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Rural Development Program measures on cultivated land in Europe to mitigate greenhouse gas emissions – regional “hotspots” and priority measures

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ABSTRACT

Agriculture is a significant source of GHG emissions, contributing 10% of total emissions within the EU-28. Emissions from European agriculture have been reduced, albeit at the expense of crop yield and the risk of production displacement (the transfer of production, and associated emissions, to land outside of Europe). This article assesses the impact on GHG emissions of selected European Rural Development Program measures, representative of a diversity of management strategies implemented on cultivated land, within nine European Member States. Climatic zone and underlying spatial environmental variables were accounted for using a novel technique, “Regional Variation Categories,” developed with European-scale GIS data sets. Production displacement is assessed with two benchmarks: (1) compared with existing crop production and (2) relative to a “minimum requirement” land management scenario, where an emissions reduction of less than this does not constitute mitigation. Most measures reduce emissions relative to the baseline crop scenario; however, many do not reduce emissions beyond the “minimum requirement,” this being limited to measures such as catch crops and within-field grass areas to prevent soil erosion. The selection and targeting of measures to maximize agricultural GHG mitigation on cultivated land within Europe is discussed.

KEYWORDS
Agriculture; leakage; mitigation measures; nitrous oxide; rural development

Introduction

Climate change, both mitigation of and adaptation to, as an issue has grown in prominence in EU policy debates, not least the EU Multi-annual Financial Framework (MFF) for 2014–2020 and the instruments that the budget will fund, including the Common Agricultural Policy (CAP). Moving to a low-carbon, resource-efficient and climate-resilient economy is a core objective of the Europe 2020 strategy [1] for smart, sustainable and inclusive growth. A reformed CAP can be identified as a key policy to achieve this goal, both through the greening of Pillar 1 funding (mandatory requirements) and, more importantly, through the mechanism that the European Agricultural Fund for Rural Development (EAFRD), otherwise known as rural development policy, implemented in Member States (MSs) [2]. In addition, under the MFF, 20% of all MS expenditure from the EU budget must be spent on climate actions, in relation to both mitigation and adaptation objectives. The sustainable management of natural resources and climate action is one of the three overarching objectives of the CAP for the period 2014–2020. As a result, climate mitigation and adaptation feature much more centrally in the priorities for Pillar 1 rural development policy, including Cross Compliance, than previously. While the ambitions of both Pillar 1 and Cross Compliance in relation to climate are becoming somewhat eroded through the CAP negotiation process, rural development policy remains key for delivering enhanced climate outcomes over the next programming period. In response to these key issues, this article will report on:

- A pilot conceptual framework developed for life cycle assessment (LCA), so as to account for spatially explicit environmental variables by defining “Regional Variation Categories” (RVCs) across the EU at a 1 km^2 resolution, utilizing GIS and a meta-modelling approach;
- The impact of selected Rural Development Program (RDP) measures on agricultural GHG emissions on cultivated land within individual EU MSs, with focus on nine MSs selected to be representative of all European climatic zones and for their RVC diversity, using the conceptual framework above;
- Prioritization of current and potential future RDP measures for individual EU MSs with respect to climate mitigation and adaptation, and potential

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for inclusion under an "agri-environment-climate" theme;

- The impact of new Ecological Focus Areas (EFAs) within the nine MSs mentioned above, and their adaptive capacity.

Spatial targeting and prioritization of operations for GHG benefits

Greenhouse gas (GHG) sources and sinks within the rural environment are multiple and complex. Greenhouse gases are emitted during the manufacture of agricultural inputs, such as fertilizer, directly on farm via the combustion of fossil fuels, and from soils as nitrous oxide (N_2O) and carbon dioxide (CO_2) due to supplementary N application, nitrate leaching and soil erosion. On wet and compacted soils, the emission of methane (CH_4) may be a further factor [3]. Sinks include carbon (C) sequestration within the soil or biomass. The impact of alteration to management on agricultural GHG emissions has been calculated by numerous previous LCA studies [e.g. 4–7], a technique that is by no means highly detailed or fully comprehensive in its assessment of the agricultural sector, and often requires supplementary techniques to provide a more holistic perspective. This is especially the case for modelling the fate, transport and end impacts of pollutants such as pesticides or nutrients, which can vary significantly temporally and spatially. Since emissions sources and carbon sinks vary in response to spatial and site-specific factors, climate change impacts, as well as mitigation and adaptation strategies, also vary spatially. For example, many studies have demonstrated that factors such as soil texture, temperature, moisture, pH, available carbon and soil nitrogen content will influence CO_2 production and emissions from the soil [e.g. 8–10]. Therefore it has been important to capture this regional variation within the assessment of the particular environmental benefits and burdens that RDP operations may provide. Direct measurements taken at each location are not a viable option over large spatial scales. A meta-modelling approach to quantify the impact of given combinations of spatial variables on agricultural GHG emissions is a potential alternative. Leip et al. [11], for example, developed a modelling framework that links the large-scale economic model for Common Agricultural Policy Regionalized Impact (CAPRI) [101] with the bio-geochemistry model Denitrification–Decomposition (DNDC) to simulate greenhouse gas fluxes, carbon stock changes and the nitrogen budget of agricultural soils in Europe. Tzilivakis et al. [5,6] and Warner et al. [12] have used combinations of models (such as Simulation of Nitrogen Dynamics In Arable Land (SUNDIAL) [13] and Pesticide risk Environmental Management for Agriculture (p-EMA) [14–16]) to assess the environmental impacts of sugar beet and strawberry crops in the UK, using a scenario approach to capture the key spatial differences and consequent impacts.

The use of detailed models can provide valuable scientific insights into the environmental impacts that arise as a consequence of different activities in different locations. However, there are a number of limitations and difficulties involved in applying simulation models for evaluation purposes. Existing models may need adapting or do not lend themselves easily to a precise assessment of many small heterogeneous schemes, and key parameters of many models may be subject to uncertainty. Agricultural-sector models typically provide only an estimate of behavioral changes (results) that the measures aim to achieve, and need to be supplemented with estimates of the environmental effects (impacts) caused by these changes. This is often done by linking farm output or input to environmental indicators such as nutrient or energy balances [17]. A further adaptation of the approach adopted by Tzilivakis et al. [5,6], Warner et al. [12] and Defra [18] develops the concept of "Regional Variation Categories" (RVCs), that define environmental risk areas for individual pollutant pathways at the 1 km^2 resolution. Spatially explicit emission factors are then allocated to each RVC, enabling coverage of impact to extend over the European scale for individual RDP measures.

Existing attempts to assess the impacts of RDPs over broad spatial scales include the Common Monitoring and Evaluation Framework (CMEF). An appraisal of the CMEF approach by Huelemeyer and Schiller [19,20] identified that although considered useful to undertake, the suggested methodological approach and the set of impact indicators provided are subject to criticism. Deficiencies include measurement of impacts at the micro and macro levels, and disentanglement of impacts from additional factors that may exert an influence, coupled with the calculation of changes that would have occurred as part of the "business as usual" scenario – that is, without the specific program intervention (also termed "deadweight"). Capturing the actual effects of the RDP on agricultural GHG emissions by accounting for production displacement, as required in the CMEF, remains a difficult task. In response, a further refinement of the RVC method accounts for, in addition to the influence of spatially explicit variables on overall GHG mitigation, the impact of production displacement.

Synergies and trade-offs with production displacement

Greenhouse gas mitigation may arise from either the maintenance of crop production but with a decrease in emissions, or replacement of the cropped area with an alternative low-input land use. A number of studies to date comment on mitigation achieved from the latter, but fail to acknowledge the risk of production displacement (i.e. the transfer of those emissions to land elsewhere with no net reduction or, worse, a net increase).

