An Roinn Talmhaíochta,
Bia agus Mara
Department of Agriculture,
Food and the Marine

16/RD/ERAGAS/4 MANAGING AND REPORTING OF GREENHOUSE GAS EMISSIONS AND CARBON SEQUESTRATION IN DIFFERENT LANDSCAPE MOSAICS

Final Report

This project was funded under the Department of Agriculture, Food and the Marine Competitive Funding Programme.

SUMMARY

Accurate and reliable datasets from agriculture and forestry were crucial for our modelling purposes. We collected some relevant datasets on greenhouse gas (GHG) and soil carbon for grassland and arable land from different national and European universities/research institutes, including Denmark and France. Some datasets for GHG emissions from grasslands in France were parameterized but had limited utility for the modelling work. A centralized database platform was created at the UCD Earth Institute and maintained. Parameterization and evaluation of models such as Holos, IFSM and the CFT were performed, though limited by the data available for validation, and GHG budgets from grassland, dairy and arable farms estimated using the simulated outputs. All models performed reasonably well for GHG mitigation/offsetting and the development of carbon-neutral farming systems. Unlike IFSM, Holos can accommodate afforestation though limited by country-specific meteorological data. The results suggest that relatively small levels of afforestation might be introduced for economically viable mitigating and offsetting of on-farm GHG emissions. A sensitivity test using Holos (V. 3.0) indicated that shifting from a single land use to a mixed farming system could have considerable potential for mitigating and offsetting on-farm GHG emissions. For achieving carbon-neutrality, a reduction in livestock units and the use of inorganic fertilizers, combined with more afforestation, would be required. Sustainability metrics for quantifying land-use efficiency and evaluating the production efficiency of Ireland's major livestock systems together with a metric to compare the efficiency with the opportunity for alternative crops has been developed to review the efficiency of human-edible protein. This includes an optimization model to forecast land-use changes to attain an environmentally and economically sustainable agriculture sector.

We disseminated the outputs through website and social/professional platforms regularly including national and international conferences/meetings/workshops and publication of articles. Recruitment delays and problems with data accessibility were significant constraining factors.

KEYWORDS

Greenhouse gases, Carbon Sequestration, Landscape Mosaics

ACRONYM	GHG-MANAGE
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PUBLICATION DATE	April 2022

Section 1 - Research Approach & Results

Start Date

01 January 2018

End Date

30 September 2021

Select Research Programme

Research Stimulus Fund

Please select the appropriate TRL Scale

TRL 3: Experimental Proof of Concept

NRPE Priority area

Sustainable Food Production and Processing

Total DAFM Award

€236,133.75

Total Project Expenditure

€214,289.93

Rationale for undertaking the Research

Agriculture and forestry play a key role in climate regulation through production/removal of GHGs and through variations in surface properties. An improved quantification of their GHG budgets would reduce the uncertainty around actual estimates. There is limited quantification of climate, silvicultural and agricultural practices on ecosystem functioning, and common emissions factors (EFs) are often used erroneously. Accordingly, the Paris Agreement points to a strongly increasing demand for mitigation associated with the

optimisation of landscape composition. This includes a reduction in non-CO2 emissions and also C sequestration at a low (or even negative) cost, by combining land use practices and management interventions.

Land-use-related GHG emissions are more difficult to quantify and are associated with large uncertainties, but include significant contributions from CH4 and N2O, including ammonia. Current guidelines for GHG reporting do not consider complex landscapes, and a relatively small number of papers describe the role of forests in non-CO2 gas turnover. There are also questions about afforestation compromising agricultural production by competing for available land area, as well as about the negative economic consequences for farmers. The development of EFs (indicators) taking into account agricultural practices and paedo-climatic conditions will contribute to the verification of GHG emissions and C sinks in landscape mosaics. For this, the development of IPCC Tier 3 approaches that use complex models are being developed. However, process-based whole farm models such as FarmSim, Holos and the Integrated Farm System Model (IFSM,) could have advantages, and be used to contribute to the identification of suitable solutions.

