Greenhouse gas research highlights

Teagasc

Agriculture and Food Development Authority

The way forward

The agri-food sector accounts for over half of Ireland's indigenous exports and represents one-tenth of the Irish economy. Indeed, the wider bio-economy contributes an estimated 30% of total national net exports, and in 2008 accounted for 179,200 jobs.

Agriculture also comprises a quarter of national greenhouse gas (GHG) emissions, which contribute to climate change. As such, reducing emissions from the sector is often considered as a strategy to meet our emission reduction targets. However, world food security has emerged as a critical global challenge. This sets a significant challenge for Teagasc and its national and international collaborators – namely, reducing emissions while increasing food supply. Delivering this will ensure that the Irish agri-food sector can and will play a key strategic role in our economic recovery, while achieving our legally binding emission reduction targets. In addition, these challenges can provide the opportunities to drive efficiencies that will ultimately reduce costs and drive profitability in the sector.

Teagasc recognises both the scale and the urgency of the challenge presented by climate change legislation. Since 2005, the organisation has been engaged in a large programme of research across all centres comprising 14 projects and almost four million Euro in order to elucidate the potential of some of these future mitigation options. Recognising the large body of cross-centre research, the Climate Change Working Group was established in 2009 to co-ordinate research and dissemination. Already, the group has been crucial to providing policy advice for the Cabinet Committee on Climate Change and liaising with other reports on agricultural emissions. Into the future, Teagasc will co-lead a pan-European project studying livestock abatement strategies.

Any proposed reductions in GHG emissions from farming must be considered in a world-wide context. Global emissions from the sector have risen by 17% between 1990 and 2008, with a larger increase (32%) for Non-Annex 1 countries. In contrast, Irish agricultural emissions have fallen by 8% over the same time period. As a consequence, any policies that reduce agricultural activity in countries with a high production/GHG quotient, such as Ireland, in a time of increased demand for food and renewable energy sources, are likely to be counter-productive in the context of reducing global GHGs. Indeed, in order to optimise global agricultural emissions abatement, food production should be focused as far as possible in those countries where GHG emissions per unit product are lowest, and existing agricultural land should be used to the maximum before new land is brought into production through deforestation.

The way forward for agriculture will be to maximise the amount of produce per unit GHG emitted. Already, this has been recognised in the retail sector and there is a market-driven demand for thorough and accurate life-cycle assessment of all agricultural practices. Part of the challenge for Teagasc will be to provide not only an accurate greenhouse gas-based analysis, but also a full sustainability index incorporating the requirements of other directives. It has been demonstrated that the application of best management practices can provide opportunities to reduce emissions while optimising production efficiency, both in terms of maximising output per livestock unit and minimising inputs, notably N fertilisers. The identification of further 'best practice' strategies is urgent, not only for meeting emissions targets, but in optimising resources and reducing costs.

Future challenges must also include the assessment of climate change impacts and climate adaptation on agricultural production. Climate adaptation will potentially touch on every aspect of the industry, but will also provide opportunities, as climate impacts on Irish agricultural production are forecast to be relatively small compared to other countries. However, the sector must be prepared and research into areas such as future pest control and the opportunities provided by longer growing seasons will be vital.

In conclusion, global food demand has risen considerably over the last 20 years and the long-term outlook for agricultural commodity markets is positive. Climate change legislation poses challenges, which ultimately may provide the opportunities to drive efficiencies that will ultimately reduce costs and drive profitability in the sector. This booklet presents an insight into the diversity of Teagasc's current research activities into reducing agricultural emissions through increased efficiency. This programme of research provides a key-pillar to the mosaic of solutions and actions required to further enhance the sustainability of Irish agriculture.

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Published by
Teagasc, Head Office, Oak Park, Carlow
2010

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All articles included in this publication were originally published in TResearch, *an official science publication of Teagasc.*

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Climate change and agriculture

FRANK O'MARA discusses the challenges facing Irish agriculture and the progress made to date in reducing greenhouse gas emissions from agriculture.

Introduction

Climate change has been identified as the most significant and threatening global environmental problem facing humanity today. There is an almost universal global consensus that significant cuts in global greenhouse gas (GHG) emissions are needed over the next century in order to stabilise concentrations of GHG in the atmosphere at twice the pre-industrial level. The Kyoto Protocol was the first major international agreement to reduce emissions. Under it, the EU agreed to an 8% reduction by 2012 and, as part of the EU target, Ireland has agreed to limit the growth in GHG emissions to 13% above 1990 levels by 2012. More recently, the 2008 December Council meeting of EU leaders agreed to a further reduction in GHG of 20% by 2020 compared to 1990, or 30% if a new global agreement is reached.

The main GHG in Ireland is carbon dioxide (CO_2), mainly arising from the burning of fossil fuel in transport, heating and electricity generation. Irish emissions of other GHGs, including methane (CH_4) and nitrous oxide (N_2O), are proportionately higher than most other developed countries. Agriculture is the main source of these, and the goal of reducing their emissions presents a major challenge for the agriculture sector. However, there are also opportunities, and growing biomass crops as a source of energy is an example.

Agriculture accounted for 26.8% of total Irish GHG emissions in 2007, down from 35% in 1990. In an international context, Ireland's profile of emissions is unusual in the developed world (**Figure 1**). New Zealand is the only developed country with a higher proportion of emissions from agriculture than Ireland, and the EU average is substantially below our level. This is due to the importance of agriculture in our economy. Over 50% of agricultural emissions are CH_4 from enteric fermentation, and most of the remainder is N_2O released from soils.

Agricultural emissions have decreased by 1.36m tonnes CO_2 since 1990, or 6.8%. The 2007 provisional data represents a 3.8% reduction on 2006 for the agriculture sector (**Figure 2**). This is accounted for by a drop in cattle numbers of 3.1%, a drop in sheep numbers of 7.6%, and a drop in N fertiliser use of 4.1%.

Recent projections from Teagasc's economic forecasting unit, FAPRI Ireland, suggest that agricultural emissions will decrease by 8.5% from 2005 to 2020. This is mainly due to a forecast drop in suckler cow numbers, as FAPRI analysis indicates that dairy cow numbers will increase to 1.2m by 2020.

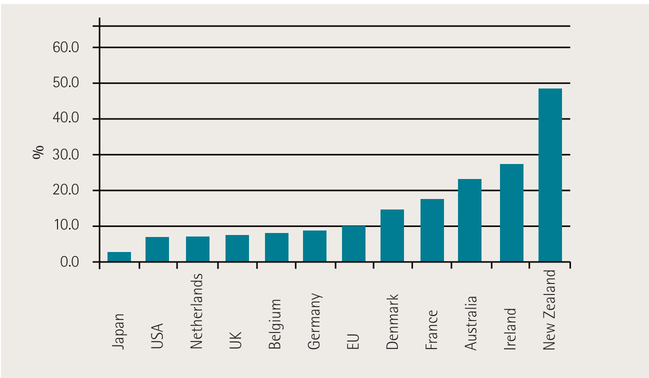

FIGURE 1: Emissions from agriculture as a percentage of total national emissions in various countries worldwide (source: UNFCCC).

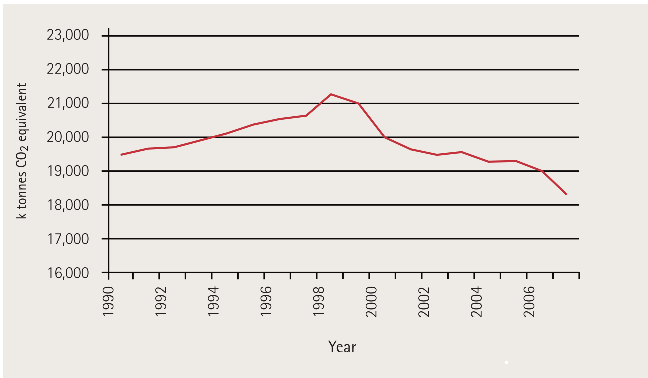

FIGURE 2: Trend in tonnes CO_2 equivalent from agriculture (1990 - 2007) (source: EPA, 2008).

Challenges for reducing emissions:

- food security will require an increase in food production;
- reducing emissions in Ireland by reducing food production will cause 'leakage' of emissions to whatever country increases production;
- gaining credits for afforestation and biomass production for bioenergy is problematic;
- there are economic, social and moral implications of reducing the livestock herd; and,
- new technical solutions require a sustained research effort.

Progress to date

Significant progress has been made over the past number of years in reducing GHG emissions from agriculture. For example, improved nutrient management has led to a 35% reduction in N fertiliser use in the last 10 years, equivalent to a reduction of over 0.5m tonnes per annum of CO_2 equivalent. We will continue to seek maximum efficiency of nutrient use in research and advisory programmes, ensuring that this trend continues.

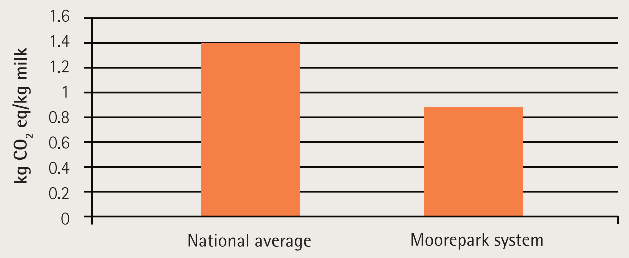

FIGURE 3: GHG emissions per kg of milk using average production data from the National Farm Survey or production data from Moorepark (Lovett *et al.*, 2008).

Decoupling milk production from greenhouse gas emissions

With the relaxation of milk quotas prior to their elimination in 2015, Ireland will have the opportunity to expand milk production significantly. If this is to happen without a serious impact on GHG emissions, then milk production needs to be decoupled from GHG emissions. Evidence to date suggests that this is possible. Technological advances in dairy production have led to a drop of 12.4% in the amount of methane produced per kg of milk between 1990 and 2006, thereby demonstrating the relationship between greater efficiency and reduced emissions. A recent study (Lovett *et al.*, 2008) indicated that while average emissions on Irish dairy farms were 1.385kg CO_2 equivalent per kg of milk produced, this figure could be reduced to less than 0.9kg by using best technology in a grass-based system (**Figure 3**). There is an urgent need to bring the national average towards this figure, and Teagasc will prioritise this in its dairy research and advisory programme. Efficient rearing of cattle leads to earlier slaughter and lower lifetime GHG emissions. Over the period since 1990, the age of slaughter of beef cattle has been significantly reduced. In 1990, 44% of male cattle were over 30 months of age at time of slaughter; this was reduced to 15% in 2006 resulting in significant reductions in GHG emissions. Teagasc now has a significant research programme aimed at reducing GHG emissions from agriculture and assessing the opportunities for carbon sequestration. The strategies being investigated for CH_4 mitigation include dietary modifications, additives or probiotics to reduce CH_4 production, breed selection, increasing the length of the grazing season, and improved pasture quality. The breeding of more efficient animals producing more product from a given amount of feed, and thus having less emissions per kg of milk or meat produced, is very important. This requires a lot of basic science to understand the physiological and genetic factors controlling digestion and microbial processes, and emissions of CH_4 from the rumen.