Where the availability of productive agricultural land is limited, its removal from production contradicts strategies that aim to maintain or increase production while reducing environmental impacts [e.g. 21,22]. The prioritization of RDP measures should not, therefore, be applied solely to maximizing emissions reduction, but rather to maximizing reduction coupled with maximizing crop yield [23].

Synergies and trade-offs with other rural objectives

The rural development policy for 2014–2020 presents a number of new or revised elements, born of evaluations of the implementation and effectiveness of current RDPs. Under post-2014 CAP greening, the introduction of EFAs requires that a minimum of 5% of land within a farm dominated by cultivated land be entered into qualifying EFA elements. Qualifying elements are defined by MSs individually and are, in most cases, comparable in management to RDP measures previously available under Pillar 2. Each element is given a weighting that defines the equivalent area permitted to contribute to the 5% area target. Many measures provide opportunities for an improved mainstreaming of climate into the next suite of RDPs, and to achieve a more integrated approach to the delivery of environmental, economic and social outcomes. Although climate actions are not specified in the rural development policy for 2014–2020, individual MSs would have the potential to develop a climate related sub-program. Adaptation to climate change, the capacity for a measure to maintain or enhance the delivery of environmental services, and economic and social benefits under predicted changes to climate, are further variables that RDPs require for inclusion in an assessment of their effectiveness. This may include, for example, adaptation to increased water stress due to an increase in temperature and a decline in rainfall. This variable, coupled with accounting for spatially explicit environmental variables and production displacement, is lacking in many evaluations of RDPs, but will be presented herein.

Methods

Management scenarios and Regional Variation Categories

Any activity that can be funded through rural development policy has been assessed. It has been ensured that all of the actions are legitimate for funding and bounded by the rules set out in the EAFRD [2] and the provisions that govern all shared management funds, the Common Provisions Regulation [24]. A definitive list of RDP operations applicable to cultivated land within Europe was derived via a review of measures and operations likely to be included post-2013. The final list included the most common and core operations.

Greenhouse gas emissions and C sequestration are quantified in two key stages. First, a baseline scenario is defined for comparison with the new management regime implemented via an RDP operation. Each RDP measure has a specific baseline, defined by the form of land use for which the RDP measure is targeted and on which it is implemented, and a management scenario following agronomic practice typical for the region. Second, the baseline GHG emissions and impact of a given RDP are subject to further variation in response to spatially distinct variables such as soil type, temperature, rainfall and topography. RVCs (Table 1) allow the

Table 1. **Regional Variation Categories (RVCs), underlying GIS data sets and emission factor range.**

RVC	Data set(s)	No. of categories	Min	Max	Units
CO_2-e emissions from fossil fuel consumed during tillage operations	Dominant soil texture	6 6	0.036[†] 0.023[‡]	0.099 0.096	tCO_2-e ha^{-1} tCO_2-e ha^{-1}
CO_2-e emissions from soil due to tillage	Dominant soil texture Elevation (< 300m)	6	0	15.0	tCO_2-e $ha^{-1}yr^{-1}$
CO_2-e emissions from soil erosion	Risk to soil erosion Percent soil organic matter (Dominant soil texture)	56	0 0.5	19.1 9.4	tCO_2-e $ha^{1}yr^{-1}$ %
N_2O loss via NO_3^- leaching	Annual precipitation Dominant soil texture	30	0.17	0.39	Proportion of N applied leached
N_2O loss via soil erosion	Risk to soil erosion Dominant soil texture	48	0	0.006	tCO_2-e $ha^{-1}yr^{-1}$
Irrigation requirement	Annual precipitation Annual evapo-transpiration Soil available water	30	407	23,860	mm ha^{-1}
CO_2-e emissions and sequestration in soil	Percent soil organic matter (Soil susceptibility to compaction)	8	0	3.3	tCO_2-e $ha^{-1}yr^{-1}$
C sequestration biomass – rate	IPCC ecological zones CORINE Land Cover	21	0.5[§]	5.4	tCO_2-e $ha^{-1}yr^{-1}$
C sequestration biomass – equilibrium	IPCC ecological zones CORINE Land Cover	21	35.9[§]	403.9	tCO_2-e ha^{-1}
N fertilizer use arable land	Dominant soil texture Annual precipitation	30	60[¶] 30[#]	220 110	kg N ha^{-1} kg N ha^{-1}
N fertilizer use arable land	Dominant soil texture Annual precipitation	30	0.002	0.018	tCO_2-e kgN^{-1}

[†] ploughing at 20 cm depth; [‡] 15 cm depth; [§] woodland/forestry; [¶] winter wheat; [#] spring barley.
Note: CORINE: coordination of information on the environment.

calculation of spatially explicit emission factors, associated with the change in management or land use for a given baseline management scenario and RDP measure. European-scale GIS data [25–30] are generated in Arcview® software, defined over 20 RVCs.

The emission factors derived for each RVC are combined to calculate net GHG emissions for a baseline scenario (the current management) and each RDP measure (Equation 1):

$$GHG\ emissions_{(RVCn)} = \Big(D_{(RVCn)} + Ia_{(RVCn)} + Im_{(RVCn)} + SN_2O_{(RVCn)} + SCH_{4(RVCn)} + SCO_{2(RVCn)}\Big) - \Big(Cseq(SOC)_{(RVCn)} + Cseq(biomass)_{(RVCn)}\Big) \quad (1)$$

Where:

D = direct emissions from machinery operation;
Ia = indirect emissions agro-chemical manufacture;
Im = indirect emissions machinery manufacture/depreciation;
SN_2O = soil N_2O emission;
SCH_4 = soil CH_4 emission;
SCO_2 = soil CO_2 emission;
$Cseq(SOC)$ = C sequestered in soil;
$Cseq(biomass)$ = C sequestered in plant biomass.

The impact of implementing an RDP measure for a given RVC is calculated as the total change (△) in GHG emissions (t CO_2-e $ha^{-1}yr^{-1}$) impacted by regional variation (i.e. those influenced by precipitation, temperature, soil type or topography) between baseline (existing land management) and RDP operation management scenario (new land management) (Equation 2).

$$\Delta\ GHG\ emissions_{(RVCn)} = (GHG\ emissions\ RDPn_{(RVCn)} - GHG\ emissions\ Baseline_{(RVCn)} \quad (2)$$

A value derived from Equation 2 of < 0 indicates a net decrease in GHG emissions associated with the change in land use through implementation of the RDP measure.

Calculation of impact on greenhouse gas emissions

Agro-chemicals and machinery

Each activity and feature (Table 2) has a potential impact on GHG emissions and carbon sequestration, the magnitude of which is dependent on the underlying RVC (Table 1). The LCA includes on-farm GHG emissions up to the farm gate. It identifies Scope 1, 2 and 3 emissions sources and follows the GHG reporting protocol [31], where Scope 1 refers to direct on-farm GHG emissions (e.g. emissions from on-farm fuel consumption or soils); Scope 2 are emissions from purchased electricity consumed on-farm (emissions during the generation process are evolved off-farm but taken into account); and Scope 3 includes off-farm indirect emissions from products consumed on-farm but for which emissions from their manufacture are derived off-farm (e.g. emissions from agro-chemical manufacture). Baseline activities that vary in response to regional parameters (e.g. N fertilizer rates as a function of soil type and annual rainfall [32]) were taken into account using GIS data sets for dominant soil texture [29] and annual rainfall [33], with the appropriate recommendation adjusted for a given crop applied to those combinations of spatially explicit variables. When an RDP operation modifies N fertilizer use in a particular location, a spatially explicit estimate of the likely change in N application rate (Table 1) and associated GHG emissions for its manufacture and application may be calculated. Spatially variable emission factors are summarized in Table 1.

