

Overcoming barriers to achieving a Net Zero agri-food sector: challenges and solutions

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1. Introduction

Agriculture is central to global food security, sustaining rural populations, and public health. Despite this, it remains a significant climate mitigation challenge. Globally, between 21–37% of total global anthropogenic greenhouse gas emissions (GHGE) are attributable to the food system (Mbow et al., 2019), with livestock production accounting for 12–14.5% (Rosa & Gabrielli, 2023; Gerber et al., 2013). In the European Union (EU), livestock production accounts for 65% of total agricultural GHGE (Scheid et al., 2025) – with agriculture expected to account for a third of total GHGE by 2050 (McGuire et al., 2023a). Notwithstanding this, soils and aboveground biomass act as a global carbon sink to balance the net contribution of agriculture to anthropogenic climate change (Amelung et al., 2020; IPCC, 2022) – with soil organic carbon (SOC) representing significant potential for additional sequestration – ~160 times the current annual anthropogenic CO₂ emission rate (Amelung et al., 2020; Friedlingstein et al., 2022; Henderson et al., 2022).

Carbon emissions and removals are fundamental for a Net Zero agri-food sector. At farm-level, there is a consensus on the abatement significance of adopting existing GHG abatement technologies (e.g. CH₄ inhibitors) and practices (e.g. CO₂ removals) to meet national and regional targets – especially for livestock production (Hristov et al., 2013; Bellarby et al., 2013). This potential has been demonstrated across dairy and beef systems in Europe, North America and Australia (Vargas et al., 2024; McNicol et al., 2024; Bilotto et al., 2025; Magowan et al., 2020). Nonetheless, the uptake of available “win–win” mitigations (low cost – high return) remains low in livestock production systems (Groher et al., 2020 pg. 2410; Kyriazakis et al., 2024).

In this context, the current study aims to address a key research question: what are the barriers impeding progress towards Net Zero for agri-food production? We place particular focus on livestock production. To address this research question, supported with (1) a literature review, (2) policy synthesis, and (3) European case-studies (including, but not limited to the UK, Ireland, and Denmark), we employ qualitative research methodologies, similar to Feliciano et al., (2014) and Whitton and Carmichael (2024) – drawing upon the outputs of an international science-policy-society workshop.

2. Literature Review

Barriers to achieving Net Zero agriculture range from conceptual challenges, such as defining Net Zero across different agricultural systems, to practical constraints including carbon accounting, mitigation costs and farm-level implementation (see Supplementary Table 2). Existing research consistently identifies barriers spanning policy and governance, economics, MRV, knowledge exchange and farmer behaviour.

Early work by Smith et al. (2007) highlighted carbon leakage, mitigation costs and uncertainty surrounding soil organic carbon sequestration (SOCS), emphasising the need for improved national greenhouse gas inventories (NGHGI) and verification systems. Subsequent studies similarly identified policy design, financial incentives, farmer knowledge exchange (KE), and behavioural change as key

determinants of mitigation uptake (Feliciano et al., 2014; Morcillo et al., 2018; Smith et al., 2020; Kundu et al., 2024; Oliveira et al., 2024; Sharififar et al., 2025). More recent research has further highlighted limitations in existing carbon markets, including inconsistent MRV, permanence, double counting, and leakage arising from trade [e.g., EU-Mercosur Trade Agreement (EMTA)] – while emphasising the need for credible carbon farming frameworks and standardised verification (Paul et al., 2023; Oliveira et al., 2024; Yang and Park et al., 2025; Debernardini et al., 2025).

In parallel, international policy frameworks, including the Paris Agreement and European Green Deal, have accelerated the development of carbon farming and carbon removal policies [e.g., European Carbon Removals Carbon Farming regulation (CRCF) and the Australian Carbon Credit Unit]. However, implementation remains fragmented across jurisdictions, with differing approaches to certification, incentives and governance.

Collectively, the literature identifies five recurring categories of barriers to Net Zero agriculture: (1) policy and governance, (2) economic and market, (3) MRV and data limitations, (4) knowledge exchange, and (5) behavioural and social barriers. Whilst existing studies tend to examine these barriers individually or within specific mitigation pathways, relatively few integrate them within a science-policy-society framework informed by stakeholder engagement. This study addresses that gap by combining qualitative workshop evidence with policy analysis and European case studies to examine how these barriers interact in practice.

3. Methods

During the summer of 2023, Queen's University Belfast held an international workshop, by bringing together global leading experts across the “quadruple helix”: (1) academia (n=12), (2) government (n=13), (3) industry (n=10), and (4) civil society (n=4), within a high impact knowledge-exchange environment.

The purpose of the workshop was to explore emerging scientific, economic, and governance barriers to achieving Net Zero in agri-food systems, especially livestock systems, and to identify priority areas for interdisciplinary research and policy engagement. The workshop formed part of a wider Queen's University Belfast initiative to develop interdisciplinary evidence supporting Net Zero agriculture. This paper presents and scrutinises the results of this workshop, which was composed of three primary aims: (1) critically identify and define the main barriers to achieving Net Zero in agri-food, (2) establish solutions, and (3) provide recommendations to overcome them.

Workshop participants (n = 40) were recruited through semi-structured interviews using snowball sampling. The most prominent barriers were identified through inductive thematic analysis of the qualitative data (Feliciano et al., 2014; Bradford et al., 2022; Whitton & Carmichael, 2024). All interviews were transcribed verbatim. Four researchers independently coded the transcripts to identify recurring concepts, patterns, relationships and divergences, before collectively reviewing and refining the coding framework through an iterative comparative process. Coding discrepancies were resolved by consensus, with related codes grouped into higher-order themes. The ten most prominent barriers

were then identified based on the frequency of references, consistency across transcripts, and relevance to the study objectives (Table 1). A full description of the workshop methodology, outputs and qualitative analysis is provided in the Supplementary Material (Table 2).

Building upon the workshop outputs, as thematically identified in Table 1, the current study establishes that barriers to Net Zero agri-food are embedded within: (1) policy, (2) MRV, and (3) positive behavioural change – especially among farmers to enhance adoption of low emission practices. These outputs were complemented by a targeted review of national and European policy documents to provide policy context for the barriers identified by participants. European case studies were selected because they reflected the principal geographical representation and policy interests of workshop participants (Ireland, the UK, Denmark and European Union institutions). Rather than providing a systematic comparison of national approaches, these case studies were used to illustrate how common barriers to Net Zero agriculture are manifested across different policy settings. The principal policy documents underpinning each case study are listed in the Supplementary Material.

