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The challenge of managing soil functions at multiple scales: An optimisation study of the synergistic and antagonistic trade-offs between soil functions in Ireland

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ABSTRACT

Recent forecasts show a need to increase agricultural production globally by 60% from 2005 to 2050, in order to meet a rising demand from a growing population. This poses challenges for scientists and policy makers to formulate solutions on how to increase food production and simultaneously meet environmental targets such as the conservation and protection of water, the conservation of biodiversity, and the mitigation of greenhouse gas emissions. As soil and land are subject to growing pressure to meet both agronomic and environmental targets, there is an urgent need to understand to what extent these diverging targets can be met simultaneously. Previously, the concept of Functional Land Management (FLM) was developed as a framework for managing the multifunctionality of land. In this paper, we deploy and evaluate the concept of FLM, using a real case-study of Irish agriculture. We investigate a number of scenarios, encompassing combinations of intensification, expansion and land drainage, for managing three soil functions, namely primary productivity, water purification and carbon sequestration. We use proxy-indicators (milk production, nitrate concentrations and area of new afforestation) to quantify the 'supply' of these three soil functions, and identify the relevant policy targets to frame the 'demand' for these soil functions.

Specifically, this paper assesses how soil management and land use management interact in meeting these multiple targets simultaneously, by employing a non-spatial land use model for livestock production in Ireland that assesses the supply of soil functions for contrasting soil drainage and land use categories. Our results show that, in principle, it is possible to manage these three soil functions to meet both agronomic and environmental objectives, but as we add more soil functions, the management requirements become increasingly complex. In theory, an expansion scenario could meet all of the objectives simultaneously. However, this scenario is highly unlikely to materialise due to farm fragmentation, low land mobility rates and the challenging afforestation rates required for achieving the greenhouse gas reduction targets. In the absence of targeted policy interventions, an unmanaged combination of scenarios is more likely to emerge. The challenge for policy formation on future land use is how to move from an unmanaged combination scenario towards a managed combination scenario, in which the soil functions are purposefully managed to meet current and future agronomic and environmental targets, through a targeted combination of intensification, expansion and land drainage. Such purposeful management requires that the supply of each soil function is managed at the spatial scale at which the corresponding demand manifests itself. This spatial scale may differ between the soil functions, and may range from farm scale to national scale. Finally, our research identifies the need for future research to also consider and address the misalignment of temporal scales between the supply and demand of soil functions.

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1. Introduction

Recent forecasts indicate that world population will grow by 2.5 billion from 2015 to 2050 (PRB, 2015). By that time, agriculture production globally must have increased by 60% from 2005 levels (WWDR, 2015). This poses challenges for scientists and policy makers to derive solutions on how to increase food production and at the same time meet environmental targets such as water protection, conservation of biodiversity or climate change mitigation. For example, the European Union (EU) Water Framework Directive (2000/60/EC) provides a framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater (EU, 2000). It requires Member States (MS) to establish river basin districts and an associated management plan for each river basin. It supersedes the Nitrates directive (91/676/EEC) which was developed to reduce water pollution caused by nitrates from agricultural sources (EU, 2010). Similarly, in 2011 the EU adopted its EU Biodiversity Strategy to 2020 to halt the loss of biodiversity and ecosystem services by 2020 (EU, 2015a). In relation to mitigating climate change, in 2007, the EU committed to reducing greenhouse gas (GHG) emissions in the year 2020 by 20% compared to 1990 levels, increasing renewable energy use by 20%, and to improving energy efficiency by 20% (EU, 2014), as part of the “EU Energy and Climate Package 2020”. This policy will be replaced by the new “EU Climate and Energy framework 2030” for the period between 2020 and 2030 (EU, 2015b), which proposes to reduce GHG emissions by 2030 by 40% compared to 1990, and to increase renewable energy use and energy savings by at least 27% compared with the business-as-usual scenario (EU, 2015b).

The growing societal pressures on the soil resource prompted the European Commission (EC) to publish the EU Thematic Strategy for Soil Protection in 2006, which set a common EU framework for action to preserve, protect and restore soil by implementing actions customised to local situations (EC, 2006). This strategy considers the different functions that the soil can perform, and also the main threats to soil quality. Soil based ecosystem services, also known as soil functions, have previously been described in a number of studies including Bouma and Droogers (2007); Haygart and Ritz (2009) and Calzolari et al. (2015). In the Netherlands, Bouma and Droogers (2007) proposed a six-step procedure for a water management unit using existing soil data related to the soil topics of soil functions, threats and quality. Haygart and Ritz (2009) proposed 18 ecosystem services that are critical for soil and land use in the United Kingdom. Also, a methodological framework of eight soil functions has been developed by Calzolari et al. (2015).

In many countries, the diverging policies put pressure on land and soil to meet both agronomic and environmental targets, necessitating a better understanding as to how and to what extent these targets can be achieved simultaneously. In response, Schulte et al. (2014) developed the concept of Functional Land Management (FLM) as a framework for optimising the delivery of five soil functions, specifically for agricultural land use:

1 Primary productivity;
2 Water purification and regulation;
3 Carbon sequestration and regulation;
4 Provision of habitat for biodiversity;
5 Nutrient cycling and provision.

Within the FLM framework the supply of these soil functions is dependent upon land use and soil type while demand is framed as policy drivers. Accordingly, challenges to sustainability will vary spatially across locations. To meet the challenge of intensifying agriculture sustainably, FLM seeks to match the supply of soil functions with demand (Schulte et al., 2014).

The FLM framework is underpinned by the multifunctionality of soils: which is that all soils perform all of these five functions simultaneously, but some parts of the land perform some functions better than others (Schulte et al., 2014; O’Sullivan et al., 2015). Central to the FLM framework is that land and soil management is aimed at optimising, rather than maximising, the supply of each of the soil functions. While maximising would seek to achieve the highest total delivery of soil functions, optimising gives priority to meeting demands at the spatial and temporal scales required by policy objectives (Schulte et al., 2015a).

Coyle et al. (2016) elaborated on the FLM framework, by relating the delivery of multiple functions to land use and soil properties, using the Atlantic pedo-climatic zone of Europe as their geographical region of interest. They showed that in this region, the delivery of soil functions is mainly determined by soil drainage properties and that augmentation of one soil function is likely to result in the alteration of other soil functions (see also O’Sullivan et al., 2015).

Furthermore, Schulte et al. (2015a) explored how the demand for different soil functions operates at different scales. For example, the demand for water purification manifests itself at a local scale, whereas the demand for carbon sequestration exists at national scale. The authors conclude that this has implications for the management of the supply for soil functions, namely: soil management for water quality at local scale, and land use management for climate mitigation at national scale.

So far, the FLM framework, and the exploration of trade-offs and synergies between the various soil functions have been largely conceptual, with the exception of the study by O’Sullivan et al. (2015) into the trade-offs between primary productivity and carbon sequestration. In this current paper, we used empirical data to explore scenarios for FLM, aimed at meeting multiple agronomic and environmental policy objectives. Using Ireland as a case study, we assessed how soil management and land use management interact in meeting multiple targets simultaneously. For simplicity, we limited our analysis to the three functions primary productivity, water purification and carbon sequestration. Two of these soil functions are part of the set investigated by Calzolari et al. (2015).

2. Materials and methods

2.1. Case study

For our case study, we used Ireland as a national example of the challenges facing the agricultural sector in relation to meeting both agronomic and environmental targets. Dairy and livestock production play a central role in Irish agriculture: 80% of agricultural land is grassland (Teagasc, 2015), and most of the herbage is grazed *in situ*, with the remainder harvested as silage that is fed during the relatively short housing seasons (2–5 months), during which it may be supplemented with various amounts of concentrates (Schulte et al., 2014). Food Harvest 2020 represents the industry strategy, supported by the Irish government, to increase national milk production between 2010 and 2020 by 50%. The abolition of the milk quota in Europe in 2015 gives Irish farmers for the first time in over 30 years the opportunity to increase their production without being constrained by quota. Food Harvest 2020 has now been followed by the Food Wise 2025 strategy which foresees a further rising of ambitions, however without defining further volume targets for production. Both strategies aim to keep volume outputs of other agricultural sectors stable while increasing export values. Following a Strategic Environmental Assessment (SEA) (EU, 2001), the preferred pathway for implementation is the ‘Sustainable Growth’ scenario, in which the increase in dairy output is achieved through sustainable intensification, that is without significant increases in pressures on the environment.

