Research Stimulus Fund

Final Report

Soil Quality and Research Assessment (SQUARE)

DAFM Project Reference No: RSF 13 S 468

Start date: 1st November 2013

End Date: 30th June 2018

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Please place *one* "x" below in the appropriate area on the research continuum where you feel this project fits

Basic/Fundamental → Applied → Pre Commercial

1	2	3	4	5	6	7
			x			

Please specify priority area(s) of research this project relates to from the National Prioritisation Research Exercise* (NRPE) report;

Priority Area (s)	I. Sustainable Food Production and Processing

Key words: *(max 4)*
Soil quality, Soil health, Soil compaction, Sustainable soil management

1. Rationale for Undertaking the Research

This section should outline the rationale for carrying out the research and identify the need / problem to be addressed

In Ireland the objectives of the Governments Food Harvest 2020 place a demand on soil to support the intensification of agriculture to meet global food security objectives. Simultaneously, greening objectives of the Common Agricultural Policy insist that increases in production must be achieved in a sustainable manner. These increased outputs must come from competitive production systems, while recognising the need for sustainability. Extended-season intensive-grazing systems for ruminant production and intensive crop production systems will underpin this increased production. However, soil resources will require careful management and monitoring to maintain, and or, enhance soil quality and resilience, as greater agricultural output is sought from both productive and marginal land. Increased emphasis on soil quality protection will be necessary to ensure the sustainability of intensive production systems and Food Harvest 2020 specifically identifies improved soil management as a strategic environmental sustainability action. Soil quality has been defined as the capacity of a soil to deliver multiple functions required for the sustainable production of food and fibre, maintaining biodiversity, partitioning water flow, filtering and buffering, cycling nutrients and sequestering carbon. Soil quality, when referred to as soil health, is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans. This definition speaks to the importance of managing soils so they are sustainable for future generations.

Soil compaction has been identified as one of the main threats to soil quality and functionality in Europe and there is limited scientific research on this significant soil threat for Irish soils. In Ireland, there have been relatively few studies on compaction caused by traffic and cultivation; grassland research indicated that silage machinery traffic was having a negative impact on grass yield. The identification of soil compaction is still considered challenging with many studies suggesting the need to combine soil profile examination with physical density or strength tests (e.g. Hatley et al., 2005; Ball et al., 2007). The main aim of this project was to investigate the impact of soil compaction on soil quality and associated soil functions pertinent to agricultural systems; these include i. the sustainable production of food and fibre, ii. maintaining biodiversity, iii. partitioning water flow, filtering and buffering, iv. cycling nutrients and v. sequestering carbon. The knowledge gaps on identification and effects of soil compaction in agricultural soils underpins the focus of the SQUARE project with objectives to;

- Develop a toolbox for farmers to assess soil structural quality
- Further develop understanding of the soil functional capacity and quality concept
- Evaluate the status of soil structural quality in grassland and arable soils across Ireland

- Assess the impact of soil structural degradation on the functional capacity of the soil

2. Research Approach

The SQUARE research project utilized an integrated multidisciplinary team of researchers and advisory personnel to study soil quality and functionality in Ireland and to develop user-friendly tools for soil structural quality assessment. The project comprises of 7 tasks articulated in the following steps:

1. Literature survey to identify key soil types and management systems vulnerable to soil compaction and erosion and knock-on effects to soil functions.
2. Field based soil quality measurement survey aiming to provide an inventory of soil quality data according to agricultural land-use and management intensity for 222 sites (181 grassland and 41 tillage sites) across Ireland. This included;
   - Collecting management information on the main practices carried out on grassland and tillage soils in Ireland.
   - Ascertain changes in soil structural quality across a range of soil management systems for grassland and tillage. This included the combined use of common indicators of soil structural quality and Visual Soil Assessment techniques.
   - Investigate the capacity of soils to preform different soil functions (i.e. Primary Productivity, Nutrient cycling, Water regulation and purification, Carbon sequestration and as a Habitat for biodiversity) to provide a multi-functional perspective on soil quality.
3. Laboratory analysis and quantification of soil attributes/indicator levels from the samples taken from each field sites to examine the relationships between soil properties and soil functions across a range of soil types.
4. Development of new toolkit, including visual soil assessment (VSA) tools, for the evaluation of soil quality to be used by researchers, farmers and advisors in Ireland.
5. Engagement of different stakeholders (farmers, advisory, industry, science and policy) to transfer the knowledge generated from the SQUARE project. The research results and practical tools were disseminated and tested widely through farmer discussion groups, to the farmers who provided access to providing the project field sites, through public and private advisory training by the project researchers and through access to the research sites and to the SQUARE research and advisory team as the work was being conducted across Ireland.