N_2O is produced from soils as part of the N cycle, and is a significant source of GHG. Technologies being researched by Teagasc to minimise its release from soils include optimising the application of organic and inorganic sources of fertiliser to further reduce N fertiliser usage and emissions, the application of nitrification inhibitors (e.g., DCD) and other fertiliser technologies, the more efficient use of clover as a source of N, and reducing the load of N excreted onto pasture.

Table 1: Potential greenhouse gas mitigation from crops.

Biofuels	270,000t CO_2
Electricity	830,000t CO_2
Heat	1,700,000t CO_2
C sequestration	50,000t CO_2
Total	**2.85MT CO_2**

Other abatement strategies

Crops production for energy can make a significant impact on mitigating GHG emissions (**Table 1**). Biofuel production is possible up to a maximum of perhaps 270,000 tonnes CO_2 equivalent, which would equate with our national 2% biofuel target. The development of one or two first generation ethanol plants would also pave the way for the second generation, by establishing a logistics infrastructure, process expertise and markets for the produce. Growing energy crops to meet the government co-firing target would mitigate approximately 830,000 tonnes of CO_2 if the target is to be supplied by energy crops exclusively. Energy crops, particularly willow, can also contribute to government heat targets (12% renewable heat by 2020). The GHG mitigation potential of using energy crops for heat depends on the acreage used for this purpose in addition to the types of fuels replaced, but could amount to up to 1.7MT CO_2 equivalent. The anaerobic digestion of agricultural waste mixed with energy crops or other organic waste also has potential. However, obstacles include the high capital cost of the equipment together with the high cost of grid connection.

Conclusions

Teagasc has an extensive research programme dealing with minimising emissions from agriculture and also with the policy issues and financial consequences of climate change and GHG mitigation. The goal of reducing GHG emissions presents a major challenge for the agricultural sector. If milk production is to expand without impacting on emissions, then it must be decoupled from emissions, which will require a big effort to improve efficiency. However, reducing emissions also presents opportunities, and growing biomass crops as a source of energy is an example. There is no doubt that research can play a significant role by developing innovative solutions. Teagasc will continue to develop the most appropriate and cost effective solutions for dealing with this issue.

Teagasc greenhouse gas research is mainly finded by the Department of Agriculture, Fisheries and Food Research Stimulus Fund.

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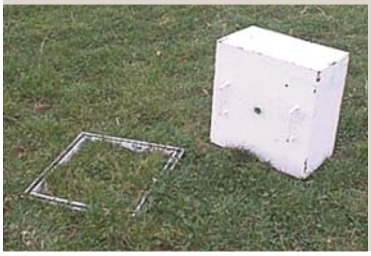
Reducing greenhouse gas emissions from agriculture



TOP LEFT: Collars to measure methane from cows.

BOTTOM LEFT: Static chambers for nitrous oxide measurement.

LEFT: Field-scale CO_2 quantified by eddy covariance.

Reducing greenhouse gas emissions from agriculture is one of the biggest challenges the industry will face in the coming decades. GARY LANIGAN describes some multidisciplinary strategies that Teagasc is engaged in to do just that.

Due to the combined effects of unprecedented economic growth and population increase, greenhouse gas (GHG) emissions are currently running at 23% above 1990 levels (10% above our Kyoto targets). Significantly, Ireland is unique among the EU countries in that 27.7% of national GHG emissions originate from agriculture. Indeed, among the developed economies, only New Zealand has a higher proportion of national GHG emissions associated with agriculture (see **Figure 1**).

Agricultural emissions are dominated by methane (CH_4) and nitrous oxide (N_2O), which are 21 times and 310 times, respectively, more effective as GHGs than CO_2. CH_4 emissions are primarily due to livestock enteric fermentation and manure management, while N_2O emissions result from chemical/organic fertiliser application and animal deposition.

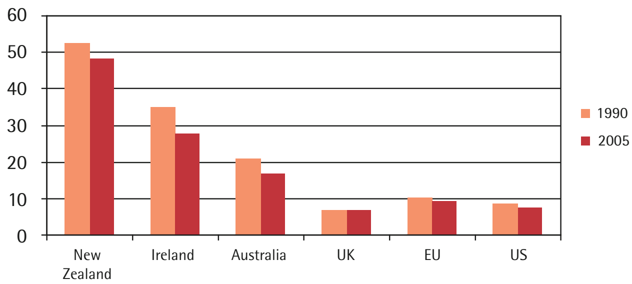


FIGURE 1: Agricultural GHG emissions expressed as a percentage of total national emissions for a range of Annex 1 (developed) countries.

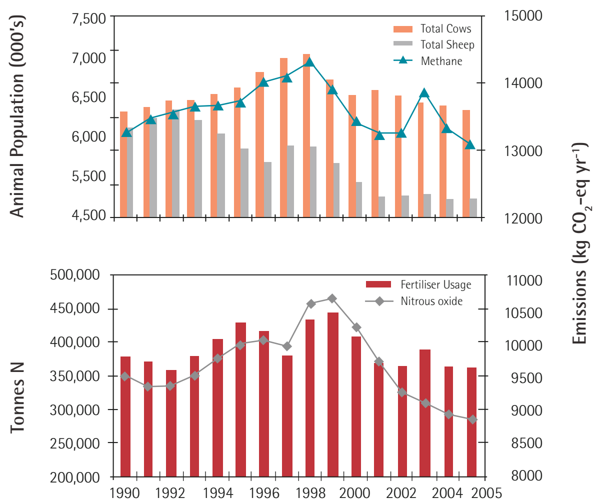


FIGURE 2: Trends in: a) national methane emissions (kT CO_2-eq) and animal numbers; and, b) national nitrous oxide emissions and fertiliser consumption from 1990-2005.

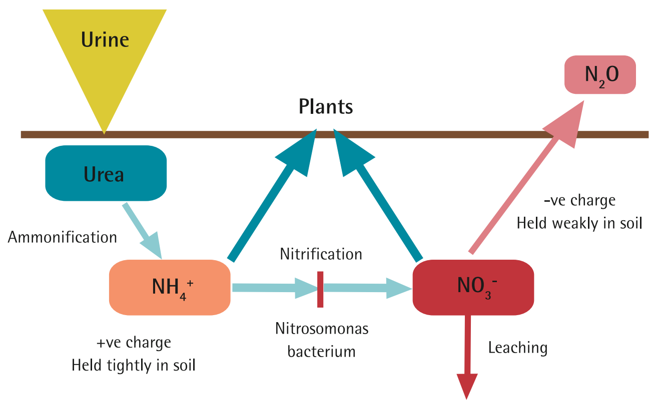


FIGURE 3: Schematic of the nitrogen cycle in soils.

It's not all bad news though. Despite being a high percentage of total emissions, agricultural GHGs have decreased by 3% relative to 1990, and 8% relative to 1998. These reductions are driven by decreases in the total number of beef cattle and sheep, leading to reduced CH_4 emissions. In addition, reductions in N_2O emissions are coupled to decreased fertiliser usage (**Figure 2**). By contrast, emissions associated with both transport and power generation have risen by 160% and 46%, respectively. Ultimately, increases in these categories have driven the large rise in national emissions.

The 20/20/2020 proposals and challenges for agriculture

The EU Commission's recent package of proposals, known as 20/20/2020, envisages a 20% EU-wide cut in emissions relative to 1990 levels (or 14.2% relative to the new proposed baseline year of 2005). This target will increase to 30% in the event of a global agreement. In addition, 20% of total energy and 10% of fuel must come from renewable sources. The burden-sharing of these cuts between member states has been allocated on a GDP per capita basis and, as a result, Ireland has been set a target of reducing emissions by 20% from the non-emissions traded sector (ETS) by 2020 compared to 2005 levels.

Why does this pose such a particular challenge to agriculture?

- As these non-ETS sectors comprise only agriculture, transport and residential, there are relatively few sectors among which to share the burden. Considering that agriculture makes up 40% of non-ETS emissions, the sector could be targeted to shoulder a large share of the burden;
- earlier projections had forecast a decrease in agricultural emissions by as much as two million tonnes by 2020. However, the effects of increased and/or abolition of quotas, combined with higher global demand, may limit the potential for reductions; and,
- in the context of increased food demand, there is a conflict between the need to meet world food demand and the 10% biofuel target (and, to a lesser extent, the renewable energy target), which will put pressure on agricultural land use.

Greenhouse gas mitigation

The proposed targets are onerous. However, GHG mitigation and the application of best management practices can provide some opportunities to optimise production efficiency. For example, N_2O emissions represent a decrease in soil N available for plant uptake, while CH_4 emissions from enteric fermentation imply a loss of carbon (C) and an unproductive use of energy. Teagasc is currently engaged in a large programme of research across all centres to elucidate the potential of some of these mitigation options.

This greenhouse gas mitigation research can be placed into three main categories:

- abatement strategies for reducing enteric CH_4 production;
- mitigation of N_2O production from agricultural soils; and,
- C sequestration via land management or land-use change.

In addition, biomass production can displace fossil fuel emissions associated with heating and electricity generation, and also carry energy security benefits.

Abatement strategies for reducing enteric methane production

CH_4 is a by-product of the fermentation of carbohydrates in the rumen's anaerobic environment, resulting in the production of hydrogen. Methanogenic bacteria utilise this excess hydrogen to reduce CO_2 into CH_4. Because enteric CH_4 production is influenced by feed quality, manipulating animal diet is the principal mitigation strategy. Currently, research into abatement strategies for beef and dairy cows is being conducted by Grange Beef Research Centre and Moorepark Dairy Research Centre, respectively. These strategies include:

Improving pasture quality

This lowers the proportion of dietary roughage, which reduces emissions by more rapid processing of food through the rumen, reducing the time available for fermentation and increasing the proportion of propionate in rumen volatile fatty acids (VFAs), which means that there is less H_2 available for CH_4 synthesis.