Barrier	Classification	Accountability
1) Policy shifts, changing policy dynamics, and political instability	<i>Policy.</i>	Government.
2) The 'one-size fits all mitigation' approach.	<i>Policy.</i>	Government; industry.
3) Agriculture positioned as "horizontal" / multi-sectoral.	<i>Policy.</i>	Government.
4) Carbon measurement, reporting, and verification (MRV).	<i>MRV.</i>	Government; industry; farmer.
5) Data access, guardianship, protection, validation (GDPR).	<i>MRV, policy, and behavioural change.</i>	Farmer; industry; government; consumer.
6) Knowledge-exchange with farmers – including technical skill development.	<i>Behavioural change.</i>	Farmer; industry; advisory group/service; government.
7) Trust and transparency.	<i>Behavioural change.</i>	Farmer; industry; government.

8) The “market” for management changes towards Net Zero.	<i>Behavioural change and policy.</i>	Farmer; industry; government; consumer.
9) Farmer societal displacement.	<i>Behavioural change.</i>	Media; farmer; industry; government; consumer.
10) The economics and costs of different GHGE mitigations.	<i>Behavioural change and policy.</i>	Farmer; industry; government.

Table 1: The 10 most prominent barriers, including classification and accountability, towards a Net Zero agri-food sector.

4. Policy Barriers

The workshop identified several policy-related barriers (Barriers 1, 2,3, and 10), and two principal policy-related barriers: (Barrier 1) policy shifts, changing policy dynamics and political instability, and (Barrier 10) the economics and costs of GHGE mitigation measures. Although presented as distinct barriers, discussions during the workshop highlighted that both ultimately converge on a common challenge: the ability of policy frameworks to create stable, long-term incentives that enable farmers to adopt and maintain low-emission practices..

The literature similarly shows that achieving Net Zero agriculture depends not only on technical mitigation options but also on policy certainty, economic viability, and alignment between environmental objectives and farm-level decision making (Henderson et al., 2022; Feliciano et al., 2014). Accordingly, this section focuses on two interconnected policy themes emerging from the literature, workshop findings, and case studies: (1) subsidy design and economic incentives, and (2) carbon leakage and policy coherence in international trade.

4.1 Subsidies and Economic Incentives

Achieving Net Zero in agri-food systems requires differentiated strategies tailored to farm economics and scale. For livestock farms, targeted public investment can overcome financial barriers to adoption of high-cost mitigations. As illustrated by Marginal Abatement Cost Curves (MACC), mitigation options span a wide range of costs and effectiveness (Teagasc, 2023). Low-cost high-return options, such as improved breeding programmes (economic breeding index), animal health enhancements, and multi-species swards, offer “win-win” solutions for farmers (left-hand side of the MACC). Conversely, high-cost high-return mitigations such as enteric CH₄ inhibitors and low emission slurry spreading require substantial investment and may be perceived as “win-loss” options for farmers (right-hand side of the MACC) (Kyriazakis et al., 2024). Public support mechanisms can facilitate uptake of these capital-intensive solutions.

Alternatively, for financially constrained farms, diversification away from GHG-intensive livestock production may represent a more economically viable pathway to Net Zero (Sakrabani et al., 2023; Henn et al., 2025). This may involve either land sparing, whereby less productive land is redirected towards conservation, or land sharing, where livestock production is integrated with biodiversity-friendly management. A combination of both approaches (“hybrid landscape”) is often considered most effective for balancing ecosystem services with food production (Balmford et al., 2012). Nonetheless, implementation remains challenging. In several European countries, including the UK, Ireland and Denmark, structural change has increasingly favoured the consolidation of smaller farms into larger enterprises. Rising compliance costs, capital requirements and regulatory demands can disproportionately affect smaller farms, potentially accelerating land consolidation and influencing the social and economic outcomes of Net Zero policies.

Farmers are more likely to participate in finance-based interventions when schemes provide flexibility and allow farmers a degree of control over implementation. Stakeholder engagement through the multi-actor approach (MAA) is therefore important given the unpredictable nature of farming (e.g. climate variability, geopolitical events and fluctuating production costs). In the UK, several support schemes now incentivise low-carbon farming through payments for public goods, sustainable land management and investment in innovation (Ortiz et al., 2021; Ayres, 2023). However, uptake may remain limited where schemes are voluntary, require long-term commitments, lack flexibility, or fail to reflect differences in farm type, scale and location. In addition, the growing number of public and private funding mechanisms can create uncertainty and inconsistencies in Net Zero implementation.

For example, in Northern Ireland (NI), ‘farmer inclusion’ proved to be a substantial issue within the Environmental Farming Scheme. This barrier was found within the minimum entry requirement for grant applications; farmers could only apply for a minimum of £2,500 funding over a 5-year agreement. This time period between farmer investment and receipt of funding resulted in ‘scheme entry’ becoming impossible for many farmers with limited cash flow. In Ireland, the Department of Agriculture, Food and the Marine (DAFM), through the National Climate Action Plan (2024), is developing a Carbon Farming Framework to support robust governance, validation and measurement of carbon farming. However, public consultation highlighted continued uncertainty regarding farmer participation. While just over half of respondents indicated they would participate in such a scheme, most believed that carbon farming and associated biodiversity measures should be funded by the State or the EU rather than individual farmers. These findings reinforce the financial barriers to wider adoption of carbon farming practices (DAFM, 2024).

Although Van Hoof (2023) argued that European low-carbon farming lacks robust legislative frameworks, several countries are increasingly shifting from subsidy-based measures towards regulatory approaches. The proposed reduction of livestock numbers in the Netherlands to meet the EU Water, Nitrates and Habitats Directives illustrates the political challenges of this transition (Boezeman et al., 2023). By contrast, Denmark's "Green Tripartite" demonstrates a more collaborative approach. Following decades of limited progress (Dalgaard et al., 2014), the prospect of stricter regulation prompted negotiations in 2023 between government, farmer organisations, ENGOS, the

food industry, trade unions and local authorities, culminating in the parliamentary approval of the *Deal on a Green Denmark* in 2024 (State of Green, 2024).