In this paper, we assess various permutations for the Sustainable Growth scenario, with a view to optimising the delivery of three soil functions, namely: primary productivity, water purification and carbon sequestration, to meet the societal demands as framed by legislation and national policy objectives.

2.2. Proxy-indicators

The demand for soil functions is framed by the agri-environmental policy framework. Based on the original work of Schulte et al. (2014) the following are the proxy-indicators defined for the current research:

1 Primary productivity: for the first soil function we identify increased milk production as the most pertinent proxy-indicator. The demand for this soil function is framed within the national Food Harvest 2020 policy documents that seeks to increased dairy production volume by 50% by 2020 (DAFM, 2015).
2 Water purification: for this soil function we selected the nitrates concentration in groundwater recharge as the (partial) proxy-indicator. The demand for this function is defined by the Nitrates Directive that indicates that groundwater nitrates-N (NO_3-N) concentrations must not exceed 11.3 mg per litre (EU, 1991).
3 Carbon sequestration: for this soil function we adopt the annual planting rate of new afforestation as the proxy-indicator (DAFM, 2015). Ireland has been allocated an emissions reduction target of 20% (EU, 2014). The EU Climate and Energy Framework 2030, currently under review, expands on this ambition and proposes and EU-wide emissions reduction target for the non-emissions trading sector (non-ETS) of 30% compared to 2005 (EU, 2015b).

In relation to the third proxy-indicator above, the European target has not yet been transposed into national targets for individual MS, but is likely to result in a target for Ireland in excess of the current 20% reduction. Assuming the Irish government chooses to implement the reduction targets equally through all sectors not covered by the European Emissions trading System and in the absence of certainty, we adopted a nominal and realistic reduction target of 25% for Irish agriculture. Previously, Schulte et al. (2012a,b) showed that the predominance of ruminants in Ireland's agricultural sector means that it is very difficult to reduce sectoral GHG emissions under a Food Harvest 2020 growth scenario: at best, GHG emissions may be kept constant while growing milk output and any further reductions will require offsetting in the form of carbon sequestration. In a subsequent study Schulte et al. (2013) identified new afforestation as the most promising pathway to increased carbon sequestration under Ireland's current land use and pedo-climatic conditions. Therefore, in our scenario assessments, carbon offsetting is achieved entirely through afforestation.

2.3. Optimisation sets

Having defined the soil functions of interest and the proxy-indicators for demand, we subsequently formulated three optimisation sets:

1) In our first set, we assessed options for land and soil management aimed at meeting the target for increased primary productivity only;
2) In our second set, we assessed options to meet targets for both primary productivity and water purification and;
3) In our third set, we assessed options to meet the targets for all three soil functions, namely primary productivity, water purification and carbon sequestration.

These optimisation sets were designed to allow the challenge of managing multiple functions simultaneously to be demonstrated. In turn, this will inform better understanding of the synergistic and antagonistic trade-offs between the three soil functions under examination and how the options for optimisation are altered as additional targets are added to the optimisation sets. Finally, this will determine to what extent the achievement of current policy demand drivers can realistically be achieved.

2.4. Optimisation scenarios

We explored the impacts of land use and soil properties on the delivery of the three soil functions of interest, informed by the land use x natural drainage class matrix developed by Coyle et al. (2016) and deployed by Schulte et al. (2015a). This framework is based upon an extensive literature review that considers the delivery of soil functions in the Atlantic pedo-climatic zone. This study identified soil drainage class as a dominant driver in relation to the delivery of soil functions for this particular climate zone.

In this regard, Schulte et al. (2015a) identified three options to manage, and hence optimise, soil functions in the Atlantic pedo-climatic zone:

1 Soil management aimed at augmenting a selective soil function (*e.g.* primary productivity) without compromising other functions (*e.g.* water purification, biodiversity). Examples include the introduction of nutrient or grazing management plans;
2 Land Use Change: the capacity of soils to supply the five soil functions is in first instance governed by land use. As a result, the local supply of soil functions may change following a change in land use. For example, a change from extensive grassland (typically associated with drystock production systems) to intensive grassland commonly found in dairy production systems is likely to result in increased primary productivity, but a concomitant decrease in the potential for water purification and biodiversity (Coyle et al., 2016).
3 Soil Drainage: additionally, the capacity of soils to supply the five functions is regulated by soil properties. In Atlantic Climates, the most important properties are those relating soil water dynamics (Coyle et al., 2016). These properties can be integrated and categorised by ascribing natural drainage classes to soils (see Section 2.5). The installation of arterial drainage systems changes the drainage class of a soil either from 'poor' to 'moderate', or from 'moderate' to 'well'. This has a major impact on the supply and composition of the suite of soil functions. Typically, soil drainage allows for increased primary productivity, but at the expense of the potential for carbon sequestration (O'Sullivan et al., 2015).

Based on these pathways for managing soil functions, we investigated five scenarios aimed at meeting the demand for soil functions, for each of the aforementioned optimisation sets. These scenarios include a baseline scenario, each of the three pathways, and a combination scenario:

1) Baseline – this scenario represents current livestock production for Ireland.
2) Intensification – this scenario is based on soil management delivering higher productivity per hectare achieved by increasing the animal stocking rates and farm inputs on dairy farms.
3) Expansion – this scenario is based on land use change, namely an expansion of the dairy production platform into lands hitherto used for drystock production. This scenario is a reflection of current developments on dairy farms that were previously constrained by quota. In this scenario, the expansion of the area devoted to dairy farming is associated with an intensification (increased stocking rates and N usage) of the drystock farming

Table 1
Land area datasets.

Managed grassland	LPIS "Permanent Pasture" data by DAFM which show farm outlines of all land held by farmers who have applied for support payments from the EU. Maps are updated annually by Mallon Technology since 1995 (Mallon Technology, 2014). This category was refined based upon the TLC95 map produced using aerial photography and satellite imagery (Fealy et al., 2009).
Soil Information System (SIS)	The Irish Soil Information System (SIS) has been prepared at a scale of 1:250,000 through the application of predictive mapping techniques in conjunction with traditional soil survey methods. The SIS was validated with a 2.5 year field survey including analysis of 11,000 auger bores (Creamer et al., 2014).
Drainage class	Drainage class based on the following diagnostic rules (Schulte et al., 2015b) was applied to Irish SIS at soil subgroup based on diagnostic features (Creamer et al., 2014): • Well: No mottling, no full argic/spodic horizon present • Imperfect: Mottling 40–80 cm AND some organic matter accumulation and argic/spodic horizon present (at least a score of 1 in either category) • Poor: Mottling within 40 cm argic/spodic horizon causing stagnation

systems, as the total number of drystock animals is assumed to remain constant, in line with the objectives of the Food Harvest 2020 and Food Wise 2025 policies.

4) Drainage – in this scenario, the productivity of land is increased, not by an increase in inputs, but rather by alteration of the static soil properties relating to drainage. Improved drainage results in higher grass growth, improved trafficability and improved grass utilisation (Schulte et al., 2012a,b). Drainage is commonly associated with an increase in fertiliser N usage to support this increased productivity (Hanrahan et al., 2013), denitrification rates and hence nitrous oxide emissions are commonly lower as a result of the reduced anaerobicity (Jahangir et al., 2012). Conversely, nitrate concentrations in drainage water may be increased (Schulte et al., 2006) and the oxygenation of the soil may induce emissions of carbon dioxide (Burchill et al., 2014; Necpálová et al., 2014).
5) Combination – this scenario represents a combination of the intensification, expansion and drainage scenarios.

2.5. Modelling framework

We simulated national livestock production in Ireland by dividing the grassland area into a matrix of land use classes and soil drainage classes.

Soil drainage classes are based upon the Irish Soil Information System (SIS) launched in 2014 that classified Irish soils at a scale of 1:250,000 (Creamer et al., 2014). Within the Irish soil classification system, Soil Subgroups are defined upon diagnostic criteria, such as gleying or stagnic properties (Table 1). Diagnostic features were then used to define natural drainage classes for Irish soils and to develop the indicative soil drainage map of Ireland, described by Schulte et al. (2015b). This allowed the soils to be clustered based upon natural drainage class here, following the matrix developed by Coyle et al. (2016).