Methodology

The project was focused on new approaches/tools to assess GHG budgets of heterogeneous landscapes and understudied land cover-soil combinations. Existing data, from past and on-going measurement networks collected through WP1 were used. This contributed to WP2 for developing new information/tools and modelling of GHG emissions and C sequestration in different land uses and management practices, and to WP3 focused on the optimisation of GHG exchange. Simulation of C and N emissions from key arable and pasture-based dairy farms was performed using whole farm models (Holos and IFSM) and the Cool-Farm Tool (CFT). Farm level GHG budgets for individual crops, grassland and livestock were estimated and compared to evaluate their performances in predicting C and N emissions. Emission factor metrics and mitigation measures were prepared using a mixed source of activity data and input parameters. Sensitivity tests were performed using the Holos model with the common input parameters considering grassland (e.g. grazed, silage and mixed), and arable (e.g., cereals, and tillage practices), management (e.g. inorganic and organic N fertilizers) and stocking/grazing intensity, and climate change variables (temperature ±1-4oC, and precipitation (±200-400mm). The

Holos model was also run using the amount, age and type of forestry to estimate yearly contributions of biomass and soil C for offsetting of agricultural GHGs. Evaluation of different land use strategies (conventional measures including milk yield and beef and nutrition measures i.e. edible protein yield) indicators of sustainability and new land use measures in the context of the production of different outputs of human edible product was carried out. For this, literature on land uses were reviewed and life cycle assessment software packages (e.g. Impact 2002+ and Ecological Scarcity Method) were used to report sustainability. The potential of each method was tested across a range of different stakeholders. Project management, dissemination and communication were performed under WP5.

Project Results

Despite several limitations, the available information/databases received during the project period from project partners and the wider scientific community, on GHGs and C sequestration were compiled, assessed and stored on a database and used for modelling purposes.

Two whole-farm models (Holos and IFSM), and the Cool Farm tool (CFT) were used for the simulation of GHGs and C balance for grassland, dairy and arable farms and estimated GHG offsetting to develop carbon-neutral farming systems. All models provided reasonable estimates. An advantage of Holos was it could encompass afforestation despite limitations in including country-specific meteorological data.

Agricultural GHGs from Irish farms for assessing the degree of offsetting through afforestation-related carbon sequestration potential was estimated. The Holos results indicated that relatively small areas of afforestation could be important in mitigating and offsetting GHGs to make a mixed farm carbon-neutral after 15 years by afforesting a part of the farmland. Afforestation of 10-46% of the farmland will be required when considering above-ground biomass carbon but could decrease to 8-28% by including below-ground C sequestration. The five best tree species to achieve carbonneutral farming were Hybrid Larch (8%), Eucalyptus (9%), Sitka Spruce (10%), Douglas fir (12%) and Poplar (14%). This suggests that forestry could be a viable option for Ireland but needs further investigation. Similar to IFSM, the CFT results indicated the largest share of GHG emissions originated from fertilizers on arable land. Enteric CH4 emissions were the largest from dairy cattle. Energy use for the production of resource inputs (e.g. fertilizer and machine operation) was the largest contributor to GHG emissions, followed by N2O emissions from spring barley production systems.

The Holos model was used for sensitivity analysis using data based on a 45ha farm (2/3 pasture and 1/3 silage with 176 livestock units). The major drivers were N fertilizer and temperature, which when reduced by 30% decreased the total onfarm GHG emissions by 9% and 18%, respectively. The major contribution to the total 865 Mg CO2-equivalent emissions was from enteric-CH4 (51%), direct-N2O emissions (22%) and manure-CH4 (17%). A reduction in dairy cattle by 10-20% decreased the emissions by 10-20% and by 86-90% when combined with silage and arable with or without forestry showed lower emissions over pasture or pasture and silage with 100% dairy cattle (837-845 Mg CO2-equivalent). The results imply that a mixed farming system, a reduction in livestock units and the use of inorganic fertilizers could mitigate and offset on-farm GHG emissions.

Sustainability metrics for quantifying land-use efficiency and evaluating the production efficiency of Ireland's major livestock production systems and the efficiency of human-edible protein compared to potential alternative crops were developed/reviewed. A linear algebraic-based optimization model (GAMS) was developed to represent Ireland's agriculture sector. It was manipulated to demonstrate the environmental and productive

effects of different agricultural activities, and included economic components to demonstrate the economic consequences of different GHG emission reduction activities. This model optimizes the choice and location of land, crops, and livestock to meet productivity demands while minimizing land-use, GHG emissions and coefficient food systems.

