methods can increase the opportunity for application of cattle slurry to grassland in spring in Ireland. Grass and Forage Science 63: 531-544.

Appendix B

Measure:	**Nitrification inhibitors**
Gas(es) involved	N_2O
Enterprises involved	Dairy, beef

Brief explanation of abatement mechanism:

Inhibitors are most efficacious at reducing N_2O emissions if used on N excreted from animals in the form of urine. The rate of urine N application to patches can reach over 800 kg per hectare per year (Bol *et al*., 2004). This rate is in excess of what the plants can utilise, it is available for nitrification to nitrate (which is also vulnerable to leaching) and for denitrification to both N_2O and N_2 – with some lost as nitrous oxide as a by-product of these processes. Soils are most vulnerable to N_2O losses during spring and autumn, as the highest emission rates occur when soil moisture is high and sward C/N ratio is low (Van Groenigen *et al*., 2005). The effectiveness of nitrification inhibitors are dependent on soil type and the economics of its use will be determined by the stocking rate as well as soil type (Merino *et al*., 2004). However, it likely that the technology will be only feasible on soils where stocking rates are high and where emissions reductions are large.

Cattle (dairy and non-dairy) currently excrete 241962 tonnes N on pasture (Appendix A). Approximately 60% of this N is in the form of urine, with DCD effective on half this amount (spring and autumn-deposited N) (Dennis *et al*., 2012). DCD reduces direct emissions by 50% and reduces leaching by 50% - resulting in reduced indirect N_2O emissions (Di & Cameron, 2002). By 2020, the total N excretion is forecast to decrease 5% (an increase in dairy N excretion will be offset by a decrease in excretion from other cattle – Appendix A). However, extended grazing will increase the time on pasture by 4% (see measures on extended grazing), which will increase the N excreted during vulnerable periods. The net effect will be that mitigation potential should be relatively constant.

Biophysical constraints accounted for	Reductions in N_2O will be low in free-draining soils. However, on these soils, nitrification inhibitors will also lead to reductions in leached nitrate and hence indirect N_2O emissions.	
Interactions with other abatement measures accounted.	Extended grazing	
Other potential environmental implications	Positive: - Reduced risk of nitrate leaching	Negative: - None

Methodology

Urine N deposition	Current	145	kt N per year	Duffy *et al*. (2011)
	FH2020	138	kt N per year	Donnellan & Hanrahan (2012)
	Target	143	kt N per year	See measures: extended grazing
Relative costs		65	€ per ha	Di & Cameron (2002)
Abatement potential (LCA global)		0.389	Mt CO_2eq	
Abatement potential (IPCC)		0	Mt CO_2eq	
Cost		197	M€	

References:

Bol, R., Petersen, S.O., Christofides, C., Dittert, K. and Hansen, M.N.J., 2004. Short-term plant uptake, soil solution dynamics and fluxes of N2O, CO2 and NH3 in a temperate grassland after urine deposition. Plant Nutrition Soil Sci., 167 (5), 568-576

Appendix B

Dennis, S., Cameron, K., Di, H., Moir, J., Sills, P. and Richards, K. 2012. Reducing nitrate losses from simulated grazing on grassland lysimeters in Ireland using a nitrification inhibitor (DCD) DOI: 10.3318/BIOE.2011.24

Di H.J. and Cameron, K.C., 2002. The use of a nitrification inhibitor, dicyandiamide (DCD), to decrease nitrate leaching and nitrous oxide emissions in a simulated grazed and irrigated grassland, Soil Use and Management 18, 395-403.

Donnellan, T. and Hanrahan, K., 2012. Greenhouse Gas Emissions by Irish Agriculture: Consequences arising from the Food Harvest Targets. Report produced for the Environmental Protection Agency. Agricultural Economics and Farm Surveys Department, Teagasc.

Duffy, P., Hyde B., Hanley, E., Dore C., O' Brien, P., Cotter E. and Black K., 2012. Ireland, National Inventory Report 2011. Greenhouse gas emissions 1990-2009 reported to the United Nations Framework Convention on Climate Change. Environmental protection Agency, Johnstown Castle, Wexford. http://erc.epa.ie/ghg/nirs/NIR_2011_IE_v2.1.pdf.

Merino, P., del Prado, A., Menendez, S., Careaga, L., Pinto, M., Estavillo, J.M. and Gonzalez-Murua, C., 2004. Reducing losses of nitrous oxide from cattle slurry and mineral fertiliser applied to grassland by the use of DMPP. Proceedings of the 12th International Nitrogen Workshop, Exeter, UK, 21-24 September, 2003.

Van Groenigen, J.W., Velthof, G., Bolt, F., Vos, A. and Kuikman, P., 2005. Seasonal variation in N_2O emissions from urine patches: Effects of urine concentration, soil compaction and dung. Plant & Soil 273: 15-27.