For land use, we focussed exclusively on grasslands. Irish agriculture is dominated by grassland, which comprises approximately 80% of the agricultural land in Ireland (Teagasc, 2015). Within this, we delineate our area of interest into modelling 'bins' dedicated to 'dairy' and for 'drystock' as representative of the main farming systems on these grasslands (Fig. 1). The total number of cattle in Ireland is ~6.4 million, including ~1.2 million dairy cows (CSO, 2015). The remaining drystock comprises of suckler cows, male and female cattle (ages less than two years), bulls and beef in-calf heifers (CSO, 2015). Due to the physiological strain on the animals producing milk, dairy farming is characterised by a higher feed demand and N excretion per head as compared to drystock farming (Shalloo et al., 2004). In addition, for the third Optimisation Set, we considered a third land use type, namely new afforestation, planted on grassland.

2.6. Data sets

All optimisation scenarios (in all optimisation sets) used the baseline scenario as the starting conditions to initialise the optimisation process. Using existing data (see Table 1) we established a baseline scenario for dairy production in Ireland before the abolition of the milk quota.

2.6.1. Land area

Our 'Managed grassland' category was derived by refining the Land Parcel Identification System (LPIS – used for administrative purposes by the Irish government Department of Agriculture, Food and the Marine) "Permanent Pasture" class through the application of a satellite image classification of land cover which classified 'Grassland' (Fealy et al., 2009). This overcame the challenge of mountain areas which are included in the LPIS "Permanent Pasture" class. Drainage classification was derived from the Irish Soils Information System 1:250,000 scale soils map (Creamer et al., 2014).

Using a geographical information system (GIS), the managed grassland class was intersected with drainage defined areas which enabled calculation of areas by class. In our scenario, dairy production occupies approximately 0.70 million hectares while 2.5 million hectares of grassland are used for drystock (Table 2).

2.6.2. Stocking rate

We derived livestock numbers from the census of Irish agriculture (CSO, 2012) which is conducted by the Irish national statistics body, the Central Statistics Office (CSO). CSO agricultural census data are available at an electoral division (ED) level in Ireland which corresponds to the Eurostat regional level LAU2 (Eurostat, 2015). The typical size of an ED is approximately 20 km^2. Again using GIS, we intersected the livestock numbers at ED level with the grass/drainage category spatial dataset. We subsequently calculated an indicative baseline stocking rate for each of the drainage classes, by regression of livestock numbers in each polygon against the grassland area of each polygon. We separated livestock numbers into 'dairy' and 'drystock', based on the dairy stocking rates reported in the Teagasc National Farm Survey (Hanrahan et al., 2013), with the remainder of the grassland areas devoted to drystock production.

The resulting stocking rates in the baseline scenario for dairy ranged from 2.04 Livestock Units (LU) per hectare for well and poorly drained soils to 1.29 LU per hectare on moderately drained soils, while the stocking rates for drystock ranged from 1.30 LU per hectare on well drained soils to 1.22 LU per hectare on moderately and poorly drained soils (Table 2). The counterintuitive finding that average dairy stocking rates on poorly-drained soils were not significantly different from those on well-drained soils may be explained by a higher internal variation within farm systems on poorly-drained soils, which include intensive systems that rely on large external inputs in the form of concentrates.

As a result, our model is based on six (for Optimisation Sets 1 and 2) to nine (for Optimisation Set 3) modelling bins (Fig. 1), for which we modelled changes in land area, stocking rate, nitrate concentration and GHG emissions.

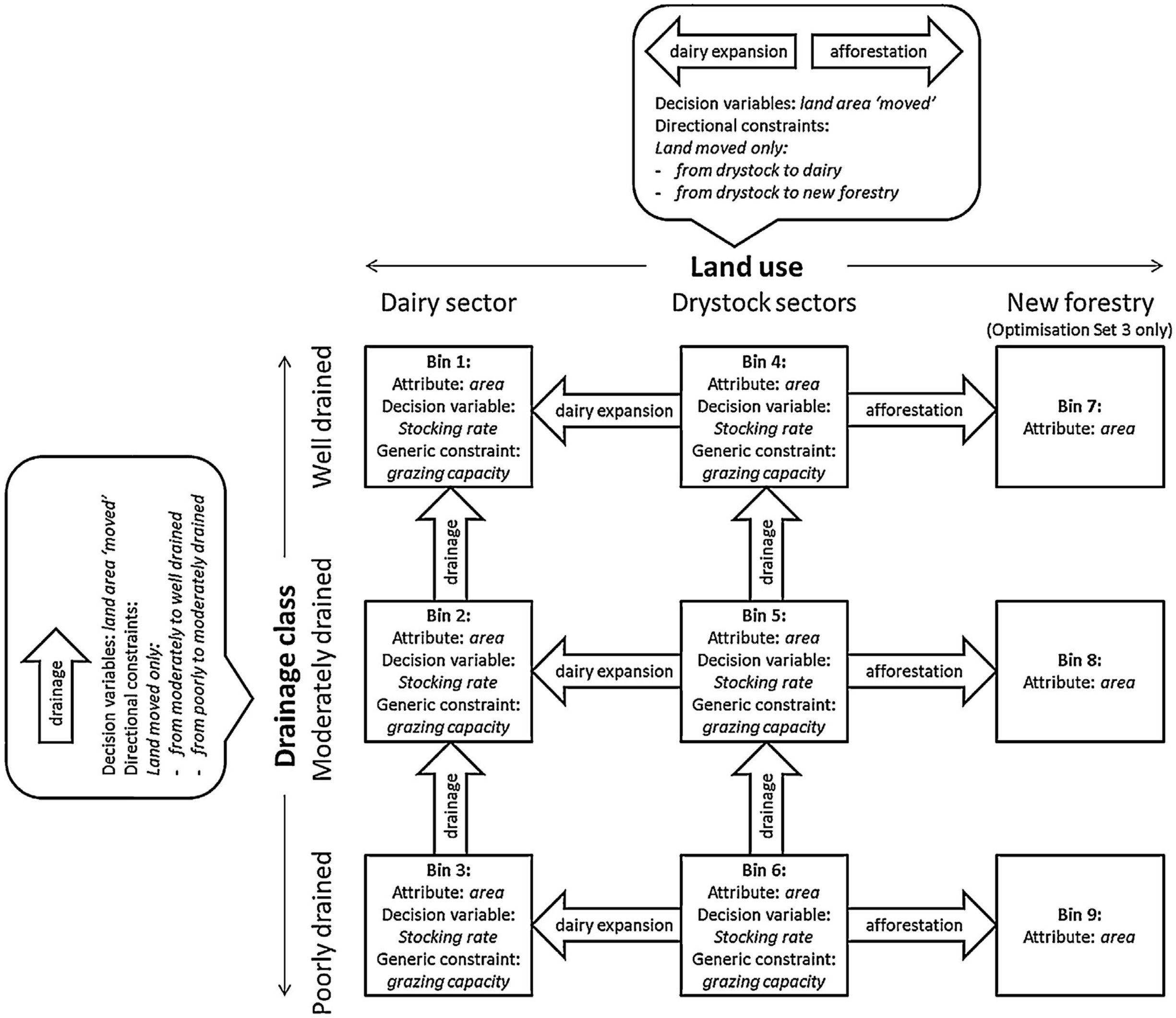

Fig. 1. Modelling framework: visualisation of modelling bins, consisting of combinations of land use and soil drainage classes, as well as decision variables and generic and directional constraints.

2.6.3. Modelling of nitrate concentrations

For each of the modelling bins, we modelled nitrate concentrations of groundwater recharge as a function of nitrogen (N) surplus and net rainfall, for an 'average farm' within each bin. Nitrogen surplus was computed through a farm gate mass balance. The total nitrogen input data was calculated from N inputs in the form of fertiliser including the amount of N available in animal manure and N imported onto the farm in the form of concentrates.

