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Functional land management: A framework for managing soil-based ecosystem services for the sustainable intensification of agriculture

Rogier P.O. Schulte [a,1,*], Rachel E. Creamer [a], Trevor Donnellan [b], Niall Farrelly [c], Reamonn Fealy [d], Cathal O'Donoghue [b], Daire O'hUallachain [a]

[a] Teagasc – Crops, Environment and Land Use Programme, Johnstown Castle, Wexford, Ireland
[b] Teagasc – Rural Economy Programme, Athenry, Ireland
[c] Teagasc – Crops, Environment and Land Use Programme, Athenry, Ireland
[d] Teagasc – Spatial Analysis Unit, Ashtown, Ireland

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ABSTRACT

Sustainable food production has re-emerged at the top of the global policy agenda, driven by two challenges: (1) the challenge to produce enough food to feed a growing world population and (2) the challenge to make more efficient and prudent use of the world's natural resources. These challenges have led to a societal expectation that the agricultural sector increase productivity, and at the same time provide environmental 'ecosystem services' such as the provision of clean water, air, habitats for biodiversity, recycling of nutrients and mitigation against climate change. Whilst the degree to which agriculture can provide individual ecosystem services has been well researched, it is unclear how and to what extent agriculture can meet all expectations relating to environmental sustainability simultaneously, whilst increasing the quantity of food outputs. In this paper, we present a conceptual framework for the quantification of the 'supply of' and 'demand for' agricultural, soil-based ecosystem services or 'soil functions'. We use Irish agriculture as a case-study for this framework, using proxy-indicators to determine the demand for individual soil functions, as set by agri-environmental policies, as well as the supply of soil functions, as defined by land use and soil type. We subsequently discuss how this functionality of soils can be managed or incentivised through policy measures, with a view to minimising the divergence between agronomic policies designed to promote increased agricultural production and environmental policy objectives. Finally, we discuss the applicability of this conceptual framework to agriculture and agri-environmental policies at EU level, and the implications for policy makers.

* Corresponding author at: Teagasc, Johnstown Castle, Wexford, Ireland. Tel.: +353 53 9171200.
E-mail address: rogier.schulte@teagasc.ie (Rogier P.O. Schulte).
[1] Twitter: @RogierSchulte.

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1. Introduction

1.1. *Global challenges on sustainable food production*

Sustainable food production has re-emerged at the top of the global policy agenda, driven by two of the contemporary challenges: (1) the challenge to produce enough food to feed a growing world population and (2) the challenge to make more efficient and prudent use of the world's natural resources, including water, atmosphere, soil, nutrients and the natural heritage in the form of biodiversity. Reflecting these twin challenges, the United Nations included the eradication of extreme poverty and hunger and environmental sustainability as two of the eight Millennium Goals (UN, 2013).

The Food and Agriculture Organisation of the UN (FAO) estimate that the world may need to increase food production by 60% compared to current levels of production, in order to feed a predicted population of more than 9 billion and increase in the *per capita* consumption of protein-rich animal produce (Alexandratos and Bruinsma, 2012). Current and projected food deficits are the result of a complex of causative factors that include: (i) lack of income in developing regions (Inter Academy Council, 2004), (ii) high levels of loss during harvest, transport and storage, specifically in developing regions, and (iii) high levels of food spoilage, specifically in developed regions (Gustavsson et al., 2011; Parfitt et al., 2010) and dietary choices (Bellarby et al., 2013). Notwithstanding this complexity, increased global agricultural production will more than likely be part of the required mosaic of solutions.

This increased production is projected to add further stress to the availability and usage of natural resources. There is an extensive literature available on the impact of agriculture on global greenhouse gas emissions (e.g. Smith et al., 2007; Marchal et al., 2012), the quantity and quality of freshwater (e.g. Evans, 2009; Bruinsma, 2009; Schulte et al., 2006), biodiversity (FAOSTAT, 2013) and competition for land.

In response to these challenges, new high-level conceptual models of global food production have been developed, including 'ecosystem services' (Hassan et al., 2005), 'sustainable intensification' (Godfray et al., 2010) and 'climate-smart agriculture' (FAO, 2010). The concept of 'ecosystem services' was developed as a framework to quantify the multi-functionality of ecosystems, including agricultural ecosystems, in providing 'services' to humankind. These include provisioning services (e.g. food, fuel), regulating services (e.g. flood mitigation, water purification), supporting services (e.g. soil formation, nutrient cycling) and cultural services (e.g. recreation, aesthetic value). Sustainable intensification refers to increasing total food production from the current global agricultural land area, thus negating increased competition for land with ecological habitats, while reducing or at least decoupling the environmental impact associated with agricultural production.

1.2. *The knowledge gap*

The concept of ecosystem services can be used to quantify the current and potential 'supply of services' from (agro-)ecosystems in relation to addressing the agricultural sustainability challenges for specific locations. However, the magnitude of each of the challenges will differ between regions and environments, e.g.: whilst in some regions of the world the main environmental challenge arising from agriculture may be habitat destruction, in others it may be unsustainable rates of water extraction. It is difficult to conceive generic agricultural systems that *simultaneously* produce more food *and* reduce greenhouse gas emissions *and* water use *and* nutrient use *and* do not compete for space with ecological habitats (e.g. Bruinsma, 2009). This means that at regional or local level, the 'supply' of ecosystem services should be targeted to match the 'demand' for these services. For example, in regions with significant precipitation surpluses (e.g. Ireland), attempts to improve the water use efficiency of agriculture could unnecessarily complicate attempts to reduce the carbon footprint or ecological footprint of agriculture. As a result, there is a need to develop a framework that allows not only the quantification of the local supply of ecosystem services, but also the demand for these services at local, regional and global scales.