Section 2 - Research Outputs

Summary of Project Findings

Agriculture and forestry play a key role in climate regulation through production/removal of GHGs, but require accurate quantification to reduce the uncertainty of GHG offsetting measures for developing carbon-neutral farming systems. This project collected available information/databases on GHGs and C sequestration for use in two whole-farm models (Holos and IFSM), and the Cool Farm tool (CFT) across Irish grassland, dairy, arable farms, and forestry. Holos was able to encompass afforestation and showed that relatively small areas of afforestation could be important in mitigating and offsetting GHGs to make a farm carbon-neutral after 15 years by afforesting a relatively small part of the farmland. The Holos model identified N fertilizer and temperature as the major targets to reduce on-farm GHG emissions. The major contribution to the total 865 Mg CO2-equivalent emissions was from enteric-CH4 (51%), direct-N2O emissions (22%) and manure-CH4 (17%). A reduction in dairy cattle in combination with silage and arable with or without forestry showed lower emissions over pasture or pasture and silage with 100% dairy cattle. This means that a mixed farming system, a reduction in livestock units and the use of inorganic fertilizers could mitigate and offset on-farm GHG emissions. The other two models demonstrated the largest share of GHG emissions originated from fertilizers on arable land and enteric CH4 emissions from dairy cattle. Energy use (e.g. fertilizer and machine operation) was the largest contributor to GHG emissions, followed by N2O emissions from spring barley crops.

A linear algebraic-based optimization model (GAMS) could represent Ireland's agriculture sector while demonstrating the environmental and productive effects of different agricultural activities, and the economic consequences of different GHG emission reduction activities. This model optimizes the choice and location of land, crops, and livestock to meet productivity demands while minimizing land-use, GHG emissions and the impact on food systems.

Summary of Staff Outputs

Research Output	Male	Female	Total Number
Post Doctorates	1	0	1
PhD Students	1	0	1

Summary of Academic Outputs

Research Outputs	Total Number	Details
Publications in Peer Reviewed Scientific Journals	4	1. Khalil, M.I., S.F. Islam, M. O'Neil and B. Osborne. 2020. Measuring and quantifying greenhouse gas emissions from agricultural activities. In: Deryng, D. (ed.), Climate change and agriculture, Burleigh Dodds Science Publishing,Cambridge, UK, 2020, (ISBN: 978 1 78676 320 4; www.bdspublishing.com). p 1-79. doi:10.19103/AS.2020.0064.12. 2. Walkiewicz, A., A. Bieganowski, A. Rafalska, M. I. Khalil and Bruce Osborne. 2021. Contrasting effects of forest type and stand age on soil microbial activities. . Biology 2021, 10, 850. https://doi.org/10.3390 /biology10090850. 3. Walkiewicz, A., P. Bulak, M. Brzezińska, M. I. Khalil and Bruce Osborne. 2021. Variations in Soil Properties and CO2 Emissions of a Temperate Forest Gully Soil along a Topographical Gradient. Forests 12: 226. https://doi.org/10.3390/f12020226 4. D.P. Hennessy, L. Shalloo, H.H.E Van Zanten, I.J.MDeBoer. The net contribution of livestock to the supply of human edible protein: the case of Ireland. The Journal of Agricultural Science: 20/10/2021 https://doi.org/10.1017/S0021859621000642
Peer Reviewed Conference Papers	13	1. Presented a poster at the European Geosciences Union (EGU) conference, Vienna, 2018. 2. Presented a poster at the AgriGHG Conference,Berlin, 2018. 3. Presented a poster at the International Symposium on Non-CO2 Greenhouse Gases, Amsterdam, The Netherlands, 12-14 June 2019.

		4. Delivered several talks at the International Symposium on Non-CO2 Greenhouse Gases, Amsterdam, The Netherlands, 12-14 June2019. 5. Two visits to Aarhus University, Denmark for datasharing, collaboration,and dissemination 6. Islam, S.F., M. I. Khalil, K. Klumpp and B. A.Osborne. 2020. Reducing uncertainty in quantifying and reporting GHG emissions and carbon sequestration from European farming landscapes. In: EGU General Assembly 2020. EGU2020-18708. 7. Walkiewicz, A., P. Bulak, B. Osborne, M.I. Khalil, S.F. Islam, B. Kruijt, R. Hutjes, D. Spengler, P. Gottschalk, T. Sachs, K. Klumpp, A. Vigan, M. Hassouna, D. Henessy and L. Shalloo. 2020. Methane uptake by various forest soils with and without litter. In: EGU General Assembly 2020. EGU2020-4900. https://doi.org/10.5194/egusphere-egu2020-4900. 8. Gottschalk, P., S. F. Islam, J. Hillier, M.I. Khalil and B. Osborne. 2020. Evaluating aspects of the Cool-farm-tool: model assessments versus measurements. Proc. 1st International Symposium on Climate-Resilient Agri-Environmental Systems (ISCRAES 2020), Virtual, 04-06 November 2020. p16. ISSN No. 2737-727X. 9. Islam, S.F., M.I. Khalil and B.A. Osborne. 2020. Reducing uncertainty in quantifying and reporting GHG emissions and carbon sequestration from European farming landscapes. Proc. 1st International Symposium on Climate-Resilient Agri-Environmental Systems (ISCRAES 2020), Virtual, 04-06 November 2020. p67. ISSN No. 2737-727X. 10. Walkiewicz, A., P. Bulak, M.I. Khalil and B.Osborne. 2020. Seasonal variability of CH4 uptake by various forest soils - the effect of temperature and precipitation. Proc. 1st International Symposium on Climate-Resilient