We based fertiliser inputs on the national nutrient recommendations (Coulter and Lalor, 2008) which provide specific N recommendations for those parts of the farm that are (i) grazed only (ii) subjected to one cut of silage, followed by grazing and (iii) subjected to two cuts of silage. The proportions of these three areas depend on the grass sward type, stocking rate and animal type. The area defined for grazing only typically does not receive organic N in the form of slurry; this is instead applied to the two other areas. The amount of N available from slurry was calculated from livestock numbers, the length of the housing period and land area available for spreading. While this slurry represents an internal cycling of N within the farm boundaries, and is therefore not directly accounted for in the farm N balance, it does determine the quantity of fertiliser N that is recommended, following the national recommendations (Coulter and Lalor, 2008) and permitted at farm level under the Nitrates regulations.

The amount of concentrate intake for each livestock type, length of the grazing season, length of housing period and milk yield were derived separately for well drained and poorly drained soils, as

Table 2
Initialisation values for land area, stocking rates and grazing capacity for both dairy and drystock production systems, used for the baseline scenario in each optimisation set.

Drainage class	Land Area (ha)		Stocking rates (livestock units/ha)		Grazing capacity (livestock units/ha)	
	Dairy	Drystock	Dairy	Drystock	Dairy	Drystock
Well	314,169	1,068,123	2.04	1.30	2.55	2.04
Moderately	205,954	700,209	1.29	1.22	2.57	2.00
Poorly	203,111	690,544	2.04	1.22	2.23	2.23

Table 3
Overview of the optimisation parameters (objective function, decision variables, and constraints) as applied to each of the five scenarios in each of the three optimisation sets.

	Optimisation set														
	Set 1 (primary productivity only)					Set 2 (primary productivity + water purification)					Set 3 (primary productivity + water purification + carbon sequestration)				
Optimisation parameters	baseline	intensification	expansion	drainage	combination	baseline	intensification	expansion	drainage	combination	baseline	intensification	expansion	drainage	combination
Objective function															
Increase milk production by 50%		▨	▨	▨	▨		▨	▨	▨	▨		▨	▨	▨	▨
Decision variables															
Increase stocking rate		▨			▨		▨			▨		▨			▨
Move land area from drystock to dairy			▨		▨			▨		▨			▨		▨
Move land area between drainage classes				▨	▨				▨	▨				▨	▨
Move land from drystock to forestry												▨	▨	▨	▨
Generic constraints															
Stocking rate <= grazing capacity of bin		▨	▨	▨	▨		▨	▨	▨	▨		▨	▨	▨	▨
Directional constraints															
Drainage: poor→moderate→well				▨	▨				▨	▨				▨	▨
Land use change: drystock→dairy			▨		▨			▨		▨			▨		▨
Land use change: drystock→forestry												▨	▨	▨	▨
Specific constraints															
NO_3-N <= 11.3 mg l^{-1}							▨	▨	▨	▨		▨	▨	▨	▨
GHG emissions: net reduction of 25%												▨	▨	▨	▨

described by Shalloo et al. (2004). For moderately drained soils, we interpolated the values for well and poorly drained soils.

We estimated the farm N surplus by subtracting N exports from N inputs. N exports were derived from stocking rate, productivity and milk and meat protein concentrations (Shalloo et al., 2004; Crosson et al., 2007) converted to N (Mariotti et al., 2008).

Part of the N surplus is lost to the atmosphere through denitrification or volatilisation of ammonia. Ammonia losses were calculated from animal housing and grazing periods according to the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines for National Greenhouse Gas Inventories. Denitrification was computed as described in Schulte et al. (2014).

The annual quantity of nitrate produced was derived by mass balance. We converted this quantity to N concentrations using the typical annual net rainfall value of 500 mm, taken from Prado et al. (2006).

2.6.4. GHG emissions

We calculated greenhouse gas emissions for each bin, in accordance with the 2006 IPCC guidelines, using national emission factors taken from the National Inventory Report of Ireland (EPA, 2014). For the dairy and other livestock sectors we calculated nitrous oxide (N_2O) emissions from fertiliser use and methane (CH_4) emissions from enteric fermentation and manure management. Emissions associated with drainage were factored into the model based on the values found by O'Sullivan et al. (2015).

In addition, for Optimisation Set 3, we calculated the offsetting potential of new afforestation, and the area of afforestation required to meet emission reduction targets, using the analysis of the "Carbon-Neutrality Report" (Schulte et al., 2013) with an indicative sequestration rate of 14.7 t CO_2 equivalent per hectare per year for a 2050 timeframe.

2.7. Optimisation

To optimise each of the scenarios, we used the Microsoft Office Excel 2010 add-in Solver. Solver is a built-in optimisation tool where users can develop a spreadsheet linear or non-linear optimisation model to find the optimal solution (Mason and Dunning, 2010). The optimisation of each set was controlled by defining the following parameters (Table 3):

- Objective function: in our case study the objective was to increase milk production by 50% (DAFF, 2010).
- Decision variables: these represent quantities that can be changed during the optimisation process in order to meet the objective function. In our case, the choice of variables depended on the scenario. For example, in our intensification scenario, the optimisation process was set to modify the values for the stocking rates for dairy on well, moderately and poorly drained soils.
- Constraints: these represent boundary conditions that the optimisation process must adhere to. Our constraints included generic, directional and specific constraints. Generic constraints included maximum stocking rates for well, moderately and poorly drained soils equating to the corresponding grazing capacities, as given in Lee and Diamond (1972). Feedlot systems with high stocking rates based on imported concentrate feeds were not considered. Directional constraints were applied to increases or decreases in the land areas of individual bins. For example, in the Drainage Scenario, soil properties can only change from moderately drained soils to well drained soils or from poorly

Table 4

Optimisation results for each optimisation set (changes in red). Optimisation Set 1 contained one objective only: to increase milk volume output by 50%. Optimisation Set 2 included the additional objective for water purification, to maintain NO_3-N concentrations below 11.3 mg l^{-1}, while Optimisation Set 3 included a further objective to reduce net GHG emissions from the agricultural sector by 25%. For a description of the various scenarios, see Table 3.

Objective		Optimisation Set 1					Optimisation Set 2							Optimisation Set 3									
		Primary productivity					Primary productivity, water purification							Primary productivity, water purification, C sequestration									
Scenario	Drainage class	increase in milk production, %	Stocking rate for diary, LU per ha	Stocking rate for drystock, LU per ha	Land area for diary, million ha	Land area for drystock, million ha	increase in milk production, %	max NO3 (dairy), mg per l	max NO3 (drystock), mg per l	Stocking rate for diary, LU per ha	Stocking rate for drystock, LU per ha	Land area for diary, million ha	Land area for drystock, million ha	increase in milk production, %	max NO3 (dairy), mg per l	max NO3 (drystock), mg per l	Stocking rate for diary, LU per ha	Stocking rate for drystock, LU per ha	Land area for diary, million ha	Land area for drystock, million ha	Emissions total, Mt CO_2 eq.	Emission offset required, Mt CO_2 eq.	Land use change to forestry, million ha
Baseline	well	0%	2.04	1.30	0.31	1.07	0%	10.8	9.4	2.04	1.30	0.31	1.07	0%	10.8	9.4	2.04	1.30	0.31	1.07	18.7	3.7	0.25
	mod		1.29	1.22	0.21	0.70		5.2	5.6	1.29	1.22	0.21	0.70		5.2	5.6	1.29	1.22	0.21	0.70			
	poor		2.04	1.22	0.20	0.69		3.4	2.7	2.04	1.22	0.20	0.69		3.4	2.7	2.04	1.22	0.20	0.69			
Intensification	well	35%	2.55	1.30	0.31	1.07	35%	11.0	9.4	2.55	1.30	0.31	1.07	35%	11.0	9.1	2.55	1.62	0.31	0.86	20.7	5.7	0.39
	mod		2.57	1.22	0.21	0.70		7.3	5.6	2.57	1.22	0.21	0.70		7.3	6.2	2.57	1.40	0.21	0.61			
	poor		2.23	1.22	0.20	0.69		2.9	2.7	2.23	1.22	0.20	0.69		2.9	3.0	2.23	1.40	0.20	0.60			
Expansion	well	50%	2.04	1.61	0.52	0.86	50%	10.8	9.2	2.04	1.61	0.52	0.86	50%	10.8	10.2	2.04	1.90	0.55	0.73	20.9	5.9	0.40
	mod		1.29	1.32	0.26	0.65		5.2	6.7	1.29	1.32	0.26	0.65		5.2	6.5	1.29	1.69	0.21	0.51			
	poor		2.04	1.38	0.28	0.61		3.4	3.1	2.04	1.38	0.28	0.61		3.4	3.0	2.04	1.69	0.29	0.50			
Drainage	well	13%	2.04	1.30	0.52	1.07	13%	10.8	9.4	2.04	1.30	0.52	1.07	13%	10.8	8.4	2.04	1.42	0.52	0.98	19.0	4.1	0.28
	mod		0.00	1.22	0	0.70		N/A	5.6	1.29	1.22	0	0.70		N/A	6.2	0.00	1.41	0.00	0.61			
	poor		2.04	1.22	0.20	0.69		3.4	2.7	2.04	1.22	0.20	0.69		3.4	3.0	2.04	1.41	0.20	0.60			
Combination	well	50%	2.55	1.30	0.32	1.07	50%	11.0	9.4	2.55	1.30	0.32	1.07	43%	9.5	8.1	2.35	1.46	0.31	0.95	20.3	5.4	0.32
	mod		2.57	1.24	0.22	0.69		7.3	5.5	2.57	1.24	0.22	0.69		6.4	6.6	1.37	1.97	0.36	0.43			
	poor		2.23	1.38	0.28	0.61		2.9	3.0	2.23	1.38	0.28	0.61		2.9	3.2	2.22	1.65	0.30	0.51			

