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Potential of agroforestry systems in preserving Europe's soil productivity in lowland and highland landscapes by limiting soil erosion by surface runoff

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Abstract. Over the past half-century, an expansion of agriculture on lands is observed, followed with increased intensification through larger fields of monoculture crops and application of high level of inputs, that increases the pressures agriculture sets upon the environment. Raising awareness of consumers and environmentalists led to the promotion of several alternative farming practices, including integrated food and non-food systems (IFNS). Here we explore the potential of different kinds of IFNS systems in delivering environmental benefits, focusing on preserving soil functions as the IFNS is the form of land use limiting the loss of soil by water erosion. All of selected IFNS systems are agroforestry systems. Six successfully implemented IFNS agroforestry systems located in UK, Poland, Italy, Denmark and Romania, were taken as a baseline to investigate their potential impact onto lowering the rates of soil loss by water erosion in their respective NUTS3 (Nomenclature of Territorial Units for Statistics) regions, when they would be applied widely on a regional scale. The results of analyses performed within GIS systems based upon European datasets revealed, that altogether the highest potential of limiting the area of soil erosion exceeding 0,5 Mg $ha^{-1}y^{-1}$ by an IFNS existing in a particular NUTS is observed in Romania, where 531 km^2 may be protected effectively with existing silvopastoral system, while applied in a longer term on non-pastoral land cover classes it could provide effective protection for another 1362 km^2. Second largest influence can be achieved in Polish NUTS region, where 125 km^2 may be taken into protection directly and an another 1140 km^2 may be transformed into agroforestry systems to lower the risk of soil erosion by water. In all investigated regions, a wide introduction of IFNS, that are already proven to be economically successful, would decrease soil loss considerably on existing land cover classes similar to IFNS systems covering 4927 km^2, while potentially on all agricultural land up to 8854 km^2.

Keywords: innovative food and non-food systems, agroforestry, soil erosion by water, RUSLE.

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INTRODUCTION

Over the past half-century, we can observe expansion of agriculture on lands and in the same time its increased intensification through larger fields of monoculture crops and application of high level of inputs, that potentially pollute environment and cause degradation of ecosystem services on which agriculture depends (Foley, 2011; Pretty, 2008). This has led to the promotion of several alternative practices (Garibaldi, 2017), including combined food and non-food systems. Ensuring food security (provision of sufficient, safe and nutritious food) and increasing the value of by-products, integrated systems could substantially reduce the climate and economic risks farmers face while deliver both food and non-food products in the same time (Bogdanski, 2012; Mullender et al., 2020). However, integration of food- and non-food production (IFNS) is not an easy task at the landscape scale. The questions arise, whether these systems enhance ecosystem services relative to conventional agriculture and what is their general impact at the local scale in terms of climate change complexities. Here we explore the potential of different kinds of IFNS systems (both modern type combining food and SRC wood production as well as traditional models producing bioenergy/bioproducts by smallholders in silvo-arable or silvo-pastoral systems) in delivering environmental benefits, focusing on preserving soil functions, especially food production.

The United Nations Food and Agriculture Organisation (FAO) estimates, based on a publication from the last decade, the global intensity of water erosion between $20 \cdot 10^9$ Mg and $200 \cdot 10^9$ Mg per year, with results exceeding $50 \cdot 10^9$ Mg per year considered as unrealistic (FAO, 2015).

The report by Jones et al. (2012) presents estimates of areas threatened by water erosion in the nineties at 105 million hectares – 16% of Europe (without Russia), while 42 million hectares are at risk from wind erosion. The results obtained in studies using various variants of the RUSLE (Revised Universal Soil Loss Equation) model indicate that approximately 17% of Europe's total land area is affected by erosion to varying degrees (Bittner et al., 2002), of which 92% by water erosion (EEA, 2003). New estimation of the risk of erosion in the model created in the JRC indicates 1.3 million km^2 of the EU-27 area affected by water erosion, while for almost 20% of this area, the erosion intensity exceeds 10 Mg per hectare per year (Panagos et al., 2015).

Accelerated soil degradation as a result of reduction of the humus level caused by erosion is considered for decades the main threat to agriculture and economy on a global scale (FAO, 2015). The rate of erosion on cultivated or intensively grazed soils is 100 to 1000 times faster than the formation of the humus level, which is well below 1 Mg ha^{-1} year^{-1} with a median of about 0.15 Mg ha^{-1} year^{-1} (FAO, 2015).