Soil N_2O

The RVC for N_2O (Table 1) identifies spatial variation for emissions from leaching, denitrification and surface run-off, generated by the N balance model SUNDIAL [13] and regression equations devised by [34] for a winter wheat or spring barley crop in receipt of recommended N (Table 2). The values account for residual soil N [32] on five dominant soil textures (sand, sandy loam, silty clay loam, silty clay and clay) for five annual rainfall categories [25] (<451 mm, 451–533 mm, 533–646 mm, 646–765 mm, >765 mm) [33]. The output modifies the direct soil N_2O emission factor, and the $Frac_{LEACH}$ and $Frac_{GASF}$ values of the IPCC [102] formula to generate N_2O emissions per kg N applied within each RVC category. The risk of surface flow of NO_3^- into water courses has been estimated for the RVCs using the risk of soil erosion as a surrogate. The quantity of NO_3^- removed by surface run-off on cultivated land and the associated indirect N_2O emissions have been estimated for each RVC using a combination of the Pan-European soil erosion risk assessment (PESERA) map [28] (eight categories) and the quantity of residual N per tonne (t) of soil for a given soil texture. The weight of soil has been calculated for each dominant soil textural class using the method described for CO_2 from soil erosion (section Soil CO_2). The residual soil N (the existing mineral NO_3^--N and NH_4^+-N, and the potential N available from mineralization of organic matter) within a soil following a winter wheat crop (Soil Nitrogen Supply = 1) is cited from Defra [32]. Soil N_2O emission is calculated with

Table 2. Baseline crop production and selected Rural Development Program (RDP) measure management scenarios.

Option	Base	Soil	Yield loss (%)	Cultivation	Fallow	Drill	N	P_2O_5	K_2O	Crop protection	Other	Type of feature
Winter wheat (WW)	–	–	–	1_{20}	–	CD	160–220	63	96	9	$L_4 + S$	
Spring barley (SB)	–	–	–	1_{20}	–	CD	110–140	35	45	6	$L_4 + S$	
Hedgerow planting on an existing field boundary	$H_{(1.5)}$	Mn	0	–	–	–	0	0	0	0	0	Boundary
Catch crop preceding a spring cereal	SB	Mn + L	0	1_{20} + Sh	–	2 CD	110–140	35	45	7	$L_4 + S$	Cover crop
In-field grass area	WW	Mn + E	100	0	–	–	0	0	0	1	M	Grass buffer + erosion
Minimum tillage	WW	Mn	< 10	Sh	–	CD	160–220	63	96	9	–	Reduced cultivation
Afforestation of buffer strips	WW	Mn	100	0	–	–	0	0	0	1	0.1 M	Grass buffer + trees
Forestry/woodland plantation	WW	Mn	100	–	–	–	0	0	0	0	0	Forestry/woodland
Buffer strips	WW	Mn	100	0	–	–	0	0	0	1	M	Grass buffer
Pollen and nectar mix	WW	Mn	100	0.5_{20}	–	0.5 CD	0	0	0	2	2 M	Sown mixture
Conservation headlands	WW	Mn	100	1_{20}	–	$CD_{(R)}$	0	0	0	5	0	Cereal headland
Uncropped cultivated margins	WW	Mn	100	1_{15}	✓	–	0	0	0	1	0	Zero cover – edge
Central fallow plots for ground nesting birds	WW	Mn	100	1_{20}	✓	CD	160–220	63	96	10	$L_4 + S$	Zero cover – center

Note: Cultivation: $1_{20}/1_{15}$ annual cultivation plough (20/15 cm) + power harrow, 0.5 biennial cultivation, Sh: shallow cultivation (5 cm with tines), CD: conventional drill, $CD_{(R)}$: reduced seed rate, MW: mown, L_3: 3 t ha^{-1} lime every 4 yrs, L_4: 4 t ha^{-1} lime every 4 yrs, S: 30 kg sulfur ha^{-1}yr^{-1}; Mn + L: mineral soil + leaching, Mn + E: mineral soil + erosion, Mn: mineral soil. $H_{(1.5)}$: 1.5 m hedge.

Equation 3:

$$N_2O_{(erosion)} = S_{er} \times N_{(soil\ 1,\ 2\ldots n)} \times 0.0075 \times 44/28 \quad (3)$$

Where:

S_{er} = mean weight of soil eroded (t ha^{-1});
$N_{(soil)}$ = residual soil N per t of soil for soil texture 1, 2…n;
0.0075 = Nitrogen leaching/runoff factor (kg N_2O-N /kg N leaching/runoff);
44/28 = conversion N_2O-N to N_2O.

Soil CO_2

Soil erosion removes a layer of topsoil and the SOC within, with the potential to oxidize to CO_2. A layer of previously undisturbed soil, equivalent to the soil removed, becomes exposed to farm operations such as tillage. Emissions of CO_2 due to soil erosion (Table 1) have been calculated for a known weight of SOC per tonne of soil and quantity of eroded soil [28] using Equation 4:

$$\text{SOC removed} = \text{Soil erosion } \left(\text{t soil yr}^{-1}\right) \times \text{SOC}_{30cm}\left(\text{tCO}_2\text{–e t soil}^{-1}\right) \quad (4)$$

The SOC_{30cm} is calculated for a given percentage of SOC [27], sand and clay content [29] and soil bulk density on arable land [1.46 - 0.0254 × ln(% clay) + 0.0279 × ln(% sand) - 0.026 × ln(% SOC)].

Carbon sequestration

Carbon sequestration in soils is influenced by annual precipitation and temperature [35,36], soil type, land use (e.g. cultivated, permanent grassland, woodland) and management practice (e.g. grass ley, zero tillage) [37,38]. Current land use RVCs correspond to distributions defined by the Coordination of Information on the Environment (CORINE) database (European Environment Agency 2006). Carbon in soils and biomass at equilibrium [102] and annual accumulation rates for a change in land use from cultivated land to a new land use or management practice [37,39,40], for a given MS and FAO Ecological Zone [102] are summarized in Table 1. Accumulation of SOC is further influenced by soil compaction [41] for which RVCs are defined by the natural soil susceptibility to compaction, also given in Table 1.

Scaling-up of impacts

Nine MSs were selected for assessment in detail to represent different climatic zones within Europe, and for their diversity in RVC and contribution to the arable area within Europe as a whole. Three countries (France, Germany and Spain) account for around 60% of the cereal area in the EU-15. France and Germany are the major cereal, oilseed and protein crop (COP) producers in the EU-15, followed by the UK, Spain and Italy. The scaling-up of impacts in each MS excluded areas where land was not currently within cultivation, as defined by the CORINE GIS data set of dominant land use (European Environment Agency 2006). Impact was restricted to the potential area of cultivated land only. The total area applicable to measures limited to field boundaries only (e.g. the planting of hedgerows or buffer strips) have been derived based on MS average field sizes [42] and the ratio of boundary to cultivated area.

Displacement risk and prioritization of measures

A further functional unit, that benchmarks emissions reduction relative to a 6-m grass buffer strip on non-vulnerable mineral soil (6m$_{GBS(nvms)}$ eq), considers production displacement risk. Where land is removed from production, a direct comparison of GHG emissions from the RDP measure management scenario relative to that of the original baseline quantifies the net change in emissions, but does not account for the impact of removing land from production, and the risk of displacement and "system leakage" [43]. The creation of grass areas on productive agricultural land, for example, may simply shift emissions elsewhere. If a theoretical displacement of productivity to a low-risk soil results (e.g. from an area of steep to low gradient), a net emissions reduction occurs equivalent to those embedded within the erosion process (NO_3^- and SOC in surface run-off). Benefit is only realized, however, where an emissions reduction of this nature occurs. Options are allocated mitigation potential and a higher priority where the emissions reduction exceeds this benchmark.