The agreement aims to: (1) reduce agricultural GHGE, (2) protect aquatic ecosystems, (3) enhance nature and biodiversity, (4) safeguard groundwater resources, and (5) maintain a competitive agricultural sector. These objectives are supported through three principal measures: (1) a phased agricultural CO₂e tax (€40 t⁻¹ CO₂e in 2030, increasing to €100 t⁻¹ by 2050) with a base deduction reflecting technically unavoidable emissions, (2) targeted regulation of agricultural nitrate leaching, and (3) land-use change, including conversion of approximately 10% of agricultural land to forestry and nature restoration (e.g. rewetting cultivated peatlands), delivered through 23 local Green Tripartite partnerships.

4.2 Carbon Leakage

Perhaps the most contentious issue of post-production emissions is that of carbon leakage, a phenomenon that can significantly undermine the efforts of local and national farmers targeting Net Zero. Carbon leakage refers to the “leakage” of emissions from one location to another, occurring when efforts to reduce GHGE in one region lead to relocation of the production and associated emissions – typically to different countries with more lenient policies. Therefore, such businesses are not subjected to emission reduction measures such as carbon pricing, this risk is particularly prevalent in energy-intensive industries (European Commission, 2023). This issue is not limited to carbon, but extends to biodiversity leakage and other socio-economic issues including forced labour – embodied in trade agreements.

For European agriculture, although free-trade agreements (FTAs) offer wider macroeconomic benefits and may improve food affordability for consumers, they have generated considerable opposition among farmers, particularly livestock producers (Matthews, 2024; Henley, 2024). Recent concerns have centred on tariff-rate quota (TRQ) agreements, including the EU–Mercosur Trade Agreement, which permits imports of 99,000 tonnes of beef into EU markets (de Oliveira et al., 2024), and the UK–Australia Free Trade Agreement, allowing approximately 110,000 tonnes of Australian beef into the UK market. Using a general equilibrium model, Gohin and Matthews (2025) estimated that, although the EU–Mercosur Agreement may generate modest indirect economic benefits for the EU cattle sector while maintaining EU sanitary and phytosanitary standards, it could reduce EU cattle farm incomes by 0.4–5.2%, increase profits for Mercosur producers, and contribute to an additional 1,500–1,800 ha (15–18 km²) of deforestation.

Such deals demand local farmers to go ‘toe to toe’ with such competitors whilst maintaining rigorous environmental and animal welfare standards (McGuire et al., 2023b) as per national and European policies (e.g. Green Deal). This may undermine the environmental integrity of Net Zero agriculture by reducing domestic agricultural emissions while shifting production and associated GHGE to exporting countries, thereby limiting reductions in global emissions – creating a disconnect between territorial emission reductions and global emissions associated with European food consumption. Given that the size of the carbon leakage problem remains unknown (Van Hoof, 2023), it is crucial to implement

policies and measures that protect and support these carbon-negative initiatives, recognising their importance in the broader mitigation landscape. Notwithstanding this, one measure attempting to overcome this is the series of legislative proposals set out by the European Commission (EC) in 2021, including the EU emissions trading system (EU ETS). The EU ETS identifies where industrial installations are at high risk of carbon leakage – receiving a higher share of free allowances compared to the other industrial installations (EC, 2023).

5. Measurement, Reporting, and Verification (MRV) Barriers

Reaching Net Zero must be both tangible and meaningful for farmers to implement effective mitigations. In this context, increasing SOC has become a key focus for agriculture's journey to Net Zero; for example, Friedlingstein et al., (2022) reported that soils contain more carbon than global vegetation and the atmosphere combined.

5.1 Measurement

The first barrier to SOC measurement is the absence of a universally accepted sampling depth. In the UK alone, a range of SOC sampling depths within the devolved nations has been recommended (see Emmett et al., 2024). While the FAO (2019) recommends reporting SOC within the 0–30 cm layer, with deeper sampling where appropriate, evidence increasingly demonstrates that substantial carbon stocks occur below 30 cm.

Both Sousanna and Lemaire (2014) and Orgill et al., (2014) reported that only 40% of SOC is in the topsoil. Conversely, in a study across the ROI, Simo et al., (2019) highlighted that most carbon stocks in Irish soils are in the top 30cm – for all mineral subgroups (between 51 and 73% of the total measured to 1m), when measuring to 50 cm, they found 74 - 88% of the total carbon (to a 1m depth). By finding consistent results across soil types, the research did recommend a sampling depth of 50cm for SOC but highlighted the “limitations associated with focussing on the SOC concentration and stocks in the top 30cm of the soil profile” (Simo et al., (2019 pg.68).

Similarly, in Germany, a study by Poeplau et al., (2020), which sampled 3104 sites found that, on average, topsoils (0-30 cm) stored $67 \pm 14\%$ of SOC, whilst subsoils (>30cm) stored $33 \pm 14\%$ of total C stocks. Of the mineral soils, croplands and permanent crops stored (on average) 61 ± 25 and 62 ± 25 Mg ha⁻¹ of SOC in the 0–30cm (topsoil) respectively. Whilst they also stored 35 ± 30 and 44 ± 28 Mg ha⁻¹ in 30–100cm in subsoils, permanent grasslands stored significantly more SOC in both the topsoil (88 ± 32 Mg ha⁻¹) and subsoils (47 ± 50 Mg ha⁻¹). Importantly, more recent research has questioned conventional findings regarding the ‘upper limit’ of carbon within agricultural soils (Begill et al., 2023; Georgiou et al., 2022; Beare et al., 2014) and the underestimation (~17%) and associated error of levels of SOC in the top 30cm soil profile (Fowler et al., 2023) – as SOCS changes soil bulk density (Rovira et al., 2022). Further, according to Balesdent et al., (2018), shorter-term changes in SOC predominantly occur in the top soil profile; however, longer-term stabilisation of SOC does occur in the deeper layers. Thus, it is noteworthy that, while deeper soil horizons may hold lower carbon

stocks, they also have the capacity to sequester significant amounts of carbon for longer as the turnover time and chemical stability of soil organic matter increases with depth (Lorenz and Lal, 2005; Stockmann et al., 2013).