One of crucial factors affecting the intensity and extent of soil erosion by surface runoff remains the density and character of canopy cover, protecting the soil surface from the energy of elements, especially water and wind (Wischmeier, Smith, 1978; Jozefaciuk et al., 2014; Borelli et al., 2017). Agroforestry presents a high protective potential against soil erosion, providing protection arising from its permanent crop component – trees (Palma et al., 2007).

The paper aims at assessing the potential of chosen existing IFNS agroforestry farming systems to limit the intensity of soil erosion caused by water at regional scale, providing, that the chosen systems are economically sound and scalable at regional scale.

METHODS

Agroforestry systems under consideration

A network of representative integrated food and non-food agroforestry systems was identified in different socio-economic and environmental settings in Northern, Eastern and Southern Europe across countries and bio-geographical zones (Fig. 1). The network comprised of both traditional and innovative systems in which trees, crops and livestock are integrated in different ways and at different spatial scales (Table 1). All of the farms chosen for this exercise are well established, economically sound farm holds, that run agroforestry as their normal agricultural practise. Protective function of agroforestry was assessed using the method proposed by Palma et al. (2007) based upon the percent area covered by trees.

Spatial analyses

A spatial modelling approach has been used to assess the risks to soil productivity and soil functions caused by water erosion in NUTS3 regions, where chosen IFNS farms where located. The aim was to investigate the current extent of soil erosion by water as a reference and calculate the area that can be protected by the introduction of agroforestry, where agroforestry:

- can be easily introduced by means of low cost transformation from similar CORINE land use classes;
- can be introduced to all farming land.

Following spatial datasets were used in the estimation of the extent and intensity of soil erosion risk by surface runoff:

- Soil erosion risk by water (Panagos et al., 2015) as a raster dataset with 100 m resolution, EU-wide;
- NUTS3 regions dataset, vector layer;
- EEA Reference Grid, INSPIRE compliant (Annex 1, theme Geographical grid systems);
- CORINE Land Cover 2018, 100 m resolution.

The input datasets were harmonized by grid and coordinate system transformations in Quantum GIS into CORINE CLC 2018 grid corresponding to EEA Reference Grid in EPSG 3035 projection. Overlay analyses were performed in SAGA GIS and ArcGIS 9.2 using standard toll boxes and Python scripting.

Table 1. Network of agroforestry farms taken in the study.

IFNS category	Site location	Farm size	Country code	NUTS3 code
Combined food and energy production systems	Experimental farm Taastrup, Denmark	11 ha	DK	DK012
Multipurpose olive tree production systems	Muzzi Farm, Bagni village, Orvieto municipality, Italy	7 ha	IT	IT122
Silvopastoral systems	Elm Farm, Berkshire, United Kingdom	85 ha	UK	UKH14
	Mihalca Farm, Petrova Municipality, Romania	85 ha	RO	RO114
	Oikos farm, Sękowa, Poland	111 ha	PL	PL218
Silvoarable systems	Wakelyns Farm, Suffolk, United Kingdom	22.5 ha	UK	UKJ11