		Agri-Environmental Systems (ISCRAES 2020), Virtual, 04-06 November 2020. p39. ISSN No. 2737-727X. 11. Donagh P. Hennessy, I.J.M. DeBoer, L. Shalloo,and H.H. Van Zanten. 2020. Does the current use of land in Ireland result in feed food competition? Proc. 1st International Symposium on Climate-Resilient Agri-Environmental Systems (ISCRAES 2020), Virtual, 04-06 November 2020. P68. ISSN No. 2737-727X. 12. Donagh P Hennessy, M. Schop, H.E.E van ZantenI.J.M DeBoer, L. Shalloo. Invited speaker at the ATF event at the 72 Annual meeting of the European Federation of Animal Scientists. 30/08/2021 13. Donagh P Hennessy, M. Schop, H.E.E van ZantenI.J.M DeBoer, L. Shalloo. Poster session at the WIAS Annual conference. Wageningen 2022.

Intellectual Property

Though limited, joint ownership of the project outputs/intellectual property rights is governed by the relevant Grant Agreement Article 16.4 and its Annex 5, Section Ownership of the results. The Parties shall have joint ownership of this work as agreed through the consortium agreement and the results will be jointly owned where applicable and shared according to their intellectual, human, material and financial contributions. Each of the joint owners shall be entitled to exploit the jointly owned results and to grant non-exclusive licenses to third parties (without any right to sub-license).

Summary of other Project Outputs

Project Outputs	Details	Total No.
New Technology	This project generated some new approaches/technologies using whole farm models, particularly Holos, with opportunities for further exploitation, for the adoption of mixed farming system including afforestration, a reduction in livestock units and the	0

	use of inorganic fertilizers to mitigate and offset on-farm GHG emissions. A linear algebraic-based optimization model (GAMS) has been developed to represent Ireland's agriculture sector to demonstrate the environmental and productive effects of different agricultural activities, and the economic benefits of reducing GHG emissions. This model could optimize the choice and location of land, crops, and livestock to meet productivity demands while minimizing land-use, GHG emissions and the impact on food systems.	
New Industry Collaborations Developed	Collaboration initiatives had been explored with the ResidueGas project (led by Jorgen Olsen) during a visit by the coordinator in early 2019. This visit did enable the UCD partner to subsequently collect data for modelling purposes. The WUR partner also had preliminary discussions with the Peatwise project leader and the INRA partner with CEDERS and MAGGE-pH. Subsequent email correspondence with the Peatwise project leader and the coordinator had indicated the possibility of future collaborations.	0

Potential Impact related to Policy, Practice and Other Impacts

Impact	Details
Environmental Sustainability	This project contributed to an understanding of the effects of land mosaics and land management on GHG emissions and C-offsetting. In addition to detailed quantification of GHG exchange characteristics of Irish/European land uses, including NH3 as a precursor to N2O emissions, whole farm models, particularly Holos can be used to refine national inventories and facilitate the development of new methodologies and GHG mitigation options,

	and contribute to environmentally-friendly future land use planning.
Socio-Economic	This project has evaluated socio-economic constraints across different land quality, management choices and livestock production systems. This includes the development of methodologies, datasets and tools/software to facilitate GHG reduction, which are economically viable and socially acceptable.

Dissemination Activities

Activity	Details
Workshops at which results were presented	1. The 1st project workshop was held in Lublin, Poland in 2019 2. The 2nd workshop on Land Use Mosaics and Greenhouse Gas Mitigation was heldthrough sponsorship from the project under the auspices of the International Symposium on Climate-Resilient Agri-Environmental Systems (ISCRAES) held in November, 2020
Seminars at which results were presented	1. European Geosciences Union (EGU) conference, Vienna, 2018. 2. AgriGHG Conference, Berlin, 2018. 3. International Symposium on Non-CO2 Greenhouse Gases,Amsterdam, The Netherlands, 12-14 June 2019. 4. EGU General Assembly 2020. 5. International Symposium on Climate-Resilient Agri-Environmental Systems(ISCRAES 2020), Virtual, 04-06 November 2020. 6. The WIAS Annual conference. Wageningen 2022.