Therefore, sub-soil layers (>30cm) are of importance in global carbon budgets and SOCS strategies (Conant et al., 2001; Batjes 1996, and Jobbagy and Jackson, 2000). Nonetheless, these inconsistencies and difference in research outputs have raised concerns regarding the appropriate sampling depth for SOC (30cm or 100cm), and may also lead to a trade off with spatial coverage when considering the increased sampling cost associated with mechanised coring to 100cm. Overall, a standard protocol to measure and compare achievable SOCS is still missing (Rodrigues et al., 2021). Thus, to establish universally comparable SOC stock baselines and sequestration rates, a global soil sampling depth is required. Notwithstanding this, the global context of different soil types and densities may make a 'one-depth-fits all approach' unfeasible. If this is not possible, robust methods for extrapolation to depth for particular soil series and cropping history may have potential.

The equivalent soil mass (ESM), an approach which measures SOC stocks using the mass of soil for a given reference layer, can be a promising alternative. Several studies have outlined the limitations of both approaches to measuring total carbon carbon stocks and SOCS; notably (1) estimates of C stock change can differ by over 100%, mainly due to changes in bulk density in surface soils, and (2) ESM, although less favourable as a global standard, is preferable to quantify SOCS (Rovira et al., 2022 and Raffeld et al., 2024). It is recommended however, that a combination of both approaches should be taken forward within a global SOC sampling framework.

Sampling frequency represents a second measurement challenge. Because SOC responds to land management, land-use change and climate variability (Smith et al., 2020; Bispo et al., 2017), repeated measurements are required. The FAO (2019) recommends resampling every 4–5 years, although evidence suggests detectable changes occur more rapidly in surface soils than in deeper horizons, where responses may require more than a decade (Badgery et al., 2014; Stahl et al., 2016; Knops and Bradley, 2009). Consequently, standardised guidance on sampling frequency remains an important gap.

Financial cost represents another major barrier. Repeated sampling to depths approaching 100 cm is labour-intensive and expensive, particularly where farmers bear the costs (Smith et al., 2020). For example, national-scale resampling of 3,000 forest plots in Finland was estimated to cost €4 million (Mäkipää et al., 2008). Consistent with these practical constraints, 40% of Australian farmers reported infrequent soil testing and 21% had never tested their soils (Lobry de Bruyn, 2019), suggesting that widespread SOC monitoring remains challenging.

Paul et al. (2023) identified an accuracy-cost trade-off between direct measurement, remote sensing and simulation modelling. Direct measurements remain the most accurate but are costly, whereas remote sensing is cheaper but currently lacks field-scale accuracy (e.g. bare soil conditions, low water content, uniform SOC content through the plough layer). Simulation models are the least expensive

and are already incorporated within several certification schemes, although they introduce substantial uncertainty without robust baseline data (Paul et al., 2023; Oldfield et al., 2022).

While maintaining soils as a major global carbon reservoir is essential, increasing SOCS will be equally important for achieving Net Zero. Reaching Net Zero requires sustained removal of atmospheric CO₂ rather than simply preserving existing carbon stocks. In some regions, however, agricultural soils—particularly drained organic soils in countries such as Ireland—can net sources of CO₂ through oxidation of previously stored organic carbon. Consequently, mitigation strategies must prioritise protecting existing soil carbon, reducing emissions from vulnerable soils, and enhancing carbon sequestration where feasible, alongside complementary measures such as afforestation (Duffy et al., 2022). The capacity of agricultural soils to sequester carbon varies considerably with soil type, climate, land use and management history. Consequently, neighbouring fields may have markedly different sequestration potentials, highlighting the need for robust MRV systems capable of accurately quantifying SOCS¹ and informing site-specific management.

Evidence suggests that relatively few land management practices consistently increase soil carbon in agricultural systems (see Paustian et al., 2016). Consequently, the overall contribution of SOCS to climate mitigation is likely to be modest. For example, in the UK, current estimates suggest a potential equivalent to around 5–10% of agricultural GHGE (Emmett et al., 2021). Nonetheless, increasing soil organic carbon should remain an important objective within sustainable land management due to the multiple co-benefits it provides, including formation and stabilization of soil aggregate structures, retention & release of plant nutrients, soil moisture, temperature, complexation of heavy metals, and more stable and climate-resilient crop yields (Prout et al., 2021).

5.2 Reporting

Before a carbon credit-trading scheme is considered, a robust reporting system is required for on-farm sequestration. When sampling is completed, a clear and transparent reporting process must be available to farmers, one that outlines where and how SOC data is reported, owned, and protected.

This is required under the risk that carbon credits generated via on-farm sequestration are sold to private industries, which are external to agri-food. Subsequently, in accordance with NGHGI (to avoid ‘double counting’) agriculture will not get the benefit of its own carbon sequestering values, resulting in agriculture remaining a net contributor of carbon emissions. Accordingly, one recommendation emerging from the current study (workshop and literature synthesis) is the development of a data-sharing software system linking farms, SOC analytical laboratories and government agencies to improve reporting of carbon sequestration within NGHGIs and strengthen estimates of net agricultural carbon emissions. Only from this will one know if there is a surplus of carbon sequestered (e.g. agriculture reaches Net Zero and becomes carbon negative) that may be sold as credits externally.

¹ It is noteworthy that there is ongoing research for expanding MRV to other emissions, including N₂O (Butterbach-Bahl et al., 2025).

There is debate and sensitivities around deciding who should create and keep these data-sharing platforms; their maintenance, functionality and securement. There is an important point for governments. Indeed, in the EU, if this carbon reporting method becomes an extension of the current Common Agricultural Policy outlook, farmers could become disenchanted. It would mean all farmers would continue to be considered equal, with those who sequester more carbon not being financially rewarded for their practice, equally, those who do not change management practice not being financially punished (unless through introduction of carbon taxation).

Indeed, a major barrier to Net Zero for agri-food is found within NGHGs, especially default estimates for assessing carbon stocks. The NGHG provide default estimates for assessing carbon stocks and emissions at three tiers of detail: Tier 1 (default values and average emission/stock changes for large eco-regions of the world using globally-available data – developed by the IPCC), Tier 2 (region specific data) and Tier 3 (high resolution methods, advanced modelling using field-based data – repeated through time) (Cardinael et al., 2018; Rodrigues et al., 2021). According to Rodrigues et al., (2021), in Europe, six countries including Denmark, France, Ireland, and the UK produce data to model changes in on-farm carbon stocks to satisfy a Tier 3 approach within respective NGHGs.