A final matrix of key indicators of soil functionality was compiled for Irish grassland soils, including their ability to inform the delivery/supply of different soil functions. Three classes of indicators (physical, chemical, and biological) were identified to provide holistic assessment of soil quality. The project used this novel methodology to study soil functional capacity.

3. Research Achievements/Results

Research achievements are summarised as follows:

SQUARE Master Database: The project produced a master database combining two independent databases: i. Management information database; ii. Soil quality parameters database. These are qualitative and quantitative data from all the farms surveyed during the project for a total of more than 10.000 entries. The collection of these data in a unique data management tool allowed combining the results to assess the multi-functionality of different soils under different soil managements and explore synergies and trades-off between and within soil functions.

The soil quality database in particular represents the first national database of this kind in Ireland and it is coupled with soil archive. It includes a large reservoir of physical, chemical and biological baseline data and soils functionality indicators for topsoil and subsoil, soil classification data and visual indicators, herbage and production data, geo-spatial data. This database has been leveraged to represent Ireland at European level (in European Environment Agency reports, used by DAFM during EU audits, and in the EU LANDMARK H2020 research project) and represents a baseline for Ireland.

Tools to assess soil structural quality: The project engaged with different stakeholders in the developing and testing of user friendly tools for the assessment of soil structural quality in grassland and tillage. These tools were developed on the principles of the Visual Soil Assessment (VSA) techniques and are user friendly methods to be used by soil surveyors and analysts who need to have a quick and approximate in-situ estimate of the structural quality for various soil functional applications in an Irish agricultural context.

Different VSA tools were developed depending upon the agricultural production system e.g. grassland production versus tillage systems and can be applied to the soil at different depths. Three VSA methodologies were developed namely i. GrassVESS, ii. Double Spade, iii. BD evaluation. These VSA methodologies were tested by groups of farmers, in discussion group settings. Here the different methods were demonstrated and then carried out by the farmers and advisors, in order to assess their practical implementation and if the results were interpreted correctly and to discuss what corrective actions, if needed, could be used. The GrassVESS and Double Spade methods had high levels of use ability and acceptance by farmers and advisors and can be deployed to assess the soil structural quality and levels of soil compaction in grassland and arable fields, respectively https://www.teagasc.ie/environment/soil/research/square/visual-soil-examination-andevaluation/.

Identification of agricultural practices with higher risk for soil structural quality: This project defined the main management practices in grassland and arable land associated with soil compaction and highlighted the challenges for achieving long-term success when using soil compaction remediation methods. It evaluated the extent of soil compaction on agricultural land across Ireland by compiling a nationally representative dataset, where a selected group of direct and indirect indicators of soil structural quality were collated. Soil structure observations collected have been analysed at horizon level and compared with trafficking data (for animal grazing and for machinery passages) in order to study the relationship between management and soil compaction.

Machinery trafficking pressure was shown to have the biggest impact on soil structural quality and hence posed the greatest risk. Poorly drained soils were identified as having the highest vulnerability to management intensity vis-à-vis machinery trafficking operations. This indicates a need to carefully manage machinery operations on poorly drained soils in particular, in order to maintain soil structural quality. Grazing trafficking pressure had much lower effect on soil structural quality. It has been observed that in Ireland the operations related to livestock management are more standardised than those related to machinery traffic. Overall the results indicate that grazing management in Ireland has much lower risk for causing severe and long-term soil compaction. However, there was some evidence that higher grazing trafficking intensity did reduce total porosity in the topsoil and an increased risk for soil structural quality damage from poaching by grazing animals especially under wet soil conditions.