Knowledge Transfer Activities

Identify knowledge outputs generated	1. The production of datasets for GHG emissions across landscapes to facilitate parameterization, simulation and validation of whole farm models (Holos and IFSM) and Cool farm Tools (CFT).

during this project.	2. Evaluated the utility of Holos, IFSM and the CFT provided GHG budgets of grassland, dairy and arable farms. 3. The provision of reasonable estimates of GHGs, C sequestration and mitigation potential, although with some limitations. 4. Identification of Holos as a suitable model, with possibilities through replacement of algorithms to include country specific data. 5. Relatively small levels of afforestation might be introduced for mitigating and offsetting on-farm GHG emissions through enhanced carbon sequestration and CH4 oxidation. 6. Shifting from a single land use to a mixed farming system could have considerable potential for mitigating and offsetting on-farm GHG emissions. 7. For achieving carbon-neutrality, a reduction in livestock units and the use of inorganic fertilizers, combined with more afforestation, would be required. 8. The sustainability metrics developed can be used to quantify land-use efficiency and evaluate the production efficiency of Ireland's major livestock systems and choose alternative crops to critically review the efficiency of human-edible protein. 9. The optimization model could forecast land-use changes to attain an environmentally and economically sustainable agriculture sector.
Identify any knowledge transfer activities executed within the project	Some early-stage knowledge transfer activities were initiated during the project on the part of the Netherlands partner as part of their involvement the with farmers in the development of technologies for on farm GHG accounting and the restoration of peat meadows used for grazing.
List any impacts resulting from the knowledge transferred	Any significant impacts of this work are only likely to be important in the longer term. Improved modelling of GHGs and carbon sequestration could, for instance, contribute to more accurate reporting and future policy

during the project	

Section 3 - Leveraging, Future Strategies & Reference

Leveraging Metrics

Type of Funding Resource	Funding €	Summary
EU R&I programmes	€0.00	This project was a critical factor in two successful grant applications, one called ReLive (Back to the Future: Reintegration of land and livestock for GHG mitigation and increased circularity) and the other called TRUESOIL (True SOC Sequestration: Understanding Trade-offs and Dynamic Interactions Between SOC stocks and GHG Emissions for Climate-Smart Agri-Soil Management).

Future Strategies

Our future strategy is to further exploit the GHG Manage results through continued collaboration with former and current collaborators, as well as to extend the work as part of the ReLIVE and TRUESOIL projects funded recently. Future confirmed collaborations with Agriculture and Agri- Food Canada will also enable us to improve the utility of the HOLOS model for a wider range of conditions and its development as an on-farm reporting tool. The data sets obtained as part of the GHG-Manage project will also be further exploited for additional modelling work.

Results from the GHG-Manage project on the effects of land surface properties, including albedo, on global warming are already being exploited within two large consortia to provide improved assessments of how these contribute to radiative forcing.

Project Publications

1. Khalil, M.I., S.F. Islam, M. O'Neil and B. Osborne. 2020. Measuring and quantifying greenhouse gas emissions from agricultural activities. In: Deryng, D. (ed.), Climate change and agriculture, Burleigh Dodds Science Publishing,Cambridge, UK, 2020, (ISBN: 978 178676 320 4; www.bdspublishing.com). p 1-79. doi:10.19103/AS.2020.0064.12.
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3. Walkiewicz, A., P. Bulak, M. Brzezińska, M. I. Khalil and Bruce Osborne. 2021. Variations in Soil Properties and CO2 Emissions of a Temperate Forest Gully Soil along a Topographical Gradient. Forests 12: 226.
4. D.P. Hennessy, L. Shalloo, H.H.E Van Zanten, I.J.M DeBoer. The net contribution of livestock to the supply of human edible protein: the case of Ireland. The Journal of Agricultural Science: 20/10/2021 https://doi.org/10.1017/S0021859621000642

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8. Gottschalk, P., S. F. Islam, J. Hillier, M.I. Khalil and B. Osborne. 2020. Evaluating aspects of the Cool-farm-tool: model assessments versus measurements. Proc. 1st International Symposium on Climate-Resilient Agri-Environmental Systems (ISCRAES 2020), Virtual, 04-06 November 2020. p16. ISSN No. 2737-727X.
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Supporting documents

the-net-contribution-of-livestock-to-the-supply-of-human-edible-protein-the-case-of-ireland (1).pdf

Walkiwiez_et_al._biology-10-00850-v3-2021.pdf

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