Appendix B

Measure:	**Reduced N fertiliser application (other)**	
Gas(es) involved	N_2O, CO_2	
Enterprises involved	dairy, suckler beef, sheep	
Brief explanation of abatement mechanism:		

This measure encompasses all farm interventions that result in more efficient use of nitrogen fertiliser on grassland, other than improved manure management and the use of nitrification inhibitors, which are described in separate measures. It includes the use of clover, nutrient management planning and further improvements to the timing and application of fertiliser nitrogen. The potential abatement potential of each of these measures is difficult to quantify and project; moreover, many of these measures will interact with each other. As a result, it is particularly challenging to disaggregate these measures. However, all of these measures ultimately lead to the same outcome: a relative reduction in national N fertiliser usage figures.

The use of fertiliser N on grassland declined from *c.* 312 kt in 2005 to *c*. 270 kt in 2009 as a result of improvements in manure and nutrient management and higher fertiliser prices (DAFM; Lalor *et al*., 2010). This was followed by a reversal of this trend since 2009. Indeed, Donnellan *et al.* (2012) estimate that N usage will continue to rise to 327 kt by 2020 under the Food Harvest 2020 reference scenario, following the projected trends in commodity volumes.

Notwithstanding this overall increase in the absolute N fertiliser usage, there is some potential for further improvements in N-use efficiency, in other words: to further reduce N fertiliser usage rates per kg produce. It is very difficult to project the extent to which such improvements will mitigate against the projected rise in N usage. As a first-order approximation, this report assumes that together, these measures have the potential to reduce the projected 52 kt *increase* in fertiliser N usage by half, to 26 kt.

A reduction in fertiliser usage reduces GHG emissions by:
- reducing direct N_2O emission, associated with fertiliser application (3.1 kg CO_2eq per kg fertiliser N);
- reducing CO_2 emissions associated with the manufacturing of nitrogenous fertiliser (6.05 kg CO_2eq per kg fertiliser N – see section 2.4).

In the LCA methodology, both reductions are included. In the IPCC methodology, only direct emissions are included: the CO_2 emissions associated with fertiliser manufacturing cannot be accounted for in the National Emissions Inventory of Ireland, since this manufacturing takes place in other jurisdictions.

Biophysical constraints accounted for	N/A	
Interactions with other abatement measures accounted for	The abatement potential for this measure has accounted for the reduction in N fertiliser use resulting from improvements in manure management.	
Other potential environmental implications	Positive: - Reduced risk of nitrate leaching	Negative: - None

Appendix B

Methodology				
N fertiliser use	Current	275,560,000	kg N	Donnellan *et al.* (2012)
	FH2020	327,473,000	kg N	Donnellan *et al.* (2012)
	Target	301,516,500	kg N	Expert assessment
Relative costs		-1.113	€ kg^{-1} N reduced	Donnellan & Hanrahan (2012)
Abatement potential (LCA global)		0.238	Mt CO_2eq	
Abatement potential (IPCC)		0.080	Mt CO_2eq	
Cost		-28.9	M€	

References:

DAFM. Annual Fertilizer Sales Statistics. DAFM, Annually published data.

Donnellan, T. and Hanrahan, K., 2012. Greenhouse Gas Emissions by Irish Agriculture: Consequences arising from the Food Harvest Targets. Report produced for the Environmental Protection Agency. Agricultural Economics and Farm Surveys Department, Teagasc.

Donnellan, T., Hanrahan, K. and Lalor, S.T.J., 2012. Food Harvest 2020 and the demand for fertilizer. Proceedings of the Spring Scientific Meeting 2012 of the Fertilizer Association of Ireland, 7 February 2012.

Lalor, S.T.J., Coulter, B.S., Quinlan, G. and Connolly, L., 2010. A survey of fertiliser use in Ireland from 2004-2008 for grassland and arable crops. Teagasc, Johnstown Castle, Wexford. 89pp.

Appendix B

Measure:	**Minimum Tillage**
Gas(es) involved	N_2O, CO_2
Enterprises involved	Tillage

Brief explanation of abatement mechanism:

In general, arable soils are a CO_2 source. Reducing tillage intensity typically increases storage of SOC relative to conventional till practices as these practices reduce soil erosion through the development of a litter layer, and also enhance aggregate stability in the soil that slows decomposition of organic matter by providing protection within soil aggregates (Six *et al.*, 2000). The SOC accumulation by minimum tillage was modelled into the future using the DNDC model and based on measurement values from Davis *et al.* (2010). This approach may underestimate actual sequestration with values for reduced tillage on sandy soils observed to be up to 20% higher (Davis *et al.*, 2010). However, the greatest source of uncertainty is inter-annual variation in sequestration activity which can result in 100% variation in sink strength activity from one year to the next. This variation is mainly driven by climate and soil type. Adoption of minimum tillage improves the water-holding capacity of the soil. This increases the proportion of water-filled pore space, which in turn increases nitrous oxide emissions (Abdallah *et al.*, in press). It is assumed that the change in C stocks will reach a new equilibrium in a 40-60 year time period. Under the IPCC scenario, C sequestration was removed, as Ireland chose not to ratify Article 3.4 of the Kyoto Protocol; as a result, sequestration arising from management changes cannot be counted towards targets. This results in a net emission from the system due to changes in the N_2O emission factor.

Cost savings arise principally from substantial reductions in fuel usage associated with switching from inversion ploughing to non-inversion techniques. Some of these reductions are offset by increased herbicide requirement and a one year-in-five yield penalty that can occur via grass weed infestation.