In general, reference values for annual grazing and machinery trafficking pressures, which are nationally representative for Irish grasslands, have been developed. The average annual grazing trafficking pressure observed was 213,914 kg * yr ha^{-1} and the average annual machinery trafficking pressure was 4,411.9 kg * yr ha^{-1}. These figures represent thresholds above which soils are at higher risk of compaction by these common soil trafficking pressures. The methodology used for calculating these threshold values proved to be efficient in characterising soil compaction risks across grassland soils in Ireland.

Soil functional quality and soil health: To study soil functions at national level grassland sites on managed farms across Ireland were preferred to specifically manipulated trial sites. This ensured more robust findings that more likely commonly occur in grasslands, despite the presence of a substantial cross variability among soils. Overall, the health status of Irish grassland soils is relatively good; however, we identified potential weaknesses under certain soils by weather or management situations where soil health may be negatively impacted. Our assessment of physical, chemical and biological indicators of soil health across grassland soils identified differences in the delivery of soil functions according to soil type, climatic region and grassland management system (i.e., grazing vs silage).

While all soils have the capacity to deliver all functions, some soils were better at delivering particular functions compared to others. We found that well-drained soils were more resilient in terms of soil compaction and had high capacity to support the primary production function once balanced nutrition was supplied. However, these soils presented higher risk in terms of water purification and climate regulation. In contrast, poorly drained soils were more prone to structural

compaction and less resilient for production, especially with high trafficking intensity. On the other hand, these soils have high capacity to sequester carbon, to provide a habitat for an active microbiome under low to moderate management intensity. In general, different microbial communities responded differently to nutrient availability/management/drainage with fungal communities responding more clearly to labile soil nutrients and management pressure than bacteria, while bacteria responding more strongly to drainage. Fungal community, symbiotic fungi in particular, showed preference for less intensive soils. These findings highlight the importance of the soil microbiota in supporting plant growth more prominently when anthropogenic input is limited.

4. Impact of the Research

This research has developed the first comprehensive baseline dataset on soil quality/ soil health across agricultural soils in Ireland. The scientific outputs, incl. data sets, soil indicators, models and soil structural quality assessment tools generated have added to national international scientific knowledge on soil quality and have been published of a large number of scientific papers. The results are important for soil quality maintenance and/or improvement and it identified links between threats and solutions. The project was able to identify soils that can be considered at risk of diminishing soil quality and functionality. It highlighted specific management factors that need most control to conserve soil quality, such as machinery pressure, and also specific types of soil (i.e. poorly drained soils for an Irish environment) more prone to suffer such managements. This have the capacity to identify future threats which can be used to inform land management policies including those related to the sustainable intensification objectives for grasslands.

The research has resulted in public good outcomes. The outputs generated support critical knowledge for building resilience and sustainability in the Irish agricultural context and for underpinning advice to farmers. The project evaluated all the different scenarios typical of Irish agricultural systems (e.g. grassland production versus tillage systems) and produced a toolbox of a range of appropriate Visual Soil Assessment methodologies. This toolbox was tested engaging groups of farmers through local farmer discussion groups aiming to demonstrate the methods and collect feedback. The dissemination activity, for this part of the project, was crucial as it allowed the development of the toolbox in a farmer-friendly way. In addition to discussion groups the project outputs were disseminated through workshops, seminar and events such as Teagasc Open days, each one attracting hundreds of farmers, researchers and practitioners. In particular, the methodologies were disseminated through the national advisory services (public and private) and industry (Co-Op, Agri-merchant and Fertiliser Association of Ireland agronomy teams) to enable the national advisors and agronomists to develop a better understanding for recognising signs of soil structural damage and/or decline in soil health. This knowledge and the practical tools and soil quality indicators developed by SQUARE have enabled them to champion the messages within farmer communities all around Ireland. The research facilities, including data sets, methodologies and knowledge established through the SQUARE project are being used to attract other national and international research funding on soil health and to build new collaborations with researchers and research institutes across Europe and the wider world.

4(a) Summary of Research Outcomes

(i) Collaborative links developed during this research

Many collaborative links were developed between the participating researchers and research preforming organizations during the SQUARE project. Collaborations and synergies in terms of research expertise and technical knowledge, sharing access to research laboratories and specialist laboratory analytic instruments and equipment, participating in joint experiments and peer reviewed research outputs and dissemination events have been established. Close collaborative links between Teagasc and University supervisors of the PhD students have been developed. In addition links have been built between the research involved and the farmers who provided access to field sites for taking measurements and conducting experiments. Collaborative links between research and industry in terms of dissemination and knowledge transfer have been developed also.