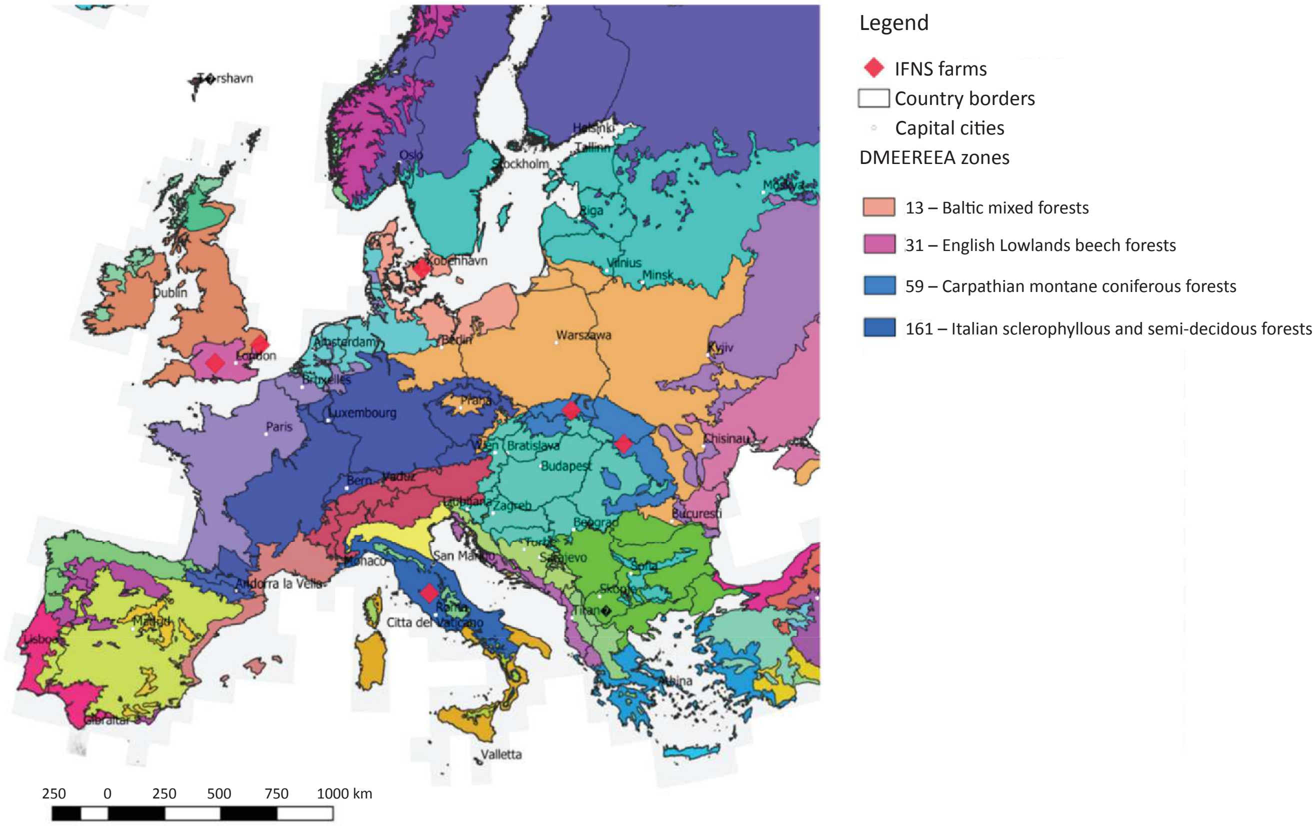

Figure 1. Chosen IFNS sites' location in ecological zones of Europe (DMEEREEA codes).