Results

Regional Variation Category risk zones

In order to allocate appropriate interventions via RDPs, the magnitude of risk and frequency of combinations of spatial variables that define that risk (for example, annual rainfall and dominant soil texture defining risk zones for NO_3^- leaching) within individual MSs require identification. This is summarized for nine MSs and grouped by 12 categories in Figure 1. Arbitrary frequency values (the number of km^2 identified by GIS for a particular RVC) have been set at low (<50 km^2), moderate (50–225 km^2) and high (>225 km^2). Risk is standardized between

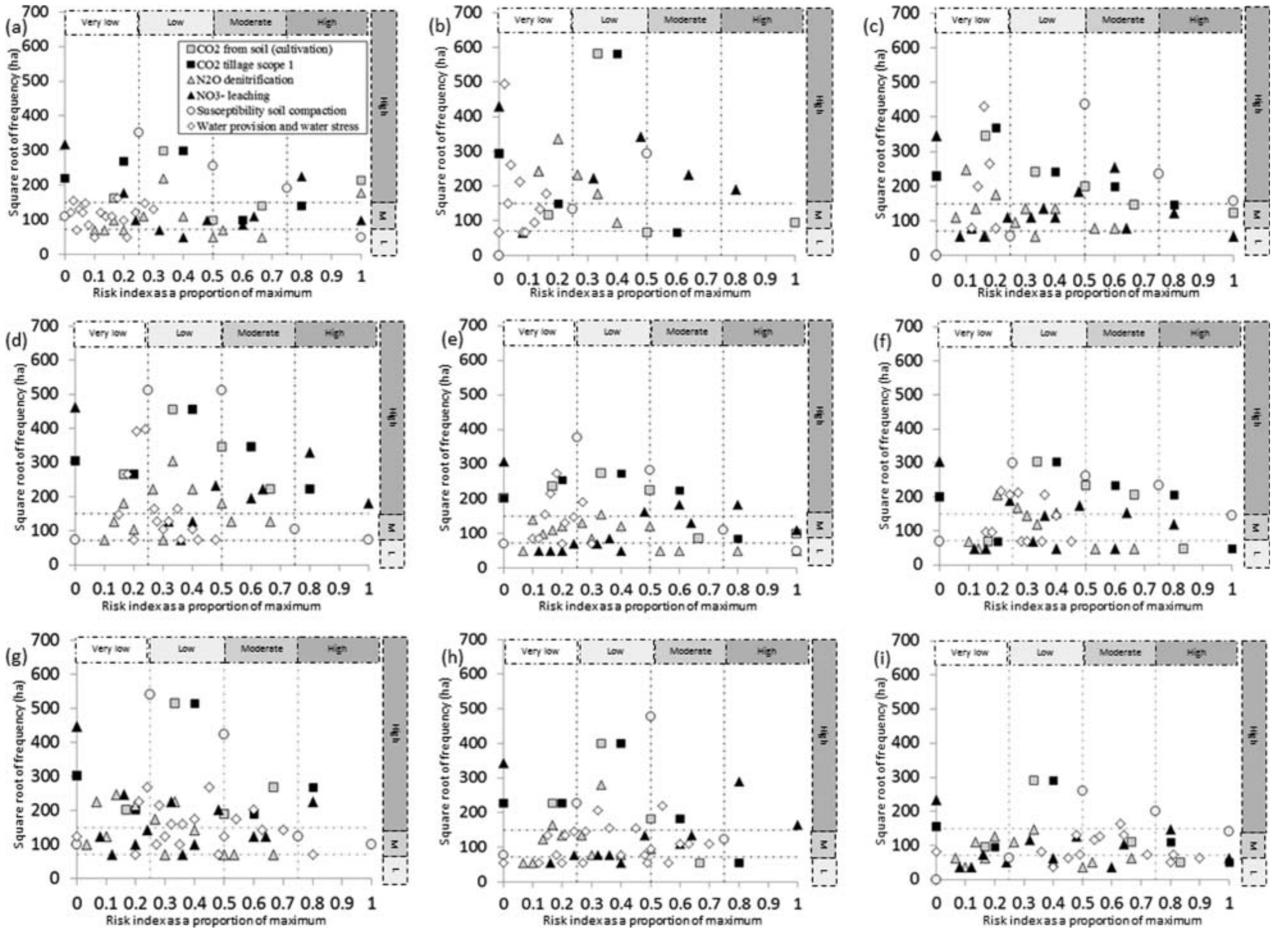

Figure 1. Area (square root ha) of very low, low, moderate and high greenhouse gas Regional Variation Category (RVC) risk (proportion of maximum RVC value) for existing cultivated land within nine Member States: (a) UK–England, (b) Sweden, (c) Poland, (d) France, (e) Germany, (f) Romania, (g) Spain, (h) Italy, (i) Greece.

Table 3. Summary scores of key Regional Variation Category risks and priorities for nine Member States identified by GIS data sets.

	UK-Eng	FR	ES	IT	GR	RO	PO	SE	DE
N_2O leaching risk	15	18	10	12	9	9	14	10	16
N_2O denitrification risk	8	4	3	0	2	2	4	0	10
CO_2 fossil fuel tillage	7	9	6	0	9	13	8	1	5
CO_2 soil tillage – loss of SOC	8	0	3	1	6	4	7	5	7
CO_2 soil (tillage/SOC) – compaction	7	0	5	2	8	5	9	0	11
Adaptive capacity: SOM stress	4	15	8	8	7	5	5	16	0
Adaptive capacity: water provision	0	0	14	7	20	0	0	0	0

Note: SOC: soil organic carbon; SOM: soil organic matter;
UK-Eng: United Kingdom – England; FR: France; ES: Spain; IT: Italy; GR: Greece; RO: Romania; PO: Poland; SE: Sweden; DE: Germany.

RVCs based on the index of maximum value (e.g. where 10 RVCs exist risk category 5 has a risk index of 0.5, where 20 RVCs exist risk category 10 has an index of 0.5). In the example of nitrate leaching, high RVC risk is defined by a combination of high annual precipitation coupled with coarse (high sand) content soils. This is present at high frequency (> 225 km^2) on land classified as "cultivated" by CORINE in the UK, Sweden, France, Germany, Spain and Italy (Figure 1).

Broadly, high annual precipitation occurs in the north and west of the UK and Sweden, the west of France and Greece, northern Spain, northern and central Germany, and western and central Italy. High-risk and high-frequency leaching risk were noted in the northern and central MSs but also Spain and Italy, albeit on a more localized region-specific basis, with low risk more prevalent in the remainder of the country. A further scoring approach has been used to assign the high-frequency, high-risk category with a weighting of 6, high-risk, moderate-frequency a weighting of 5, down to moderate-risk, low-frequency with a score of 1. Each weighting is multiplied by the number of RVC priority zones (Figure 1) identified within that weighting category, and summed to provide the values in Table 3 for each of the nine MSs.

Leaching risk overall is identified as a key issue in UK, France, Poland and Germany, although it is also potentially an issue in other MSs, albeit more locally. Member states such as Spain, Italy and Greece have areas of high potential water stress, principally to the south or east. Finer particulate soils coupled with high annual precipitation, where impeded drainage may potentially create anaerobic soil conditions suitable for denitrification to proceed, are present in greater frequency in the UK and Germany. The frequency of soil susceptibility to compaction is predicted to be greatest in Poland; the more abundant heavier soils in Romania result in greater fuel consumption attributed to tillage. Vulnerability to CO_2 emission from tillage is highest in the UK, corresponding to areas with higher SOC, the fenland in the eastern central areas in particular.

Impact of RDP measures

Figure 1 and Table 3 identify key GHG risks from cultivated land for nine MSs. The impact of 12 RDP measures, representative of potential differences in management strategies, on net GHG emissions, broken down by source, for individual MSs overall (Table 2) are summarized in Figure 2.