(ii)Outcomes where new products, technologies and processes were developed and/or adopted

Three Visual soil assessment (VSA) methodologies were developed namely i. GrassVESS, ii. Double Spade, iii. BD evaluation. The GrassVESS and Double Spade methods had high levels of use ability and acceptance by farmers and advisors and can be deployed to assess the soil structural quality and levels of soil compaction in grassland and arable fields, respectively https://www.teagasc.ie/environment/soil/research/square/visual-soil-examination-andevaluation/. A soil structural quality assessment field handbook was developed "The Soil Structure ABC. A practical guide to managing soil structure. *Teagasc* Available at: https://www.teagasc.ie/media/website/environment/soil/The-soil-structure-ABC.-A-practicalguide-to-managing-soil-structure.pdf

(iii) Outcomes with economic potential

This work clearly shows that soil compaction can have a negative effect on agricultural output (grass and crop production) and on the environment (water drainage, nutrient runoff, soil biodiversity and green house gas emissions) however, soil assessment using the VSA technologies and soil quality indicators developed by SQUARE and subsequent remediation using best soil management practices to restore soil quality has economic and environmental benefits.

(iv) Outcomes with national/ policy/social/environmental potential

This national scale research has developed a baseline for soil quality/soil health for agricultural soil in Ireland. These data and scientific papers been used to support Ireland/ policymakers when responding to EU audits of soil quality/soil biodiversity under CAP and other directives. The SQUARE project also provides baseline /reference overview of agricultural soil quality status in Ireland over the period 2013-2018, linked with soil type, land-use and agricultural management. The project has defined a set of practical and sensitive soil quality indicators for future national soil health monitoring

schemes and to inform and potentially underpin aspects of future soil and environmental policy (incl. CAP, EU Green Deal, Biodiversity Strategy 2030 to name but a few) when responding to future soil threats and challenges for land management under changing climate, agricultural land use and intensity.

4 (b) Summary of Research Outputs

(i) Peer-reviewed publications, International Journal/Book chapters.

1. Bondi, G., O'Sullivan. L., , Fenton, O., Creamer, R., Marongiu, I., Wall, D.P. (2020) Trafficking intensity index for soil compaction management in grasslands. *Soil Use and Management.* https://onlinelibrary.wiley.com/doi/full/10.1111/sum.12586
2. Graça, J., Daly, K., Bondi, G., Israel, I., Crispie, F., Cabrera-Rubio, R., Cotter, P., Schmalenberger, A. Drainage class and soil phosphorus availability shape belowground microbial communities in Irish grasslands. *Applied Soil Ecology*. *Under review*.
3. Bacher, M., Schmidt, O., Bondi, G., Fenton, O. Influence of dung pats on soil physical quality mediated by earthworms: From dung deposition to decay and beyond. *Soil research* 58(5):421429.
4. Emmet-Booth, J. P., Holden, N. M., Fenton, O., Bondi, G., Forristal, P. D. (2019). Exploring the sensitivity of visual soil evaluation to traffic-induced soil compaction. *Geoderma regional*. e00243
5. Emmet-Booth, J. P., Forristal, P. D., Fenton, O., Bondi, G., Holden, N. M. (2019). Visual soil evaluation – spade vs. profile methods and the information conveyed for soil management. *Soil & Tillage Research*. 187, 135-143.
6. Bacher, M., Fenton, O., Bondi, G., Creamer, R., Karmarkar, M., Schmidt, O. (2018). The impact of cattle dung pats on earthworm distribution in grazed pastures. *BMC Ecology*. 18(1), 59.
7. Bacher, M., Schmidt, O., Bondi, G., Creamer, R., Fenton, O. (2019). Comparison of soil physical quality indicators using direct and indirect data inputs derived from a combination of in-situ and ex-situ methods. *Soil Science Society of America Journal*. 83(1), 5-17.
8. Bondi, G., Creamer, R., Ferrari, A., Fenton, O., Wall, D.P. (2018). Using machine learning to predict soil bulk density on the basis of visual parameters: Tools for in-field and post-field evaluation. *Geoderma*. 318, 137-147.
9. Emmet-Booth, J. P., Bondi, G., Fenton, O., Forristal, P. D., Jeuken, E., Creamer, R., Holden, N. M. (2018). GrassVESS: a modification of the visual evaluation of soil structure method for grasslands. *Soil Use and Management*. 34(1), 37-47.
10. Fenton, O., Vero, S., Schulte, R. P. O., O'Sullivan, L., Bondi, G., Creamer, R. (2017). Application of Dexter's soil physical quality index: an Irish case study. *Irish Journal of Agricultural and Food Research*. 56(1), 45-53.
11. Emmet-Booth, J. P., Forristal, P. D., Fenton, O., Ball, B. C., Holden, N. M. (2016). A review of visual soil evaluation techniques for soil structure. *Soil use and management*. 32(4), 623-634.