Nonetheless, a significant limitation for agri-food is the limited activity on reaching Tier 3 measurements for carbon sequestration – this is also reflected within leading national policies such as the UK ELMS – which has no link to NGHG. For example, according to Simo et al., (2019), most models and inventories of SOC stocks only account for carbon dynamics in the upper 30 cm of the soil profile. Moving forward, high-resolution field-based data must be a priority, with a specific focus on farm type, soil type, land use, land management, and land-use change². Importantly, for now, unit changes in sequestration are not accounted within NGHGs. Thus, land management practices undertaken by farmers which accelerate atmospheric CO₂e removal, especially through SOCS, are not credited. This discredits on-farm Net Zero measurements for agri-food, and this lack of granularity may create barriers to drive positive behavioural change among the farming community.

A further barrier for agri-food is the multi-sectoral scope of emission estimates within NGHGs. Agriculture is frequently found across 4 different silos³ in NGHGs, applying different accounting approaches, here, significant disparities arises concerning sequestration and renewables, wherein unit changes are not credited to agriculture, but are instead credited to other silos. The development of joined energy and land-use policy frameworks could be incentivised, facilitating a public-private partnership and not two separate vehicles – as reflected recently within the (2nd annual) European Carbon Farming Summit (Climate KIC, 2025) in Dublin, Ireland.

5.3 Verification

To inset and offset agricultural carbon emissions, data must be based on robust science and independently verified, providing accuracy and integrity to NGHG in carbon trading agricultural

² Caution is needed however, as some of the measures taken to enhance soil carbon may enhance nitrous oxide emissions, partly offsetting soil carbon sequestration effects (Grados et al., 2022).

³ (1) Energy; (2) Land use, land-use change and forestry; (3) Waste; (4) Agriculture.

commodities. Agreement on this verification process at national and global levels, especially in the context of trade, needs significant collaboration. Complete verification of SOC measurements needs to take place both on-farm and within laboratories, to eradicate potential fraud and improve accuracy of results. Similarly, verification of reporting is needed to ensure lab results are being inputted onto databases. Secondly, the frequency of verification needs consideration – in conjunction with the 5-year cycle of SOC sampling and analysis. Thirdly, due to the global nature of trade, net carbon emissions and removals of agricultural products should be taken into consideration and translated from one country to another – like currency. Fourthly, there is a gap in measuring and reporting in low-income countries, and how respective inventories and credits are incorporated into a global food trading system, one that wants to move to a carbon in-setting and offsetting data sharing and trading system.

6. Interactions Between Policy and MRV Barriers:

6.1 Regulation

Many governments, particularly in Europe, have avoided regulatory approaches to agricultural emissions, relying primarily on strategic policy frameworks (Van Hoof, 2023). This creates a governance gap: without mandatory MRV protocols, policy effectiveness and emissions reductions cannot be reliably assessed. Integrated policy frameworks combining regulatory measures, knowledge transfer programmes, and market-based incentives are therefore required, alongside centralised MRV systems to ensure transparent tracking of progress towards Net Zero targets (Henderson et al., 2022; Van Hoof, 2023).

To regulate the integrity of such carbon MRV, several issues must be considered. First, it is noteworthy that for many farm businesses (especially intensive livestock systems), despite improved efficiencies and low-cost high-return mitigations, (e.g. conservation tillage, precision fertilisation, improved animal health and genetics); there will be an inevitable mitigation cost (high-cost high return) to reach Net Zero. This cost needs recognition. Currently, two common markets are available, (1) the Compliance Market (CM), for example, the CM within the EU Emissions Trading Scheme, which reached 73 euros per tonne of C in September, 2025, and (2) the Voluntary Market (VM) (common to the land based sector). For many farmers, the cost within the VM is too low, and is not sufficient to drive positive behavioural change towards low-carbon farming.

The higher value of carbon in compliance markets largely reflects the use of a single, standardised MRV protocol, whereas voluntary markets rely on multiple protocols with varying levels of rigour, reducing confidence and market value. This raises a fundamental question: who should finance robust and consistent MRV for agricultural emissions and removals? One potential solution is a public-private partnership, whereby governments fund and oversee credible MRV systems to support mandatory reductions in on-farm emissions and increased carbon removals. Any surplus carbon credits could then be traded within private markets without additional verification costs. To avoid double counting,

however, credits should only be sold once. Where credits are transferred outside agriculture, they can no longer be claimed by the farm business within national GHG inventories.

This priority is acknowledged through, for example, the EC's Sustainable Carbon Cycles (SCC), which recognises the need to pay farmers on "results basis", and has set an ambitious target that farmers should know their carbon balance by 2028 – delivered mainly through the CRCF. The EC aims to achieve this through a standardised MRV protocol, based on 'QU.A.L.ITY' (quantification, additionality, long-term storage and sustainability) carbon removals, providing voluntary certification for EU carbon farming. Such certifications could be recognised within NGHGI to improve their intelligence and accuracy. Indeed, frameworks that employ empirical SOC quantification modules (field-based SOC quantifications/data), for example QU.A.L.ITY within CRCF, could influence NGHGI to help acceleration towards Tier 3 estimation(s) of carbon removals and emissions. However, this would require alignment of methodologies and data sources within the NGHGI and certification schemes.

The potential for public-private partnerships to support carbon farming through CRCF-certified credits has recently been recognised by the European Commission (EC, 2025). Drawing on interviews and workshops with prospective buyers, investors and project developers, the Commission identified net-zero commitments, supply-chain resilience and brand value as key drivers of investment, while highlighting persistent uncertainties surrounding MRV, permanence and cost. The report concluded that successful partnerships will depend on de-risking strategies, blended finance, hybrid effort- and results-based payment models, long-term commitment, price stability and market competitiveness (EC, 2025). To support credible certification, the CRCF will incorporate independent third-party verification under the QU.A.L.ITY framework, enabling certified removals to contribute to robust MRV of carbon removals. Although the SCC/CRCF aligns with the FAO's ambition to sequester an additional 10 Gt of carbon in cropland and pasture soils by 2050 (FAO, 2023), concerns remain regarding the feasibility of cost-effective monitoring, advisory support and long-term financing.

Northern Ireland's Soil Nutrient Health Scheme (SNHS) demonstrates how government-led investment can support both sustainable land management and agricultural MRV. The programme combines national baseline soil sampling with nutrient management training for approximately 26,000 farmers to improve nutrient management while establishing a credible carbon monitoring framework. Farmer participation is primarily motivated by improved nutrient management, future support payments, profitability and environmental concerns (Wen et al., 2024).