Replacing roughage with concentrates

This also increases the proportion of propionate. In beef cattle, if concentrates are supplied *ad libitum* the rate of daily carcass gain increases, thereby reducing finishing times. The lifetime production of CH_4 by beef cattle can also be shortened by finishing at a lighter weight. A large-scale shift to concentrates would depend on the price and would lead to the need to import large quantities, thus reducing its GHG mitigation potential.

Extending the grazing season

This can decrease emissions because enteric CH_4 production from a grass diet is lower than that from a silage-based diet. Also, lower emissions are associated with reduced quantities of stored manure.

Supplementing diets with oils

This has been shown to substantially decrease emissions by reductions in rumen protozoa that can form symbioses with the methanogens. The emissions associated with the production and importation of these oils must also be taken into account.

The quantification of the emissions associated with different breeds and cow genetic merits will identify low emission breeds and also enable a greater refinement of the CH_4 emission factors that are inputted into the national emission inventories. In addition, life-cycle analyses will allow a more accurate assessment of the most effective strategies.

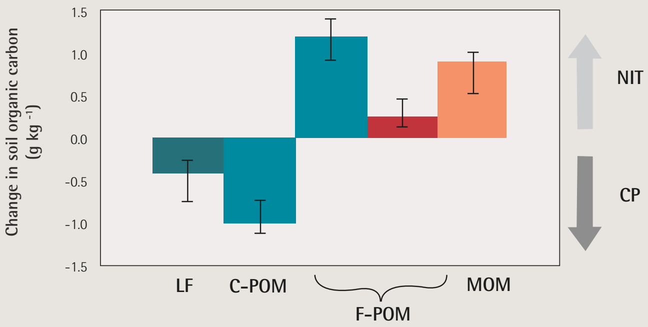


FIGURE 4: The difference in C content (g/kg^{-1}) of various aggregate-size classes between non-inversion tillage (NIT) and conventionally ploughed (CP) plots.

Abbreviations:
LF = light free C;
C-POM = coarse particulate organic matter;
F-POM = fine particulate organic matter; and,
MOM = mineralisable organic matter.

The residence time of C fractions in the soil is MOM>F-POM>C-POM>LF. Positive values indicate that a higher amount of C is associated with non-inversion tillage, with a negative value indicating a higher proportion associated with ploughing.

Mitigation of N_2O production from agricultural soils

N_2O production in agricultural soils primarily results from nitrification and de-nitrification processes (**Figure 3**). The Inter-governmental Panel on Climate Change (IPCC) Guidelines estimate direct emissions of N_2O from agricultural soils as a fixed percentage of the additional N inputs. These 'default' emission factors are 1.25% of applied N for fertiliser application and 2.25% for urine-deposited N. Also, indirect N_2O formation is induced by emissions and consecutive deposition of reactive nitrogen species (NOx) and ammonia, and nitrogen leaching and runoff.

Mitigation research conducted by Teagasc Johnstown Castle Environment Research Centre, in association with partners from UCD and AFBI Hillsborough, is focused on four main questions:

Manipulating animal diet to reduce the amount of N deposited by livestock

Reducing the amount of crude protein or supplementing the diet with amino acids has been shown to decrease the amount of N excreted. Also, feeding maize grain can reduce excreted N without impacting performance, as it is a low protein feed with a higher content of net energy than most concentrate feed ingredients.

Nitrification inhibitors in pasture and tillage

Nitrification inhibitors, such as nitrapyrin and dicyandiamide (DCD) can reduce the nitrification of ammonium to nitrate by inhibiting nitrifying bacteria. As a result, both N_2O and N leaching can be reduced. Inhibitors are most efficient at reducing N_2O emissions if used in conjunction with urea or on N excreted from animals in the form of urine. As the rate of urine N application to patches can reach over 800kg per hectare per year, and this is in excess of what the plants can utilise, it is available for nitrification to nitrate (which is also vulnerable to leaching) and for de-nitrification to both N_2O and N_2 – with some being lost as N_2O as a by-product of these processes. Soils are most vulnerable to N_2O losses during autumn, as the highest emission rates occur when soil moisture is high and sward C/N ratio is low. Current work on DCD application to urine patches has shown that N_2O emissions can be reduced by up to 50% on heavy soils, while there may be reductions in leaching on lighter soils. New work includes research into the application of DCD in association with different tillage methods.

Increasing clover in swards

Conversion to clover pastures is a multi-gas abatement measure. Teagasc Moorepark, in association with UCC, is investigating N_2O mitigation associated with clover pastures. Lower N_2O emissions are essentially based on a reduction in the fertiliser N requirement. As clover is more digestible than grass, there is also the opportunity to reduce CH_4 emissions. Other legumes containing high levels of condensed tannins can further reduce CH_4 and N excretion from animals. In addition, clover has a high rate of photosynthesis, and is efficient at sequestering C, with this sequestration potential increasing at higher CO_2 levels relative to ryegrass.

Altered timing of fertiliser application/land-spreading techniques

Optimal timing of fertiliser application matched to plant growth can reduce excess N availability. The relationship between reduced ammonia volatilisation and indirect N_2O emissions is unclear. Early season spreading of slurry or conversion from splash-plate to trailing shoe will also reduce atmospheric N deposition, thus reducing indirect N_2O emissions. However, associated N_2O emissions could, in fact, be higher, as these practices should increase the soil N pools. New projects investigating these trade-offs and adding inhibitors to slurries are being undertaken at Johnstown Castle.

Carbon sequestration

GHG emissions can also be reduced by removal of a proportion of CO_2 via photosynthesis. These 'carbon sinks' can be either perennial woody tissue or soil organic C (SOC). Land-use and land-use conversion to forestry (LULUCF) is the principle C sink used under the Kyoto Protocol, and Irish forests currently sequester approximately one million tonnes CO_2-equivalents/yr^{-1}. Altered land management practices can also increase soil C sequestration. For pasture systems, sward diversity and increases in clover can also increase total sward productivity and SOC sequestration.

Ireland is unique among the EU countries in that 27.7% of national GHG emissions originate from agriculture.

The highest losses of C from agricultural systems are associated with tillage practices. Research by Teagasc Johnstown Castle Environment Research Centre, in conjunction with University College Dublin, Trinity College Dublin and Teagasc Crops Research Centre Oak Park, is seeking to quantify the effects of reduced tillage, cover cropping and residue incorporation on ecosystem C balance. Alternative tillage practices can reduce the amount of C lost by reducing soil disturbance, reducing fallow season C losses and increasing C inputs. Most importantly, increases in the amount of resilient C that persists for long periods of time can be promoted by adoption of these practices (**Figure 3**). In addition to reducing C losses, these measures can improve soil quality and reduce erosion.

Current/future issues and research gaps

Realignment of agriculture and forestry

Following a meeting of officials in Bangkok to set rules for C sinks in the context of future agreements, it was recommended that the LULUCF sector be merged with agriculture to form agriculture, forestry and other land-use (AFOLU). This realignment will allow agriculture to claim credit for C sequestered in agricultural land converted to forestry.

Threats to C sink inclusion

However, the use of C sinks to 'remove' CO_2 may not be included in 20/20/2020 proposals as mentioned above, unless there is a global agreement. This would take away a large proportion of the abatement potential available up to 2020. COFORD (National Council for Forest Research and Development) estimate that between three and five million tonnes CO_2-eq could be sequestered by 2020. Therefore, it is vital that sinks be included in any final agreement.

Concept of leakage

A unilateral EU emissions reduction target may also not produce a reduction in global emissions, particularly from the agricultural sector. Reductions in Irish agricultural output would simply be balanced by increased production elsewhere. Considering that the GHG efficiency (unit product per unit GHG emitted) of Irish agriculture is relatively high, especially compared to the developing world (where emissions from deforestation are particularly high), the net effect could be an increase in global agricultural emissions.

Effects of climate change on emissions

While higher CO_2 levels and the extension of the growing season due to global warming may result in higher rates of photosynthesis, increased soil temperature will increase microbial activity. This will increase soil CO_2 emissions from both short-term and long-term soil C stores and will reduce soil SOC. N_2O emissions also increase with temperature. Ultimately, some ecosystems that are currently C sinks may flip and convert to C sources. However, there is currently a deficit of research, which needs to be addressed.

Effects of climate change on agricultural production

The effects of future climate change on agricultural productivity need to be addressed. Increased warming in the medium term could extend the grazing and growing season, and permit the cultivation of new crops. However, summer water deficits could have implications for summer sward production and push up costs with the requirement to irrigate. There may also be a shift in disease threat. While a decrease in fungal pathogens is predicted, increases in insect-borne diseases and pests are also predicted. Indeed, the spread of blue tongue disease from the Mediterranean region to northern Europe and the UK has been attributed to viral survival and vector longevity during milder winters, which are a consequence of climate change.

Future research

Current mitigation research will deliver some reductions in agricultural GHG emissions. However, it is clear that there is no single 'magic bullet' and significant reductions will involve implementation of a mosaic of solutions. Research priorities include the development of farm-scale management systems of soil C and N cycles that result in reduced GHG emissions and are attractive to uptake by the farming community. The development of farm-scale GHG decision-support models that incorporate C and N-cycle flows is, therefore, crucial. Underpinning future mitigation strategies is the need to further understand the interaction between the C and N cycle processes. Also, given that a degree of climate change is already inevitable, the effects of climate change scenarios on both agricultural production and GHG emissions/abatement strategies is vital.

Teagasc recently held a seminar on 'Greenhouse Gas Emissions – A Role for Agriculture', the full proceedings of which are available at: www.teagasc.ie/publications.

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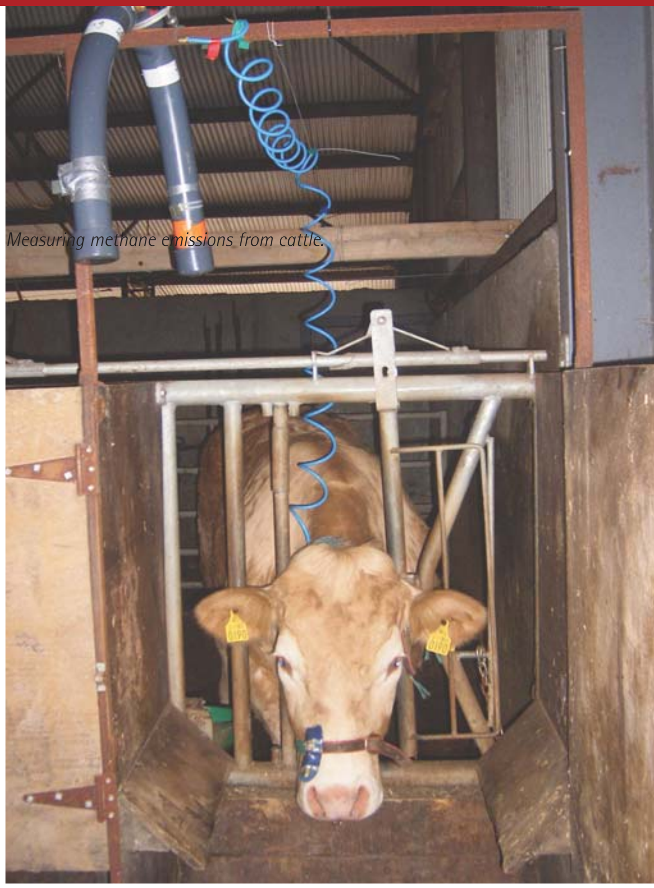
Reducing methane emissions from cattle



Measuring methane emissions from cattle.