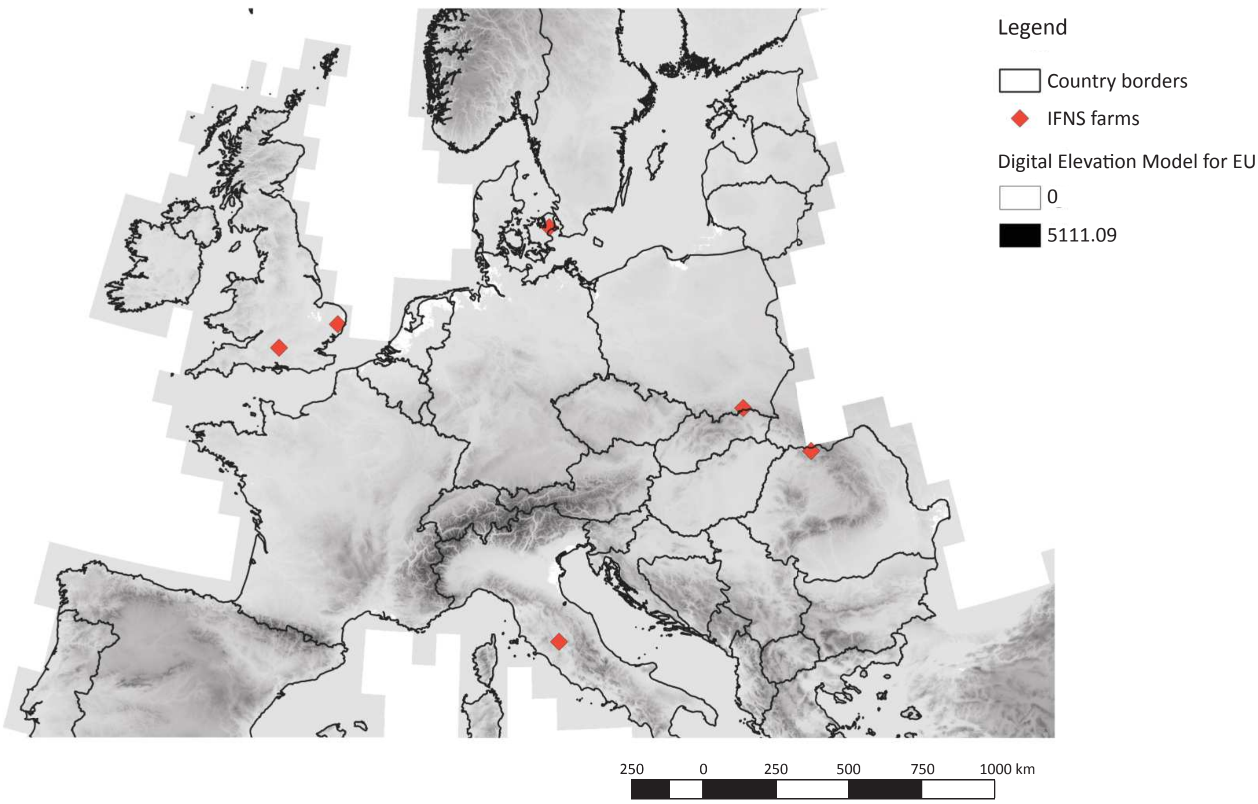

Figure 2. IFNS locations within EUDEM.

Additionally spatial analyses of terrain elevation, slope and aspect were conducted to emphasize the variability of landscape characteristics the chosen agroforestry farms are located. European digital elevation model (EUDEM) downloaded from the EEA was used to derive terrain features of the area where IFNS are located, providing an overview of the farming conditions in each of the case studies.

RESULTS

Topography

Six chosen IFNS are located within two different groups of landscapes: lowland flat landscape of United Kingdom (UK) and Denmark (DK) and highlands and mountains of Italy (IT), Poland (PO) and Romania (RO) (Fig. 2). The highest share of high terrain slope values are observed in Romania, then Italy and Poland (Fig. 3).

In highly diverse landscapes, especially those at high elevation, the terrain aspect tend to be a crucial terrain feature for agricultural activities, shaping evapotranspiration, soil temperature, water storage etc. The "hottest" terrain aspect is observed in Italian IFNS, while the "coldest" in Romanian and Polish IFNS (Fig. 4).

Risk of soil erosion by water in chosen IFNS and their regions

Soil erosion by water is one of the major threats to soils in the European Union, with a negative impact on ecosystem services, crop production, drinking water and carbon stocks (ESDAC, 2015). The European Commission's Soil Thematic Strategy has identified soil erosion as a relevant issue for the European Union, and has proposed an approach to monitor soil erosion (COM 46 (2012)). According to recently published study based upon RUSLE method utilizing input factors (Rainfall erosivity, Soil erodibility, Cover-Management, Topography, Support practices) from recently available pan-European datasets (Panagos et al., 2015) in high resolution of 100 m (Figure 5), the mean soil loss rate in the European Union's erosion-prone lands (agricultural, forests and semi-natural areas) was found to be 2.46 t ha^{-1} y^{-1}, resulting in a total soil loss of 970 Mt annually (Panagos et al., 2015). The study revealed 4 million hectares of croplands is under threat of severe soil loss rates of more than 5 t ha^{-1} y^{-1}, and to which policy measures should be targeted.

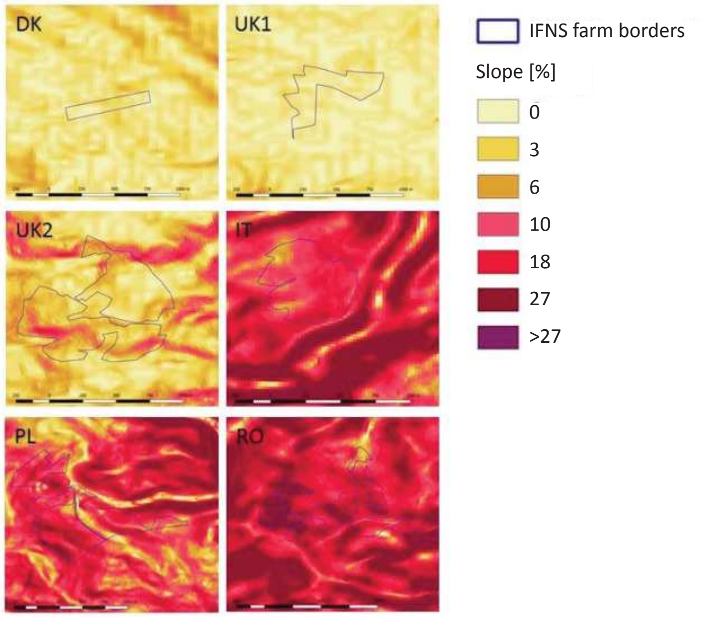

Figure 3. Terrain slope in IFNS case study landscapes.