7. Barriers to Positive Behavioural Change

Ultimately, for agri-food, success in implementation of policies targeting Net Zero will depend upon the attitudes, behaviours, and level of engagement from those who are expected to implement them (Whitton and Carmichael, 2024). Farmer's decisions are complex and often non-directional processes, shaped by numerous external (at a society, landscape, community, value chain, and farm level) and internal factors (Klebl et al., 2024). Farming practices with proven economic success are likely to continue and be passed onto future generations. While a wealth of experience and success

through this 'trial and error' training may not be recorded, it does provide practical ways to deliver society with food which is high quality, safe, healthy, and nutritious.

7.1 Knowledge exchange

A key challenge for positive behavioural change is KE between actors across the agri-food industry, with farmers at the centre. Although the development of new knowledge for low-carbon farming continues to grow, implementation and uptake within the industry is slow. For effective uptake, farmers require buy-in. The incentives, markets, opportunities and financial gains of investing in green technology and regenerative practices is a fundamental question – why should farmers respond to an externality that is not priced? Thus, according to Mills et al., (2019), the perceived lack of private (e.g. economic) benefits of Net Zero practices has been identified as a significant barrier to their uptake. Moreover, applicability of measures depends on regional conditions in addition to knowledge of local environmental conditions, both of which farmers may lack (Burgess et al., 2019; Sykes et al., 2020 as cited by Henderson et al., 2022). Policies driven by averages, proxies, and aggregated modelling can be counter-productive, as the representation of change needed, required action, and adaptive capacity is not equal across farms. For policymaking to be effective, farmers need confidence to take ownership of their own Net Zero journey⁴.

Messages communicated through knowledge transfer are not always clear, often coming from different sources with different approaches, and motivations (e.g. selling a product/service), which can confuse and even misdirect farmers. A major factor within effective KE for low-carbon farming is education, pivoted by platforms that aid delivery of up-to-date advice from qualified advisors to farmers. It is also essential that advisors can produce farm-specific recommendations, which account for landscape, climate, soils and socio-economic factors unique to that farm – ensuring implementation of the right-measure in the right-place. Building upon this, peer-to-peer learning within the farming community is one of the most unique and powerful KE approaches available, or as Sutherland and Marchand (2021 pg.567) find, 'other farmers' are farmer's most frequently reported source of information (as cited by Garforth et al., 2003). In the UK, examples of such include the Farmer Field Labs and Monitor Farms (UK), GrowIn and Field for the Future (NI).

The role of targeted, effective, and transparent KE within agriculture's journey to Net Zero is not limited to KE with farmers. Indeed, whilst technology developments and respective KE with farmers is central to sustainable low-carbon agriculture, their levels and rate of social acceptance can become a major barrier. A recent example is the (social media) backlash towards the feed-additive, Bovaer (3-Nitrooxypropanol – 3-NOP), wherein Arla Foods have aimed to trial its implementation on 30 UK dairy farms to reduce enteric CH₄ (Eardley et al., 2024). The backlash came despite empirical evidence, including a meta-analysis by Kebreab et al., (2023⁵) illustrating the ability of 3-NOP to reduce CH₄

⁴ A flexible carbon tax can be effective, but it needs to consider the feasibility of adoption measures. An example is the Danish CO₂-tax, wherein there is a base emission deduction – applied to viable emission reductions.

⁵ The study incorporated 14 different experiments (including 48 different treatment means)

emissions by ~30%, its application in Brazilian, Chilean, and Danish Farms⁶, and the evidence of zero food safety implications. Although the value of this mitigation to Net Zero agriculture is substantial, a prominent barrier threatens its implementation; this barrier is a fault-line between (1) science/evidence-based technology development, (2) which gains regulatory approval but becomes impeded by (3) social acceptability. These are three different stages to 'technology implementation', with all three posing different barriers.

7.2 Society, culture, and values

Despite agriculture's central role in food production and environmental stewardship, many farmers increasingly perceive themselves as marginalised within society. One contributing factor is the negative portrayal of conventional farming across traditional and social media, which can undermine confidence and increase resistance to policy interventions (McAteer, 2020; Murphy, 2021; Buddle et al., 2021; Duley, 2002). Behavioural responses are influenced by personal values, farming objectives and perceptions of economic risk, with adoption of mitigation measures more likely where clear environmental or financial benefits are evident (Dessart et al., 2019).

This displacement extends beyond public perception to encompass economic, social and cultural dimensions. Farming communities face increasing economic pressures, regulatory demands and structural change, including farm consolidation and an ageing population (Brew et al., 2016; Hansen et al., 2020), while being expected to simultaneously deliver food security, biodiversity enhancement and climate mitigation. As farmers identify strongly as food producers and stewards of the land (Burton, 2004), policies perceived to overlook local knowledge or place perceived disproportionate responsibility for climate mitigation on agriculture may foster feelings of marginalisation and reduce trust in policy institutions. Building and maintaining trust between farmers, policymakers and wider society is therefore fundamental to successful behavioural change – especially when Net Zero relies on credible MRV systems, policy certainty and sustained farmer engagement.

8. Solutions and Recommendations:

8.1 Policy

Recent international conflicts and geo-political issues should, in principle, encourage national energy securities. Governments also need to be cautious of the implications of carbon and biodiversity leakages under FTAs, and how this will influence farmer behaviour and attitudes in local food production. This undermines 'home' journeys to Net Zero, causing backlashes among local farming communities and may disincentivise their adoption of home policy measures – particularly if they compromise productivity. Such deals must integrate an effective and transparent MAA. Moreover, in a new era of "public money for public goods", farmers require targeted subsidy to mitigate emissions; this public investment could remove the financial barrier of so-called "win-loss" mitigations, which are

⁶ It has also been granted approval in Australia, USA, Canada, the EU, and the UK

pivotal within highly productive intensive systems. Importantly, in the absence of this support, for agriculture, the cost of such mitigations is not reflected/compensated within the voluntary carbon market and, thus, will fail to drive positive farmer behavioural change.

Achieving Net Zero agriculture must comply with a One Health approach and safeguard long-term food security. Policies that reduce agricultural emissions without maintaining resilient domestic food production risk increasing reliance on imported food and transferring environmental impacts elsewhere. As public investment inevitably competes with wider governmental priorities, policy measures should prioritise interventions that deliver multiple environmental, economic and food-security benefits.