Teagasc Animal Production and Grassland Research Centres in Grange and Moorepark are collaborating with University College Dublin, the Department of Agriculture, Fisheries and Food, and the AgriFood and Biosciences Institute of Northern Ireland in a multi-pronged approach to reducing methane emissions from cattle.

Greenhouse gas effect

Much of the solar energy absorbed by the earth is radiated back into the atmosphere as infrared heat. This would quickly be lost to outer space and the mean temperature of Earth would be some 30°C lower than at present were it not for the insulating effect of both clouds (water droplets) and greenhouse gases (GHGs).

The main GHGs are water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorinated compounds and ozone (O_3). When molecules of these gases absorb infrared radiation they vibrate and emit radiation, and this radiant energy will likely be absorbed by an adjacent GHG molecule. This absorption–emission–absorption cycle helps to keep heat energy near the earth's surface. In contrast, nitrogen (N_2) and oxygen (O_2), which between them account for 99% of air, are too tightly bound together to vibrate in this way and thus they do not absorb infrared energy and are not GHGs.

Global warming potential

Besides individual anthropogenic GHGs differing in the 'efficiency' with which they 'trap heat' in the atmosphere, they also differ in how long they endure. CH_4 has a radiative efficiency of 3.7×10^{-4} W m^{-2} ppb^{-1} and a standard lifetime in the earth's atmosphere of 12 years, while N_2O has corresponding values of 3.03×10^{-3} W m^{-2} ppb^{-1} and 114 years. The global warming potential (GWP) of a GHG is an index of its ability to absorb and emit infrared radiation (and therefore act as a GHG) adjusted for its standard lifetime, and is expressed relative to CO_2. Values are typically expressed for a 100-year horizon, and CH_4 and N_2O have GWP values of 25 and 298 carbon dioxide equivalents, respectively. This means that over a 100-year horizon, 1kg of CH_4 has 25 times the global warming effect of 1kg of CO_2.

National emissions

Internationally agreed and binding limits (e.g., the Kyoto Protocol and EU-2020) restrict the amount of GHGs Ireland can emit. Current official calculations indicate that agriculture accounts for 27% of our total national emissions and that CH_4 produced by the digestive system of livestock contributes half of the output coming from agriculture. Most of this enteric CH_4 is produced by beef and dairy cattle, for which it represents a 2-12% loss of the gross energy ingested.

Rumen

Ruminants are unique in the extent to which they access the energy in fibrous feeds. This access reflects the symbiotic relationship with bacteria, protozoa and fungi in their rumen. Much of this energy is released by microbial digestion as fermentation acids. A by-product of this process is the production of metabolic hydrogen, the amount of which must be kept very low in the rumen if fibre digestion is to continue efficiently. CH_4-producing bacteria (methanogenic Archaea) facilitate this process within the mixed microbial ecosystem in the rumen – they derive their energy for growth and multiplication from being able to combine hydrogen with CO_2 to produce CH_4. The availability of hydrogen depends on the particular fermentation acids produced by rumen microbes – processes yielding acetic (typically 60-70% of fermentation acids) and butyric (5-15%) acids release hydrogen and thus facilitate methanogenesis, while the formation of propionic acid (15-20%) utilises hydrogen and thus competes with methanogens, thereby reducing methanogenesis. Some of these methanogens exist in symbiosis with protozoa, often being found within or adhering to the surface of protozoal cells.

Rumen CH_4 is mainly disposed of by eructation (the gas is passed up the oesophagus and into the lungs before being exhaled) but a small proportion is absorbed into the blood and expired through the lungs. Whereas most enteric CH_4 originates in the rumen, hindgut fermentation can account for 6-14% of daily CH_4 production. Most of the latter is also absorbed and excreted via the lungs but a small amount exits through the anus.

Mitigating enteric methane

A reduction in enteric CH_4 emissions from the existing population of ruminants will require a combination of strategies for reducing methanogenesis and improving animal productivity. Ultimately, however, in order to properly assess the value of any particular mitigation approach, it is essential that it is evaluated in terms of its overall GHG effect – this means that a full life-cycle analysis would be undertaken to account for all direct and indirect GHG fluxes up to the point where animal product is sold from a farm.

1. Reduce methanogenesis

(a) **Animal genetics**: Considerable variability exists between animals in enteric CH_4 output, and selecting breeding animals for lower methanogenesis could provide valuable reductions in CH_4 output for traits that are heritable. These effects could be mediated through intrinsic differences between animals in their enteric microbial ecosystem or characteristics such as retention time of feed particles in the rumen.

(b) **Feed ingredients and management**: Increasing feed intake and/or digestibility, although it can increase daily CH_4 output per animal, will usually reduce it per unit feed intake. Higher intakes or digestibility reduce residence time for feed in the rumen and this conflicts with the dynamics of methanogens, and favours propionic acid production and a lower pH. The latter is hostile to protozoa, with which methanogens associate closely. Practices that favour these outcomes include ensuring that animals have *ad libitum* access to feed (grazed or conserved), grazing and ensiling leafy herbage rather than herbage with a high content of stem or dead material, grinding or alkali treatment of low digestibility forage, etc.
Changing the type of carbohydrate consumed by ruminants alters the proportions of fermentation acids and the pH in the rumen contents. Generally, CH_4 per kg intake is lower with starch, intermediate with sugar and higher with fibre. Practices that favour these outcomes include using leafy grass, combining grass with clover, using high sugar grasses, increasing the grain content of the diet (including strategic supplementation with concentrates), using silage rather than hay, etc.

(c) **Newer technologies**: There are various minor ingredients that have the potential to reduce CH_4 output when included in the diet. In each case it is necessary that the ingredients do not have negative side effects and that their effects persist for as long as they are fed. Thus, a range of methanogen inhibitors (e.g., 2-bromoethanesulfonic acid, tannins), ionophores (e.g., monensin), propionate enhancers (e.g., fumarate, malate), probiotics (e.g., *Saccharomyces cerevisiae*), defaunation agents (e.g., saponins) and fats (C8-C14 fatty acids, particularly when unsaturated) have been assessed. For example, coconut oil reduced enteric CH_4 output by defaunation, favouring propionate production and providing an alternative hydrogen sink via bio-hydrogenation.
Immunising ruminants against their own methanogens is an interesting concept. The highly diverse methanogenic community in the rumen presents a difficult challenge, but genomic information may permit development of more targeted vaccines. Exploratory research is ongoing with bacteriocins against hydrogen-producing microbes, with archael viruses and with selecting acetogenic bacteria from the hindgut (where they use hydrogen to reduce CO_2 to acetic acid) that might impact in the rumen. The prospects of adapting CH_4-oxidising bacteria to mitigate rumen methanogenesis seem negligible.

2. Improve animal productivity

Practices that increase the efficiency with which ruminants produce meat, milk or progeny reduce CH_4 output per unit product. The result is that fewer 'CH_4-producing' animals are required to produce a given amount of product or that animals need only produce enteric CH_4 for a shorter duration. Examples of factors influencing this include:

(a) **Animal genetics**: Selecting high genetic merit animals that are more efficient at converting feed to meat or milk, that have greater reproductive longevity, etc., increases the amount of animal product sold per unit enteric CH_4 emitted.

(b) **Animal management**: Practices that optimise the fertility of breeding animals or that greatly limit ill health will improve productivity.

(c) **Animal nutrition**: Ensuring that ruminants have *ad libitum* access to a high quality, nutritionally balanced diet promotes high performance and thus increases the amount of animal product sold per unit enteric CH_4 produced.

(d) **Performance stimulants**: these have a similar effect to improved nutrition, but some are not permitted in the EU.

Benefits to industry

To conform to internationally binding agreements Ireland must reduce its emissions of GHGs. The contribution by ruminant agriculture can come from a reduction in the GHG output per animal rather than from a reduction in animal numbers. Reducing the output of CH_4 from the digestive activities of ruminants will come from a combination of changes in farm practice rather than from adopting a single new technology. Farmers will be most likely to adopt those technologies that simultaneously enhance their profits.

Funding for the research associated with this article was provided under the National Development Plan, through the Research Stimulus Fund administered by the Department of Agriculture, Fisheries & Food.

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Minimum tillage to reduce fuel use in crop production

High energy costs impact on the production costs of most goods. Agriculture is no exception, with oil/energy prices affecting many of the factors of production. Today's tillage crop production systems are quite energy intensive. Can this energy input be reduced? Research at Oak Park Crops Research Centre is indicating that fuel/energy inputs can be reduced, but this requires considerable change in practices, which cannot be undertaken lightly, explains DERMOT FORRISTAL.

Ireland's tillage crop growers produce some of the highest crop yields in the world, with winter wheat and spring barley averaging almost 10t/ha and 7t/ha, respectively. The production systems used, however, could be described as 'high-input', where all inputs, including fertiliser, plant protection agrochemicals and machinery inputs, are optimised to allow the high yielding capacity of our soils and climate to be exploited. This approach involves a considerable energy input and, consequently, must be challenged in today's energy scenario. While oil prices will always fluctuate, supply and demand factors will result in a trend towards higher energy costs.

In crop production systems, high fuel costs directly affect machinery operating costs and crop drying and transport costs. Oil prices also impact on fertiliser costs (particularly nitrogen [N]) and plant protection products and, to a lesser extent, on all purchased inputs. Research at Oak Park Crops Research Centre indicates that there is scope to reduce both the direct and indirect fuel-related costs in tillage crop production. This article focuses primarily on the direct fuel costs incurred by the use of machinery in crop production.