Biophysical constraints accounted for	The use of minimum tillage techniques is constrained to arable soils.	
Interactions with other abatement measures accounted for	N/A	
Other potential environmental implications	Positive: - Reduced SOC loss, reduced N leaching.	Negative: - Increased water holding capacity with higher associated N_2O emissions; - Greater potential for yield loss due to grass invasion; - Greater use of herbicides.

Methodology

Application of Minimum Tillage across cereal production: Note minuses indicate *NET EMISSIONS*			Reference
Change in soil organic carbon per hectare	0.77	t CO_2eq ha^{-1} yr^{-1}	Davis *et al.* (2010)
Change in N_2O emissions	-0.1	t CO_2eq ha^{-1} yr^{-1}	Abdallah *et al.* (2012, in press)
Net Abatement (LCA)	0.67 t CO_2eq ha^{-1} yr^{-1}		
Net Abatement (IPCC)	0.10 t CO_2eq ha^{-1} yr^{-1}		
Applicable Area (2020 projections)	220,400	ha	Donnellan & Hanrahan

			(2012)
Total Abatement Potential (LCA)	0.148	Mt CO_2eq	
Total Abatement Potential (IPCC)	-0.02	Mt CO_2eq	
Relative Costs	-29.20	€ ha^{-1}	Forristal (2010)
Total Costs	-43.58	M€	

References:

Abdallah, M., Hastings, A., Lanigan, G.J., Forristal, D., Osborne, B.A.,Smith P. and Jones, M.B., 2012. Assessing the effectiveness of reduced tillage and cover crop management for mitigating greenhouse gas emissions under present and future climates. Agriculture & Forest Meteorology (in press).

Davis P.A., Clifton Brown J., Saunders M., Lanigan G., Burke J., Connolly J., Jones M.B. and Osborne B., 2010. Assessing the effects of agricultural management practices on carbon fluxes: Spatial variation and the need for replicated estimates of Net Ecosystem Exchange. Agricultural and Forest Meteorology 150 (2010) 564–574

Donnellan, T. and Hanrahan, K., 2012. Greenhouse Gas Emissions by Irish Agriculture: Consequences arising from the Food Harvest Targets. Report produced for the Environmental Protection Agency. Agricultural Economics and Farm Surveys Department, Teagasc.

Forristal P.D., 2011. Machinery - Controlling your largest cost. In: Proceedings of the national tillage conference 2011 Teagasc Carlow, 19-35.

Six, J., Elliott, E.T. and Paustian, K., 2000. Soil macroaggregate turnover and microaggregate formation: a mechanism for C sequestration under no-tillage agriculture. Soil Biology and Biochem.istry 32, pp. 2099–2103.

Appendix B

Measure:	**Cover Crops**
Gas(es) involved	N_2O, CO_2
Enterprises involved	Tillage

Brief explanation of abatement mechanism:

The principal loss pathway for carbon within a tillage system is the extended fallow period, during which time there is no uptake of CO_2, whilst ploughing affects the recalcitrant C pools (Willems *et al.*, 2011). Cover crops are traditionally used to reduce leached N emissions to groundwater during the fallow period. However, winter cover has also been observed to reduce net soil CO_2 emissions, due to the fact that there is net photosynthetic uptake of CO_2 by the cover crop (Ceschia *et al.*, 2010). The principle crop used is mustard (*Sinepsis alba*), due to the fact that it is fast growing and has good N uptake characteristics. The net change in annual GHG fluxes is 1.49 t CO_2 ha^{-1} yr^{-1}. This is due to both a reduction in C-loss (1 t CO_2 ha^{-1} yr^{-1}) and a reduction in indirect N_2O losses associated with reductions in leached N (0.49 t CO_2eq ha^{-1} yr^{-1}). As with minimum tillage, the greatest source of uncertainty is inter-annual variation in sequestration activity which can result in 100% variation in sink strength activity from one year to the next. Under the IPCC scenario, C-sequestration was removed, as Ireland chose not to ratify Article 3.4 of the Kyoto Protocol; as a result, sequestration arising from management changes cannot be counted towards targets. Therefore, only emission reductions associated with alterations in the indirect losses of N are counted. It should be noted that application of cover crops will principally be restricted to spring cereal crops. It is assumed that the change in C stocks will reach a new equilibrium in a 40-60 year time period. The costs involved include the purchase of seed and fuel costs associated with cultivation of the crop.