Measures a–d have a negligible impact on crop yield. Hedgerows utilize existing boundaries (Figure 2a), but may be managed to enhance biomass C further. Measures targeted specifically at N leaching (Figure 2b), for example winter cover crops [44], reduce N_2O emissions from leaching but also offer the potential to increase SOC through additional biomass. In areas subject to high leaching risk, a decrease in emissions beyond those associated with cover crop husbandry (additional seed, drilling, tillage or herbicide application) results (Figure 3). Low-risk zones experience a net increase in GHG emissions (> 0), since emissions associated with catch crop agronomy are greater than those attributed to the reduction in NO_3^- leaching. This is further influenced by the method of catch crop removal; a light cultivation as opposed to application of herbicide results in a net increase in GHGs on fine and very fine soils in a moderate-risk rainfall zone.

Areas devoid of precipitation coupled with high rates of evapo-transpiration and soils of low available plant water (e.g. Spain and Greece) benefit most from RDP measures to store water (Figure 2c), although more northerly MSs may also benefit, albeit over lower frequency and magnitude of emissions reduction. The enhanced use of gray water reduces consumption of mains treated water. Reduced-depth non-inversion cultivation (Figure 2d) replaces a 20-cm plow and power harrow combination with a single pass of a disc harrow, decreasing diesel consumption and emissions by between 0.06 and 0.15 t CO_2-e ha^{-1}yr^{-1}, depending on the dominant soil texture. Soil organic carbon is enhanced by, on average, 0.37 t CO_2-e ha^{1}yr^{-1} [37], although this may be reduced in the presence of soil compaction. Estimates of the yield penalty for this system, and the impact on production displacement, vary between 0 and 5% [45], although this also depends on the time elapsed since inception of the reduced cultivation program [45].

Measures that remove cropping reduce GHGs (Figure 4e–k), but this is often confined to the sole removal of land from production (Figure 4e–h). Grass buffer strips vary in their GHG reduction potential

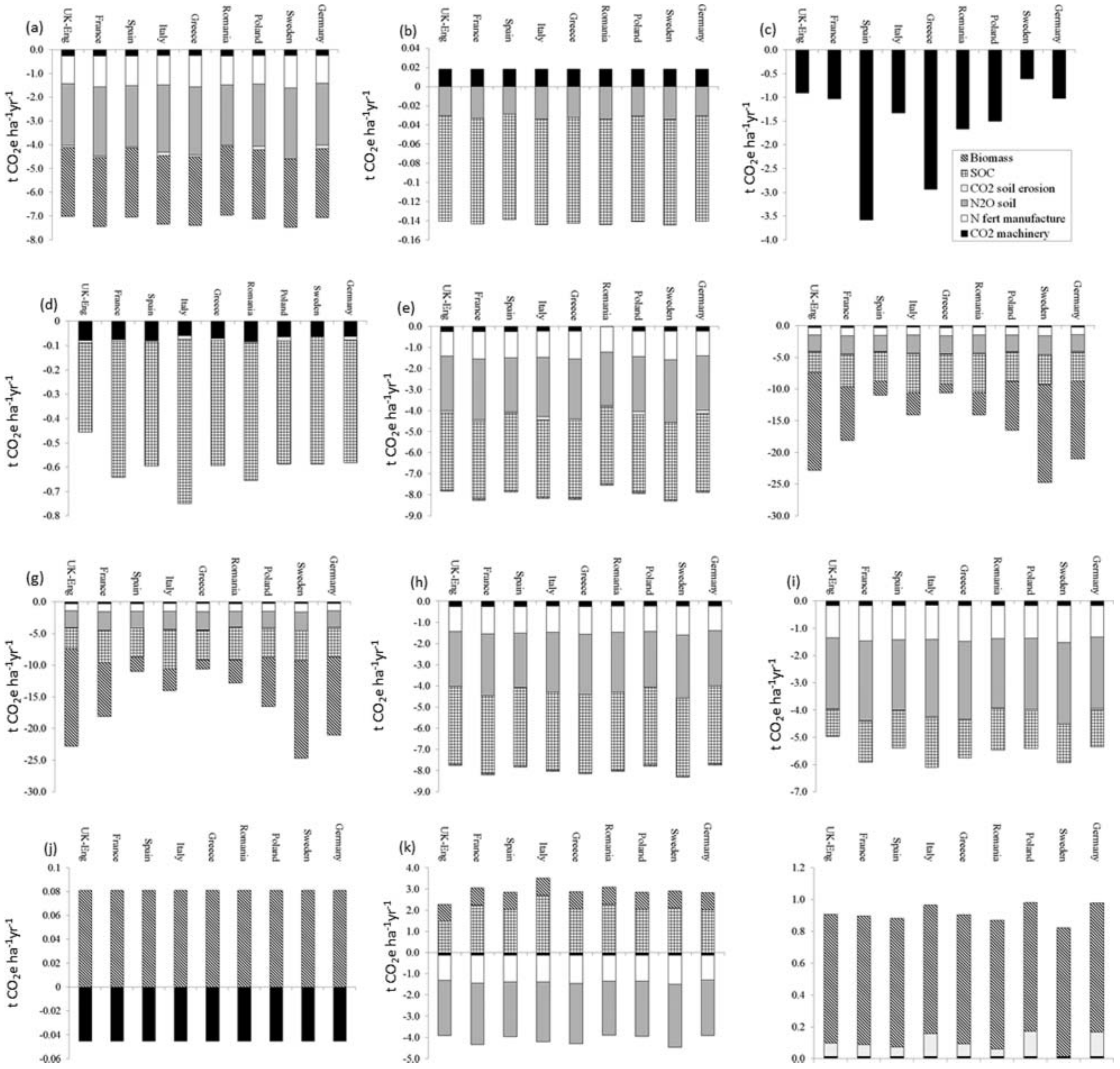

Figure 2. Mean greenhouse gas reduction (t CO$_2$-e ha^{-1}) relative to a winter cereal baseline (except c) for 12 Rural Development Program (RDP) measures (years 1 to 10): (a) hedgerow planting on an existing field boundary, (b) catch crop preceding a spring cereal, (c) on-farm reservoir to utilize gray water, (d) minimum tillage, (e) in-field grass area, (f) afforestation of buffer strips, (g) woodland creation (coniferous), (h) buffer strips, (i) pollen and nectar mix, (j) conservation headlands, (k) uncropped cultivated margins, (l) central fallow plots for ground nesting birds, implemented in nine Member States on applicable (existing cultivated) land.

subject to appropriate spatial targeting and in response to the risk of soil erosion and surface run-off. Figure 3 compares options where production is removed but sets a grass buffer strip on low-erosion-risk land as a “minimum requirement” benchmark. Greatest reductions are observed in MSs where soil erosion risk is higher (Figure 4c), for example Italy, or where risk is combined with greater areas of cultivated land and higher SOC, for example Germany. Where buffer strips are not located on vulnerable soils, emissions reductions are limited solely to the removal of land from agricultural production and, if agricultural displacement is taken into account, no net reduction in emissions is achieved. Within-field grass areas targeted specifically at mitigating erosion risk reduce emissions associated with the erosion process, beyond the emissions attributed to the crop itself.