Indirect fuel costs

If tillage farmers could reduce their inputs of fertiliser and agrochemicals, such as fungicides and herbicides, the use of energy in crop production would decrease, and the impact of oil prices on crop production costs would be reduced. A long-running cereal systems trial at Oak Park, which compares 'low' and 'high' input strategies, indicates that energy input savings can be made in certain situations. With winter wheat production, a reduction of 20% in the N fertiliser rate and 50% in the herbicide and fungicide rates only reduces crop yields by about 8%. Even in times of low oil prices (< $50/barrel), this low input strategy is more profitable for winter wheat producers, in addition to being more energy efficient. However, the response is crop specific. When a

TABLE 1: Typical fuel requirements for field operations.

Operation	Fuel consumption (litres/hectare)
Subsoiling	15
Ploughing	21
Heavy cultivation	13
Light cultivation	8
Rotary cultivation	13
Fertiliser distribution	3
Grain drilling	4
Rolling	4
Spraying	1
Combine harvesting	11

TABLE 2: Estimated power input and fuel consumption of different tillage operations.

Operation	Power available (kWh/ha)	Power used (prop)	Energy input (kWh/ha)	Specific fuel consumption (kg/kWh)	Fuel use (kg/ha)	Fuel use (litre/ha)
Plough	82	0.80	59.04	0.30	17.71	21.61
One pass	44.7	0.85	34.20	0.33	11.11	13.56
Roll	15.6	0.50	7.02	0.35	2.46	3.00
Min. tillage cultivator	21.3	0.85	16.29	0.30	4.89	5.96
Min. tillage drill	29.9	0.70	18.84	0.30	5.65	6.89

similar low input strategy is applied to spring barley, the average 18% reduction in yield results in lower profits despite the indirect energy saving. While input levels can impact on energy use, the low input strategy must be approached carefully to avoid profit penalties.

Direct fuel use in machinery

The machinery used in the field to establish, tend and harvest crops uses significant levels of fuel. While there are many sources of fuel use data, few relate to Irish crop production conditions. A detailed Teagasc machinery cost survey indicated that cereal production required approximately 85 litres of fuel per hectare (or 7.5 gallons/acre), but this varied considerably from farm to farm. At today's prices, fuel costs about €68 per hectare and now accounts for about 20% of total machinery costs, compared to just 8% less than a decade ago. However, this research does not allow factors influencing fuel use to be determined. To indicate the scope for fuel savings, it is useful to examine the fuel consumption of individual operations. Fuel use rates for individual machine operations are given in **Table 1**. This highlights the high rates of fuel consumed during cultivation.

Many factors influence the level of fuel consumption on tillage farms. Some, like soil type and weather conditions, are outside of the grower's control. Others, like machine system choice, can be determined by the grower.

Choice and use of machinery

One option for fuel saving is to choose machines with efficient engines and operate them efficiently in the field. While savings made with these approaches can be significant, they are relatively small. To achieve large fuel savings, the entire machine systems used must be considered. In crop production, there is significant scope for energy reduction in the cultivation practices that are used to establish the crop. Minimum tillage (min till), where shallow non-inversion cultivation is used in place of deeper plough-based systems, offers scope for considerable energy and fuel savings.

Min till to save fuel

Min till systems offer scope for fuel saving. The source of this potential is primarily the shallower cultivation depth compared to ploughing (typically 75mm compared to 200+mm) and, occasionally, some reduction in the intensity of cultivation. While the energy requirement and fuel use of cultivation systems was researched in the past in other countries, there has been little research into the power/fuel requirement of the systems that have currently evolved under Irish conditions.

As part of the Oak Park research programme on min till, an intensive survey of machine work rates (i.e., time taken to complete work) on a number of tillage farms was undertaken. While fuel consumption was not directly measured in this study, estimates could be made using tractor engine power output, engine loading factors and specific fuel consumption values. This allowed the fuel use per hectare for different machinery operations to be calculated (**Table 2**).

The calculated fuel consumption figures correlate reasonably well with those from earlier UK research where comparable operations are available.

Cultivation system fuel requirements

The estimated fuel consumption figures can be compiled to allow us to compare the fuel efficiency of commonly used plough-based and min till establishment systems, each of which use a number of operations. Four such systems are compared in **Figure 1**. A plough system that uses a power harrow

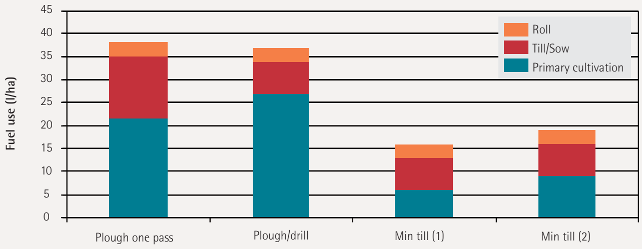

FIGURE 1: Estimated fuel consumption rates for different crop establishment systems.

and mounted drill (one pass system) has a similar fuel use rate to that using a furrow press and a cultivator drill (plough/drill system). These are currently the two most commonly used establishment systems in Ireland. The min till systems have a much lower fuel demand at approximately 50% of that of the plough-based system, depending on whether one (min till 1) or two passes (min till 2) of the stubble cultivator are needed. Growers using min till generally use just one stubble cultivator pass.

These fuel use differences are substantial (Figure 1). Using a fuel cost figure of €0.80/litre, min till systems save about €18/ha in fuel costs alone. The difference in total machinery cost between the two systems is much greater, as the lower energy consumption of the min till system requires a reduced power input, which results in a similar reduction in machine capital (depreciation and interest) costs and wear/repair rates. The lower fuel use of the min till systems also contributes to a direct reduction in greenhouse gas output.

Min till adoption

A relatively small number of growers, farming large areas, have adopted min till crop establishment systems to date. To have a significant impact on our national fuel/energy use, the rate of adoption must be increased. The changeover requires serious consideration by growers as it involves machinery investment and higher levels of management. Risk is also increased due to the unknown long-term effects of adopting the system and limited research on its performance with spring barley. Our current research programme is targeted at these areas with the aim of underpinning future uptake of min till.

This research is funded by the Teagasc Core Programme.

Min till

The minimum tillage (min till) system is a shallow cultivation system where the soil is not inverted and is worked to a depth of just 50mm to 100mm during cultivation and sowing operations. Traditional plough-based systems cultivate to a depth of 200mm to 250mm and invert the soil to achieve a level of weed control. Variations of the min till system have been tried since the 1960s, with little commercial interest in this country until recently. Today, developments in drilling technology and weed control strategies give the system a better chance of success. The system has potential cost and labour advantages, and may also have a positive impact on soil fauna such as earthworms, and soil structure protection. Grass weed control, suitability for wet autumns, and uncertainty about its role with crops established in the spring, are among the system's drawbacks. Research at Oak Park has focused on the impact of min till on winter wheat and, more recently, spring barley performance, with particular emphasis on yield stability, soil fauna, power requirements and the time taken to prepare the soil, i.e, work-rate (ha/h). To date, the performance with winter wheat has been acceptable, with good yield stability, but grass weeds can be problematic.

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Fuels of the future

If the Irish biofuel industry is to develop to a significant scale, and we are to avoid a scenario of replacing mineral fuel imports with biofuel imports, ways of improving the profitability of native production must be found. BERNARD RICE explores our options.

Research on energy production from biomass now has a high priority in most developed countries. The reasons for this are obvious – global warming, increasing oil prices and concerns about supply security, and declining profitability of traditional farm enterprises. In Ireland, the most likely biofuel prospects are shown in **Table 1**. They fall into two categories: liquid biofuels for diesel or petrol cars, and solid or gaseous fuels for heating or electricity production. Some of these biofuels are already being produced in Ireland; others will start up over the next few years.

Liquid biofuels

The rise in oil price in recent years is stimulating a lively consumer interest in alternative transport fuels. The Government has recently rolled out the Biofuels Mineral Oil Tax Relief (MOTR) scheme, which invited potential producers of biodiesel, pure plant oils and ethanol to submit proposals for biofuel production on which excise would be remitted. The MOTR scheme envisages the use of 163 million litres of road biofuel per annum (2% of our transport fuel usage) by 2010. If this were all produced from native raw materials, it would require about 70,000 ha of tillage land, and most of the excise foregone would be recouped as VAT, income tax, etc., generated by the additional economic activity. But, from the results of the MOTR allocation, it appears that much of the biofuel will be imported. In this case, the Irish Government will suffer the loss of excise revenue, with no benefit to agriculture and little improvement to fuel supply security. It will also result in avoidable long-distance transport of biofuels. So a big effort is required from all sides to ensure that, in future, as much as possible of our road biofuels is produced at home. For research, one of the challenges will be to reduce the cost and assure the quality of home-produced fuels, so that they can match imports in the marketplace.

Solid biofuels

The 'Bioheat' and 'Greener Homes' schemes introduced in 2006 are providing capital grant aid for the purchase of biomass boilers and stoves. These schemes have generated huge interest in biomass heating fuels and, at present, this interest is concentrated in three areas:

- **Wood chips as boiler fuel for buildings with a big, continuous heat demand, such as hotels or hospitals.**
  The chips will come initially from forest and sawmill residues. The main research challenge will be to develop handling systems that are cost efficient and also allow the residues to be air dried to an acceptable moisture level. Short-rotation willow is a medium-term possibility for this market, and establishment grants promised in the budget will generate much interest in this option.

Harvesting of the energy crop miscanthus, or elephant grass, at Teagasc, Oak Park.

Oil seed rape provides high quality raw material for biodiesel production.

- **Biomass pellets for urban residential stoves and small boilers.** Sawdust will be the preferred raw material initially for pellet production, but supplies of this material are limited. When this is exhausted, wood residues, energy crops such as willow or miscanthus, and cereal or rape straw are other possible feedstocks. Again, research will be needed to determine the suitability of these materials for the production of high quality fuel pellets.

- **Cereal grains for heating farm homes.** This will be concentrated initially on tillage farms, but may spread to other rural dwellings. Research is underway at Oak Park to determine the suitability of the various grain species and the moisture contents needed for good combustion.

A big effort is required from all sides to ensure that, in future, as much as possible of our road biofuels are produced at home. For research, one of the challenges will be to reduce the cost and assure the quality of home-produced fuels, so that they can match imports in the marketplace.

TABLE 1: Medium-term biofuel options.

Plant oil or biodiesel		
Rape-seed oil Recycled vegetable oil Tallow	→	Replace diesel
Ethanol		
Cereals Beet	→	Replace MTBE* *(oxygen enhancer)* in petrol
Bale, chop or pellet		
Wood residues Straw Grain, miscanthus Willow	→	Replace oil/gas in: Stoves Boilers Power stations

This generating station at Edenderry is well suited to the burning of biomass co-fired with peat; payment policy changes and research support will be needed for a smooth transition.