12. Coyle, C., Creamer, R. E., Schulte, R. P., O'Sullivan, L., Jordan, P. (2016). A functional land management conceptual framework under soil drainage and land use scenarios. *Environmental Science & Policy*. 56, 39-48.

(ii) Popular non-scientific publications and abstracts including those presented at conferences

1. Bondi, G., Emmet-Booth, J. P., Forristal, P. D. (2019). SQUARE: Tools to assess soil structural quality in tillage soils. *Teagasc National Tillage Crops Conference 2019, Kilkenny, Ireland.* Oral Presentation.

2. Bondi, G., Wall, D.P. (2018). Assessing and monitoring soil quality in Irish grassland soil. *BSAS Annual Conference 2018. 9th April 2018 - 11th May 2018, Dublin, Ireland.* Oral Presentation.

3. Bondi, G., Wall, D.P. (2018). Assessing and monitoring soil quality in Irish grassland soils: an index of management intensity to support soil quality for sustainable intensification. *International Fertiliser Society (IFS) Cambridge, December 2018*. Poster Presentation.

4. Wall D.P, Bondi, G., O'Sullivan, L. (2018). The multi-functionality of grasslands for delivering soil based ecosystem services. *27th General Meeting of the European Grassland Federation, Cork, Ireland, conference proceedings. 691-693, ISBN : 9781841706436.* Oral Presentation.

5. Bondi, G., Wall D.P, Bacher M., Emmet Booth, J., Graça, J., Marongiu, I., Creamer, R. (2017). Impact of grassland management in microbial communities and soil structure. *SSSA, ASA and CSSA Meeting 2017. Tampa, Florida, https://scisoc.confex.com/crops/2017am/webprogram/Paper108897.html*. Oral Presentation.

6. Bondi, G., Wall D.P, Bacher M., Emmet Booth, J., Graça, J., Marongiu, I., Creamer, R. (2017). Assessing soil structural quality in Irish grassland. *Wageningen Soil Conference 2017. Wageningen, Netherlands, conference proceedings.* Oral Presentation.

7. Bondi, G., Wall, D.P, Bacher, M., Emmet Booth, J., Graça, J., Marongiu, I., Creamer R. E. (2017). Role of soil biology and soil functions in relation to land use intensity. *19th EGU General Assembly 2017. Vienna, Austria. http://adsabs.harvard.edu/abs/2017EGUGA..1915021B.* Oral Presentation.

8. Emmet-Booth, J. P., Forristal, P. D., Fenton, O., Bondi, G., Creamer, R. E., Holden, N. M.(2017). Impacts of soil moisture content on visual soil evaluation. *EGU General Assembly 2017. Vienna, Austria. http://adsabs.harvard.edu/abs/2017EGUGA..19.8129E.* Oral Presentation.

9. Emmet-Booth, J. P., Forristal, P. D., Fenton, O., Bondi, G., Creamer, R. E., Holden, N. M.(2017). Impacts of soil moisture content on visual soil evaluation. *EGU General Assembly 2017. Vienna, Austria. http://adsabs.harvard.edu/abs/2017EGUGA..19.8129E.* Oral Presentation.

10. Bondi, G., Wall, D.P., Bacher, M., Emmet Booth, J., Graça, J., Marongiu, I., O'Sullivan, L., Creamer R. (2016). Multi-functional capacity of soils in relation to national soil landscapes. *European Ecosystem Services (EES) conference, Antwerp, Belgium, conference proceedings.* Oral Presentation.