8.2 MRV

A standardised MRV protocol of Net carbon emissions and removals should be central to this carbon market, one that enables measurable and comparable levels of SOC baselines and sequestration values. To achieve this, a global recommended soil sampling depth is missing, one that incorporates the global context of different soil types and densities through a combination of fixed-depth sampling and ESM method(s). In addition, the agri-food sector is constrained by limitations of emission and sequestration reporting within NGHGs. Whilst this lack of high-resolution data within measurement and reporting, supported with transparent regulation, exposes agriculture to carbon 'double counting' and the loss of sequestration 'crediting', it will also be insufficient to drive positive farmer behaviour change.

The results of the current study encourage the development of joined energy and land-use policy frameworks, facilitating a public-private partnership that enables coordinated action across sectors. In practice, this would bring together farmers, agri-food companies, energy providers, financial institutions and policymakers to jointly develop and finance mitigation initiatives. Examples may include on-farm renewable energy deployment, bioenergy systems using agricultural residues, and carbon sequestration programmes linked to carbon markets or carbon farming schemes. Similar governance and financing structures have been successfully applied in the European energy transition. Applying this partnership-based model to agri-food could help align incentives across NGHGI, facilitate coordinated investment in mitigation technologies, and accelerate the deployment of integrated climate solutions spanning land-use and energy systems.

Recent discussions at the second European Carbon Farming Summit in Dublin further highlighted growing interest in such coordinated approaches linking carbon farming, renewable energy deployment and agricultural land management. A data-sharing platform between farmers, soil carbon laboratories, and government should be central to this partnership, which integrates national and regional frameworks that employ empirical SOC quantification modules. This approach (1) smartens efficient data collection for SOCS, (2) enables accountability of land management changes effecting SOCS, (3) aids 'results-based payment' approaches, and (4) prevents multiple vehicles informing NGHGs. Due to the perceived lack of private (e.g. economic) benefits of Net Zero practices, this

partnership could enable governments to pay for and oversee the credibility of MRV to meet mandatory reductions in on-farm net emissions.

8.3 Behavioural Change

Fundamentally, farmers are central to Net Zero agriculture, but it must be acknowledged that successful implementation/uptake of certain mitigations are conditional on parameters that are beyond the control of farmers. In some cases, the responsibility belongs to the farmer, in other cases it belongs to research and development, local governments, or societal acceptability. The differences in these responsibilities and capacities may mean that both the definition and pathway(s) towards Net Zero agriculture, or a Net Zero food system, will differ among stakeholders. Therefore, a shared co-written communication of each stakeholder's definition of Net Zero is recommended, one that is nation specific, and can be streamlined into the EC.

9. Conclusion:

Building upon the outputs of an international science-policy-society workshop, supported by literature and policy review, this study identifies three interdependent barriers to achieving Net Zero agri-food: (1) policy, (2) measurement, reporting and verification (MRV), and (3) positive behavioural change. Using European case studies, we examine these challenges, propose potential solutions, and provide recommendations to address them. Further, we demonstrate that these barriers should not be considered in isolation. Rather, policy certainty, robust MRV systems, and farmer engagement are mutually reinforcing components of successful Net Zero pathways.

A key finding of this study is that barriers to Net Zero agriculture are not independent; weaknesses in policy design, carbon accounting, and behavioural uptake reinforce one another. Consequently, addressing any single barrier in isolation is unlikely to deliver sustained progress towards Net Zero. Public-private partnerships have the potential to strengthen these interactions by supporting credible MRV, reducing financial barriers associated with "win-loss" mitigation measures, and creating long-term confidence for farmers to invest in low-emission practices.

Ultimately, achieving Net Zero agriculture will depend not simply on developing new mitigation technologies, but on integrating agricultural, climate, and trade policy with robust carbon accounting and farmer-centred implementation strategies – embedded within a One Health agenda for global food security.

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Supplementary Material:

Workshop Output Summary

Stakeholder	Qualitative data
Practitioners	Identified barriers
<i>Farmers and industry representative's across the agri-food supply chain.</i>	• Detailed MRV at regular time points to allow soil carbon changes to be recognised. • Key to appreciate that some farms will never meet net zero and some will soar past it, it's about the industry average, meeting in the middle on an industry level. • Support for diversification: multi-species swards improved water penetration, reducing run off risk, and water quality, improved animal performance also as well as obvious nitrogen benefits. • Definitions of Net Zero: on farm vs national scale. • Farmers reputation is consistently degraded online etc, in particular ruminant farming. • Farmers need to know where they are on their own Net Zero journey, in the hope to motivate them going forward. • It's not our scientific knowledge but our practical understanding. • Encourage farmers to not "sell" as they will need it to 'keep their own house in order'. • Double counting ... what does it mean for the sector? • Agriculture is a unique multisector that spans across sectors. • Policy must engage with farmers on this topic to drive major behavioural changes to allow farmers to take ownership of their own carbon journeys and empower them to face criticisms. • Knowledge transfer and advice: best to be farmer to farmer, consistent up to date advice from advisors. • When should a farmer join the carbon market?

	• Different funding mechanisms available to farmers to mitigate emissions, each with different approaches and paperwork. • Net Zero is the average of industry reaching it... not individual farms!
Policy	Identified barriers
<i>UK Policy:</i> <i>Department of Environment, Food, and Rural Affairs.</i>	• Consistent information for consumers around environmental and climate impacts of products. • Marketing schemes and labelling leading to consumers disengaging on the topic. • Lack of joint approach both within and outwards of government, industry, and government • Improve knowledge-exchange of science to practice for farmers – this should also include technical skills. • Farmers are getting confused with different information. • Goals must satisfy policy requirements but must be feasible for farmers and industry. • What is the definition of Net Zero? Have we defined it properly? • There will be substantial changes to systems but agricultural productivity and environment must work together. • 4 areas of significance: (1) Afforestation, (2) Biomass, (3) Peat, (4) decarbonisation of livestock production. • Sustainable pathways which deliver long-term goals remains difficult. • Soil... monetising it as a carbon gain. But this is a potential danger area, risking losing carbon or poor regulation leading to cheap money. • Sustainable intensification or reducing national herds both have potential to free up land.
<i>European policy:</i> <i>European Commission</i>	• Barriers to carbon farming, bioenergy with carbon capture, farm crops for bio-plastics and wood based construction products. • Barriers to measure, report, and verification (MRV).