Biogas

The production of biogas from animal manure, food wastes and energy crops is expanding rapidly in Germany. The gas is mainly used in boilers or combined heat and power plants. A combination of low green electricity prices and animal health concerns with food wastes has militated against development in Ireland to date. But with looming organic waste disposal problems, we need to start researching every option for its utilisation as a biofuel feedstock.

Co-fuels

We are at the beginning of an interest in the use of biomass as a co-fuel at the modern peat-burning electricity plants. These stations burn a total of three million tonnes of peat per year. The recent Green Paper, 'Towards a Sustainable Energy Future for Ireland', sets a 30% biomass substitution target for these stations. Allowing for differences in calorific values, this would require about 700,000 tonnes of biomass; a daunting but achievable target. To allow this development to get underway, action is needed on two fronts:

- the price currently paid for peat would not cover the cost of producing energy crops. The payment system must be modified to allow the saving in carbon credits to the electricity producer to be used to top up the raw material price paid to the grower; and,
- to minimise the cost and environmental impact of long-distance transport of bulky material, production would have to be concentrated close to the power stations. All the impacts of such a development need to be researched carefully, and an appropriate mix of energy crops developed. Intensive local energy crop production could affect catchment hydrology, scenic aspects, biodiversity and local traffic. Careful planning and species selection would be needed to overcome these problems. The social benefits of providing alternative employment for workers currently engaged in peat harvesting would be substantial.

Changing landscape

So some opportunities are beginning to emerge for the transfer of significant areas of land from food/feed production into energy crops. This will bring improvements in our energy supply security and greenhouse gas balance; a reduction of food/feed production should also help to stabilise prices for these products. But, there is still a major problem in that the profitability of producing and processing biofuel crops remains very low. If the industry is to develop to a significant scale, and if we are to avoid a scenario of replacing mineral fuel imports with biofuel imports, ways of improving the profitability of native biofuel production must be found. This will require a number of changes at policy level and an intensive research effort at a number of levels. The main areas in need of immediate research are concerned with: agronomy and cost of feedstock crop production; profitable utilisation of the by-products of biofuel production and processing; the quality of native and imported solid and liquid biofuels; and environmental impacts of more intensive energy crop production. In the longer term, systems for small- to medium-scale electricity production from biomass and for liquid biofuel production from the cellulose component of plants, will be approaching commercialisation and will need to be evaluated.

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Life-cycle assessment of energy crops

JOANNE FITZGERALD, Teagasc Oak Park Crops Research Centre, is evaluating the environmental consequences of miscanthus cultivation using life-cycle assessment.

Currently, 12% of global greenhouse gas (GHG) emissions arise from agricultural production, with a further 10% from agriculturally-induced land use change. It is generally accepted that a global cut of 50% in GHG emissions is necessary by 2050. Timely moves to meet this target are vital if we are to retard the ongoing accumulation of GHGs in the atmosphere. The agricultural sector contributed almost 28% of Ireland's GHG emissions in 2005 (with the majority of this input coming from livestock production), while the Irish energy sector contributed 23% of Ireland's overall GHG emissions in the same period. The Kyoto protocol limits Ireland to a 13% rise in its GHG emissions over recorded 1990 levels by 2012, and the Irish Government has recognised that its energy policy must achieve a substantial reduction in GHG emissions. The Government's Energy White Paper of 2007 contains a target that biomass will contribute to 30% of energy input at peat electricity-generating stations by 2015, with a second target of 12% of heat generation to be reached by 2020. The use of bioenergy provides an opportunity to reduce GHG emissions originating from both the energy and agricultural sectors. However, the large-scale cultivation of bioenergy crops such as miscanthus requires landscape-scale changes, and the environmental and social consequences of such significant changes are not fully understood at present. In a global context, problems associated with both rapid population growth and climate change have led to questions being asked as to the wisdom of dedicating significant land resources to energy crops. However, Ireland is in a unique position, possessing a large agricultural area relative to its population size of just over 4.2 million people. Miscanthus has much to offer in this Irish context, being a renewable (and close to carbon-neutral) source of energy.

Because of reasons already outlined, it is advisable to quantify the environmental impacts of growing new crops in large quantities and to develop sound recommendations for their cultivation and utilisation.

Life-cycle assessment

This project uses life-cycle assessment (LCA) as a tool in the evaluation of the environmental impacts of large-scale miscanthus cultivation. LCA provides a robust method for the analysis and assessment of environmental impacts caused by product systems. According to the ISO 14000 standards, LCA is divided into four steps, which are: (1) goal and scope definition; (2) inventory analysis; (3) impact assessment; and, (4) interpretation. The life cycle of any production system consists of all the stages involved in its production, distribution, use and eventual disposal. For miscanthus production, the analysis includes all impacts related to the production of raw materials (such as minerals and fossil fuels) and farm inputs (such as fertilisers, herbicides, pesticides, machinery and rhizomes). By identifying where the main impacts lie within the miscanthus life cycle, the LCA method points clearly to where remedial action is needed.

Two distinct LCA approaches are taken in this work. The first is known as 'consequential' life-cycle assessment (CLCA), where the consequences of increased

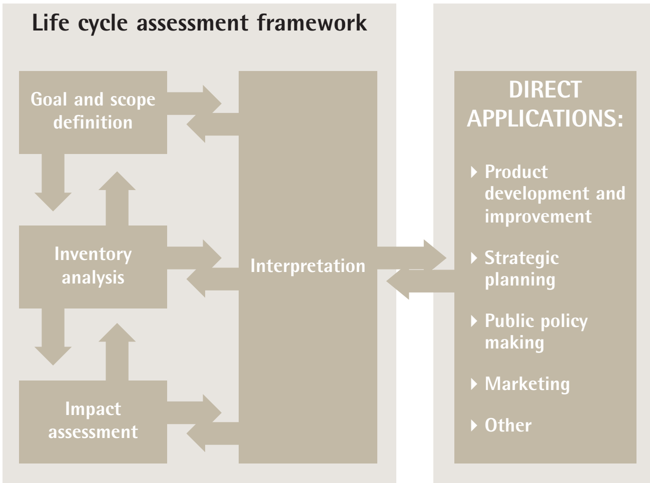

FIGURE 1: Phases of an LCA Study (ISO14040: 2006).

miscanthus production (and the potential displacement of other agricultural systems) are considered. This approach is useful with respect to evaluating the indirect local and global consequences of a specific course of action.

The increased cultivation of miscanthus in Ireland could occur at the expense of other agricultural systems. It is currently assumed that the demand for a displaced crop (or product) will be compensated for either by intensifying its production in Ireland, expanding the Irish land area involved in production, or by sourcing it from another country (which may involve that country also having to intensify production or expand land use). Intensification increases the yield of a given area by additional inputs (such as fertiliser). Expansion is defined as the transformation of a previously unused land type, (e.g., natural areas) into land for agricultural use. It is important to include the emissions related to land transformation in the LCA. As such, the geographical and system boundaries used in LCA are vital. For example, an LCA using the Irish border as its geographical boundary would exclude any increased production in a country overseas.

The CLCA focuses on the land use element of the system and the system boundaries can be described as 'cradle to farm-gate', i.e., the processing and end use of miscanthus is not considered at this stage. In order to meet the heat and co-firing targets, 90,000ha of miscanthus would need to be planted. This would displace existing agricultural systems, primarily grass-based beef production. The CLCA also contains a reference system, based on electricity, heat production and land use in 2005, as a means of comparison.

LCA may also be used to evaluate optimum supply chains and end uses of a product such as miscanthus from an environmental perspective by a method known as 'attributional' LCA (ALCA). ALCA differs from CLCA in that it does not

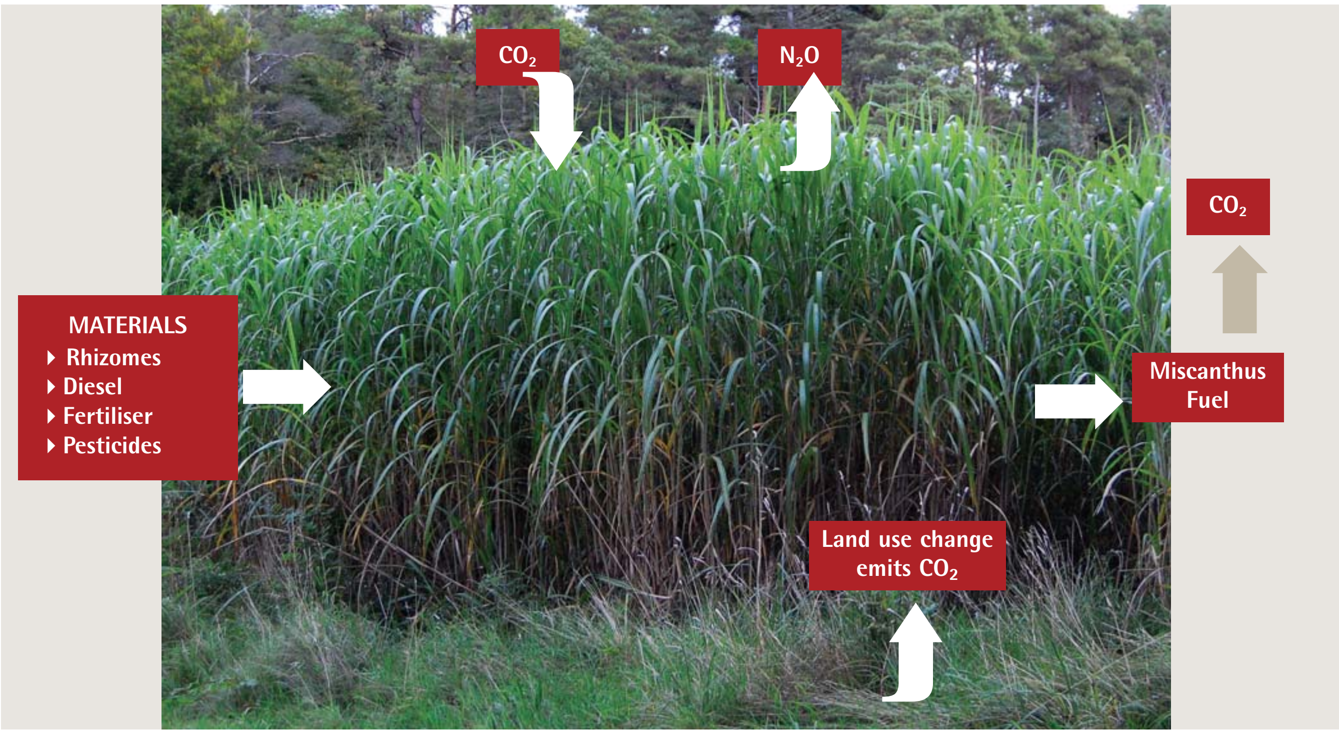

FIGURE 2: Some elements of the miscanthus life cycle.

consider indirect effects arising from changes in the output of a product or system. Several scenarios and end uses of miscanthus production are compared on the basis of a 'functional unit' in order to recommend optimum supply chains from environmental and sustainability perspectives. The functional unit is a quantified output that is used as a reference unit in LCA. All inputs and outputs of the life cycles are related to it. It is derived from the function of the product system, i.e., heat and energy production.