1.3. *Objective*

In this paper, we develop such a framework that allows for the quantification of both the supply of, and demand for, agricultural ecosystem services. In this framework, we focus explicitly on soil-based ecosystem services, hereafter referred to as soil functions, since many of these soil functions represent the direct interface between agriculture and the wider environment: it is increasingly recognised that greater scientific knowledge and management of soils will be critical in meeting the twin challenges of food security and environmental sustainability (e.g. Creamer and Holden, 2010; European Commission, 2006a; Hartemink, 2008; Haygarth and Ritz, 2009; RSC, 2012).

We use a national scale case-study, i.e. agriculture in Ireland. Ireland can be considered a microcosm of the challenges that face agriculture globally, specifically the challenge to grow the export-based agricultural sector sustainably within an increasingly stringent context of environmental legislation.

In this study, we approximate the supply of and demand for soil functions in Ireland. Through scenario analyses, we subsequently derive a new concept of Functional Land Management, in which the multi-functionality of soils and land use is optimised to meet both agricultural and environmental targets at local and national levels. Finally, we assess the extent and methods by which the same framework can be applied at larger scales, i.e. at European level.

2. Conceptual framework

2.1. *Soil type, land use and soil functions*

Our concept of soil functions builds on the soil-based ecosystems services, summarised by Haygarth and Ritz (2009). Relating these functions specifically to agricultural land use, Schulte et al. (2011) and Bouma et al. (2012) rearranged these functions as:

Fig. 1 – Freestyle illustration of typical suites of soil functions under contrasting land use types.

1. Production of food, fibre and (bio)fuel, which traditionally is the soil function that provides a livelihood to farmers and associated sectors in the rural environment.
2. Water purification.
3. Carbon sequestration.
4. Habitat for biodiversity.
5. Recycling of (external) nutrients/agro-chemicals.

Key to the concept of soil functions is the multi-functionality of soils: in principle, all soils perform each of these functions to some extent simultaneously (Haygarth and Ritz, 2009). However, soils differ in their relative capacity to perform each of these functions. For example, it is well known that some soils have a higher capacity to produce fuel, fibre and biofuel than others, depending primarily on their chemical, physical and pedogenetic characteristics and the agroclimatic environment (Eliasson et al., 2010; Schulte et al., 2012). Similarly, soils differ in their capacity to filter water, sequester carbon, provide a habitat for biodiversity and recycle nutrients, as will be discussed below (Section 3.3: 'proxy-indicators').

In second instance, the capacity of soils to perform each of the five soil functions depends on land use, with some land use types incentivising specific functions. For example, whilst carbon sequestration rates and water purification rates are typically higher, *ceteris paribus*, under grassland than under tillage (O'Mara, 2012; Stark and Richards, 2008; Jahangir et al., 2012b), the reverse is the case for total dry matter offtakes of agricultural produce per hectare. We have visualised this diversity of potential 'functional suites' in Fig. 1.

2.2. *Managing soil functions*

Following from these relationships between soil type, land use and soil functions, there are two pathways through which soil functions can be manipulated and managed, i.e.: (i) through direct alteration of soil properties and (ii) through land use change. Alteration of soil properties refers to common farm management actions such as fertilization (altering soil chemistry), ploughing (altering soil physical properties) or the installation of artificial soil drainage (altering soil structural properties). In this pathway, the augmentation of one soil function may, or may not, result in the suppression of one of the other functions, depending on the nature of the intervention. This is exemplified in the hypothetical scenarios visualised in Fig. 2: in Fig. 2a and b, the function 'food, fibre and fuel production' is augmented in two different ways. In Fig. 2a, production is augmented at the expense of other soil functions, such as water purification. This reflects a scenario where, for example, fertilization is increased irrespective of seasonal crop nutrient demands. Contrastingly, in Fig. 2b production is augmented without affecting the other soil functions, thus increasing the overall capacity of the total suite of soil functions. This represents scenarios where, for example, nutrient applications are synchronised more precisely over space and time in line with crop nutrient demands. Finally, Fig. 2c represents the second pathway through which the magnitude of soil functions can be manipulated, i.e. through land use change. In this specific example, the soil function carbon sequestration is augmented at landscape-

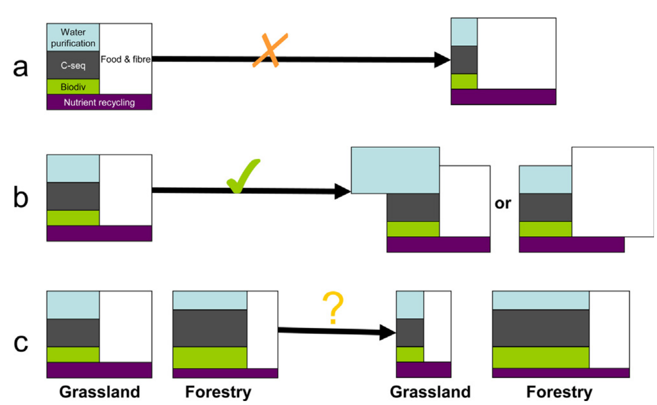

Fig. 2 – Interactions between soil functions. In example a, one soil function (e.g. Food and fibre production) is augmented at the expense of the other soil functions. In example b, individual soil functions (e.g. water purification, food and fibre production) are augmented, while the other functions remain unaffected. In example c, particular soil functions are augmented (e.g. carbon sequestration) through an expansion in the land area of a selected land use type (e.g. forestry).

scale, to some extent at the expense of annual primary output of food, fibre and fuel.

3. Data and methods

3.1. Case-study: agriculture in Ireland

We use Ireland as a case-study, for two reasons: (i) land use in Ireland predominantly consists of agriculture, which accounts for 64% of the total land area (CSO, 2010), and (ii) Ireland has explicit policies with agricultural growth targets and environmental targets, as will be explained here.