11. Bondi, G., O'Sullivan, L., Wall, D.P., Marongiu, I., Creamer R. E. (2016). An innovative index of land use intensity in Irish grassland soils. *Soil - our common future: European Society for Soil Conservation (ESSC) International conference, Cluj Napoca, Romania. Presa Universit. Clujeană. 25, ISBN 978-973-595-9821.* Oral Presentation.
12. Graça, J., Bondi, G., Creamer, R.E., Schmalenberger, A., Daly, K. (2016). Assessing changes in soil microbial biomass in grassland soils. *Society for Applied Microbiology (SfAM) Summer Conference Edinburgh, UK, conference proceedings.* Poster Presentation.
13. Graça, J., Bondi, G., Creamer, R.E., Schmalenberger, A., Daly, K. (2016). Taping into phosphorus reserves in Irish grassland soils. *ENVIRON 2016, 26th Irish Environmental Researchers' Colloquium, Ireland, Limerick, conference proceedings.* Oral Presentation.
14. Bacher, M., Fenton, O., Creamer, R., Schmidt, O. (2016). Earthworms and Dung pats. *ENVIRON 2016, 26th Irish Environmental Researchers' Colloquium, Ireland, Limerick, conference proceedings.* Oral Presentation.
15. Graça, J., Bondi, G., Creamer, R.E., Schmalenberger, A., Daly, K. (2016): Organic phosphorus fractions in extensive and intensive Irish grasslands. *Organic Phosphorus Workshop (OP2016), 'Organic Phosphorus in the Environment: Solutions for Phosphorus Security', Lake District, England, conference proceedings.* Oral Presentation.
16. Bacher, M., Fenton, O., Creamer, R., Schmidt, O. (2016). Underestimation of earthworms in grassland. *ASA, CSSA & SSSA International Annual Meetings, at Phoenix, U.S., on the 6th – 9th of November, 2016.* Oral Presentation.
17. Emmet-Booth, J. P., Forristal, P. D., Fenton, O., Holden, N. M. (2016). A simple procedure for estimating soil porosity. *EGU General Assembly 2016. Vienna, Austria.*
18. Bacher, M., (2015). Seminar "Soil Science – Diggin' it" - *at University College of Dublin, Soil Science Society of Ireland on the 3rd December 2015.* Oral Presentation.
19. Graça, J., (2015). Seminar "Soil Science – Diggin' it" - *at University College of Dublin, Soil Science Society of Ireland on the 3rd December 2015.* Oral Presentation.
20. Jeuken E., Fenton, O., Coyle, C. (2016). *Soil Fertility Conference 2016, Kilkenny, Ireland.* Oral Presentation.
21. Bondi, G. (2019). The soil beneath our feet. *Teagasc Today's Farm, September-October 2019*, Vol.30, №5, 24-25. Available at: https://www.teagasc.ie/media/website/publications/2019/Environment---The-soil-beneathour-feet.pdf
22. Bondi, G., Fenton, O., Daly, K., Wall, D.P. (2019). Putting soil health on the agenda. *Teagasc T-Research*, Vol.14, №1, 24-25. Available at: https://www.teagasc.ie/media/website/publications/2019/TResearch_Spring2019_SoilHealth_p24-25_proof.pdf
23. Wall, D.P., Fenton, O., Clagnan, E., Buckley, C., Tuohy, P., Bondi, G. (2018). Nutrient balances and soil condition: effects on dairy grassland productivity (2018). *International Fertiliser Society (IFS) Cambridge*, December 2018. Proceedings №. 828, pp: 1-28. ISBN 978-085310-465-0

24. Emmet-Booth, J. P., Forristal, P. D., Fenton, O., Bondi, G., Wall, D.P., Creamer, R. E., Holden, N. M. (2018). The Soil Structure ABC. A practical guide to managing soil structure. *Teagasc* Available at: https://www.teagasc.ie/media/website/environment/soil/The-soil-structure-ABC.A-practical-guide-to-managing-soil-structure.pdf

25. O'Sullivan, L., Bampa, F., Bondi, G., Coyle, C., Creamer, R., Murphy, P., Simo, I., Wall, D.P. and Schulte, R. (2014). Functional land management. How can we get the most from our land? *Teagasc T-Research,* Vol.9, №3, 34-35.