Biophysical constraints accounted for	Use of cover crops is constrained to spring cereals.	
Interactions with other abatement measures accounted for	None explicitly, but can be combined with minimum tillage practices	
Other potential environmental implications	Positive: - Reduced SOC loss, reduced N leaching	Negative: - Greater use of herbicide when killing off the crop in spring

Methodology

Application of Minimum Tillage across cereal production. Note minuses indicate *NET EMISSIONS*			Reference
Change in soil organic carbon per hectare	1	t CO_2eq ha^{-1} yr^{-1}	Ceschia *et al.* (2010)
Change in N_2O emissions	0.49	t CO_2eq ha^{-1} yr^{-1}	Kindler *et al.* (2010)
Net Abatement (LCA)	1.49	t CO_2eq ha^{-1} yr^{-1}	
Net Abatement (IPCC)	0.49	t CO_2eq ha^{-1} yr^{-1}	
Applicable Area	160,900	ha	Appendix A
Total Abatement Potential (LCA)	0.24	Mt CO_2eq	
Total Abatement Potential (IPCC)	0.08	Mt CO_2eq	
Relative Costs	71.20	€ ha^{-1}	O'Keeffe *et al*. (2005)

Total Costs	11.46	€ ha^{-1}
References: Augustenborg, C.A., Hepp, S., Lanigan, G..J., Hochstrasser, T., Kammann, C. and Müller, C., 2011. Carbon dioxide emissions from spring ploughing of grassland in Ireland. Agriculture, Ecosystems & Environment doi:10.1016/j.agee.2011.10.001 Ceschia, E. *et al.,* 2010. Management effects on net ecosystem carbon and GHG budgets at European crop sites. Agriculture, Ecosystems and Environment 139, 363–383. Kindler, R., Siemens, J., Kaiser, K. *et al*., 2011. Dissolved carbon leaching from soil is a crucial component of the net ecosystem carbon balance. Global Change Biology, 17, 1167–1185. O'Keeffe, E. , Hackett, R. and Schmidt, O., 2005 The use of winter cover crops in spring barley production systems in Ireland in Proceedings of the Agricultural Research Forum, Tullamore p60. Willems, A.B, Augustenborg, C.A., Hepp, S., Lanigan, G.J., Hochstrasser, T., Kammann, C. and Müller0, C., 2011. Carbon dioxide emissions from spring ploughing of grassland in Ireland. Agriculture, Ecosystems & Environment doi:10.1016/j.agee.2011.10.001.		

Appendix B

Measure:	**Willow and *Miscanthus* for the production of electricity**
Gas(es) involved	N_2O, CO_2
Enterprises involved	Beef production

Brief explanation of abatement mechanism:

The production and use of willow and *Miscanthus* crops for electricity production will (partially) substitute imports of fossil fuels and hence fossil CO_2 emissions. Direct GHG emissions associated with the production of these crops are accounted for in the calculation of their abatement potential.

An average farm model was constructed following the example of Casey & Holden (2004) and based on Styles & Jones (2007). All relevant inputs to the system and induced processes (e.g. soil N_2O emissions) were then considered in a life cycle inventory up to the point of the farm gate. All major inputs and sinks of the major greenhouse gases (GHGs), CO_2, CH_4 and N_2O were considered. Willow life cycle assumptions have been described in the appendix on the production of willow for heat.
The first stage of ground preparation for *Miscanthus* cultivation includes herbicide application followed by subsoiling and ploughing. Rhizomes are planted in the spring following rotavation, ridging and pick-up of 3 year old *Miscanthus* rhizomes, where 1 ha supplied rhizomes to plant 10 ha at 20,000 rhizomes ha^{-1} at a total energy intensity of 4,000 MJ ha^{-1} (Bullard & Metcalf, 2001). Herbicide application was assumed to consist of two pre-planting applications, one application in each of the first three years and thereafter every two years, two herbicide applications were assumed to be necessary to remove the crop. It was assumed that no fertiliser was used in the first two years and in the last year. N requirements for Miscanthus were defined by Plunkett (2010) to vary between 30kg N ha^{-1} and 100 kg N ha^{-1}, depending on soil nutrient status. In contrast, Clifton Brown *et al.* (2007) suggested that nitrogen offtakes from a Miscanthus crop grown on former grassland in Co. Tipperary could be met by a combination of soil reserves and atmospheric deposition. For this study, we assumed that nitrogen fertilization was necessary to replace crop offtakes and that nitrogen fertilization rates ranged from 50 kg N ha^{-1} to 100 kg N ha^{-1} with a mid-point of 75 kg N ha^{-1}, which was used in this study.

Gross GHG abatement from the substitution of fuels for electricity were based on fossil fuel replacement and the emission factors used by the Environmental Protection Agency in their 2011 inventory report. Net GHG abatement was calculated by substracting the GHG footprint of willow /miscanthus production from gross GHG abatement. The cost of this measure was calculated using returns for willow/miscanthus production produced by Thorne (2011), converted to 2020 figures.

Yields of 10 tonnes DM ha^{-1} yr^{-1} for both crops were assumed. It was assumed that 1/3 of the energy crop requirement for electricity generation would come from *Miscanthus* and the remainder from willow.

Biophysical constraints accounted for	It was assumed that willow and *Miscanthus* production for electricity (15,000ha) would take place on land previously used for beef production. However, it was assumed that willow and *Miscanthus* production would not affect beef production as beef production would be maintained by increasing stock density as stock densities on beef farms are low.