Irish agriculture is characterised by ruminant (dairy, beef, sheep) farming, with *c.* 90% of agricultural land devoted to improved and unimproved grassland. The farming systems are largely based on *in situ* grazing of grass, with relatively short housing seasons, during which the animal diets consists mainly of home-grown silage, supplemented with various amounts of concentrates. The Irish tillage sector (*c.* 10% of agricultural land area) is largely characterised by cropping of cereals, mainly for animal feed and the brewing industry. Forest cover represents the biggest single land use change in recent years, increasing from 6.8% in 1990 to 11% in 2012, the result of government afforestation schemes. However, it is still significantly lower than the European average of 30%.

3.2. The agri-environmental policy framework: the 'demand' for soil functions

The main framework for agricultural growth is captured in the industry-led Food Harvest 2020 strategy, supported by government (DAFF, 2010). This strategy sets out ambitious *targets for growth* in each of the commodity sectors up to 2020. Most of these targets are value targets, except for the dairy sector, for which a volume increase of 50% is envisaged by 2020, following the abolition of EU milk quotas by 2015. The vision laid out in the Food Harvest 2020 strategy is based on 'smart, green growth', in which 'smart' refers to its emphasis on research-led innovation in achieving the growth targets. 'Green' refers to the central role for environmental sustainability underpinning the growth in output value.

At the same time, the agricultural industry in Ireland is expected to meet increasingly stringent *environmental targets*, set out in national and EU legislation. For example, the current implementation of the EU Water Framework Directive (EU, 2000) requires that all waterbodies are restored to at least 'good' ecological status by 2015, and that waterbodies of 'pristine' condition are maintained in this condition. The National Action Programme for the implementation of the Nitrates Directive (EU, 1991) sets the regulatory framework for nutrient management on Irish farms and is expected to reduce nutrient losses from agriculture to water sufficiently to allow surface and groundwater bodies to be restored to 'good' status over time. However, the second challenge, i.e. maintaining 'pristine' water quality where currently present, may require additional mitigation measures to be implemented over time (Tunney et al., 2009).

In terms of greenhouse gas targets, whilst Ireland has met its Kyoto obligations, it has committed to a 20% reduction in emissions (increasing to 30% in case a new global agreement on emissions reductions is reached) from the non-Emissions Trading Sector (non-ETS) by 2020, compared to the EU baseline year of 2005. The non-ETS sector comprises the residential sector, power generation, transport and agriculture, and no specific reduction targets have yet been set for any of the individual sectors within the non-ETS in Ireland.

Ireland's third explicit agri-environmental policy pertains to the maintenance of biodiversity, much of which consists of farmland habitats and wildlife. The EU Biodiversity Strategy to 2020 (European Commission, 2011) aims to halt the loss of biodiversity and the degradation of ecosystem services by 2020, and restore them in so far as possible. This policy is framed by the EU Habitats Directive (EU, 1992), the EU Birds Directive (EU, 2009) and also by the EU EIA Directive (EU, 2011). These Directives have been implemented, *inter alia*, by the designation of Natura 2000 sites (including Special Areas of Conservation, Special Protection Areas and Natural Heritage Areas). On occasion, the specific transposition and implementation of the aforementioned Directives into national law has been challenging and challenged, culminating in a negative judgement by the European Court of Justice in December 2012. The 2nd National Biodiversity Plan (DAHG, 2011), launched in 2011, identifies actions for the State to complete this process at a national scale.

3.3. Selection and parameterisation of proxy-indicators

In principle, each of the five soil functions listed in Section 2.1 encompasses a complex set of biogeochemical processes. For example, the function 'food, fibre and fuel' production involves the mineralisation of nutrients, as well as the provision of water, oxygen, and space to plants. For the purpose of this analysis, it was neither feasible nor necessary to quantify each of these processes for each soil type and land use combination. Instead we selected proxy-indicators for each of the soil functions, based on relevant agri-environmental indicators that dominate the contemporary policy debates on the interactions between agriculture and the environment. These proxy-indicators are as follows:

1. Food, fibre and fuel production: for this soil function, we selected 'maximum soil carrying capacity' as the primary proxy-indicator, as defined by Lee and Diamond (1972). This proxy-indicator is of particular relevance to Ireland, given the predominance of grass-based ruminant livestock systems in Irish agriculture. Alternative or additional potential proxy-indicators could include: soil suitability for tillage production, as defined by Gardiner and Radford (1980b), herbage dry matter yields, cereal dry matter yields, or 'field capacity days' as an indicator of soil trafficability, and hence potential soil utilisation (Schulte et al., 2012).
2. Water purification: for this function, we selected two proxy-indicators: (a) the capacity of soils to remediate nitrate leaching through denitrification, and (b) the capacity of soils to adsorb excess phosphate. Nitrate and phosphate are the main elements of concern in relation to the quality of groundwater and surface water bodies, respectively (Schulte et al., 2006; Lehane and O'Leary, 2012). Alternative

or additional proxy-indicators for the purification functionality of soils could include the capacity to eliminate pathogens (e.g. Brennan et al., 2010; Moynihan et al., 2013) or agro-chemicals, as well as the capacity to retain structural integrity and prevent sediment loss.