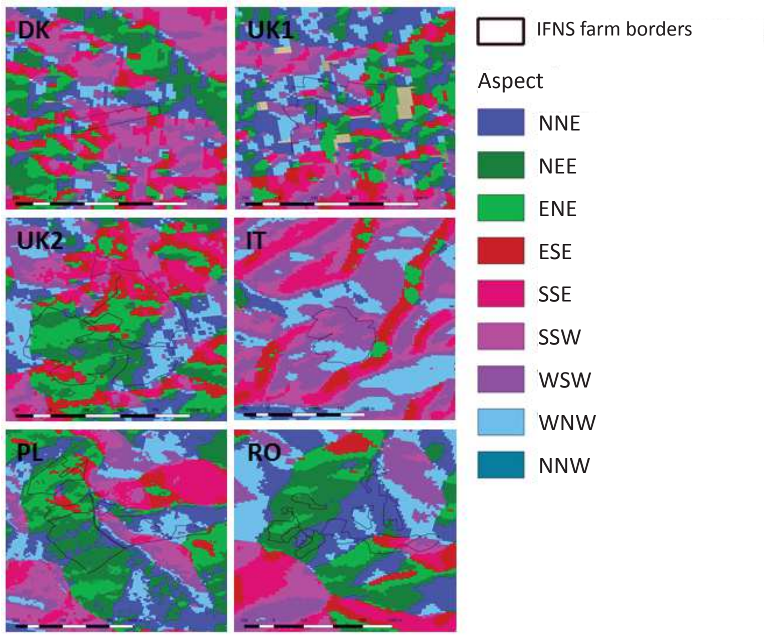

Figure 4. Terrain aspect in IFNS case study landscapes.

The IFNS and their regions differ considerably in each of soil erosion threat index (Fig. 6, Table 2), Italian IFNS is highly at risk of soil superficial erosion according to RUSLE (Panagos et al., 2015) due to its location in highly diverse terrain and soil susceptible to water erosion.