drained soils to moderately drained soils. Other directional constraints included land use change from the drystock sector to the dairy sector, and from the drystock sector to farm forestry. Specific constraints were applied to individual optimisation sets: in Optimisation Sets 2 and 3 the nitrates concentrations were constrained to remain below the requirements of the Nitrates Directive (<11.3 mg l^{-1}) (EU, 1991). Optimisation Set 3 included the additional constraint for net GHG emissions (*i.e.* baseline emissions plus increase in emissions minus carbon offsetting through afforestation) to be reduced by 25% compared to the baseline emissions (2005). In line with the Marginal Abatement Cost Curve for Irish agriculture (Schulte et al., 2012a,b), we assumed that gross emissions can be reduced by 1.1 Mt of CO_2eq through technical abatement, with the remainder being offset through new afforestation (Schulte et al., 2013).

3. Results

Table 4 shows the results from all scenarios under all optimisation sets. Under the intensification scenarios, the stocking rates for dairy changed in all optimisation sets. Also, the stocking rates for drystock changed under Optimisation Set 3 due to changes in land area for drystock. Under the expansion scenarios, land area moves from land area for drystock to land area for dairy which is the reason for the change in stocking rates for drystock. Other changes in stocking rate for drystock can be attributed to land use change from drystock to forestry under Optimisation Set 3. Under the drainage scenarios, land area changes are due to the changes in land area between drainage classes, with the exception of Optimisation Set 3, where land area for drystock is also moved to forestry. The stocking rate for drystock changes in all optimisation sets because the number of drystock animals was assumed to remain constant.

In Optimisation Set 1, we assessed the pathways for achieving one objective only, namely to increase the supply of the function 'primary productivity' to meet the societal demand to increase dairy production volumes by 50% in Ireland. Of our four different scenarios (intensification, expansion, drainage and a combined scenario), this demand can only be met in the expansion and the combination scenarios (Fig. 2). In these scenarios, the land area available to dairy is increased at the expense of land available to drystock, resulting in an increased stocking rate for drystock. By contrast, the demand for 50% more milk volume could not be met solely through intensification or drainage. In the intensification scenario; dairy stocking rates on all drainage classes reach carrying capacity, while in the drainage scenario, all moderately-drained land (which had the lowest dairy stocking rates) is converted to well-drained land, before the 150% milk volume target could be met. The combination scenario represents a combination of intensification, expansion and drainage scenarios. The higher milk production is due in part to higher stocking rates for well, moderately and poorly drained soils, similar to those under the intensification scenario., combined with dairy expansion onto land previously used for drystock production

In the second Optimisation Set, we assessed opportunities to increase two soil functions simultaneously: primary productivity and water purification. Similar to the first Optimisation Set, the productivity target was met only in the expansion and combination scenarios. However, Fig. 3 and Table 4 show that in all scenarios of Optimisation Set 2, NO_3-N concentrations on well drained soils can be expected to approach the Maximum Allowable Concentrations (MAC) of 11.3 mg l^{-1}.

In the third Optimisation Set, we also considered pathways to meet the demand for the soil function carbon sequestration, which limited the number of solutions in which the demands for primary productivity, water purification and climate mitigation were met fully simultaneously. While the carbon offsetting objective is met in all scenarios through increased afforestation, Fig. 4 and Table 4 show that the primary productivity target is now only met in the expansion scenario. This scenario now requires a total new afforestation area of 400,000 ha. While the combination scenario would also include the expansion scenario, it was characterised by a complex solution space with numerous local optima, in which

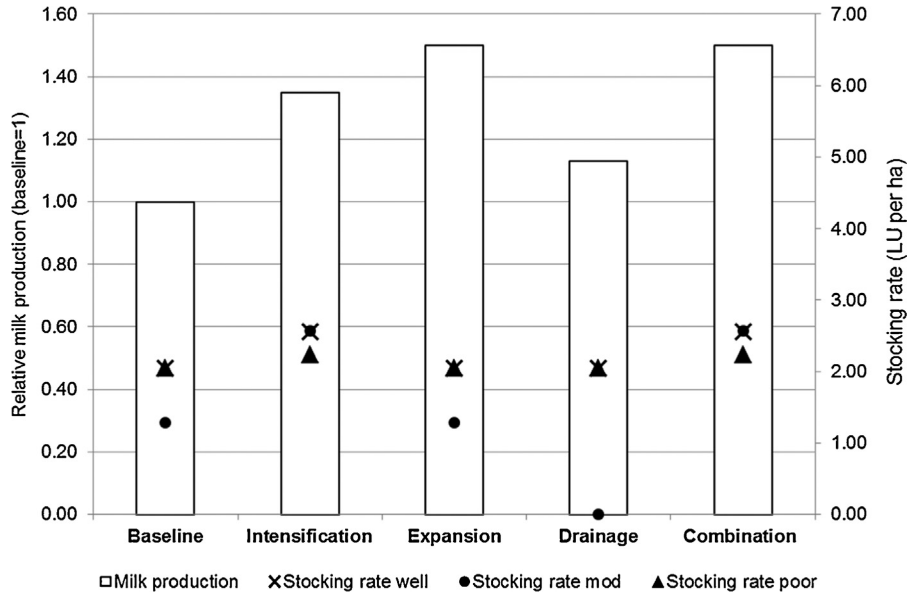

Fig. 2. Outcomes of Optimisation Set 1 (Primary productivity): Relative changes (baseline scenario = 1) in milk volume production and associated stocking rates on poorly, moderately and well drained soils under the five scenarios shown. The Baseline Scenario represents the current situation in the bovine sector in Ireland.

the optimisation algorithms could not identify the global optimum in which all objectives were fully satisfied simultaneously. Instead, the combination scenario returned multiple 'local' optima that partially met the objectives, the best performing of which is shown in Fig. 4.

Fig. 5 shows that, when the demands for primary productivity, water purification and carbon sequestration are consider simultaneously, each scenario is associated with complex synergistic and antagonistic trade-offs between the soil functions and as a result provides a different suite of functionality.

For example, the expansion scenario delivers on the target for primary productivity, but requires the highest rate of afforestation to offset sectoral GHG emissions. In addition, in this scenario, the supply of the water purification function barely matches demand, translating into nitrate-N concentrations close to the MAC. In contrast, the combination scenario requires a less dramatic increase in the rate of afforestation, and has 'spare capacity' for the water purification function. However, in this scenario the demand for increased primary productivity is not fully satisfied.