3. Carbon sequestration: for this soil function, the selection of a proxy-indicator was explicitly shaped by the current international policy frameworks pertaining to reducing agricultural greenhouse gas emissions. Whilst carbon sequestration in grassland soils undoubtedly represents the largest 'soil carbon sink' in Ireland (Abdallah et al., 2013), this sequestration potential cannot be 'counted' under the current IPCC reporting rules, as it is uncertain which proportion (if any) of this sequestration potential is additional to the carbon sequestration in the baseline years of 1990 (IPCC) or 2005 (EU 2020 proposals). This is the topic of ongoing international research (Conant, 2010) and EU policy negotiations. Therefore, for the purpose of the current study, we selected the main proxy-indicator that is relevant – and that can be counted – in the context of the IPCC reporting mechanisms, i.e. carbon sequestration by 'post-Kyoto' afforestation, i.e. by forests planted after 1990.
4. Habitat for biodiversity: soils provide a habitat to both above and below ground biodiversity. It is difficult to disentangle above and belowground biodiversity, as they are strongly linked through food–web interactions (Wardle et al., 2004). Whilst there is a wealth of information on the linkages between aboveground biodiversity, soil type and land use (Brussaard et al., 2007), it is widely acknowledged that the equivalent belowground linkages have remained virtually unexplored to date (e.g. see the special issue of Science Vol. 304, Issue 5677: 'Soils–the Final Frontier'). In any case, the soil function "habitat for biodiversity" differs from soil functions 2, 3 and 5, in that biodiversity explicitly requires space. To some extent, this places this soil function in direct competition with soil function 1, i.e. the production of food, fibre and fuel, although co-existence of intensive agriculture and some degree of biodiversity is possible when managed at a landscape-scale (e.g. Benton, 2012a; Zimmerer, 2013). To explore this in further detail, we selected 'the areal extent of High Nature Value farmland' as a preliminary proxy-indicator for this soil function in this study, to be replaced when the outputs of current EU research programmes (e.g. www.ECOFINDERS.org) elucidate the relationships between soil type, land use and soil biodiversity.
5. Recycling of (external) nutrient inputs: this soil function refers to the capacity of soils to absorb, store, and re-release nutrients to crops over time. Generically, this capacity includes all forms of nutrient inputs, including fertilizer inputs and organic nutrient inputs (i.e. animal dung and urine), both those produced on, and imported onto the farm. Under current legislation, fertilizer inputs and on-farm manure management are regulated under Ireland's National Action Programme for the implementation of the Nitrates Directive, so that total inputs are restricted to rates equalling crop offtakes. The additional 'demand' for the soil function 'recycling of nutrients' pertains specifically to the recycling and use of external, organic nutrient inputs in the form of either manure or sewage sludge that is imported onto the farm. In Ireland, this largely comprises of pig slurry, which is generally produced on large scale intensive pig farms that have a limited land base and therefore rely on the export of slurry to other farms. Therefore, for the purpose of this study, we selected 'recycling of imported phosphorus in pig slurry' as the proxy-indicator for this soil function. Note that following implementation of the EU Sewage Sludge Directive (EU, 1986) recycling of nutrients in sewage sludge is likely to be of equal future importance for this soil function.

For each of these proxy-indicators, Table 1 summarises the policy drivers, targets, data sources, as well as the computational frameworks for the quantification of the projected national demand and maximum supply for each of the soil functions.

4. Results: supply of and demand for soil functions

The outcomes of our assessment, i.e. the supply of, and projected demand for, soil functions in Ireland are presented in Table 2. In summary:

1. Food, fibre and fuel production: there is significant 'spare' biophysical capacity to increase total stock numbers. This largely reflects the relatively low average stocking rates on Irish farms, compared to similar livestock production regions across Europe (FADN, 2011).
2. Water purification: most of Ireland's agricultural soils are subject to significant denitrification of nitrates in the soil water to either nitrous oxide or dinitrogen (Fenton et al., 2009; Dennis et al., 2012; Jahangir et al., 2012a,b). As a result, the 'demand' for denitrification (i.e. the amount of denitrification required to ensure that the nitrogen (N) surplus leaving the rooting zone does not lead to groundwater nitrate concentrations in excess of the maximum allowable concentration (MAC) of 50 mg nitrate per litre) is well below the 'supply' of this soil function, although this is subject to significant variation between regions and soil types. With regard to phosphorus (P): more than half of Ireland's soils are currently deficient in P (Murphy, 2013): their capacity to adsorb P sustainably ('supply of soil function') exceeds the average P-surplus at national level ('demand for soil function').
3. Carbon sequestration: offsetting 30% of agricultural GHG emissions projected for 2020 (with additional measures scenario) requires a significant acceleration of afforestation from current rates of 7000 ha p.a. (Forest Service, 2011) to 20,000 ha p.a. Analysis by Farrelly et al. (2011) show that in principle, sufficient land is available to facilitate this acceleration, albeit with the caveat that this may ultimately compete with land currently classified as HNV.
4. Habitat for biodiversity: comparing the 'demand' and 'supply' of habitats, discrepancies do not necessarily arise from the areal extent of high nature value farmland, but rather from the degree and implementation of protection associated with these areas. Specifically, Ireland's

Table 1 – Key data sources and references for the computation of the projected demand for and maximum supply of the proxy-indicators for each of the five soil functions.