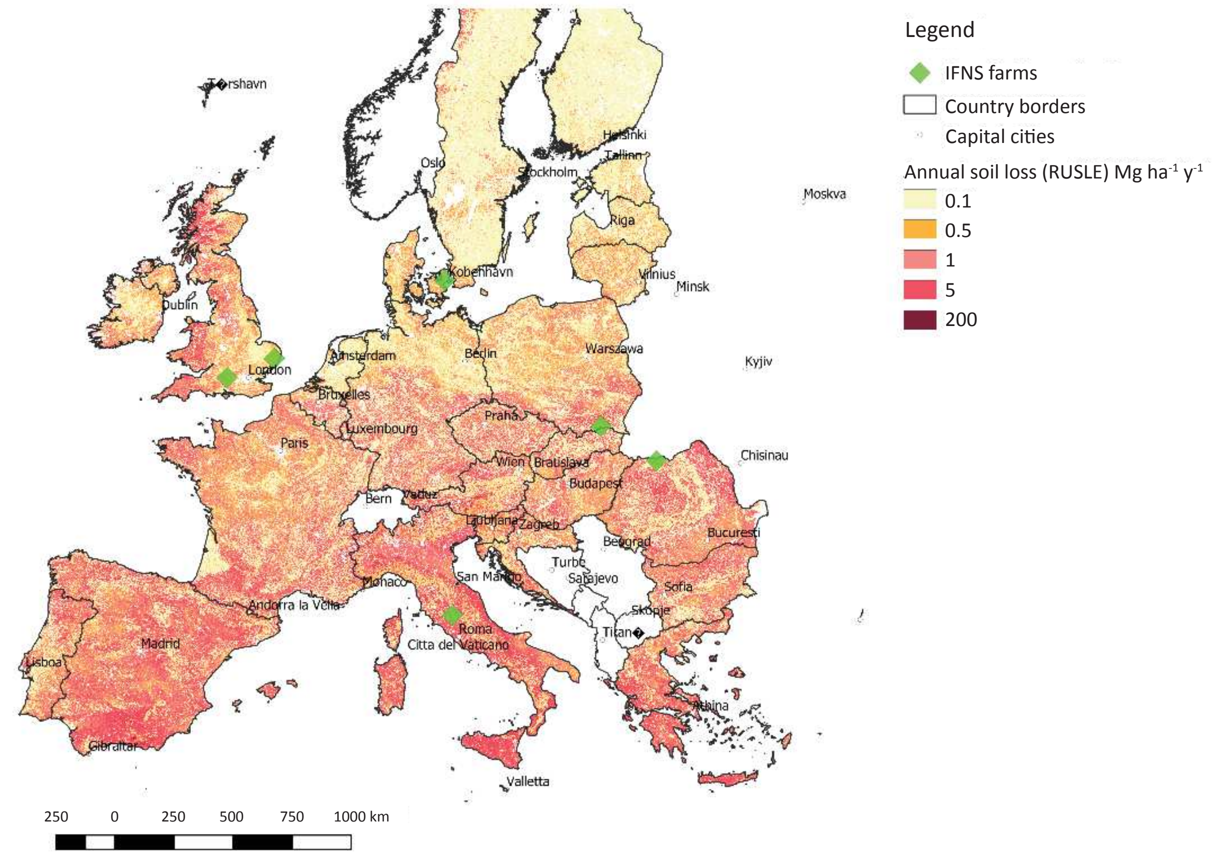

Figure 5. Soil loss by superficial water erosion (RUSLE, source: ESDAC) [Mg ha^{-1} y^{-1}].

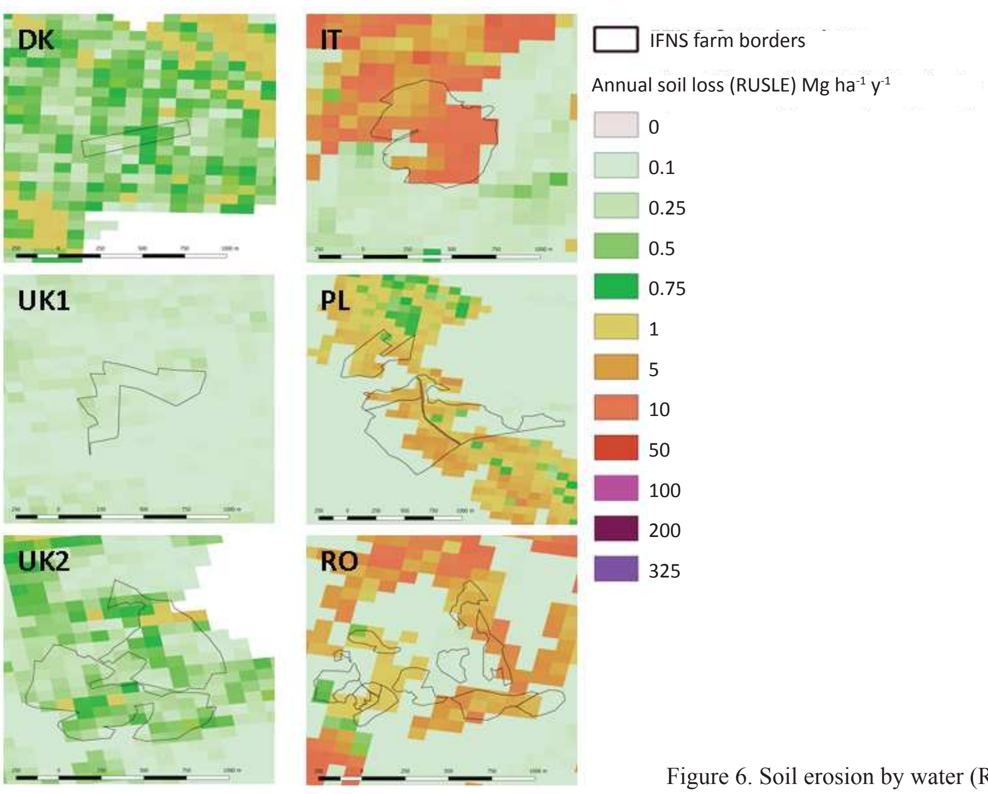

Figure 6. Soil erosion by water (RUSLE, source: ESDAC).

Table 2. Average soil loss by water in agricultural space for NUTS of chosen IFNS.