(iii) Workshops/seminars at which results were presented

The findings from the project and the methodologies developed were presented on multiple occasions at various events during the project. Details these events are as follows;

Advisory and farmer discussion groups and workshops:

- 28th of June 2018. SQUARE project final workshop at DAFM buildings and Teagasc Research Farm, Johnstown Castle, Co. Wexford. Talks and field demonstrations were given by all members of the project.
- 7th June 2016. SQUARE results and tools were presented to farmer discussion groups in Macroom, Co. Cork. A brief talk followed by field demonstration was given by Rachel Creamer, Giulia Bondi, Eileen Jeuken and Jeremy Emmet-Booth
- 9th of November. SQUARE results and tools were presented to farmer discussion group in Colooney, Co. Sligo. A presentation on "Soil Structure Quality" and a field demonstration on GrassVESS technique were given by Eileen Jeunken.
- 14th of November 2016. SQUARE results and tools were presented to farmer discussion group in Calry, Co. Sligo. A presentation on "Soil Structure Quality" and a field demonstration on GrassVESS technique were given by Eileen Jeunken.
- 15th March 2016. SQUARE results and tools were presented at an ITLUS open day held at Teagasc, Johnstown Castle, Co. Wexford. Talks and field demonstrations were provided by David Wall, Rachel Creamer, Giulia Bondi, Jessica Graca, Dermot Forristal and Jeremy EmmetBooth.
- Cereals 2015 at Teagasc, Oak Park Open day, Co. Carlow. The SQUARE project had an exhibition on soil structure, drainage and earthworms. This was hosted by Rachel Creamer, Jeremy Emmet-Booth and Matthias Bacher.
- Moorepark 2015 at Teagasc, Moorepark Open day, Co. Cork. This grassland farming event attracts over 5000 farmers from around the country. The SQUARE project had an exhibition on soil structure. This was hosted by Giulia Bondi and Jeremy Emmet-Booth.
- 28 September 2015. Carlow advisor and farmer workshops on soil structure. Meetings were led by Rachel Creamer, Giulia Bondi and Jeremy Emmet-Booth.
- 23 October 2015. Wexford advisor and farmer workshops on soil structure. Meetings were led by Rachel Creamer and Jeremy Emmet Booth.

Lectures:

- 26th February 2016. A demonstration was given to Waterford IT under-grad students on visual soil evaluation and hand texturing by Giulia Bondi and Jeremy Emmet-Booth. Furthermore, two lectures on "Soil drainage" and "Soil Fertility Management" were provided by Owen Fenton and David Wall.
- 21st March 2016. A lecture on Soil Fertility Management and a demonstration on visual soil evaluation were given to the UCD under-grad students by David Wall and Giulia Bondi.
- 2nd of November 2016. A presentation on "Soil Structure Quality" and a field demonstration on GrassVESS technique were given to the Green Certificate level 5 students in Teagasc Athenry, Co. Galway by Eileen Jeunken.
- 7th – 8th November 2016. A demonstration on hand texturing and on GrassVESS technique was given to Carlow IT under-grad students by Giulia Bondi and Eileen Jeunken.
- 2nd – 3rd November 2016. Two lectures on "Nutrients applications" and "Soil Drainage" were given by David Wall and Owen Fenton during the "Crops Nutrient Management Course" in Teagasc, Johnstown Castle. Furthermore A demonstration on hand texturing was given by Giulia Bondi.
- 5th of July, 2016, a brief talk on soil functions and a demonstration on on GrassVESS technique were given by Eileen Jeuken and Cait Coyle at the Beef Open Day at Grange, Co. Meath.
- November, 2016 a demonstration of the GrassVESS method to the public was given by Eileen Jeuken in the Research Showcase during the "Science Festival" event at IT Sligo.
- November 2015. Two lectures on "Nutrients applications" and "Soil Drainage" were given by David Wall and Owen Fenton during the "Crops Nutrient Management Course" in Teagasc, Johnstown Castle. Furthermore a demonstration on hand texturing was given by Giulia Bondi.

(v) Intellectual Property applications/licences/patents

All project outputs and technologies are for public good and available to the public.