Interactions with other abatement measures accounted for	N/A	
Other potential environmental implications	Positive: - Potential use of willow as buffer strips to reduce nutrient and sediment loss through overland flow	Negative: - None

Methodology			
Relative costs	-€213	€ ha^{-1}	Thorne (2011)
Abatement potential (LCA global)	0.281	Mt CO$_2$eq	
Abatement potential (IPCC)	0.298	Mt CO$_2$eq	
Cost	-€3.19	M€	

References:

Bullard, M. and Metcalf, P., 2001. Estimating the Energy Requirements and CO$_2$ Emissions of the Perennial Grasses *Miscanthus*, Switchgrass and Reed Canary Grass. Energy Technology Support Unit, Harwell, UK.

Casey, J.W. and Holden, N., 2004. Analysis of greenhouse gas emissions from the average Irish milk production system. Agricultural Systems 86, 97-114.

Clifton-Brown, J.C., Bruer, J. and Jones, M.B., 2007. Carbon mitigation by the energy crop, *Miscanthus*. Global Change Biology, 13, 1-12.

Dawson, M., 2007. Short rotation coppice willow best practice guidelines. RENEW project. ISBN 0-948870-07-9.

Duffy, P., Hyde B., Hanley, E., Dore, C., O’ Brien, P., Cotter, E. and Black, K., 2012. Ireland, National Inventory Report 2011. Greenhouse gas emissions 1990-2009 reported to the United Nations Framework Convention on Climate Change. Environmental protection Agency, Johnstown Castle, Wexford. http://erc.epa.ie/ghg/nirs/NIR_2011_IE_v2.1.pdf.

Plunkett, M., 2010. Application of sewage sludges and biosolids to energy crops.In‘*Energy Crops Manual 2010* (eds. B. Caslin & J. Finnan) 27-31. Teagasc, Oak Park, Carlow, Ireland.

Styles, D. and Jones, M., 2007. Energy crops in Ireland: Quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. Biomass and Bioenergy 31, 759-772.

Thorne, F., 2011. An economic analysis of the returns from biomass crops compared to conventional agriculture. Internal Teagasc document.

Appendix B

Measure:	**Willow for the production of heat**	
Gas(es) involved	N_2O, CO_2	
Enterprises involved	Beef production	
Brief explanation of abatement mechanism:		
The production and use of willow crops for heat production will (partially) substitute imports of fossil fuels and hence fossil CO_2 emissions. Direct GHG emissions associated with the production of this crop are accounted for in the calculation of its abatement potential. An average farm model was constructed following the example of Casey & Holden (2004) and based on Styles & Jones (2007). All relevant inputs to the system and induced processes (e.g. soil N_2O emissions) were then considered in a life cycle inventory up to the point of the farm gate. All major inputs and sinks of the major greenhouse gases (CO_2, CH_4 and N_2O) were considered. It was assumed that willow planting is preceded by two herbicide applications, subsoiling, ploughing and tilling. Coppicing (cut-back) in year 1 and each subsequent harvest (with the exception of the last harvest) is followed by a herbicide application and by fertilization. The last harvest is succeeded by two herbicide applications to kill the crop and ploughing to remove the crop. Fertilization rates up to 120-150 kg nitrogen, 15-40 kg phosphorus and 40 kg potassium per hectare per year have been suggested by Dawson (2007). Plunkett (2010) suggested nutrient application rates of 40-130 kg N ha^{-1} yr^{-1}, 0-34 kg P ha^{-1} yr^{-1} and 0-155 kg K ha^{-1} yr^{-1}, depending on the nutrient levels in the soil. For this study, it was assumed that fertilization of willow is necessary to replace crop offtakes and that nitrogen fertilization rates ranged from 50kg N ha^{-1} yr^{-1} to 130 kg N ha^{-1} yr^{-1} with a mid-point of 90kg N ha^{-1} yr^{-1}. Herbicide application was assumed to comprise of two pre-planting applications, followed by a post cut-back application and an application after each harvest, one additional application was considered necessary to remove the crop. Average yields of 10 tonnes of dry matter per hectare were assumed. Gross GHG abatement from the substitution of fuels for heat (kerosene) was based on fossil fuel replacement and the emission factors used by the Environmental Protection Agency in their 2011 inventory report. Net GHG abatement was calculated by substracting the GHG footprint of willow production from gross GHG abatement. The cost of this measure was calculated using returns for willow production produced by Thorne (2011), converted to 2020 figures.		
Biophysical constraints accounted for	It was assumed that willow production for heat (35,000 ha) would take place on land previously used for beef production. However, it was assumed that willow production would not affect beef production as beef production would be maintained by increasing stock density as stock densities on beef farms are low. Yields of 10 tonnes DM ha^{-1} yr^{-1} were assumed.	
Interactions with other abatement measures accounted for	N/A	
Other potential environmental implications	Positive: - Potential use of willow as buffer strips to reduce nutrient and sediment loss through overland flow	Negative: - None

Appendix B

Methodology			
Relative costs	-€195	€ ha^{-1}	Thorne (2011)
Abatement potential (LCA global)	0.376	Mt CO_2eq	
Abatement potential (IPCC)	0.419	Mt CO_2eq	
Cost	-€6.825	M€	

References:

Casey, J.W., Holden, N., 2004. Analysis of greenhouse gas emissions from the average Irish milk production system. Agricultural Systems 86, 97-114.