NUTS code	RUSLE [Mg ha^{-1} y^{-1}]		
	minimum	maximum	average
DK012	0.000	4.915	0.405
ITI22	0.000	200.000	8.410
PL218	0.000	200.000	4.078
RO114	0.000	138.975	2.127
UKH14	0.000	5.306	0.236
UKJ11	0.000	15.498	0.617

Agroforestry in limiting soil erosion by water

An important part of evaluating soil erosion risk by water with RUSLE model remains the canopy cover factor C and supporting practices P, that influence the final ratios of soil loss vastly. To estimate the soil loss reduction by agroforestry systems we used the method proposed by Palma et al (2007) of calculating a C-factor as a combination of crop-only C-factor and tree-only C-factor:

$$C = [\text{Covera Ca}] + [\text{Coverf Cf}]$$

where Covera and Coverf are the proportions of the total area occupied by the arable and forestry component, respectively (0–1), and Ca and Cf are the related C-factors for the arable and forestry component. Considering the characteristics of particular IFNS in terms of the ratio of canopy cover coverage and supporting practices (in terms of leaving crops residues on soil in a no-till soil preparation schemes) agroforestry schemes of chosen IFNS can limit soil loss by water even by 48% compared to typical farming practices characteristic for a given area and land cover type in particular NUTS (Table 3). We compared C factor estimates based on literature (CLC-lit), remote sensing (CLC-RS) and agroforestry (IFNS), characterised as an indicator of % tree cover (Palma et al., 2007).

Regional potential for agroforestry as soil erosion limiter

Analysis of the abundance of soil erosion risk in land cover classes from the CORINE land Cover 2018 datasets revealed a high potential of lowering erosion risk by applying the IFNS systems existing in each of NUTS regions under consideration. Table 4 summarizes the spatial overlaying of RUSLE soil erosion risk map and agricultural land cover classes in considered NUTS.

Altogether the highest potential of limiting the area of soil erosion exceeding 0,5 Mg $ha^{-1}y^{-1}$ by an IFNS existing in a particular NUTS is observed in Romania, where 531 km^2 may be protected effectively with exiting silvopastoral system, while applied in a longer term on non-pastoral land cover classes it could provide effective protection for another 1362 km^2. Second largest influence can be achieved in Polish NUTS regions, where 125 km^2 may be taken into protection directly and an another 1140 km^2 may be transformed into agroforestry systems to lower the risk of soil erosion by water. Although the NUTS region in Italy has the highest average soil loss rate, relatively low rates are observed on pastures and olive groves, the existing IFNS is consisting of, however the introduction of silvopastoral IFNS could still save 114 km^2 of soil with 106 km^2 being under severe soil erosion threat exceeding 5 Mg $ha^{-1}y^{-1}$. The highest risk is still observed on agricultural land with cereals and other seasonal crops. Olive orchard would be difficult to accept by the farmers on these lands but other agroforestry systems, that include cereals could be introduced, saving potentially up to 784 km^2. In all observed regions, a wide introduction of IFNS, that are already proven to be economically successful, would decrease soil loss considerably on existing land cover classes similar (marked in green on Table 4) to IFNS systems covering 4927 km^2, while potentially on an agricultural land up to 8854 km^2.

Table 3. USLE crop cover factor for chosen IFNS (following Palma et al., 2007).

NUTS code	IFNS type		CLC2018	C factor		
	type	% tree cover	Land cover class for main crop	IFNS	CLC-lit	CLC-RS
DK012	cereals/SRC	16	211	0.168	0.20	0.20
ITI22	olives/grass	48	223/231	0.118196	0.1–0.3	0.2273
PL218	trees/grass	20	231	0.07224	0.05–0.15	0.0903
RO114	trees/grass	20	231	0.07224	0.05–0.15	0.0903
UKH14	cereals/SRC	42	211	0.116	0.20	0.20
UKJ11	trees/grass	42	231	0.052374	0.05–0.15	0.0903

CLC-lit – C factor estimates based on literature; CLC-RS – C factor estimates based on remote sensing IFNS – C factor estimates for IFNS

Table 4. Soil erosion by water risk in regions of chosen IFNS farms (green indicates areas that can be easily transformed into agroforestry).