(vi) Other

Both public and private advisory services have received training on the VSA techniques developed by SQUARE and have disseminated and utilised this knowledge with individual farmers to investigate /diagnose problems and as topics at farmer's discussion group meetings, industry fieldday events for farmers, agronomists, etc.

5. Scientists trained by Project

Total Number of PhD theses: __3__

- 2018: Dr. Jessica Graça; Thesis: Evaluation of Phosphorus Supply Capacities in Irish Grassland Soils. Teagasc and University of Limerick, Ireland.

- 2018: Dr. Jeremy Emmet-Booth; Thesis: Evaluation of Visual Soil Structure Assessment methods for research and management deployment in temperate maritime grassland and arable soils. Teagasc and University College Dublin, Ireland.

- 2018: Dr. Matthias Bacher; Thesis: Earthworms and soil physical quality in grazed grasslands in Ireland. Teagasc and University College Dublin, Ireland.

Total Number of Masters theses: __0__

6. Permanent Researchers

Institution Name	Number of Permanent staff contributing to project	Total Time contribution (person years)
Teagasc (JC)	6	2.32
Teagasc (OP)	1	0.41
University College Dublin	2	0.41
University of Limerick	1	0.25
IT Sligo	1	0.58
Total	**11**	**3.98**

7. Researchers Funded by DAFM

Type of Researcher	Number	Total Time contribution (person years)
Post Doctorates/Contract Researchers	1	3.9
PhD students	3	12
Masters students	0	
Temporary researchers	3	5
Other	0	
Total	**7**	**20.9**

8. Project Expenditure

Total expenditure of the project: € 977,061

Total Award by DAFM: € 1,017,315

Other sources of funding including benefit in kind and/or cash contribution(specify): € 0

Breakdown of Total Expenditure

Category	Teagasc	University College Dublin	University of Limerick	IT Sligo	Total
Contract staff	135,304.30	0.00	0.00	0.00	135,304.30
Temporary staff	0.00	0.00	0.00	21,999.84	21,999.84
Post doctorates	182,158.25	0.00	0.00	0.00	182,158.25
Post graduates	87,999.98	92,466.54	72,744.08	0.00	253,210.25
Consumables	57,859.31	8,827.30	7,205.52	425.31	74,317.44
Travel & subsistence	38,006.29	17,609.37	6,187.78	5,298.41	67,101.85
Sub total	**401,328.10**	**118,903.21**	**86,137.38**	**27,723.56**	**734,092.28**
Durable equipment	975.32	0.00	8,328.74	0.00	9,304.06
Other	4,455.51	4,555.00	3,227.32	1,200.00	13,237.83
Overheads	150,398.40	35,670.96	25,841.21	8,317.07	220,227.68
Total	**657,157.40**	**159,129.17**	**123,534.65**	**37,240.63**	**977,061.85**

9. Leveraging

The data, information and tools developed in the SQUARE project has helped to place Ireland at the forefront of soils research knowledge and expertise internationally. The researchers have leveraged this position to successfully compete for EU Horizon 2020 research funding (e.g. LANDMARK, SOILCARE, SOIL-MISSION-SUPPORT and the EJP-SOIL focused on sustainable soil management.

10. Future Strategies

SQUARE has established a baseline of soil quality across agricultural soils across Ireland and provides a key reference for subsequent surveys of soil quality that have been encouraged in the EU Soil Health and Food Mission, EU Farm to Fork Strategy and EU Biodiversity Strategy 2030 for EU Member States. A subsequent national soil sampling campaign with measurements and analysis of soil physical, chemical and biological indicators is required to build on this SQUARE soil quality baseline dataset and requires funding for research to provide new insights to protect and enhance of soil health in Ireland for future generations. The set of soil quality (soil health) indicators and soil assessment tools

identified and evaluated during SQUARE require wider deployment across soils, land uses and agricultural managements to expand the soil quality database for Ireland. Based on this research the effects of soil trafficking intensity leading to soil compaction was established, and similarly, the effects of other soil management practises including, nutrient management, pesticide management, soil inversion and tillage, grazing and cutting regimes, crops and grass species and crop rotations, etc. on soil quality needs to be understood. This information is required to develop recommendations for advising on best soil management practices for farmers and land managers in future and to inform agri-environmental policy for the protection of soils.