Proxy-indicator	Policy-driver/target	Projected demand	Maximum supply
Stocking rate	Food Harvest 2020 (DAFF, 2010). Targets include *inter alia*: 50% volume increase in dairy production, 20% value increase in beef production by 2020	Donnellan and Hanrahan (2013)	Lee and Diamond (1972)
Denitrification capacity	Nitrates Directive (EU, 1991): nitrate groundwater concentrations to remain below 50 mg l^{-1}	Current nitrogen (N) surplus: Lalor et al. (2010); Eurostat (2013) Projected increase in N surplus: Donnellan and Hanrahan (2013) Effective rainfall (for conversion of N-surpluses into soil water N-concentrations): Schulte et al. (2012) (met data courtesy of Met Eireann)	Fractional denitrification rates for poorly drained, moderately drained and well drained soils: Jahangir et al. (2012c) Relative geographical coverage of poorly drained, moderately drained and well drained soils: Gardiner and Radford (1980a,b)
Phosphorus adsorption	National Action Programme for the implementation of the Nitrates Directive (Government of Ireland, 2009): target soil phosphorus (P) index (Morgan's) = between 5 and 8 mg l^{-1}	National P-surplus: Lalor et al. (2010), Eurostat (2013)	National P 'build-up capacity' = soils with Morgan's P concentrations < 5 mg l^{-1}: Teagasc soil testing database; Murphy (2013) Permitted P build-up application rates on soils with Morgan's P < 5 mg l^{-1}: Coulter and Lalor (2008)
Carbon sequestration by post-1990 afforestation	EU 2020 proposals (European Commission, 2013): reduce greenhouse gas emissions from non-ETS sector by 20% by 2020 (target for Ireland)	Total agricultural greenhouse gas emissions: EPA (2012)	Species specific carbon sequestration potential per hectare of new afforestation: Byrne and Black (2003)
Areal extent of high nature value farmland	Habitat Directive (EU, 1992), Birds Directive (EU, 2009), EIA Directive (EU, 2011)	Habitat Directive: SAC designation: EU (1992) Birds Directive: SPA designation: EU (2009) Strengthen conservation within designated habitats (EU, 2011)	Designated Natura 2000 sites: National Parks and Wildlife Service (2005) Natural Heritage Areas (NHA): National Parks and Wildlife Service (2013) Wildlife Act (rare species): EEA (2008)
Total quantity of P in pig slurry	National Action Programme for the implementation of the Nitrates Directive (Government of Ireland, 2009): all pig slurry to be recycled on soils with a P requirement, i.e. either tillage soils or grassland soils with Morgan's P < 5 mg l^{-1}	Total number of pigs: CSO (2009) Total P production per pig: S.I. 101 (Government of Ireland, 2009)	Total area of tillage soils: CSO (2009) Total area of grassland soils with Morgan's P < 5 mg l^{-1}: (Lalor et al., 2010)

obligations with regard to the Birds Directive and the strengthening of conservation efforts within existing designated areas, are currently not being met (European Court of Justice, 2007; NPWS, 2008).

5. Recycling of (external) nutrients: our analyses show that there are more than sufficient tillage P-deficient grassland soils available to supply a 'home' for P contained in pig slurry, even when accounting for the projected 35% increase in P excretion in a Food Harvest 2020 scenario. However, it is noteworthy that this capacity is unequally distributed between regions and that there is an increasingly competing demand for this capacity of soils to recycle P, from the landspreading of sewage sludge and other bio-waste materials.

5. Discussion

5.1. *Scenario analysis*

The results of our case-study show that – in principle, and at national level – the multi-functionality of soils has the capacity to deliver soil-based ecosystem services to such an extent that current agronomic and environmental targets can be met simultaneously. However, this generic outcome comes with two important qualifications.

Firstly, it is of crucial importance that the large variability between soils – and their capacity to deliver on each of the soil functions – is recognised and accounted for. For example, whilst soils – on average – have sufficient capacity to denitrify nitrates to such an extent that groundwater nitrates concentrations remain below the MAC, this average masks the fact that some of the soils are limited in this capacity and are at risk of failing this soil function in the face of increased nitrogen surpluses.

Secondly, in our analysis we assessed the capacity of *individual* soil functions, not accounting for potential interactions. Whether individual soils can indeed continue to fully perform all soil functions simultaneously in the context of increased agricultural production, depends to a large extent on the scenario through which this is achieved. In Fig. 3, we compare three contrasting scenarios of increased production to the current *status quo* ('baseline scenario') and in Table 3 we

Table 2 – National 'supply' and 'demand' for five soil functions, as defined by proxy-indicators.				
Soil function	Proxy (in this study)	Projected 'demand'	Maximum 'supply'	Caveats/notes
Food, fibre and fuel production	Stocking rate	1.2 LSU[a] per hectare	1.5–1.8 LSU per hectare	Large differences in carrying capacity exist between contrasting soil types, from 0.5 to 3.0 LSU per hectare
Water purification	Denitrification capacity	8 kg N per hectare per year	24 kg N per hectare per year	Large differences in denitrification capacity between soils and regions, from 5 to 63 kg per hectare per year
	Phosphorus (P) sorption (Index 1 and 2 soils)	National P-"surplus": 2.2 kg per hectare per year	National soil P build-up capacity: 2–5 kg per hectare per year	The lack of P sorption capacity in soils with an organic matter content >20% (Daly et al., 2001) has been accounted for in these figures
Carbon sequestration	Sequestration capacity by farm-afforestation	3.1–5.0 Mt CO_2e[b] per year	5.8 Mt CO_2e[b] per year	Requires significant acceleration in farm-afforestation rates to meet government targets Potential conflict with extent of High Nature Value areas
Habitat for biodiversity	Areal extent of high nature value farmland	Habitat Directive & Birds Directive: assign designated Natura 2000 sites from list of proposed Candidate Natura 2000 sites Full implementation of the Wildlife Act (rare species) Strengthen conservation within designated habitats	- Natura 2000 sites: 934,300 ha = 14% of land area - SPA designations - Proposed NHAs = 65,000 ha - Possibly: non-designated peatland = 11,000 ha - Rare species: 222,452 ha - Other HNV farmland	Obligations regarding Birds Directive and strengthening of conservation within designated habitats are currently not fully met. Legislation is in place to meet this demand but implementation has proved challenging
Recycling of (external) nutrients	Recycling of P in pig manure	5674 t P per year	Tillage + suitable grassland (Index 1 and 2): 29,509 t P per year	Large differences exist between regions in the availability of suitable tillage and grassland soils Emerging demand for recycling of sewage sludge (EU Sewage Sludge Directive) may compete for recipient soils

[a] Livestock unit.
[b] Carbon-dioxide equivalent.