Dawson, M., 2007. Short rotation coppice willow best practice guidelines. RENEW project. ISBN 0-948870-07-9.

Duffy, P., Hyde B., Hanley, E., Dore, C., O' Brien, P., Cotter, E. and Black, K., 2012. Ireland, National Inventory Report 2011. Greenhouse gas emissions 1990-2009 reported to the United Nations Framework Convention on Climate Change. Environmental protection Agency, Johnstown Castle, Wexford. http://erc.epa.ie/ghg/nirs/NIR_2011_IE_v2.1.pdf.

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Styles, D. and Jones, M., 2007. Energy crops in Ireland: Quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. Biomass and Bioenergy 31, 759-772.

Thorne, F., 2011. An economic analysis of the returns from biomass crops compared to conventional agriculture. Internal Teagasc document.

Appendix B

Measure:	**Oilseed Rape for biodiesel**
Gas(es) involved	N_2O, CO_2
Enterprises involved	Tillage

Brief explanation of abatement mechanism:

The production and use of oil seed rape for use as biodiesel will (partially) substitute imports of fossil fuels and hence fossil CO_2 emissions. Where direct GHG emissions associated with the production of this crop are different from the direct emissions associated with previously grown crops, these differences are accounted for in the calculation of its abatement potential.

An average farm model was constructed following the example of Casey & Holden (2004) and based on Styles & Jones (2007). All relevant inputs to the system and induced processes (e.g. soil N_2O emissions) were then considered in a life cycle inventory up to the point of the farm gate. All major inputs and sinks of the major greenhouse gases (CO_2, CH_4 and N_2O) were considered. It was assumed that oilseed rape would be grown on farms as a break crop. Agronomic operations were assumed to consist of ploughing, tilling, sowing, rolling, spraying, applying fertiliser and harvesting. It was assumed that the oilseed rape area is divided into spring oilseed rape and winter oilseed rape and that spring oilseed rape accounts for 1/3 of the total area. Seed rates, pesticide inputs and the timings of pesticide and fertiliser applications were taken from Hackett *et al.* (2006). It was assumed that winter crops would receive an autumn herbicide, two sprays of fungicide/insecticide, one spray of boron and a dessicant spray prior to harvest. Nitrogen fertilization of winter oilseed rape is limited to a maximum rate of 225 kg N ha^{-1} by Statutory Instrument No 610 of 2010 (Good Agricultural Practice for the Protection of Waters Regulations). Fertiliser use data on winter oilseed rape is not available. It was therefore decided to use an application rate of 180 kg N ha^{-1} for winter crops and 125 kg N ha^{-1} for spring crops; these levels correspond to the nitrogen recommendations of Hackett *et al.* (2006). The corresponding rates of phosphorus and potassium recommended by Hackett *et al.* (2006) were also used. It was assumed that winter crops would receive 35 kg S ha^{-1} and 3 kg B ha^{-1} and that spring crops would receive 20 kg S ha^{-1} (Hackett *et al.*, 2006) and that all crops would receive 3 tonnes of lime per hectare once every five years. While the central statistics office publishes annual data on oilseed rape yields, the yields are an average of those obtained from winter oilseed rape and spring oilseed rape. Data from the CSO (Area, Yield and Production of Crops, 2010) give average oilseed rape yields for 2008, 2009 and 2010 of 3.6, 3.7 and 3.5 t ha^{-1} with an average of 3.6 t ha^{-1}; this figure was used in this study. After harvest, it was assumed that the oilseed rape straw was collected and baled for energy use, straw yields were taken from El-sayed *et al.* (2003). The calorific value of rapestraw was taken from Keppel (2010).

Gross GHG abatement from the substitution of fuels for heat, transport and electricity were based on fossil fuel replacement and the emission factors used by the Environmental Protection Agency in their 2011 inventory report. Net GHG abatement was calculated by subtracting the GHG footprint of imported spring barley feed as well as the difference in cultivation emissions between spring barley and oilseed rape from gross GHG abatement. The cost of this measure was calculated using Teagasc costs and returns for oilseed rape and spring barley production from 2009, 2010 and 2011 (O'Mahony, 2009; O'Mahony, 2010; O'Donovan, 2011), data from these three years were converted to 2020 figures.

Biophysical constraints	It was assumed that the land needed to produce oilseed rape for

accounted for	biodiesel and pure plant oil production would come from the existing tillage base and replace spring barley currently used for animal feed production. The realistic scenario for oilseed rape is based on the production of oilseed for a biodiesel plant with a capacity of 30,000 tonnes annually.
Interactions with other abatement measures accounted for	There may be interaction between this measure and (1) the production of winter wheat for bioethanol production (2) the production of sugar beet for bioethanol production It is possible that there may be some competition between these three measures. However, both sugar beet and oilseed rape are break crops which should complement winter wheat production.