LCA is used in both cases to calculate the effects of meeting policy targets with miscanthus on several environmental receptors, namely energy use, GHG emissions, acidification, eutrophication, resource depletion, land use, and water quantity and quality. Over the time scale of this two-year project the combination of the CLCA and ALCA approaches will be able to answer some pertinent questions about miscanthus production in Ireland such as: to what extent are GHG emissions reduced?; and, does increased miscanthus uptake result in better sustainability over the production line?

Conclusions

Polices encouraging the uptake of biofuels, such as the Energy White Paper of 2007, require life cycle GHG reporting in order to ensure that biofuels achieve GHG reductions and improved sustainability relative to fossil fuels. This is necessary both in determining optimal land use and supply chains. Policy makers should be aware, when using LCAs to inform decision making, that the proponents/detractors of given scenarios often approach LCA (particularly CLCA) with a particular modelling framework that supports their world view. For example, proponents of biofuels may see a place for bioenergy within a more carefully stewarded use of land. They may point to land areas with low productivity, which offers room for higher yields.

On the other hand, detractors of bioenergy may emphasise how rising population and consumption is putting unnecessary pressure on the world's resources. Therefore, it is important to carefully examine the assumptions and boundaries of LCA. However, LCA is extremely effective in helping policymakers to make choices for the longer term, as it helps to avoid shifting environmental problems from one life cycle stage to another, from one environmental receptor to another, or from one geographical area to another. As such, it is an invaluable tool in the evaluation of the environmental impacts associated with large-scale energy crop cultivation.

This research is funded by the Department of Agriculture, Fisheries and Food Research Stimulus Fund.

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Discovering subsurface denitrification

Full denitrification has been notoriously difficult to measure, but now researchers at Johnstown Castle and Irish universities are opening the black box below the topsoil, to investigate how we can coax the responsible denitrifying microbes to work even harder for us.

Subsurface denitrification: friend or foe?

Full denitrification is a microbial underground process that silently cleans nitrates and nitrous oxides from our soil, and converts these to dinitrogen, a harmless gas. Nutrient research at Johnstown Castle aims to maximise the utilisation of nutrients by grass and crops, thereby reducing direct costs and risk of losses to the environment. Surplus nitrogen (N) may be lost to water through leaching as nitrate (NO_3^-), or lost to air as nitrous oxide (N_2O), a major source of greenhouse gas emissions. However, not all losses of N impact negatively on the environment; for example, dinitrogen (N_2) is an environmentally inert gas, comprising most of the air we breathe. It is the ultimate end product of complete denitrification, in which NO_3^- is sequentially stripped of its oxygen (O). Research at Teagasc Johnstown Castle aims to quantify full denitrification as a pathway for the control of NO_3^- and N_2O emissions.

Known knowns

N_2O emissions result from incomplete denitrification of NO_3^- to N_2, which is carried out by a range of soil microbes and fungi under low oxygen conditions. Under such anaerobic conditions, these microbes use the O in the NO_3^- ion as an O source for respiration; this process requires carbon (C) as a substrate. Under ideal subsurface conditions, i.e., low O concentration, a supply of C and a suitable pH, these microbes can strip the last O ion from N_2O, leaving N_2 as the end product. Predicting where these conditions occur simultaneously in space and time allows us to predict where N losses to water and air are likely to be low as a result of full denitrification.

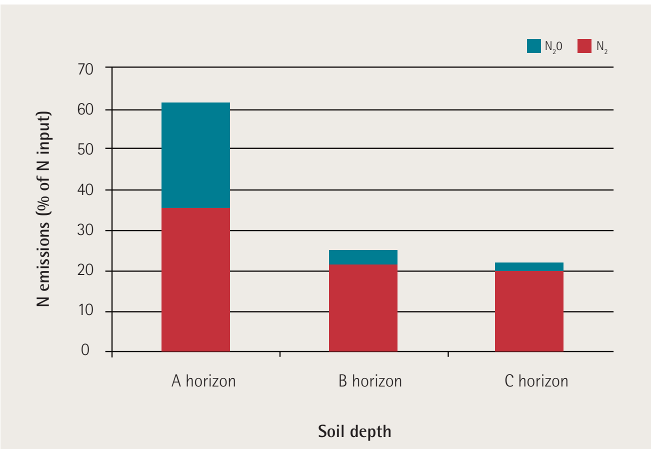

FIGURE 1: Proportion of N_2 and N_2O emitted as a percentage of the N applied. A horizon: topsoil; B horizon: subsoil; C horizon: parent material.

Known unknowns

To date, science has struggled to understand the full complexity of the agricultural N cycle, because of the multitude of pathways and interactions; the full denitrification pathway has been particularly challenging to quantify. Conversion of NO_3^- to N_2 has challenged scientists for decades, since dinitrogen makes up 79% of the atmosphere; this is a major source of contamination for laboratory and field experiments. Therefore, most research has focused on N_2, which is much easier to measure. Even less is known about N_2 and N_2 emissions from subsoils, i.e., soil below the agriculturally important topsoil. However, subsoils may be many metres thick, and have potential to contribute significantly to the clean-up of NO_3^- and N_2O into N_2.

Our research programme

Since 2007, Teagasc and research partners have embarked on a major research programme to understand and quantify subsurface denitrification. This programme involves a multi-disciplinary team of soil scientists, microbiologists and hydrogeologists. Our goal is to quantify subsurface denitrification, and to understand the drivers of full denitrification. Building on this new knowledge, we aim to develop environmental technologies to enhance complete soil denitrification for the abatement of NO_3^- leaching and N_2O loss to the atmosphere. We have measured soil and subsoil denitrification in laboratory and field studies for a range of Irish subsoils. Although total denitrification (N_2+N_2O) decreases with soil depth, possibly due to the greater substrate availability and prevalence of denitrifying microbes in the top soil, emission of environmentally benign N_2 was significantly greater in subsoil horizons compared to the surface horizon, accounting for about 90% of the total N_2+N_2O emissions (**Figure 1**), compared with 58% in topsoil (Khalil *et al.*, 2009). This suggests that denitrification in subsoil occurs at lower rates, but produces mainly environmentally inert N_2.

Slower is better

Subsoils can be many metres deep, and percolating water may take months or years to migrate vertically through the subsoil profile. This potentially long residence time of water in subsoils is important, as it allows time for full denitrification to take its course. We have measured spatial variation in denitrification on a number of experimental sites, representing grassland,

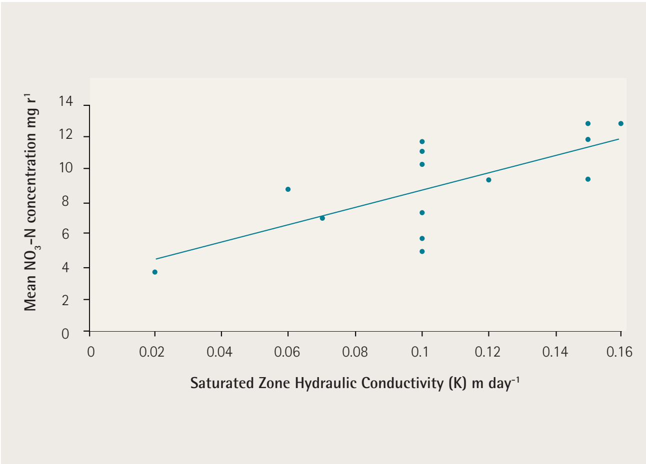

FIGURE 2: The positive relationship (p=0.003) between groundwater NO_3^- and the speed of groundwater movement (saturated zone hydraulic conductivity, K_{sat})(Fenton et al. *2009).*

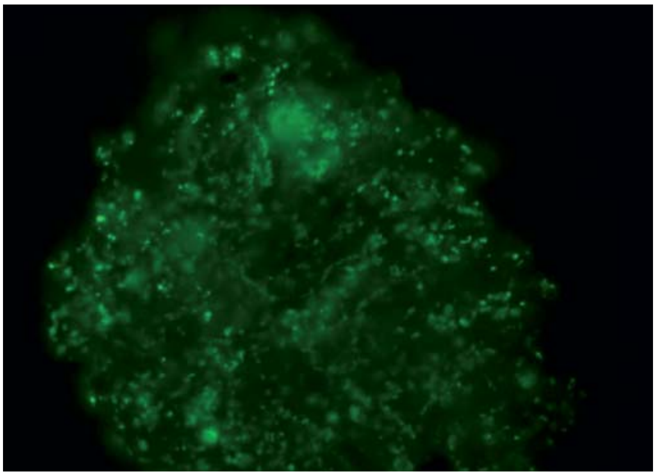

FIGURE 3: Epifluorescent micrographs illustrating the results of in situ *hybridisations carried out on soil profiles containing microbial biomass.*

tillage and a range of soil/hydrogeological settings. Recently published results confirm our hypothesis that groundwater NO_3^- levels are lower with longer residence times in an aquifer (**Figure 2**).

Opening the microbial black box

To help us understand which soil conditions are limiting the denitrifying activities of microbes in the subsoil, researchers at the Department of Microbiology at NUI Galway are using advanced molecular tools to quantify the number of organisms related to N_2 and N_2O emissions, and to identify where exactly these are located in the subsoil and groundwater (**Figure 3**), and preliminary results confirm that abundance decreases with depth below soil surface (Barrett *et al.*, 2008).

We are now using this new knowledge and understanding to develop innovative technologies to enhance full subsurface denitrification and to remediate groundwater with elevated NO_3^- , while simultaneously reducing N_2O emissions. Such technologies include the installation of reactive barriers that introduce carbon into groundwater as an available source of energy for the denitrifying microbes (Fenton *et al.*, 2008). We are testing a variety of carbon sources for costs and effectiveness. In addition, we are evaluating technologies to manipulate the water table in buffer strips, in an attempt to control and extend anaerobic conditions over a larger part of the subsurface profile, thereby increasing the depth over which full denitrification can operate (Haria *et al.*, 2009). Building on a deeper understanding of the processes that drive subsurface denitrification, these technologies help us to develop solutions where productive farming contributes to a sustainable environment.