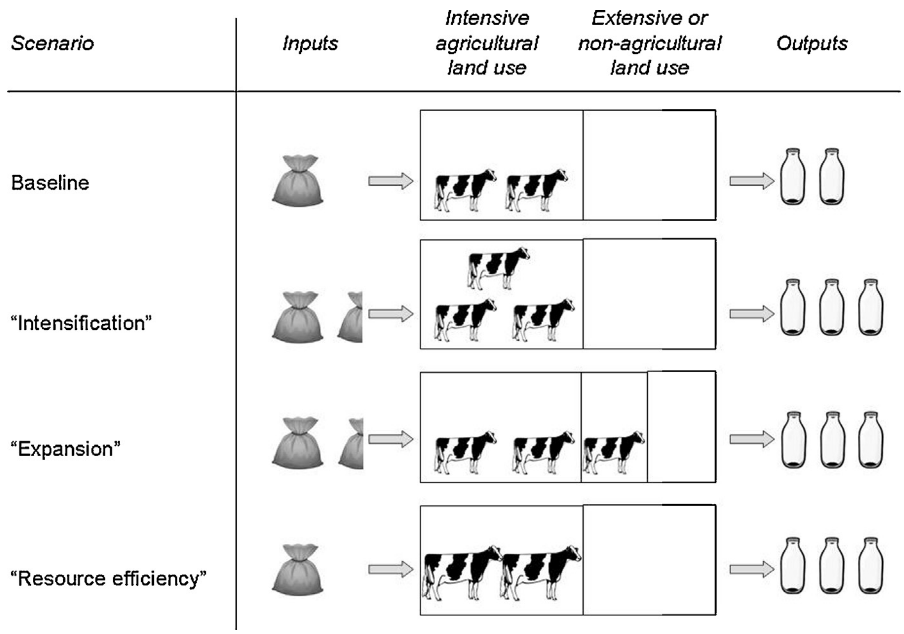

Fig. 3 – Visual representation of three contrasting scenarios for increased agricultural production.

Table 3 – Projected primary impacts of three contrasting scenarios of increased agricultural production on five aspects of sustainability. ' + ' and '−' indicate positive and negative effects, respectively, and 'o' indicates no effect.

Scenario	Economic sustainability	Water quality	Greenhouse gas emission intensity[a]	Biodiversity	Nutrient recycling
Intensification	+	−	o	o/−	o
Expansion	+	o	−	−	+
Resource efficiency	+ → −	+	+	o	o

[a] Emission intensity is defined as the greenhouse gas emissions per unit of agricultural produce, using life cycle analysis.

summarise (using collective expert judgment) the scientific evidence to date on known impacts of each of these scenarios on five indicators of sustainability, corresponding to each of the five soil functions. Originally, we developed these scenarios for Ireland's Food Harvest 2020 strategy, but they are of equal relevance to European and indeed global agriculture.

Scenario 1 can be described as 'land intensification' and is based on higher productivity per hectare, by increasing inputs and agricultural activity (e.g. stocking rates in the case of livestock farming). In a post milk-quota era, this scenario is likely to occur on dairy farms where productivity has thus far been constrained by milk quotas. Resulting from our assessment of soil functions, the main challenge to sustainability in this scenario will arise from the likely increase in N-surpluses, specifically on well drained soils with a limited denitrification capacity (Table 3).

Scenario 2 can be described as a 'land area expansion' scenario since it is based on an increase in the land area that is primarily devoted to agricultural production, with no change in the average productivity per hectare. This scenario, too, is associated with higher inputs, albeit that inputs per hectare would remain unchanged. Therefore, the challenge to sustainability in this scenario would not necessarily be related to groundwater quality. Instead, our analysis of soil functions suggests that the primary impacts would be on the areal extent of habitats for farmland biodiversity and on the greenhouse gas emissions intensity of agricultural produce, since the expansion of agricultural land will be at least partially in competition with farm-afforestation and habitats, and conversion of (semi-) natural land to agricultural land is known to be associated with a loss of soil carbon, both at local scale (Eaton et al., 2008) and global scale (West et al., 2010).

Finally, Scenario 3 can be described as a 'resource efficiency' scenario, where higher productivity is achieved through more efficient use of inputs, such as fertiliser and energy, and through more intensive use of R&D, for example by using livestock with higher genetic merit. In this scenario, increased outputs are decoupled from resource inputs. At first sight, this scenario appears favourable in that gains in resource efficiency (e.g. nutrient use efficiency) are likely to reduce both pressures on the agricultural environment, and improve economic efficiency through a reduction in the direct costs of production per unit of output at farm level. However, the extent to which increased agricultural production can be achieved through efficiency gains alone is limited in the medium term. For example, Schulte and Donnellan (2012) demonstrated that efficiency measures can indeed reduce greenhouse gas emission intensity of livestock produce by c. 5%, but that further reductions would progressively require prohibitively expensive capital investment (see also Moran et al., 2011, for an equivalent analysis for UK agriculture), while other studies showed similar results for measures aimed at reducing P-losses (Schulte et al., 2009) and N-losses (Chyzheuskaya et al., 2012), respectively. These case studies suggest that scenario 3 is unlikely to fully deliver a solution when the required increase in production is significant and the environmental constraint is challenging.

5.2. *Towards functional land management*

The corollary of our scenario analysis is that a sustainable increase in agricultural production requires a mosaic of solutions, i.e. a targeted mosaic of the three scenarios above. Obviously, the 'efficiency' scenario is preferable from an environmental perspective, but this scenario on its own is unlikely to deliver on the Irish 2020 agricultural growth targets, because of the aforementioned diminishing economic returns. As a result, it is likely some form of both 'expansion' and 'intensification' will be required, both at national scale (in our case-study) and indeed global scale. Here, we introduce the concept of 'Functional Land Management', where these scenarios are managed with a view to achieve the growth targets, while minimising impacts on the environment. For example, 'expansion' is environmentally preferable over 'intensification' in areas where soils have limited capacity for denitrification, and where the expansion of agricultural land area does not compete with habitats of high nature value. Contrastingly, 'intensification' may be preferable in areas where soils have additional 'spare' capacity for denitrification and nutrient cycling, and where farmland is surrounded/intermixed with valuable habitats.