Measures 4a–d decrease GHG emissions below that of implementing grass buffer strips and have been classed as having mitigation potential. If displacement to land not subject to, for example, soil erosion results, a net decrease in GHGs occurs. They have been prioritized after measures with negligible impact on crop yield. Buffer strips may be enhanced for GHG reduction by planting with trees to enhance biomass, for example afforestation of buffer strips or planting new hedgerows on existing cultivated areas (Figure 4a and b). The IPCC [102] differentiates the biomass potential

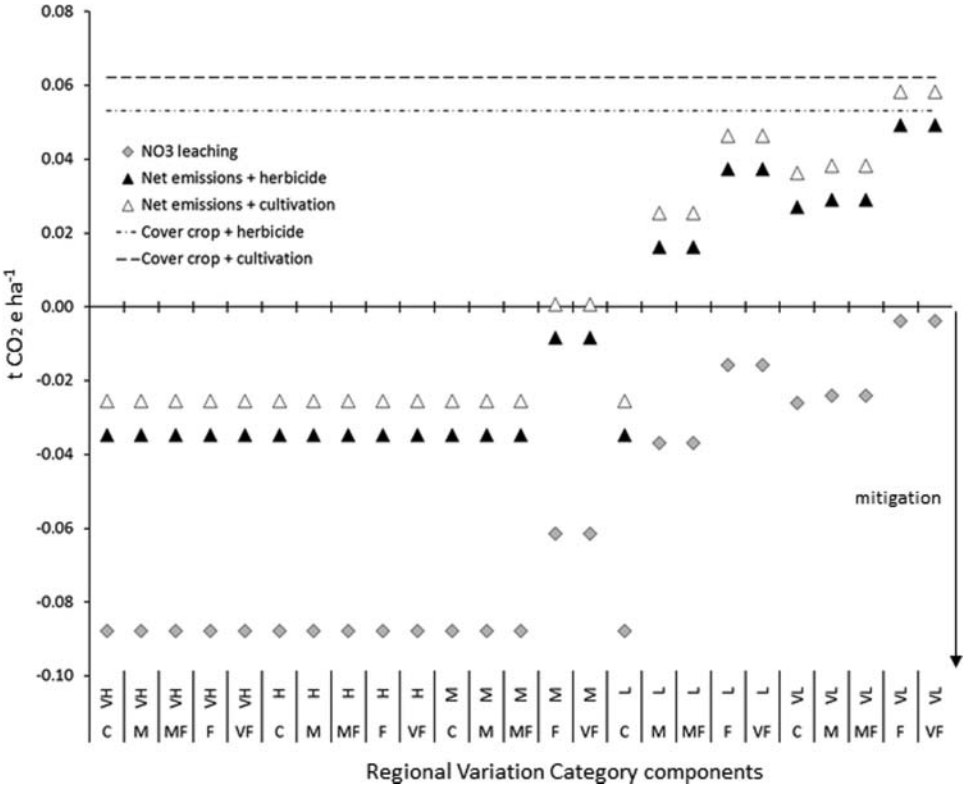

Figure 3. **Greenhouse gas emissions (t CO_2-e ha^{-1}) associated with the Regional Variation Categories for nitrate leaching and the impact of growing a catch crop. Components consist of permutations of annual rainfall (VH: very high, H: high, M: moderate, L: low, VL: very low) and soil texture (C: coarse, M: medium, MF: medium fine, F: fine, VF: very fine).**

of woodland/forestry between FAO Ecological Zones, with lower values at equilibrium corresponding to the MSs Italy, Greece and Spain compared to, for example, the Oceanic Temperate zone (e.g. the UK).

Measures that remove land from production but that maintain cultivation either biennially (e.g. pollen and nectar mixtures) or annually (cultivated crop margins for rare arable flora) achieve an emissions reduction relative to the cropped baseline (Figure 3i–k), but not compared to a grass buffer strip on low-erosion-risk soil (Figure 4e–g). They are not considered to be of value as measures to mitigate agricultural GHG emissions, since emissions reductions are not as great as that achieved by removal of land from production and replacement with the “minimum requirement” benchmark.

Each selected RDP measure type, its post-2014 nearest EFA equivalent, and its potential for selection within a climate-related sub-program are given in Table 4. Cover crops are selected for inclusion in those MSs (Table 4) where leaching risk is identified by RVCs as posing the greatest risk (Table 3), although it receives a relatively low weighting as an EFA qualifying element of 0.3. Environmental variables conducive to leaching risk exist in the three MSs that do not select this option, although they are more local in scale. Buffer strips and hedgerows/afforestation of buffer strips receive a higher weighting of 9 or 10, respectively; both measures have potential GHG mitigation benefits above the minimum grass buffer strip benchmark, where located appropriately. Measures below the minimum threshold to be considered of value for GHG mitigation include cereal headlands (weighted at 1.5) and uncropped cultivated areas (weighted at 1), selected in most of the nine MSs under consideration.

Discussion

The task of developing rural development measures and operations is a complex and multi-faceted process and an ongoing challenge for managing authorities across the EU-28. Tackling single issues is highly complex, and tackling multiple objectives compounds this complexity. Nevertheless, there is a need to find effective solutions that address objectives as optimally as possible. It is important to understand the synergies and trade-offs that different measures and operations may provide, in terms of not only production, but also other environmental (and/or socio-economic) objectives, for example protection of the soil, water, air and biodiversity, and also other climate change objectives such as adaptation. In any policy intervention, it is important to have the best available scientific knowledge and understanding to enable better informed decisions to be made. Additionally, scientific knowledge and understanding need to be presented and communicated in a way that supports the policy