Acknowledgements

This research is funded through a combination of Teagasc Core funding and the Department of Agriculture, Fisheries and Food Research Stimulus Fund.

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Unlocking farm forest potential

A new Teagasc project, funded by COFORD, has commenced in Athenry and will provide a framework for quantifying the wood resources from farm forests in order to maximise potential markets. NIALL FARRELLY, BRIAN CLIFFORD and STUART GREEN explain how this new research will provide a significant stimulus to the farm forestry sector, and its potential contribution to the national wood supply chain.

A critical mass of private and farm forestry is now developing in Ireland, with over 219,000 hectares planted since 1980. Many of these plantations are coming to the stage where decisions on management requirements need to be made. Currently, 105,000 hectares of private forests are over 10 years of age and 40,000 hectares are over 16 years of age. The majority of private forest owners are farmers (84%). Recent research conducted by Teagasc and reported in the *Small-scale Forestry* journal indicates that if only 50% of private owners decided to thin their plantations, the annual output from farm forest first thinning could potentially rise to in excess of 200,000m^3 (Farrelly, 2007a). COFORD (National Council for Forestry Research and Development) estimates that the private sector's market share will rise to 23% by 2015 (Gallagher and O'Carroll, 2001). However, the actual supply from the private sector is still far short of this target, with many farm forest plantations in Ireland currently unthinned for many reasons, including the high cost of harvesting, economies of scale, lack of knowledge about when to thin, and the price attained for farm forest produce.

New research

While we have a general picture of the area of forest approaching first thinning age, there is very little information at a local level on exactly where the resource is located and which plantations are suitable for thinning in the next five to 10 years. In addition, there are few structures in place to quantify, locate or market the timber for owners, and there is a danger that the resource will be overlooked if the potential is not fully recognised. It is timely then that Teagasc, with the support of COFORD, intend to conduct research to address critical issues facing farm forestry, such as the the lack of local level information about forests for specific market requirements. This research will address the critical issue of economies of scale among small forest owners. A cluster-based approach will be developed so that the management, thinning, harvesting and marketing requirements of farm forests can be achieved for a particular district. The outputs of this research should improve the ability of farm forest owners to market and sell their produce. The work will quantify the material from farm forests by providing a methodology for assessment of the wood resource within any particular location, and link that resource to sawmills and wood energy markets.

New methodology

The 'cluster' methodology involves the capturing and compilation of high-level inventory or growth information on forest plantations, using available database resources from the Forest Service, remotely sensed imagery such as aerial photography, satellite imagery and airborne laser scanning (LiDAR), and field-based measurements.

The first phase of the study utilises a geographic information system (GIS) in order to provide information about the location of forest plantations. The research uses a cluster approach performed in a GIS for locating areas with large concentrations of private forest cover (**Figure 1**). The method is extremely efficient in grouping large concentrations of forestry together and concentrates survey resources where forest cover has reached a critical mass.

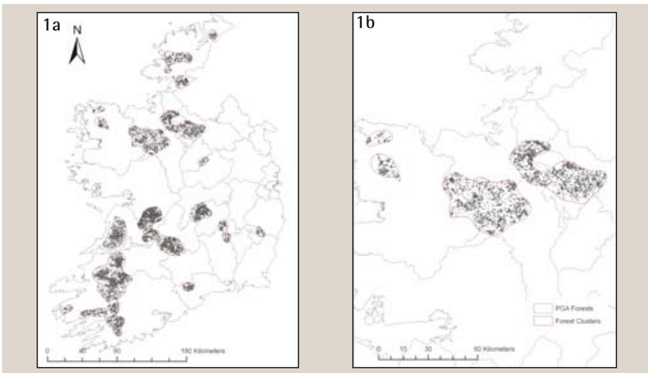

FIGURE 1a and 1b: GIS cluster analysis used to locate large concentrations of farm forest plantations in Ireland and showing cluster locations in the west of Ireland.

Thinning promotes revenue returns in farm forests.

Forest clusters were identified at a national level based on two parameters:

- private forestry in excess of 5% of the total land use; and,
- cluster area greater than 10,000 hectares.

Some 16 separate areas matched these requirements spread throughout the country (**Figure 1a, Table 1**). It would appear from this preliminary analysis that private grant-aided (PGA) forestry does have spatial concentrations. A total of 42% occurs within identified cluster areas, while these cluster areas make up less than 14.5% of the total national land area (**Table 2**).
Of these cluster areas, four were identified as being priority areas. These priority areas include the Ballaghaderreen (**Figure 2**), Glenamoy, Bellacorrick and Leitrim clusters (**Figure 1b**). These areas were chosen based on the initial intention of this research programme to concentrate on the west of Ireland. Therefore, 10% of PGA forestry will be assessed by concentrating resources in only 0.3% of the national land area (**Table 2**).

Remote sensing methods

Work is underway in identifying the best available methods for determining forest stand parameters. The latest aerial photography is being used in order to capture value-added data about plantations in the cluster areas. This involves determining field boundaries, identifying development stage and stocking levels, and providing information on roadways and access (**Figure 3**). This will be further aided by SPOT satellite imagery, which will be made available from the Teagasc Spatial Analysis Unit in 2008.

TABLE 1: Cluster areas identified at national level.

Cluster	County	Forest area (hectare)
Limerick, Kerry, Cork	Limerick, Kerry, Cork	28,400
Killaloe	Galway, Limerick, Tipperary	13,455
Ballaghaderreen	Mayo, Sligo, Roscommon	9,693
Ennis/Ballyea	Clare	8,922
Leitrim	Leitrim, Sligo, Cavan	8,901
Glenties/Stranorlar	Donegal	4,287
Kilcormac	Westmeath, Laois	3,506
Donegal Town	Donegal	2,219
Castlecomer	Kilkenny, Laois	2,041
Bellacorick	Mayo	1,440
Buncrana	Donegal	1,200
Cappoquin	Waterford, Tipperary	1,104
Waterville	Cork	881
Moatfarrell	Longford, Westmeath	768
Glenamoy	Mayo	728
Tinahely	Wicklow	715

Mature Sitka spruce.

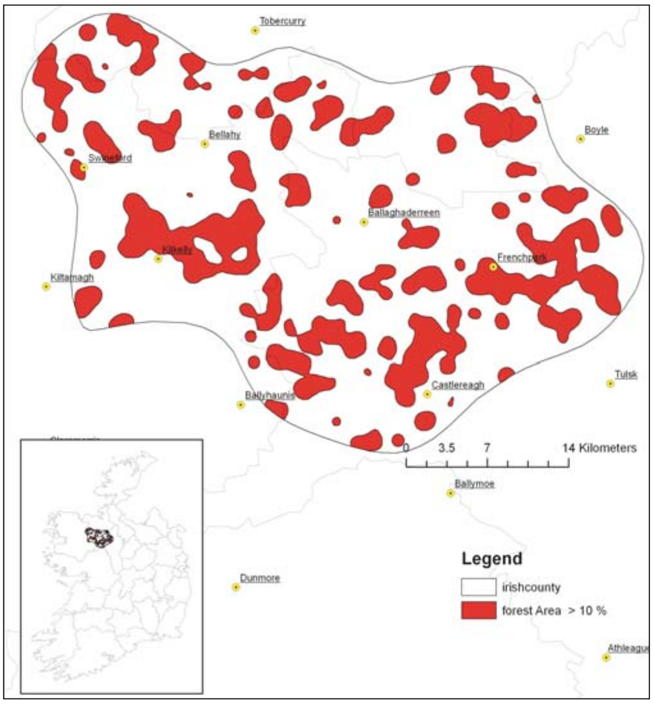

FIGURE 2: Illustration of the Ballaghaderreen cluster in Mayo, Sligo and Roscommon.

TABLE 2: A breakdown of area by total cluster area and forest cover within clusters.

	Area (hectare)	% of national land area
Total national land area	6,984,799	100.0%
Total cluster area	1,015,565	14.5%
Total PGA forestry	207,897	3.0%
Total PGA forestry in cluster	88,260	1.3%
Cluster area to be surveyed	20,762	0.3%

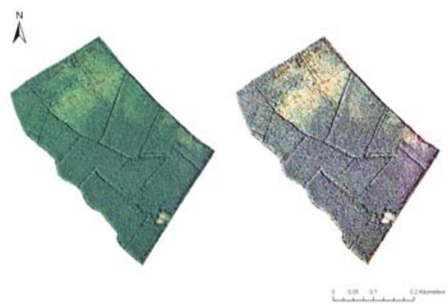

FIGURE 3: Identification of resource details using aerial photography. The left image is a traditional aerial photograph showing forest boundaries and the right image is enhanced to show areas where the crop has failed in yellow (Copyright Ordinance Survey Ireland – license 6155).

Glaspullagh, Co. Limerick.

The potential of LiDAR (Light Imaging Detection and Ranging) in obtaining stand-related parameters is also being assessed. LiDAR is a remote sensing system, which appears to have great applicability for the estimation of canopy height models that can be used to estimate other forest parameters, such as stand heights, stand volume and the structure of the forest canopy. In turn, canopy structure gives vital information on stocking density and wind damaged areas (Naesset, 1997; Suarez *et al*, 2005). Therefore, this research will evaluate the potential of these new technologies for analysing species, spatial distribution, monitoring forest cover fragmentation, planning of forest road networks and the monitoring of forest land cover change.

Field assessment and production forecast

All plantations within a cluster that are approaching first thinning stage or have passed first thinning stage (or a certain age criteria) will be visited in the field, where an assessment of timber quality and volume will be performed in each stand using tried and trusted forest sampling methods The field survey will be based on capturing forest growth parameters. All the data will be compiled into a field database and the volume of each stand will be computed using the COFORD Dynamic Yield Model 'Growfor' (COFORD, 2007). These models will be used to generate forecasts of volume production by projecting the growth of stands forward to a reference age and quantifying the effects of thinning a crop (Farrelly, 2007b). A forecast for timber production for each stand in the cluster will be made and will be used as the main tool for further development work, especially in the identification of suitable locations for new market opportunities. Further analysis will be performed using GIS technologies such as: distance from sawmill; optimum haulage route; and, optimising the location of additional wood utilising facilities (such as wood energy boilers).

Acknowledgements

The Cluster Research Programme has been part-funded by the Council for Forest Research and Development (COFORD). This work is also funded by the Teagasc Core Programme.

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