Other potential environmental implications	Positive: - not applicable	Negative: - not applicable

Methodology			
Relative costs	-€52.78	€ ha^{-1}	See above
Abatement potential (LCA global)	0.112	Mt CO_2eq	
Abatement potential (IPCC)	0.174	Mt CO_2eq	
Cost	-€1.25	M€	

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Appendix B

Measure:	**Winter Wheat for bioethanol production**
Gas(es) involved	N_2O, CO_2
Enterprises involved	Tillage
Brief explanation of abatement mechanism:	

The production and use of winter wheat for the production of bioethanol will (partially) substitute imports of fossil fuels and hence fossil CO_2 emissions. Where direct GHG emissions associated with the production of this crop are different from the direct emissions associated with previously grown crops, these differences are accounted for in the calculation of its abatement potential.

An average farm model was constructed following the example of Casey & Holden (2004) and based on Styles & Jones (2007). All relevant inputs to the system and induced processes (e.g. soil N_2O emissions) were then considered in a life cycle inventory up to the point of the farm gate. All major inputs and sinks of the major greenhouse gases (CO_2, CH_4 and N_2O) were considered. Inventory mass balances were summed and converted into a final Global Warming Potential (GWP) expressed as kg CO_2eq and considered over a 100 year timescale, according to IPCC guidelines. LCA outputs were calculated and expressed as kg CO_2 eq per hectare of land and per year. Fertiliser application rates of 180 kg N ha^{-1}, 19 kg P ha^{-1} and 52 kg K ha^{-1} were taken from Lalor *et al.* (2010). Additionally, it was assumed that crops would receive 20 kg S ha^{-1} and 3 tonnes of line per hectare once every five years. It was assumed that crops would receive one herbicide application, one insecticide application, three fungicide applications and a growth regulator application. Average winter wheat yields were taken from the CSO (Area, yield and Production of Crops, 2010). After harvest, it was assumed that the straw would be baled and available for energy use whereas it was assumed that the straw from winter wheat for feed production was previously shredded.

Gross GHG abatement from the substitution of fuels for heat, transport and electricity were based on fossil fuel replacement and the emission factors used by the Environmental Protection Agency in their 2011 inventory report. Net GHG abatement for the full LCA was calculated by substracting the GHG footprint of imported winter wheat feed and the difference in cultivation emissions from gross GHG abatement.

The cost of this measure was calculated using Teagasc costs and returns for winter wheat production from 2009, 2010 and 2011 (O'Mahony, 2009; O'Mahony, 2010; O'Donovan, 2011); data from these three years were converted to 2020 figures.

Biophysical constraints accounted for	It was assumed that the land needed to produce winter wheat for bioethanol would come from the existing tillage base and replace winter wheat currently used for animal feed production. The scenarios used for the production of bioethanol from winter what was based on the assumption that the minimum viable size of plant is 100 million litres, the corresponding realistic areas of winter wheat (29,952 ha) is the area of this crop required to supply such a plant. It was assumed that 3.5 tonnes of fresh grain at 16% moisture would be needed to produce 1 tonne of bioethanol (1,266 litres) (El-Sayed, 2003).

Interactions with other abatement measures accounted for	There may be some interaction between this measure and (1) the production of sugar beet for bioethanol production (2) the production of oilseed rape for biodiesel/pure plant oil production However, these two crops are break crops which complement and enhance the production of other cereal crops. Consequently, these two abatement measures may well complement the production of winter wheat for bioethanol production.		
Other potential environmental implications	Positive: - not applicable	Negative: - not applicable	
Methodology			
Relative costs	-€11.2	€ ha^{-1}	See above
Abatement potential (LCA global)	0.223	Mt CO_2eq	
Abatement potential (IPCC)	0.318	Mt CO_2eq	
Cost	-€0.33	M€	

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Casey, J.W. and Holden, N., 2004. Analysis of greenhouse gas emissions from the average Irish milk production system. Agricultural Systems 86, 97-114.