NUTS id	Soil loss	Non-irrigated arable land	Fruit trees and berry plantations	Olive groves	Pastures	Annual crops associated with permanent crops	Complex cultivation patterns	Land principally occupied by agriculture, with significant areas of natural vegetation
	Mg ha^{-1} y^{-1}	km^2	km^2	km^2	km^2	km^2	km^2	km^2
DK012	0.0–0.5	27.8	0.1	-	0.9			7.1
	0.5–1.0	22.8	0.1	-				2.3
	1.0–2.0	6.6	0.1	-				0.6
	2.0–5.0	0.9		-				0.1
	> 5.0			-				
ITI22	0.0–0.5	24.0	-	6.3	1.5	0.1	16.3	7.7
	0.5–1.0	6.4	-	0.1	0.1		1.8	1.0
	1.0–2.0	26.9	-	0.3	0.9		6.5	4.6
	2.0–5.0	90.6	-	3.1	3.6	0.3	27.3	18.2
	> 5.0	378.0	-	96.0	9.5	2.7	176.0	113.4
PL218	0.0–0.5	37.3	0.8	--	12.2		18.8	17.4
	0.5–1.0	17.3	0.5	-	12.1		16.6	11.4
	1.0–2.0	52.3	1.8	-	30.8		44.9	24.3
	2.0–5.0	155.0	8.7	-	55.0		121.6	107.1
	> 5.0	568.4	26.6	-	26.9		151.4	195.9
RO114	0.0–0.5	54.9	5.7	-	86.6		28.5	33.8
	0.5–1.0	86.3	6.0	-	33.8		11.0	16.0
	1.0–2.0	155.7	12.9	-	63.8		26.4	35.6
	2.0–5.0	179.1	38.8	-	186.1		98.5	77.7
	> 5.0	208.6	7	-	246.9		262.4	156.4
UKH14	0.0–0.5	2479.3	-	-	382.5		4.4	61.2
	0.5–1.0	260.6	-	-	20.8		0.1	3.9
	1.0–2.0	33.8	-	-	2.5			0.7
	2.0–5.0	1.9	-	-	0.1			
	> 5.0		-	-				
UKJ11	0.0–0.5	198.8	1.4	-	244.2			0.9
	0.5–1.0	124.8	0.1	-	63.3			0.1
	1.0–2.0	89.4		-	26.8			
	2.0–5.0	40.2		-	9.1			
	> 5.0	3.3		-	1.4			

The results indicated, that according to the land cover map of CLC 2018, the area of highly productive agroforestry can be increased in all of the NUTS3 regions under investigation. The effects of this transition could decrease the area of land exposed to soil erosion by surface runoff by 1092 km^2 – 1172 km^2 on arable land and by 2834 km^2 – 3656 km^2 on pastures, only on investigated NUTS3.

Humanity stands before a heavy challenge of sustaining growing population, while being exposed to climate change and land degradation (FAO, 2015). Growing interest and transformation of traditional and currently not effective farming practices into agroforestry, observed i.a. in India (Gupta et al., 2021) and Africa (NPC, 2017; Cheikh Mbow et al., 2014), already show high soil protection and at the same time – economical potential of this traditional yet till recently abandoned farming systems. FAO (FAO and ICRAF, 2019) treats agroforestry as a key farming systems in the quest to spread climate-smart agricultural practices across the world.

CONSLUSIONS

The aim of this paper was to investigate how much area can be easily turned from a traditional farming, practiced in a particular region, into an agroforestry system, that has been proven to provide enough income to sustain a farming family in the same region.

1. Our research confirms potential of protecting significant areas under the risk of soil erosion caused by surface runoff in chosen 6 NUTS 3 European regions, with a well-established and economically sound agroforestry systems. Those systems have advantages in decreasing soil erosion risk, maintaining good durable income for farmers and increasing landscape biodiversity and hence its resilience against stress factors, including climate change impacts.

2. Agroforestry systems that consist of arable land, present in Denmark and the UK, have the potential to be widely applied on non-agroforestry land cover classes: non-irrigated arable land and complex cultivation patterns, providing a potential protection against soil erosion by water for 58 km^2 in NUTS DK013 and 2776 km^2 in the UKH14 NUTS3 region.

3. Silvopastoral agroforestry systems, present in the regions of UKJ11, RO114, PL218 and IT122 could be relatively easily introduced into pastoral land cover classes with potentially good impact against soil erosion by water onto 16 km^2 in IT122, 137 km^2 in PL218, 490 km^2 in RO114 and 345 km^2 in UKJ11. Additionally in IT122 106 km^2 of olive groves may be easily transformed into silvopastoral systems analogue to the Muzzi farm, that was chosen as example for that region.

4. Land cover class of land principally occupied by agriculture with significant areas of natural vegetation has the potential to be transformed to agroforestry systems, however its suitability is hard to assess due to variability of the plant cover in various regions. Potentially it can be turned into productive agroforestry systems, which will be especially important in hilly and mountainous NUTS under consideration in Poland (203 km^2 under severe and very severe soil erosion risk), Romania (234 km^2 under severe and very severe soil erosion risk) and Italy (131 km^2 under severe and very severe soil erosion risk).

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