4. Discussion

4.1. Model performance

Despite the relative simplicity of the optimisation model, modelled animal numbers, GHG emissions and nitrate concentrations

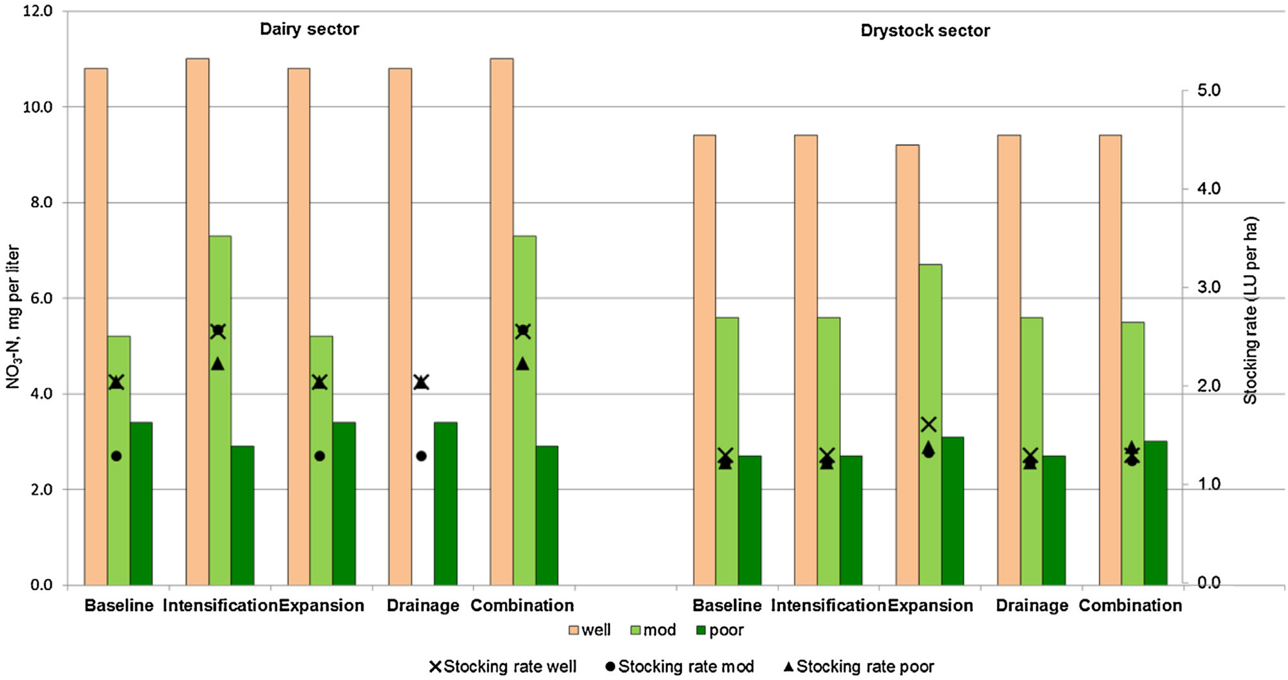

Fig. 3. Outcomes of Optimisation Set 2 (Primary Productivity + Water Purification): Optimised stocking rates (symbols) and associate nitrate concentrations (bars) on well, moderately and poorly drained soils for the dairy sector (left) and the drystock sector (right) for the five scenarios.

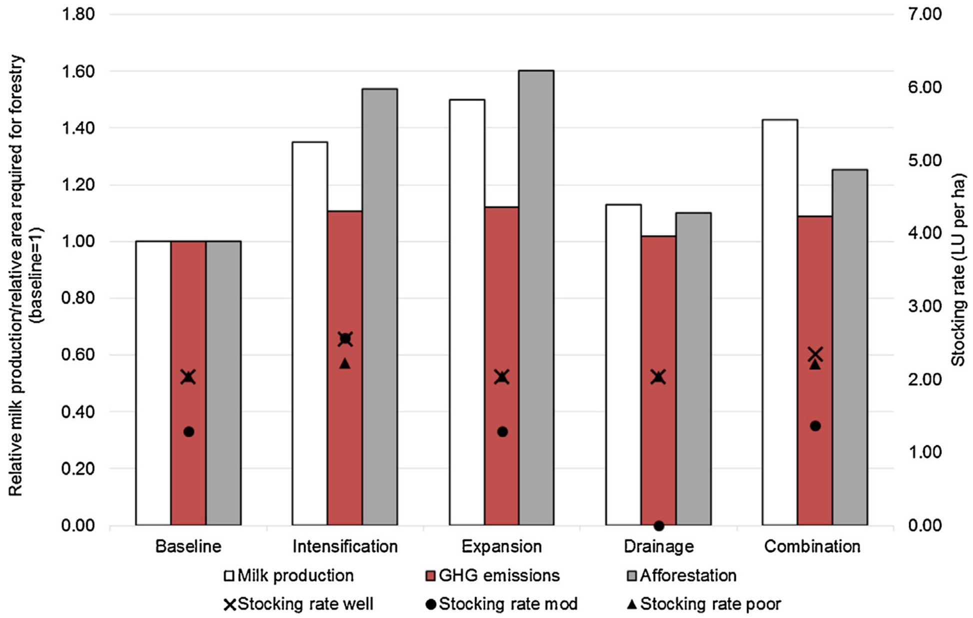

Fig. 4. Outcomes of Optimisation Set 3 (inclusion of GHG reduction targets) Changes in milk production volume, sectoral greenhouse gas emissions and area of afforestation required to meet GHG reduction targets.

closely aligned with previous empirical observations. For example, in the period 2007–2012, the average nitrate concentration in groundwater in Ireland was below 8.5 mg per litre at 96% of the monitoring sites (EPA, 2015). Our modelled GHG emissions in the baseline scenario of 18.7 Mt per annum closely matches the reported agricultural emissions in 2005 (the reference year for EU Climate and Energy framework 2030) at 18.9 Mt per annum.

Efforts were made to evaluate an alternative nitrogen mass balance model (Velthof et al., 2009) to compute nitrate concentrations, but this resulted in GHG emissions that were much higher, and nitrate concentrations that were much lower, than those reported in the Irish National Inventory Report (EPA, 2014). We traced the cause of this misalignment to the order of calculations in the Velthof et al. (2009) model, in which denitrification is the 'rest' fraction established from mass balance once ammonia and nitrate losses have been deducted. In our computation, we reversed the order of computations and derived nitrate losses as the 'rest fraction' once ammonia and denitrification were accounted for.

However, despite the realistic outputs of our model, we must bear in mind that the purpose of the model is not to predict environmental impacts *per se*. Therefore, emissions and nitrate concentrations should not be interpreted as precise predictions. Instead the purpose of the model is to explore the trade-offs, both synergistic and antagonistic, between soil functions, and to illustrate the complexity of managing soil functions at multiple scales.

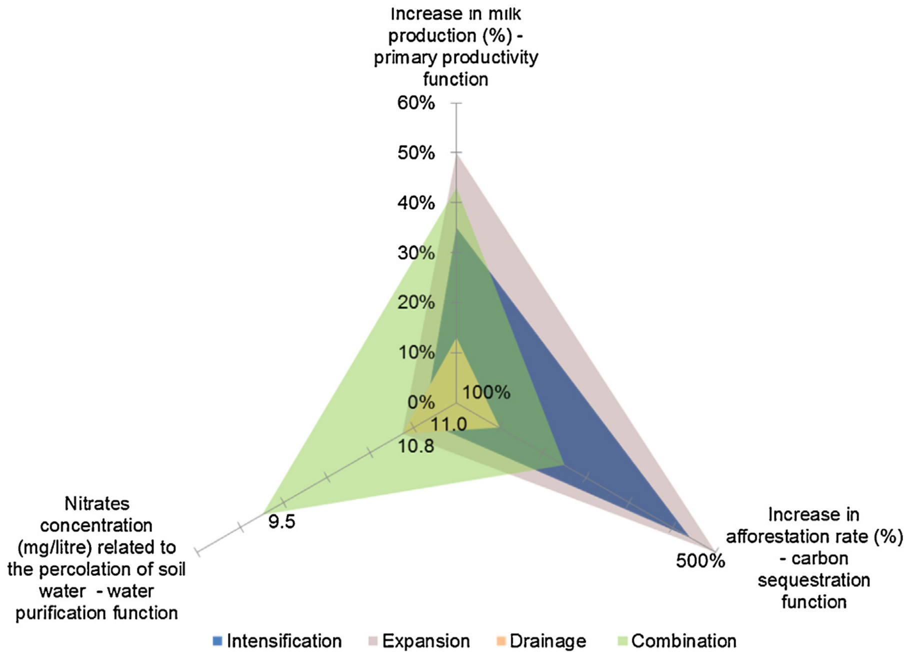

Fig. 5. Illustration of the contrasting suites of soil functions (visualised using the proxies of milk production, nitrates concentration and afforestation rates), resulting from the different scenarios in Optimisation Set 3, which considers all three soil functions.