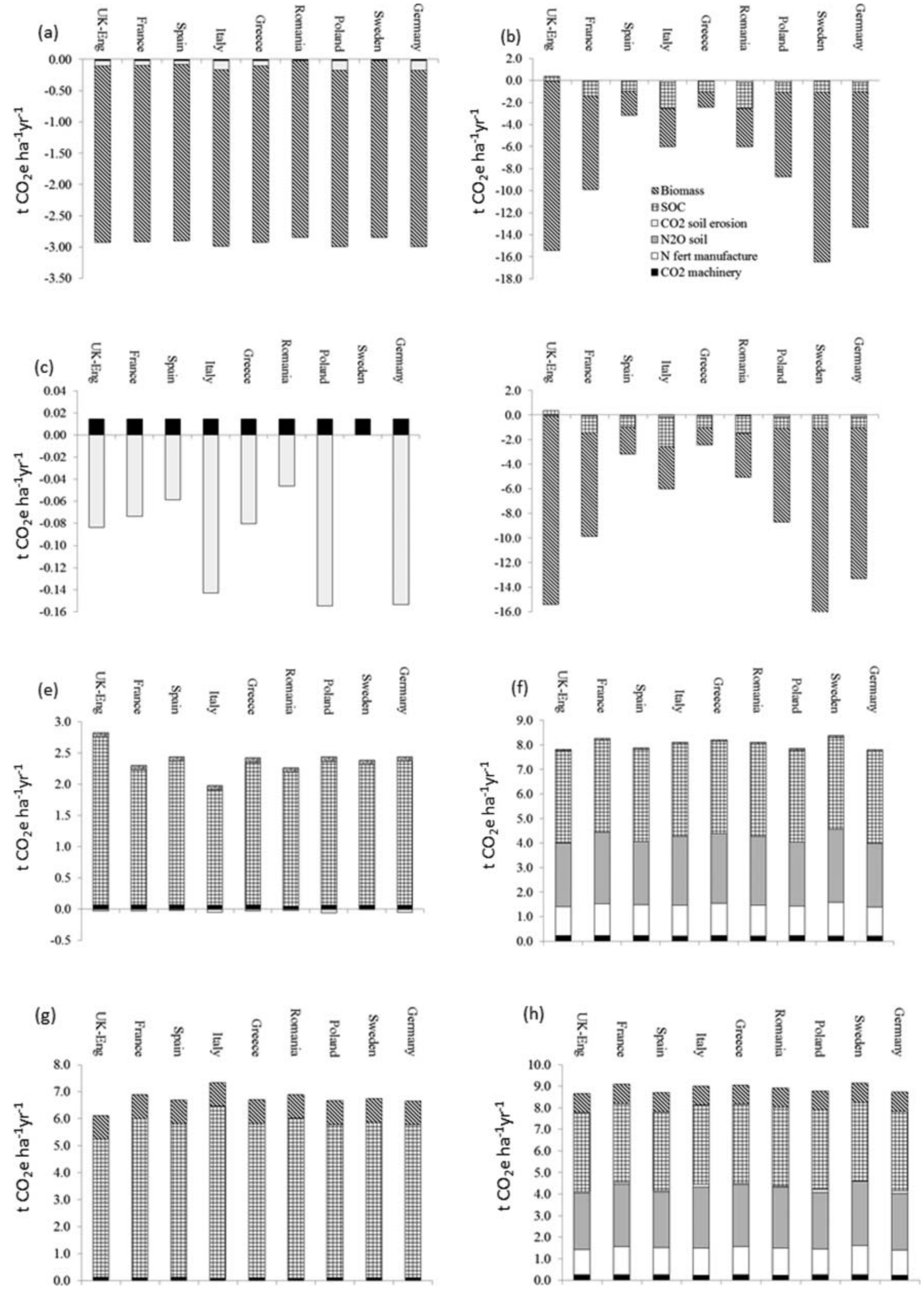

Figure 4. Mean greenhouse gas reduction (t CO_2-e ha^{-1} yr^{-1}) relative to a grass buffer strip (zero erosion) baseline for eight Rural Development Program (RDP) measures with a yield reduction of >30% implemented in nine Member States on applicable (existing cultivated) land (years 1 to 10). (a) hedgerow planting, (b) afforestation of buffer strips, (c) in-field grass areas, (d) woodland creation (coniferous), (e) pollen and nectar mixture, (f) conservation headlands, (g) uncropped cultivated margins, (h) fallow plots for ground nesting birds.

development process. Information that is too detailed, and information that is too simplistic and hides important detail, will both be unsuitable. The provision of a managing authority with 200 journal papers on agricultural GHG emissions, for example, is unlikely to be helpful. At the other extreme, saying an RDP operation will reduce GHG emissions by 10 t CO_2-e $ha^{-1}yr^{-1}$ in Europe is too simplistic.

Table 4. Selected pre-2014 Rural Development Program (RDP) measures, their post-2014 equivalent, impact on displacement, potential for inclusion within a climate related sub-program, availability and weighting within nine individual Member States under current CAP reform. The EFA weight states the area of individual EFA elements deducted from the target 5%, where applicable the conversion factor (in brackets) is multiplied by the weighting factor.

Pre-2014	Post-2014 equivalent	GHG mitigation	Displacement	Climate sub-program	UK-Eng	FR	ES	IT	GR	RO	PO	SE	DE
Hedgerow planting	Hedges	C-seq	N	✓	2 (5)	2 (5)	—	2 (5)	—	2 (5)	2 (5)	—	2 (5)
Catch crops	Catch crops/green cover	N_2O -L	N	✓	0.3	0.3	—	—	—	0.3	0.3	0.3	0.3
On-farm reservoir	—	I	N	✓	—	—	—	—	—	—	—	—	—
Minimum tillage	—	CO_2-FT, CO_2-SOC, CO_2-E	N	✓	—	—	—	—	—	—	—	—	—
In-field grass area	Buffer strips[†]	CO_2-E, CO_2-SOC	Y	✓	1.5 (6)	1.5 (6)	—	1.5 (6)	1.5 (6)	1.5 (6)	1.5 (6)	—	1.5 (6)
Afforestation of buffer strips	Landscape features — trees in a line	CO_2-E, CO_2-SOC C-seq	N	✓	—	2 (5)	—	2 (5)	2 (5)	2 (5)	2 (5)	—	2 (5)
Woodland creation	Landscape features — trees in a group	C-seq	Y	✓	—	1.5	—	1.5	1.5	1.5	1.5	—	1.5
Woodland creation	Area (ha) of agroforestry	C-seq	Y	✓	—	1	1	1	—	—	—	—	1
Buffer strips	Buffer strips	CR	Y	—	1.5 (6)	1.5 (6)	—	1.5 (6)	1.5 (6)	1.5 (6)	1.5 (6)	—	1.5 (6)
Pollen and nectar mix	Fallow land	CR	Y	—	1	1	1	1	1	—	1	1	1
Conservation headlands	Landscape features — field margins	CR	Y	—	—	1.5 (6)	—	1.5 (6)	—	1.5 (6)	1.5 (6)	1.5 (6)	1.5 (6)
Uncropped cultivated margins	Fallow land	CR	Y	—	1	1	1	1	1	—	1	1	1
Central fallow plots	Fallow land	CR	Y	—	1	1	1	1	1	—	1	1	1

[†] Equivalent function subject to appropriate location.

Note: CAP: common agricultural policy; EFA: ecological focus area; C-seq: C sequestration; N_2O -L: N_2O from NO_3^- leaching; I: Irrigation; CO_2-FT: CO_2 fuel consumption tillage, CO_2-SOC: soil CO_2 via SOC loss, CO_2-E: soil CO_2 via soil erosion; CR: Crop removal only; UK-Eng: United Kingdom — England; FR: France; ES: Spain; IT: Italy; GR: Greece; RO: Romania; PO: Poland; SE: Sweden; DE: Germany.

The proposed RVC categories demonstrate, in a readily interpretable format, how the environmental impact on GHG emissions of RDPs implemented on cultivated land varies from one MS to another, in response to the type and frequency of each category. Measures with potential for GHG mitigation in one MS may have a negligible or even detrimental impact in another, and therefore require targeting appropriately. Further, the positive impact within one MS may be localized and risk being overlooked where policy is decided based on an average impact for the MS overall. It is acknowledged that the accurate modelling of N_2O from agricultural soils, and any change in SOC, is inherently difficult and subject to a potential source of error, resulting in uncertainty, and the need to exercise an element of caution in the interpretation of the results. There is a need to further improve the accuracy of predicted GHG emissions from agriculture as a function of location and land management. The method used here does, however, represent an improvement in spatial resolution compared with the IPCC [102] Tier 1 and 2 methodologies, by accounting for localized environmental variables such as dominant soil texture, annual rainfall and risk of soil erosion. The underlying data also represent one of the most extensive and complete spatial data sets currently available for Europe.

Spatial targeting of RDP measures using RVCs to improve GHG mitigation potential in MSs

The development of the RVC approach that accounts for variation in baseline spatial factors, such as soil texture and climate, allows the calculation of location-specific impacts for individual RDP measures. These measures may then be prioritized within each MS and within specific regions of a MS, accounting for differences between north and south, for example, as was evident for NO_3^- leaching risk in Spain. Mitigation potential has been assessed based on two key criteria: first, a reduction of GHG emissions per unit area without compromising agricultural yield, where a decrease in emissions per unit of output results; and, second, where land is removed from agricultural production, the emissions reduction achieved is greater than that of a grass buffer strip implemented on land not vulnerable to soil erosion or present on organic soils. The second prioritization method eliminates RDP measures where a decrease in emissions is restricted solely to the removal of land from production, with no additional benefit gained from the mitigation of emissions associated with, for example, soil erosion or NO_3^- leaching.

Leaching of NO_3^- was identified as a potential high-risk and high-frequency issue in six of the nine MSs evaluated in detail, with high risk and moderate frequency identified in the remaining three. The high risk category is attributed to sandy soils in combination with above moderate (> 600 mm yr^{-1}) levels of rainfall. It concurs with published literature as a potential issue throughout Europe, including the northern and central case study MSs: the UK [46], Sweden [47], Poland [48], France [49], northern Spain [50,51] and Germany [52]. Italy [53,54] and Greece [55] in the south also report NO_3^- leaching from cultivated land, a factor further influenced by irrigation during drier periods of the year [56]. The mitigation of N leaching on cultivated land is applicable to all MSs although it may be restricted to a smaller number of regions in the south of Europe, which at a lower spatial resolution may be overlooked. Mitigation via pre-2014 RDP measures included winter cover crops [44], and their inclusion in measures should be prioritized within these high-risk areas to reduce indirect emission of N_2O. This would entail inclusion of RDP measures in MSs where leaching is not necessarily widespread, as demonstrated by the RVCs within the southerly regions, but high-resolution spatial targeting may potentially have a significant impact per ha within those localized areas. Further, early crop establishment immediately following autumn plowing reduces soil compaction risk and leaching and adds organic matter and carbon (C) upon removal [57,58], and may mitigate both water and wind erosion on vulnerable soils [59]. This may also be pertinent to MSs such as Spain, where both erosion pathways are of concern [60].