In other words, 'Functional Land Management' means that the use of land is managed in such a way that the total suite of soil functions is maximised, or – put colloquially – that 'each soil performs those functions that it is good at', in line with contemporary thinking (e.g. Haygarth and Ritz, 2009; Benton, 2012b; Fresco, 2012).

In targeting soil use towards specific soil functions, it is important to consider that some soil functions can safely be 'offset' between geographical areas, whilst others cannot. For example, from a global warming perspective, reductions in greenhouse gas emissions do not need to be locationally bound – the spatial origin of reductions is irrelevant in the context of their global warming potential. Contrastingly, measures aimed at protecting water quality (and to some extent biodiversity) cannot be 'offset' or 'traded' between geographical locations, as the targets for good water quality are spatially ubiquitous. This has implications for the spatial scale at which Functional Land Management is best applied and this may vary by soil function: on the one hand, catchments or river basin districts are the appropriate scale for matching the supply and demand for water purification, whilst on the other hand, the matching of supply and demand for carbon sequestration could ultimately be managed at global scale. For the function 'provision of habitats', the optimum scale may be more difficult to define and to some extent depends on value judgements on the demand for this function: do we expect land to deliver a diversity of habitats in each region, in each country, on each continent or globally?

5.3. *Incentivisation*

At this point, it is important to consider that implementation of Functional Land Management does not equate to legislative 'zoning' of land use. Rather than legislating for particular land management practices, an alternative would see the development of land use policies with the provision of incentivisation mechanisms to ensure that actual land management decisions reflect policy. In principle, the European Union has a long tradition of such incentivisation, largely through payments under the Common Agricultural Policy, including payments for less favourable areas (European Commission, 2009), which are aimed to support the production of food, fibre and fuel in areas with 'natural handicaps' and payments under various national agri-environmental schemes, which are aimed at providing a financial incentive to maintain and improve habitats for biodiversity. Therefore, mechanisms for incentivisation are – in principle – already in place.

5.4. *The European context*

Whilst our case-study focussed specifically on Ireland, the concept of 'supply' and 'demand' for soil functions, the three scenarios of increased agricultural production, as well as the our concept of 'Functional Land Management' are all equally applicable and of equal relevance to European and indeed global agriculture.

At European level, many of the datasets required for similar analyses are already available (see e.g. http://eusoils.jrc.ec.europa.eu/library/maps/maps.html). Of particular interest and policy relevance would be the question whether specific soil functions (e.g. carbon sequestration, agricultural productivity) could and should be offset between Member States. In other words: could and should Functional Land Management, and the maximisation of soil functions, be applied across national borders? For example, should agricultural intensification be incentivised in those (international) regions and on those soils that have the largest capacity to deliver this intensification sustainably? Likewise, should carbon sequestration be targeted and incentivised in those (international) regions and on those soils that have the largest capacity to do so? Whilst this will undoubtedly be challenging from a policy perspective, the application of Functional Land Management at European level could represent a logical step towards meeting the global twin challenges of food security and environmental sustainability.

5.5. *Further research requirements*

The objectives of this paper were to (1) develop the concepts of demand and supply of soil functions; (2) coin the concept of Functional Land Management, and (3) provide 'proof-of-concept' by exemplifying these concepts using a case-study at national level. In many respects, our study raises as many questions as it answers. First of all, there is a need to further develop our categorisation of soil-based ecosystem services into five soil functions – conceivably these five functions can be refined or expanded on. Secondly, our case-study used only one or two proxy-indicators per soil function, representing the primary indicators used in the framing of contemporary agri-environmental policy. As suggested in Section 3.3, there are many more proxy-indicators of relevance that could be included in more detailed assessments. Furthermore, the assessment of demand and supply of soil functions is by definition a dynamic and iterative process, since demand and supply will change over time as policy priorities and market conditions evolve.

Following this refinement and expansion of the list of proxy-indicators, the next logical steps in research are:

1. To *underpin* the concept of the proportional multi-functionality of soils as a function of land use (Fig. 1) with quantitative or semi-quantitative data sources;
2. To *expand* on Fig. 1 by considering this multi-functionality not only as a function of land use, but additionally as a function of soil type;
3. In light of the variation in functionality between soil types: to *refine* this study by accounting explicitly for regional variations in soil type and the associated impact on functionality;
4. To assess the menu of farm management options (Fig. 2b) and/or land management options (Fig. 2c) that can maximise the functionality of contrasting land use × soil type combinations (Fig. 2b).

We are currently beginning to investigate these topics in Ireland's new Soil Quality Assessment Research (SQUARE) project.

5.6. *Further considerations for policy makers*

Our concept of Functional Land Management is closely aligned to, and builds upon, the original EU Thematic Strategy on the Protection of Soils, published in 2006 (European Commission, 2006a), which first specified the multi-functionality of soils. Since the publication of this strategy, a proposed Soil Framework Directive (SFD) was drafted (European Commission, 2006b), but progress on the development of this Directive has stalled in recent years (Creamer et al., 2010). It is noteworthy that the draft Directive did not fully utilise the concept of soil functions. Instead, it was based broadly on a delineation of seven 'threats to soil quality'. The implicit implication of this change in emphasis is that the proposed SFD appeared to assign an 'intrinsic value' to soil quality, similar to the intrinsic value commonly assigned to biodiversity, whereas the original Thematic Strategy emphasised the 'functionality' of soils to provide services to the human environment. This change of emphasis did not go unnoticed by some of the main stakeholders of these policies, and is summarised in the response by COPA-COGENA (2008), which 'supports the Thematic Strategy' but 'rejects the bureaucratic new directive'. Indeed it is our experience that farmers understand and appreciate the functionality of soils in providing goods and services to humankind (be it in the form of food, fibre or fuel, or in the form of maintaining and improving the rural environment) and generally welcome measures and incentives that enhance this functionality. Contrastingly, farmers are concerned about prescriptive regulations to protect a perceived intrinsic value of part of their enterprise (in this case: soil), if it is not apparent how this protection relates to functionality.