4.2. Limitations

Our research was subject to a number of limitations that must be borne in mind in the interpretation of results:

1 For our function 'water purification' (Optimisation Sets 2 and 3) we only considered the ability of soils and the societal demand for soils to (partially) denitrify nitrates derived from farm N surpluses. The nitrates concentrations calculated in this paper are based on the average denitrification behaviour of well drained, moderately drained and poorly drained soils. Under local conditions, values will vary around this average. As the optimisation process moves the average nitrate concentrations in groundwater recharge closer to the legal limit for groundwater concentrations, the risk of exceeding this limit in some places increases. In addition, an important second aspect of water purification is the ability of soils to attain surplus phosphorus (P) and thus mitigate against freshwater eutrophication (see *e.g.* Schulte et al., 2006; Coyle et al., 2016). Recent results from the Irish Agricultural Catchments Programme suggest that P dynamics may be of greater importance in maintaining surface water quality than nitrogen dynamics (Murphy et al., 2015) The inclusion of this into the FLM framework is the subject of on-going research, as part of the LANDMARK (LAND Management: Assessment, Research, Knowledge base) project (Creamer, 2014).

2 Throughout this study, we focussed exclusively on three of the five soil functions: we did not consider the functions 'provision of a habitat for biodiversity' or 'nutrient cycling and provision' or other soil functions, which are described in Haygart and Ritz (2009) and Calzolari et al. (2015). Therefore, the results of this study must be interpreted with caution: the outcome of our Optimisation Set 3, where we consider all three soil functions, suggests that the expansion scenario is superior over the alternative scenarios. However, this outcome is likely to change when 'provision of biodiversity' is considered as a fourth objective: at national level, biodiversity is specifically at risk from conversion of (typically less intensive) drystock production to (more intensive) dairy production and from the intensification of drystock production resulting from this expansion of dairy production.

3 In this study, we considered afforestation as the sole mechanism to offset GHG emission over and above the cost-effective abatement options for emission reductions assessed in the Marginal Abatement Cost Curve for Irish Agriculture (Schulte et al., 2012a,b). An alternative option for offsetting is the reduction of emissions from drained carbon rich soils trough reducing drainage depth or through rewetting of sites; the potential of this approach for Irish agriculture is explored in Gutzler et al. (submitted). Other options include the production of biofuels and the displacement of fossil fuels, as described in the "Carbon-Neutrality Report" (Schulte et al., 2013), or the management and accounting of soil carbon sequestration as a function of land use and land management (Calzolari et al., 2015)

4.3. Scenarios for one, two and three soil functions

Previous research (Schulte et al., 2014; O'Sullivan et al., 2015) illustrated how managing soil functions and land use is likely to result in trade-offs between production and the environment. In this paper, we managed, for the first time, to quantify these synergistic and antagonistic trade-offs. We showed that the number of trade-offs, and the complexity of their associated management, increase sharply as we increase the number of functions that we expect our land to deliver. In Optimisation Set 3, few management options remain to meet the specified targets for the three soil functions simultaneously.

All optimisation sets showed that the increase in primary productivity cannot be achieved through intensification or drainage scenarios alone: therefore, achieving the ambition of the Food Harvest 2020 and Food Wise 2025 Strategies will require a degree of expansion. In practice, the expansion scenario is hindered by the very low level of land mobility in Ireland. For cultural reasons, the level of land transfer by sale is minimal, with sale levels in 2011 equating to merely 0.3%. The difficulty to obtain farmland is exemplified by the problem faced by younger farmers in Ireland in finding farmland for sale (Bogue, 2013).

When we also consider the soil function water purification, then nitrate concentrations become of concern on well drained soils, where they may approach the MAC. Interestingly, this MAC is breached more or less when stocking rates exceed the carrying capacity of the land. In other words: in the grazing-based dairy systems that are prevalent in Ireland, both the primary productivity and water purification functions reach their maximum capacity at more or less the same stocking rate, implying that 'best practices in animal husbandry and grassland management' should largely suffice to maintain nitrate concentrations below the MAC.

In Optimisation Set 3, where we also consider the carbon sequestration and GHG mitigation function of land, the menu of management options is further reduced. The outcome of this optimisation suggests that the Expansion Scenario may allow for all three targets (primary production, water purification, carbon sequestration) to be met simultaneously (see Table 4). However, apart from the aforementioned concerns regarding biodiversity in the Expansion Scenario, we must appraise this outcome in the context of the current Irish Forestry Programme 2014–2020, which aims for the planting of approximately 43,000 ha over the five-year period to 2020 (DAFM, 2015), equating to just over 8000 ha per annum. This is in sharp contrast with the requirements for afforestation in the expansion scenario, which amount to approximately 400,000 ha. As our model does not include a time dimension, our assessment does not specify the timeframe within which this planting has to be achieved. However, if we consider the time horizons of the current Food Wise 2025 Strategy and the EU Climate and Energy Framework for 2030, then it is reasonable to assume that the planting of the 400,000 ha of new afforestation would have to be completed within a 15-year period, amounting to *c.* 27,000 ha per annum, *i.e.* more than thrice the rate currently planned for.

In practice, the Combination Scenario is both more likely to materialise (as individual farmers are likely to choose different scenarios), and more pragmatic. However, this scenario, too, is not without caveats that must be taken into account. A Combination Scenario can be either 'managed' or 'unmanaged'. In an unmanaged scenario, the individual choices for intensification, expansion and drainage are not based on, nor optimised for, knowledge about soil type, soil properties, soil nutrient levels, or soil carbon contents. Fig. 5 shows that this may inadvertently lead to expansion onto vulnerable soils or into high nature value grassland, or to drainage of high carbon soils. By contrast, in a managed scenario, these pathways are customised for the properties of individual fields, soils or catchments. For example, in the managed scenario in Fig. 6 drainage is limited to low-carbon soils, thus minimising the environmental trade-offs (O'Sullivan et al., 2015), while expansion is limited to soils that have 'spare capacity' for water purification in the form of low nitrate concentrations (see Teagasc, 2012).

4.4. Scale

The 'managed combination scenario' presents a challenge with regard to the point of obligation. Put simply: who is responsible to ensure that the Combination Scenario amounts to a 'Managed Combination'? In a recent paper, Schulte et al. (2015a) explored how the demands for different soil functions operate at very different