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Appendix B

Measure:	**Sugar Beet for bioethanol production**
Gas(es) involved	N_2O, CO_2
Enterprises involved	Tillage
Brief explanation of abatement mechanism:	
The production and use of sugar beet for the production of bioethanol will (partially) substitute imports of fossil fuels and hence fossil CO_2 emissions. Where direct GHG emissions associated with the production of this crop are different from the direct emissions associated with previously grown crops, these differences are accounted for in the calculation of its abatement potential. An average farm model was constructed following the example of Casey & Holden (2004) and based on Styles & Jones (2007). All relevant inputs to the system and induced processes (eg soil N_2O emissions) were then considered in a life cycle inventory up to the point of the farm gate. All major inputs and sinks of the major greenhouse gases (CO_2, CH_4 and N_2O) were considered. It was assumed the sugar beet would be grown on tillage farms as a break crop. Agronomic operations comprised ploughing, tilling sowing, rolling, fertilization, spraying and harvesting. All sugar beet crops were assumed to receive three herbicides, and either an insecticide or a fungicide (four sprays in total) during the growing season. Nitrogen fertilization of sugar beet is limited to a maximum rate of 195 kg N ha^{-1} by Statutory Instrument No 610 of 2010 (Good Agricultural Practice for the Protection of Waters Regulations). A fertiliser use survey conducted in 2000 showed that sugar beet crops in Ireland received an average of 159 kg N ha^{-1}, 43 kg P ha^{-1} and 157 kg K ha^{-1} (Coulter *et al.*, 2002). These fertiliser rates were used in this study. Additionally, crops were assumed to receive 20 kg S ha^{-1} and 3 kg B ha^{-1}. (Coulter and Lalor, 2008) and three tonnes of lime per hectare once every five years. Annual average fresh yields of clean sugar beet were provided by the Central Statistics Office up until 2005. Yields over the period 2000 until 2005 ranged from 42 t ha^{-1} to 60 t ha^{-1}. The average beet yield used in this study was 50t ha^{-1} of clean beet. Gross GHG abatement from the substitution of fuels for heat, transport and electricity were based on fossil fuel replacement and the emission factors used by the Environmental Protection Agency in their 2011 inventory report. Net GHG abatement for the full LCA was calculated by substracting the GHG footprint of imported spring barley feed, as well as the difference in cultivation emissions between spring barley and sugar beet from gross GHG abatement. The cost of this measure was calculated using Teagasc costs and returns for sugar beet and spring barley production from 2009, 2010 and 2011 (O'Mahony, 2009; O'Mahony, 2010; O'Donovan, 2011), data from these three years were converted to 2020 figures.	
Biophysical constraints accounted for	It was assumed that the land needed to produce sugar beet for bioethanol would come from the existing tillage base and replace spring barley currently used for animal feed production. The scenarios used for the production of bioethanol from sugar beet was based on the assumption that the minimum viable size of plant is 100 million litres, the corresponding realistic areas of sugar beet (20,316ha) is the area of this crops required to supply such a plant It was assumed that 12.86 tonnes of clean sugar beet were needed to produce 1 tonne of bioethanol (1,266 litres) (El-Sayed *et al.*, 2003).

Interactions with other abatement measures accounted for	There may be some interaction between this measure and (3) the production of winter wheat for bioethanol production (4) the production of oilseed rape for biodiesel/pure plant oil production It is possible that there may be some competition between these three measures. However, both sugar beet and oilseed rape are break crops which should complement winter wheat production.		
Other potential environmental implications	Positive: - not applicable	Negative: - late harvesting of sugar beet may increases risk of soil compaction, degradation and loss of sediment and nutrients through overland flow, if adverse weather conditions prevail before, during or immediately after harvesting.	
Methodology			
Relative costs	€175.9	€ ha^{-1}	See above
Abatement potential (LCA global)	0.093	Mt CO_2eq	
Abatement potential (IPCC)	0.147	Mt CO_2eq	
Cost	€3.57	M€	

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Appendix B

Measure:	**Anaerobic digestion (pig slurry)**	
Gas(es) involved	CH_4, CO_2	
Enterprises involved	Pigs	
Brief explanation of abatement mechanism:		
This abatement measure involves using pig slurry in combination with grass silage in an anaerobic digester to convert methane to energy based on a study carried out by Nolan *et al*. (2012). A study by Xie *et al.* (2011) demonstrated the potential for co-digestion pig manure with grass silage. They recommended a ratio for commercial application of 1:1 on a volatile solids basis. The results from this study have been used in the modelling exercise presented in this study with the specific methane yield of 302 ml g^{-1} VS, which was reduced by 15%, based on the results of Blokhina *et al*. (2011). Energy efficiency for the combined heat and power plants was assumed to be 30% for electricity and 50% for heat (NNFCC, 2010), which are comparable with international research. The plant's electrical consumption (parasitic electricity demand of the biogas plant) was based on the energy required per tonne of feedstock fed to the digester. It was assumed that 6.0 and 5.4 KWh are required per tonne of grass silage and pig manure fed respectively (P. Frost, pers. comm.). The daily parasitic heat demand was calculated according to Ludeuvice (2001), as the sum of the heat required to heat the feedstock to 35 degrees with the ambient temperature taken at 9 degrees, with heat loss from the digester taken into account. In the analysis, all of the investment costs were included, i.e. both the construction of a plant and connection to the grid as well as the maintenance and the labour costs, with the finance costs carried out over a 15 year period.		
Biophysical constraints accounted for	It was assumed that anaerobic digestion of pig slurry is not feasible on small pig units (<250 sows). Nationally, these account for 41% of pig units, or 11% of sows.	
Interactions with other abatement measures accounted for	Pig manure has been taken into account in this analysis. The benefit achieved here is from the reduction in the electricity that is produced in a standard form. The emissions associated with standard electricity production mechanisms are reduced. In terms of the addition of grass silage, it is expected that any feedback to other mitigation measures (through availability of silage) will be negligible and non-significant.	
Other potential environmental implications	Positive: - Reduced slurry volumes may increase flexibility of export of pig manure to suitable recipients.	Negative: - None

Methodology				
Anaerobic digestion (pig slurry)				Reference
	Current	n.s.		
	FH2020	n.s.		
	Target	59% of units = 89% of sows		Pig Sys Dataset, 2008
Relative costs		157	€ t^{-1} CO_2eq	Nolan *et al*. (2012)
Abatement potential (LCA global)		0.188	Mt CO_2eq	
Abatement potential (IPCC)		0.188	Mt CO_2eq	
Cost		23.1	M€	
References:				

Appendix B

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