	- Challenges to MRV include cost efficient monitoring (quality standards, digital earth observation), advisory services and financing (public funding, food/biomass value chain, carbon credits outside value chain). - A target that every farmer by 2028 should know their farm's carbon balance. - Proposed regulation on the voluntary certification of carbon removals in the EU. - A combination of frameworks (criteria and credible certification) and tailored certification methodologies which should be developed together with expert groups. - Short term certificates where farmers commit for 10-15 years, where the farmer commits to using a specific mitigation practice, one methodology for certificates that should be applied across Europe. - Further steppingstones towards a post 2030 EU carbon removal policy. - The need for schemes which pay farmers on a results basis. - The need to move beyond Tier 1 and 2 emission and removal estimations.
Republic of Ireland policy: <i>Department of Agriculture, Food, and Marine.</i>	- Issues around uncertainty on when a farmer should buy into the carbon market. - De-risking through monetary incentives to offset the potential economic downsides that may be faced when farmers 'try' these new mitigation strategies. - Precision based knowledge – necessary on a farm basis.
International focus: <i>United Nations Food and Agriculture Organization</i>	- Livestock farming is key to poor livestock keepers, as well as key to food and nutrition security. - Tier 2 estimations must be achieved at a minimum. - Data access & MRV limitations, technical support for farmers. - Systems perspective: understand the drivers of supply chain emissions – Scope 1 – Scope 2 emissions. - Farm-level investments are essential to supporting mitigation efforts ... but who should compensate this "risk"? - Rethinking the carbon equivalence.

Non-government Organisations	Identified barriers
ENGOS: <i>Environmental non-government organisations</i>	• Instability of government is a major barrier to net zero. • Subsidy systems not focusing sufficiently on sustainability – more so on intensification. • Lack of policy cohesion both within and between government departments. • Engagement between government departments, food industry, and ENGOS' is weak. • Policy push and supply chain pulls acting in harmony.
Case studies	Identified barriers
UK: <i>Harnessing Interdisciplinary Science for Net Zero Policy Design</i>	• Costs of different mitigations. • Technical/biophysical support and verification. • Data access/collection. • KE of farm data to farmers is key in farmer education • IPCC carbon emission factors needs to be down to farm type, soil type region etc., to increase accuracy and reliability. • Farmers more likely to participate in finance-based interventions if they have some control in their implementation. • System wide transformation requires system wide thinking. • Livestock emission mitigations needs subsidy – especially for enteric fermentation and manure management. • The strategic land use question should focus on food, trees and biomass (crops and livestock). • Adopting a diet that is both healthy and sustainable. Not a single focus. • How to talk sensibly and constructively about the meat question, rather than extreme points reaching farmers, consumers.
Denmark:	• Sufficient measures to enhance soil organic carbon is needed.

<i>'A Pathway to Carbon Neutral Agriculture in Denmark: Lessons Learned'.</i>	• Permanence of soil carbon. • Global warming increases soil carbon decomposition. • The possibilities for enhancing SOC depends on the balance between enhanced C inputs and enhanced SOC decomposition and it will likely be challenging just to maintain current SOC levels. • Circulatory is essential as are technologies, for sustainable systems. • Dietary changes are a crucial part of reducing GHGE, specifically a planetary health diet Lancet diet. • The agricultural income situation could also be improved when adopting this diet.
Focus group / feedback session <i>After the above deliveries, participants were (1) allocated into focus groups (n=8) to further identify and scrutinize barriers – supported with potential solutions.</i> <i>Afterwards, (2) a feedback session was held for each focus group – with a supporting Q&A.</i>	
Case studies	Discussion
'Focus group' (n=8) Discussions and Synthesis on Barriers and Supporting Solutions to Achieve Net Zero in Agri-food.	• Who will pay the price of mitigation? A Compliance Market / Voluntary Market for Agri-food? • Public-private partnerships offer a great opportunities. • Why would farmers respond to an externality that is not priced? • Farmers should not sell carbon until their 'own house is in order'. • Farmers are getting hammered for something they have little control over... • Important net zero is appreciated by the individual farm, and is respective to the individual farm, to his/her behavioural change etc. They cannot control other farms. Policy driven approaches can be dangerous creating volatile responses because the representation of change and action is not equal across farms. • Is the science behind SOC storage clear?

	• Agricultural is a “horizontal sector” across the economy and national GHG national inventories. Thus, agriculture is not getting fair credit from the energy side. • Energy and land-use policy and frameworks could be a solution – on a public-private approach. • Influencing the inventory to tier 3 emissions seems great, but does it control for a products full life span – cradle to cradle? • Double counting is an issue – especially for soil carbon. • Give farmers confidence to take ownership of their own net zero journey – this is buy in. • But do not put SOC into an “offsetting” bucket only – it has a broader role. • Data itself is a barrier Access. GDPR. Validation. Trust. • For farmers, a major barrier is policy but some policies, such as the Northern Ireland Soil Nutrient Health Scheme, removes barriers and provides benefits – so where is the “fine line” for policy-makers? • Carbon leakage... can be a ‘slap in the face’ for local and national farmers who farm carbon, abide by stringent environmental targets, and may be already Net Zero. • Net zero is a major cultural shift – are we asking too much? • How does Net Zero differ across stakeholders? • Visibility, transparency and inclusivity is key – double counting of carbon will ruin transparency. • Why are farmers now being displaced from societal values? • Multiple options for a farmer to utilise subsidy to farm more sustainably – which one? Govt, banks, industry? This causes confusion. • Certain mitigations require subsidy, but are farmers aware of the low hanging fruit mitigations – “win-win” approaches. • Toxic lobbying is detrimental to farmers attitudes and acceptance of inclusivity – why does the extreme voice receive so much reception? • It is not one size fits all – policy must accept this – regardless how difficult. • Adaptation is mandatory – we cannot hide from the effects of CC.
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	• Governmental instability is painful... visualises confusion for the sector. • Multiple eco-labelling options coming through – this will confuse the consumer and dis engage them – eco labelling also does not show the nutritional benefits of the product. • Energy resilient systems. The Ukraine war ... has this caused a consideration of re-nationalising of food policy. A sector based on cheap energy... the relationship/model between fossil fuels and renewables has not changed... as we exploit the cheap energy we increase GDP. • Unregulated media is a huge problem. Better engagement and representation of the media... to deliver the accurate information to consumers is needed. • Post farm gate/supply chain emissions are of equal (if not higher) – food processing, transportation and food waste. • The definition of Net Zero... we need a shared co-written communication piece of each stakeholders definition.
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