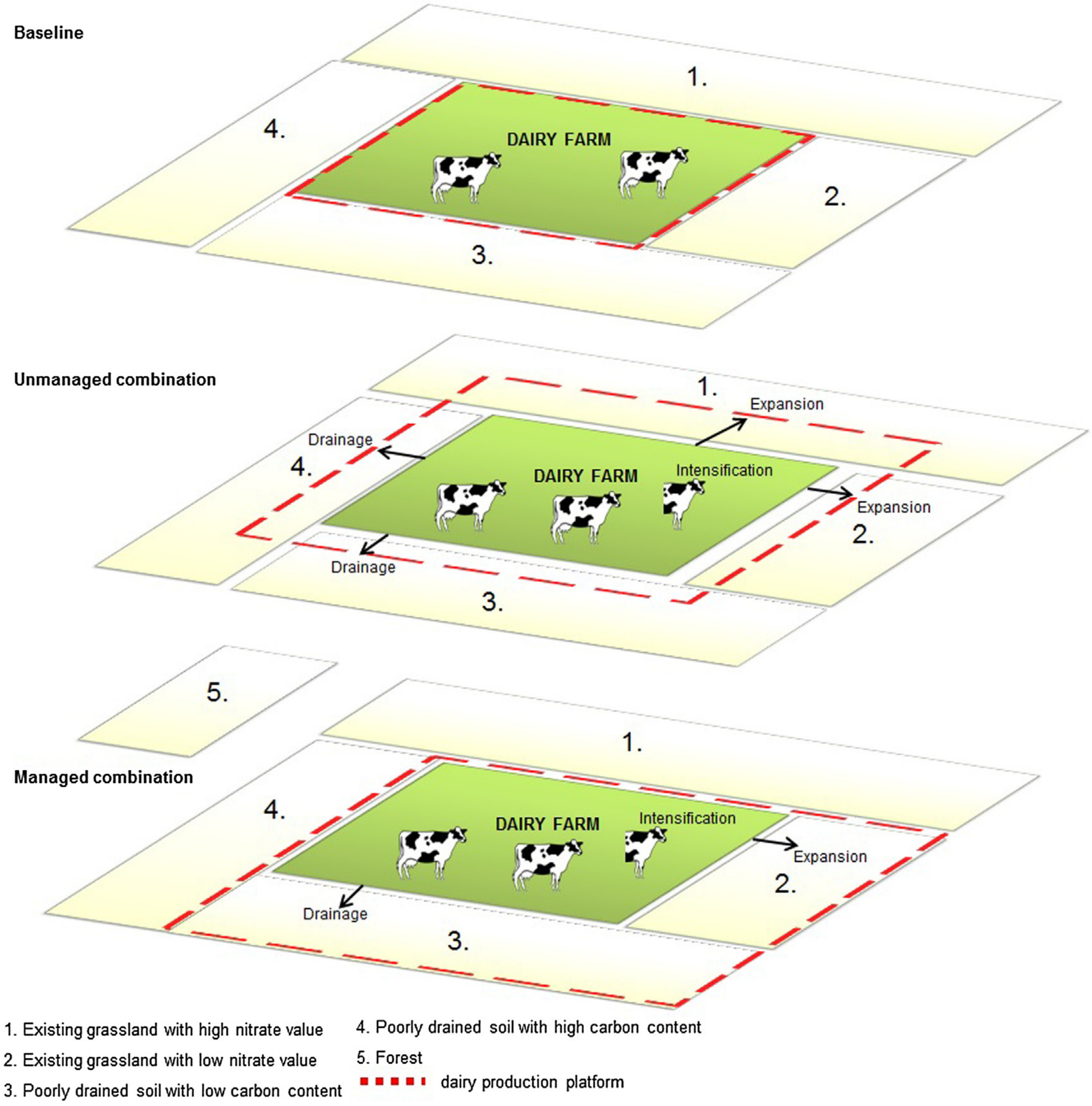

Fig. 6. Visualisation of an unmanaged and managed Combination Scenario on a typical dairy farm.

spatial scales. In our study, this translates as follows: the demand for increased primary productivity, while specified at national level, also operates at farm level, as it is of economic interest to individual farmers to increase milk output following the abolition of EU milk quota. By contrast, the demand for carbon sequestration applies at national level and is primarily driven by societal concerns. Decisions at local (farm) level by thousands of individual farmers aimed at increasing output, will ultimately impact on the ambition required at national level to meet GHG reduction targets. For example, Fig. 4 shows that the Expansion Scenario provides the most promising pathway for farmers, but this scenario is also associated with the most challenging demand for afforestation, which may prove to be unrealistic. This misalignment in the spatial scale of the supply and demand for soil functions has implications and challenges for management: there is a need to link management at national level and local level to ensure that the 'Combination Scenario' is proactively managed to account for soil properties.

Schulte et al. (2015a) identified 15 existing governance instruments (*i.e.* market instruments and both mandatory and voluntary instruments) to manage soil functions from local to national level. They concluded that, rather than developing new policy tools, there may be merit in customising existing instruments to account for differences between soils and landscapes. The SQUARE (Soil QUality: Assessment & Research) project is currently collecting detailed data and information on soil structural quality and soil functional capacity in grassland and tillage systems across Ireland. When this functionality is linked to the new Soil Information System, this will results in high-resolution spatial data to support implementation of FLM.

4.5. *Requirements for further research*

In previous papers on FLM, we considered the spatial mismatch between the supply and demand for individual soil functions. This paper shows that there is a need to also consider the temporal mismatch between the supply and demand for soil functions, as exemplified by the temporal misalignment between the supply and demand for carbon sequestration to offset GHG emissions. Both the Food Harvest 2020 Strategy (DAFF, 2010) and the Food Wise 2025 Strategy (DAFM, 2015) anticipate rapid growth of the dairy sector up to 2020, in response to the abolition of the milk quote, after which production is expected to stabilise. This creates a demand for carbon offsetting through afforestation. However, while this demand may ultimately be met by new afforestation, the supply of this offsetting mechanism is likely to be asynchronous with, and lag years behind, this demand, resulting in a significant challenge to meet the GHG reduction targets over the shorter term to 2030. Furthermore, the major part of mitigation resulting from afforestation is due to the built up of biomass stock. Once this stock has been established, annual mitigation rates are reduced, while emissions from livestock farming are assumed to continue at similar levels. Therefore, afforestation at the described rates may be successful at offsetting GHG emissions in the medium term, but much higher afforestation rates would be needed in the long term. Effects at different time scales are also relevant in relation to soil processes, stocks and microbial communities following changes in nutrient input, stocking rate or soil moisture content. These temporal effects are still not fully understood but are likely to influence the investigated soil functions, especially the water purification function through changes in the denitrification rate.

Despite the complexity of soil processes, the sustainable management of soil functions requires the co-production and integration of knowledge and technologies that can span research scientists, policy-makers and land managers (Bouma et al., 2012). While compartmentalised research is essential for understanding tipping points, thresholds and drivers, the research has tended to be too compartmentalised (Abson et al., 2014) and reflects a lack of research integration and a lag in implementation (O'Farrell and Anderson, 2010). Here, we use the FLM as an integrative framework to frame our optimisation study, however, few other similar studies were found.

Further research is also required to consider the functions of biodiversity and nutrient cycling. As this will add further complexity to the optimisation procedure, this will necessitate more sophisticated optimisation tools, such as Bayesian Belief Networks. This is the topic of the current five year LANDMARK project, which aims to perform this optimisation at EU scale.

5. Conclusions

Functional Land Management seeks to optimise land use by accounting for different biophysical conditions and potentials of soils and by accounting for the fact that only some targets need to be met at the local scale while other targets are defined at the national scale. There are several options on how to achieve both production and environmental targets at the same time. Our paper showed that in principle, it is possible to meet production targets, water quality targets and climate change mitigation targets through optimised land management. The formal requirements for water quality target were fulfilled by almost reaching, but not exceeding the MAC. However, spatio-temporal variations in nitrate concentration may still give rise to local breaches of the MAC.

Afforestation is an effective mechanism to offset GHG emissions from livestock agriculture and meet a reduction target of 25%. However, both the planting of new forests, and the subsequent carbon sequestration in newly afforested areas are long term processes. For this reason, farm afforestation may not be sufficient to meet 2030 GHG reduction targets by 2030.

Because soil functions interact with each other, ambitious targets for one function may make it difficult to fully meet the targets for other functions. In our case study, we were able to reconcile the targets for primary productivity, water purification and carbon sequestration, but it is most likely that the inclusion of the remaining two soils functions, namely the provision of a home for biodiversity and nutrient cycling, or the inclusion of additional indicators per function, would result in additional limitations.

While on paper, the results indicate that an expansion scenario could meet all of the objectives investigated in the current study, in reality this scenario is highly unlikely to materialise. Key constraints identified in this regard relate to fragmentation of farms and low land mobility levels in Ireland and the afforestation rates required for achieving the objectives. What is more likely to occur in the absence of targeted policy interventions are unmanaged combinations. The challenge henceforth is how to move from an unmanaged combination scenario towards a managed combination scenario. At a policy level, target setting should consider the multifunctional demand on land and possible trade-offs between targets. This also needs to take into account the likelihood of unmanaged developments and may necessitate a reappraisal of targets. The FLM concept has the potential to optimise land use, but requires the implementation of policy tools to ensure that land use developments are managed in a way that converges towards the optimal scenario.

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