In this context, the concept of Functional Land Management, developed in this paper, provides a useful tool to realign emerging policies on soils with the original concept of soil functions, as outlined in the Thematic Strategy. It allows for the harmonisation of diverging agri-environmental policy objectives, and provides a quantitative framework to recognise and incentivise the utilisation of land-based ecosystem services – thus providing a platform for the implementation of the sustainable intensification of agriculture.

6. Conclusions

Soils perform a range of synchronous ecosystem services or 'soil functions' such as food, fibre and fuel production, water purification, carbon sequestration, nutrient cycling and the provision of habitats for biodiversity. Soils differ in their relative capacity to perform each of these functions, as determined by land use and soil properties. The global twin challenges of food security and environmental sustainability require that the supply of soil functions is maximised to meet future demand for each of these functions, at local, national and supranational scales. In this paper, we presented a conceptual framework for the quantification of the supply of, and demand for soil functions, using proxy-indicators. Using Ireland as a case-study, we demonstrated that – in principle, it is possible to meet agronomic as well as environmental policy targets simultaneously through optimisation of soil functions at local and national scale. However, realisation of this potential will require proactive and targeted incentivisation of land use in relation to soil types, to ensure that each soil 'performs the functions that it is best at'. In addition, it will require careful incentivisation and management of scenarios towards increased agricultural production, i.e. 'intensification', 'expansion' and 'increased resource efficiency'. The resulting concept of 'Functional Land Management' is closely aligned to the original EU Thematic Strategy on soils, which was broadly supported by key-stakeholder groups, and provides a logical step for the sustainable intensification of European agriculture.

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Dr. Rogier P.O. Schulte is Leader of Translational Research in Sustainable Food Production at Teagasc, the Irish Agriculture and Food Development Authority. He works on the interface between agricultural research and environmental policy, at national and international level. He has a Ph.D. in Production Ecology and Resource Conservation from Wageningen University, The Netherlands, and has over 15 years experience in research and research management in the area of agricultural sustainability.

Dr. Rachel E. Creamer is responsible for the Soil Quality and Classification sub-programme at Johnstown Castle Environment Research Centre. Rachel is co-ordinating a large scale soil survey programme to develop a new soils map for Ireland at a scale of 1:250,000 using a combination of new predictive modelling techniques and traditional soil survey methods. Rachel is also has a specific interest in the application of soil biological indicators to assess changes in status of soil quality; this includes the Ecofinders project which is a large FP7 consortium project studying the diversity and abundance of soil biodiversity across Europe and their potential use as biological indicators of soil quality.

Trevor Donnellan is a Principal Research Officer at the Rural Economy Research Centre, Teagasc and a member of the FAPRI-Ireland policy modelling team for 15 years. He specialises in modelling dairy, pigs and input markets and also examines the environmental impacts of the agricultural sector, particularly the area of Greenhouse Gas emissions. He has worked on a variety of EU and nationally funded projects and has examined issues including the impact of environmental policy, CAP reform and WTO trade reform. This work informs agri-food industry stakeholders and supports policy formation and decision making by the Irish government.

Dr. Niall Farrelly graduated from University College Dublin in 1995 with a B.Agr.Sc (Hons). (Forestry). From 1995 to 2000 he worked with Coillte R&D & UCD Forestry School as a Forestry Field Researcher. Between 2000 and 2003, he worked with Teagasc as a Researcher on Forest soils and Forest productivity. He joined the Forest Service in 2003 and between 2003 and 2005 worked as project manager on the National Forest Inventory, before rejoining Teagasc in 2005. He was awarded Ph.D. in 2011 from UCD. His research programme focuses on determining how environmental factors and forest management practices affect the productivity composition and structure of forest ecosystems.

Reamonn Fealy's work entails both research and technical development and implementation of spatial analysis. He has responsibility for the strategic management of the infrastructural aspects of GIS work and its application across Teagasc. He has a diverse research portfolio including the development of spatial analytical methods to assist national government departments in policy assessment at European level through to conducting applied research projects at national and regional level. He is particularly interested in the complex interface between agriculture and

environment and the role of spatial analysis in development of policy, risk assessment and the legislative aspects that arise in this domain.

Dr. Cathal O'Donoghue is Head of the Teagasc Rural Economy and Development Programme and head's the Executive of the Commission for the Economic Development of Rural Areas and Adjunct Professor at UCD and NUI Galway. His research interests lie in the development of economic simulation models for public policy analysis. He has a Ph.D. from the London School of Economics and has studied at UCC, UCD, Oxford and Warwick. Prior to joining Teagasc Cathal worked at NUI Galway, the University of Cambridge, the Irish Economic and Social Research Institute and for the UK Government.

Dr. Daire O'hUallachain is a researcher in Functional Ecology at Teagasc, the Irish Agriculture and Food Development Authority. He has a Ph.D. in Zoology from the National University of Ireland, Galway, and has over 10 years experience in agri-environment research. His research interests include the provision of ecosystem services from agricultural ecosystems, farm management options to maintain and enhance biodiversity and water quality, and analysis of agri-environmental policy and practice.