The additional GHG emissions associated with the culture of a winter cover crop are eliminated where leaching is reduced by in excess of 15 kg N $ha^{-1}yr^{-1}$, equivalent to the moderate- and high-risk zones identified in Figure 3. It is important that cover crops are not applied to RVCs where leaching is deemed to be of low risk, for example on heavier soils such as clay, as the fuel required to undertake an additional tillage operation to remove the cover crop is greater [4,7]. Measures to mitigate N leaching specifically via RDPs (e.g. catch crops) were identified by the rationalization process for Germany, Italy, Sweden and the UK. The RDP measure to grow winter cover crops in England was available only on sandy soils [61], avoiding a net increase in emissions through inadequate reduction in N leaching. Inclusion of support for such measures through RDPs in other high-risk, high-frequency MSs such as France and northern Spain would be of benefit. In the case of Spain, the northern region only is categorized as high risk, but availability as an RDP measure pre-2014 at the MS level was absent. At a lower spatial resolution (i.e. MS NUTS1 level [NUTS: nomenclature of territorial units for statistics]) the area is, on average, of low risk and this absence of availability is justified. At a higher spatial resolution, as indicated by the 1-km^2 RVC categories, specific regions within Spain (e.g. at NUTS3 level) would potentially benefit from the availability of this measure.

Catch crops represent an RDP measure that may reduce GHG emissions where appropriate RVCs are present, without compromising crop yield, but whose value may be obscured when considered over broad spatial scales. Inappropriate location of such options may result in an increase in emissions; when combined with areas where emissions decrease, the net impact appears negligible. Another class of RDP measure prioritized for GHG mitigation are those that reduce GHG emissions, again subject to appropriate spatial targeting, but which are coupled with a decrease in or elimination of crop yield. Although the removal of productive agricultural land risks transfer of emissions elsewhere, with zero mitigation overall, mitigation is achieved where baseline emissions exceed typical levels because of localized environmental variables such as soil erosion or surface water run-off. The hypothetical transfer of crop production to a low-risk RVC, where baseline emissions are lower due to the absence of such variables, results in a potential net decrease in emissions. Using a grass buffer strip located within a low-risk RVC as a benchmark, emissions are reduced relative to this but appropriate spatial targeting is critical; otherwise, the measure will function in the same capacity as a grass buffer strip within a low-risk RVC, for which the decrease in the CO_2-e results only from the removal of productive agricultural land. Soil erosion is identified in Figure 4c as having potential for mitigation within all MSs, although this was greatest overall in Italy, Germany and Poland. All MSs report areas vulnerable to soil erosion [28] and RDP measures, such as winter cover crops, minimum cultivation, undersowing followed by a grass ley and within-field grass areas or buffer strips, to ensure healthy soils and a reversal of soil erosion, were available across the EU-28 pre-2014, conducive to GHG mitigation where targeted appropriately. The benefit attributed to minimum cultivation is on the condition that soil compaction induced by farm traffic is avoided. Failure to do so risks an increase in emissions of N_2O or CH_4 [62–64]. This caveat is of particular relevance to MSs with extensive areas of high soil compaction risk, such as Poland. A number of these measures remain available through the post-2014 EFA options including grass buffer strips, trees on buffer strips, and catch crops and green cover. Although effective at pinpointing localized regional high-risk areas, particularly beyond the broad spatial scales at MS NUTS1 level, it is acknowledged at the farm level that field-specific topography and soil erosion risk are often below 1 km^2 resolution. The RVC approach seeks to provide region-specific guidance and highlight areas obscured by broad spatial coverage, but not to replace direct on-farm assessment and advice.

Measures that do not reduce emissions beyond the equivalent of establishing a grass buffer strip within a low-risk RVC are considered limited in their GHG mitigation potential, and have not therefore been assessed in detail. Their implementation will, in many cases, reduce emissions compared to those of an existing cropped baseline due to the removal of the crop. If production displacement is assumed, no net emissions reduction results, as indicated in Figure 4e–h. Their purpose is for the benefit of ecosystem services other than GHG mitigation, such as pollination. The RVCs offer potential to highlight where such options may maximize other ecosystem service benefits while simultaneously minimizing GHG emissions. An example might be avoiding the implementation of measures that create areas of bare soil to benefit ground-nesting birds in locations where RVCs highlight soil erosion as a potential risk.

Future policy and adaptation

The past decade has seen climate change policies evolve to encompass adaptation to climate change as an equal objective alongside mitigation, in recognition that we need to respond to the changes in climate that are occurring as well as reduce GHG emissions to prevent more severe climate change in the future [65]. As with GHG emissions, climate change adaptation issues vary spatially across Europe; consequently, policy interventions also require a targeted approach. Work undertaken by Tzilivakis et al. [66] adopted a similar approach to spatial targeting with respect to identifying vulnerabilities to ecosystem services across Europe. Overlap exists between the spatial parameters that influence climate change vulnerabilities and GHG emissions, with scope for synergies and trade-offs between them. Combining spatial information provides the opportunity to find optimal and multifunctional solutions and interventions.

The introduction of EFAs, while being more focused on biodiversity, also has a role to play in GHG mitigation. Winter cover crops, for example, a measure identified as priority in a number of MSs, are included in the EFA catch crop/green cover component. The implementation of these high-priority measures is now, therefore, included under Pillar 1 as opposed to Pillar 2 in these MSs, offering potential for an increase in uptake. This has, however, come at a cost. The lower weighting of both options (0.3) within EFAs does not correspond to the identified GHG mitigation priority compared to, for example, the weighting of 1 assigned to fallow land [67,68], deemed a significantly lower GHG mitigation priority. It must also be taken into account that implementation of catch crops on land not vulnerable to leaching will have limited mitigation potential, but risk an increase in emissions associated with sowing the catch crop and its subsequent removal. If a more multifunctional approach was applied to account for GHG mitigation, and the EFA catch crop/green cover elements were part of a climate related sub-program, an increase in area weighting would be justified.

Conclusions

The appropriate spatial targeting of RDP measures within MSs provides the opportunity to reduce GHG emissions and minimize production displacement. The variation in GHG emissions on cultivated land between MS, the potential mitigation strategies available through RDPs and their effectiveness are demonstrated by the novel RVC category approach. It highlights potential deficiency in policy when determined in a broader sense, based on an impact average for the MS overall. It would also seem that existing RDP measures beneficial to GHG reduction will be continued. Many EFA elements achieve the minimum GHG reduction requirement, suggesting a mostly positive impact on agricultural GHG emissions from EFA implementation across Europe, subject to appropriate spatial targeting.

The spatial targeting of ecosystem service vulnerability in agricultural systems throughout Europe has overlap with both greenhouse gas mitigation and RDP interventions to facilitate climate change adaptation. Agriculture makes a significant contribution to GHG emissions across Europe, but options exist to reduce it, and not solely through the removal of productive agricultural land from cultivation. An awareness of the synergies and trade-offs that exist between them through the aggregation of spatial information on GHG emission and vulnerability to climate change provides a platform to optimize solutions and interventions via multifunctional approach. The introduction of, for example, a climate related sub-program would provide the capacity to focus on, and target appropriately, RDP measures with GHG mitigation potential.

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